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Ph.D. thesis, 2004

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Abstract. The two-century period prior to the publication of Newton's *Principia* (first edition 1687; third edition 1726) was most important in terms of the radical changes that occurred in the observation, perception, and understanding of celestial objects that in turn spurred Newton to deduce his laws of gravitation and motion. Surprisingly, much of the available observational data embedded in contemporary texts from that two-century period has remained unused by modern astronomers, and this thesis (a) describes large amounts of data that were found and reanalyzed during the course of this Ph.D. research project, (b) places these data and their resulting analyses in context with the astronomy of the early-modern era, and (c) shows how modern astronomers and historians benefit from such information. The emphasis is placed here on west-European observations, as observations made elsewhere (eastern Europe, Asia) were isolated (not communicated for convenient rapid use by contemporary astronomers elsewhere) and did not develop or employ the level of precision that was utilized by western European astronomers through the extensive discussions that developed from correspondence and publication in Europe.

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2004

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List of Common Symbols

Below is a list of common symbols used in the text of this thesis, for the handy reference of the reader.

α = right ascension (equatorial coordinate)

δ = declination (equatorial coordinate)

λ = celestial longitude (ecliptic coordinate)

β = celestial latitude (ecliptic coordinate); rarely also used to denote phase angle

AU = Astronomical Unit

i = orbital inclination

e = orbital eccentricity

ω = argument of perihelion (orbital element)

Ω = longitude of the ascending node (orbital element)

T = time of perihelion passage

P = orbital period

a = size of orbital semi-major axis, usually in AU

q = perihelion distance, usually in AU

Δ = object's distance from the earth, usually in AU

r = object's distance from the sun, usually in AU

ϵ = elongation of celestial object from the sun in the sky

h = altitude of a celestial object above the horizon

UT = Universal Time

TT = Terrestrial Dynamical Time

ET = Ephemeris Time

$O - C$ = observed value minus the computed value

m_1 = total visual magnitude

m_v = visual magnitude

H = absolute magnitude

n = exponent of ($\log r$) term in power-law photometric equation

$H_{7.5} = H(n = 3)$ = absolute magnitude when $n = 3$

$H_{10} = H(n = 4)$ = absolute magnitude when $n = 4$

μ = proper motion of a star

V = Johnson V-band magnitude

Preface

My concept of a Ph.D. thesis is some original research that has some useful material, both in the way of ideas and in the way of conclusions. I entered into this doctoral research program at the University of Durham after having spent two decades doing research and archiving of astronomical data, including particularly data on comets and supernovae (the main focuses of this thesis). But it was only recently that I began to look at rare-book libraries beyond the rich collection at Harvard University (where I have been based since 1980), and by visiting such centuries-old library collections of astronomy books across Europe during the last several years for my thesis research, I have become fully aware of the immense amount of data in old books and manuscripts that have not yet been tapped for their astronomical/scientific potential. A rough summation of my time spent in rare-book libraries gathering data for this thesis yields a figure near 13 solid weeks looking at around 1100 tracts and manuscripts on comets and supernovae produced between the 15th and 18th centuries. This has given me great familiarity with the European literature on comets from the late-medieval and early-modern periods and has yielded much data not known to the modern astronomical community.[1] While I have thus far been able to access a good percentage of the relevant astronomical rare-book collections in the United States, England, and Germany, there are notable collections that I have yet to see (particularly in Rome, St. Petersburg, and Prague).

This thesis stems from research that focussed on observations of comets and supernovae made in the 16th and early 17th centuries. But the results necessarily complement (and supplement) data obtained on these objects since that time, especially including recent observations in the 20th and early 21st centuries. Future work will include additional analyses of comets in the target period as well as research into comets before and after this early-modern period. Archives of astrometric and photometric data for 20th-century comets that the author has helped to create and develop will be extended to include comets going back as far as is practical. As such, the work undertaken for this thesis falls well into the category "applied historical astronomy", which is the discipline within the Physics Department in which I have worked at the University of Durham.

When I started work on my Ph.D. research under Prof. Stephenson in 2001, he asked if I would kindly use the procedures that I was developing (for analyzing old cometary astrometry) on the supernovae of 1572 and 1604, which he was including in an updated book (published in 2002) on historical supernovae. I realized that this would be an interesting project that would

[1] It should be noted that, while east-Asian records of comets and novae go back more than two millennia, east-Asian positional data from the late-medieval (European) era are much inferior to the European observations (as shown at the end of Chapter 7 in this thesis). The east-Asian records of such objects do have other merits, including especially observability (and indeed sometimes the only record of the appearance of objects at all), but generally are not treated in this thesis.

help to tune my techniques for my historical comet work, and I eagerly took on what turned out to be an immense amount of work on the two supernovae, which now take up two chapters of the present thesis (one of which has already been published in slightly different form, and the other of which has been submitted for publication). It is also interesting to note that I have done my work on these supernovae exactly 400 years after the publication of Tycho's monumental tome on the 1572 *nova stella* and the appearance of the 1604 *nova stella*.

My plan for this Ph.D. project was first to refine my work on the 1577 comet (begun in the late 1990s during my Master's thesis work in the History of Science Department at Harvard University), and then to look at other comets observed by Tycho Brahe. During the course of the thesis research (which began formally in 2001), however, a couple of interesting comets were discovered that pushed me to change direction a bit, because they appeared to be possibly connected to comets seen long ago, encouraging an immediate look at (and analysis of) the older data to explore the establishment of any connections. Completion of work (begun here) on the remainder of the seven comets observed by Tycho and his assistants (along with other comets in the century centred on Tycho's career), therefore, will be undertaken in the years to come.

In my regular work at the Harvard-Smithsonian Center for Astrophysics, I am involved in the archiving and publishing of cometary photometry, astrometry, orbits, and ephemerides of currently observable comets (see Marsden, Green, and Williams 1994) — with the established goal of working back to collect data on older comets as time permits (the work prior to this thesis work having chiefly covered only 20th and some 19th-century comets). However, the reduction of comet observations prior to the 20th century is increasingly time consuming as one works back in time, because the standards now in place for reporting comet positions have changed over the years. A standard procedure that was widely (but often not) used since the time of Tycho Brahe was that of measuring (and recording) the distance of a comet (or new star, or planet) from nearby catalogued stars — and this procedure can be used by present-day astronomers to reduce data via modern star catalogues. Curiously, little work has been done in this area for many "old" comets until now.

I am also Director (since 2000) of the International Astronomical Union's Central Bureau for Astronomical Telegrams, which announces the discoveries of new comets, supernovae, novae, etc., to the astronomical community (and the world at large). So, when comet C/2002 C1 was discovered in February 2002, I was naturally engaged in looking at the early orbital analyses, which showed that it had a 'longish' short period. As per usual practice, we check our catalogue of cometary orbits to look for similarities of the orbital elements of new apparent or potential short-period comets with the orbital elements of past comets, and in this manner, the comets of 1532 and 1661 popped out as possibilities (and the orbital period was initially very uncertain). I proceeded to consult the old astronomical literature from the sixteenth century to extract as much data as I could on the 1532 comet, observed by Peter Apian and others in Europe. That decade was an important period in cometary astronomy (and, really, in astronomy in general) because of the appearance of five comets in the 1530s (including 1P/Halley in 1531) that attracted considerable

attention. This led to the establishment of more methodical standards in the observation of comets in particular and of astronomical objects in general, leading in important ways to the work of Tycho Brahe and others later in the same century.

As I was working laboriously through the 1532 data, it became clear (with the growing arc of observational data in 2002 of the new comet) that the orbit of comet C/2002 C1 (Ikeya-Zhang) had a shorter period and so could not be identical to the 1532 comet, but was more likely associated with the 1661 comet observed by Johannes Hevelius and others in Europe. So, I turned my attention to digging out what observational data I could find on the celestial positions of the 1661 comet from the contemporary literature. My reductions of these data allowed the 2002 comet to be definitively tied to the 1661 comet, and it was formally numbered 153P/Ikeya-Zhang (such numbering is done for comets observed at two or more returns to perihelion when their orbits are well established). While working to refine the work undertaken so far for this thesis, another new comet was discovered in January 2003 that turned out to have a much shorter period than the 341 years for comet 153P. The evidence began to suggest a possible identity of this P/2003 A1 with a comet observed by Edward Pigott and others over two centuries ago, an object now formally designated D/1783 W1. So I turned my attention to locating and reducing the astrometric data in the contemporary literature on Pigott's comet.

My work on these various comets — undertaken during my research for this thesis — are all described herein. They are all typical examples that reveal how modern, useful astronomical results can be extracted from the old literature. Each case provides slightly different techniques that need to be used to analyze data that are acquired in varying ways by the observers from different periods in astronomical history. Each step of the way, my techniques had to be revised for the particular case in question, and computer programs had to be written or modified to deal with issues particular to each case. Following contextual introductions to astronomical observation in the late middle ages, I outline procedures for analysis used to reduce the observations into data forms that are useful for modern astronomical assessment. Then I elected to order the analyzed astronomical subjects in general chronological (historical) order, partially to show how one must adjust the analytical process depending upon the techniques employed by the contemporary astronomers of each "era": addressing first the supernovae of 1572 and 1604 in separate chapters, and then the various comets that I have explored in the course of this research.

As with any Ph.D. thesis, one has to determine at some point where to stop writing and acknowledge that much more useful work will logically follow from what has been accomplished thus far. This task was particularly difficult in this thesis, but the compromise that now seems reasonable has been to show what great potential is available in the rare-book and manuscript library collections, to show the techniques that can be used to analyze that data, and to give some instructive examples of data reduction from these centuries-old sources that highlight their usefulness to modern astronomy.

Acknowledgements. There are many people for me to thank in my journey to finish this Ph.D., but first and foremost must be my parents (Dr. Lowell C. Green, and my mother, Violet E. Handahl Green), who so encouraged me in my dream to become an astronomer. I only wish that my mother had lived to see me finish this degree. Next has to be my first astronomy mentor and wonderful friend, Prof. Thomas L. Rokoske (Appalachian State University), who has never stopped urging me to finish this degree work.

I thank my second astronomy mentor, friend, "boss", and colleague of over more than two decades, Dr. Brian G. Marsden (Smithsonian Astrophysical Observatory), for giving me encouragement and opportunity, as well as advice on comets and historical matters as only he can give, with his encyclopedic knowledge of such things. It is a pleasure to acknowledge the advice and knowledge that I have gained from Prof. Owen Gingerich (Harvard University) over many years regarding historical astronomy. Both Marsden and Gingerich filled me with an interest in applied historical astronomy, and their enthusiam for detective work and for thoroughly examining references has enabled me to become a better scientist and historian.

Regarding computer-programming help, I thank Gareth V. Williams (SAO), Conrad Bardwell (SAO, now retired), and Syuichi Nakano (Sumoto, Japan) for sharing their valuable expertise with me and helping my meager computer programming to become better. I thank Mrs. Pauline Russell at the University of Durham, Department of Physics, for her patient and expert help in finishing off three figures used in this thesis.

I thank all at the Department of Physics, University of Durham, for being so kind and helpful to me. In particular, I thank my advisor, Prof. F. Richard Stephenson, for taking me on as the last of his many graduate students and for his wonderful support and advice. It would be hard to imagine a better Ph.D. advisor. Always appreciated has been the ongoing support and advice of John Steele, who was at Durham during my first two years there and with whom I have kept in touch. I thank Stephenson, Gingerich, and Dr. Paula Chadwick (internal examiner at Durham) for constructive commentary on the manuscript thesis.

I thank my wife, Lina, for her help with translating various old Italian passages about comets and novae, and for her overall encouragement. Also appreciated is the help with translating some old Latin from my son, Andrew (currently a student at Amherst College and a multi-Latin-award student). Brian Marsden has also lent his expertise in French to me when I have been stuck occasionally, and my Dad his expertise in reading some difficult German passages.

I also thank my many friends, colleagues, and other family members for their never-failing encouragement. This includes especially my three sisters (Kathy, Sonja, Barb) and my aunt, Carol Grender. Steve O'Meara has been a constant source of encouragement for me, as has Charles Morris. And many discussions with others have helped in the long road to finishing this thesis, including especially Prof. Kenneth Brecher at Boston University, but also Tim Spahr, Barbara Welther, John Chambers, and the late Alain Porter. I thankfully acknowledge the help and encouragement at the Harvard-Smithsonian Center for Astrophysics of Joan Jordan, Donna Thompson, Dan Collins and Bill Duggan, and the late Don Lautman. Others over the years who

have provided welcome encouragement include John Cannizzo, Michael Rudenko, Mario Motta, Bernie Volz, Charlie Sodini, Dan Grigg and family, Martha Gentry, Lori Heyl, and Veronica Passalacqua, — and I'm sure others to whom I apologize for not naming here.

And last, but certainly not least, I must acknowledge all the hard work done by the astronomical observers of our past, without whom I would not have a source for the wonderful information that underlies this thesis. The research and writing of this thesis occurred around the times of the 400th anniversaries of the death of Tycho (1601) and the appearance of the 1604 supernova; also, 300 years ago, Halley was hard at work preparing his first-ever catalogue of cometary orbits. It has been such a pleasure and inspiration to look not only at the many old printed volumes that were the results of much hard work by the authors (and artists, typesetters, and printers), but especially to hold the original handwritten manuscripts with observations and notes by such men as Tycho Brahe, Michael Maestlin, Isaac Newton, and Edmond Halley. Often I have wondered what it must have been like to have lived and observed in that late-medieval and early-modern era, and what it might have been like to have had a conversation about comets with such leading-edge astronomers. Opening the actual observing logbooks of Tycho, it is easy to imagine him sitting by candlelight, scribbling down the measurements and comments from his viewing the comet of 1577, for example.

Chapter 1.
Background: The Status of Comets in the Late Middle Ages

Several generalizations can be drawn from observations of comets that were made prior to the efforts at explaining them through the work of Tycho Brahe, Isaac Newton, and Edmond Halley : (1) comets were seen to be different from the planets via their motions on the sky and via their inexplicable and sudden appearances and disappearances; (2) comets were often and even generally seen in an astrological sense, in that they influenced (for better or, usually, for worse) the activities of mankind; and (3) comets were often linked with meteors, though both were phenomenena that were beyond certain explanation. Because of these perceptions of comets, it is important to understand all this in the context of observations being made in the late middle ages and early-modern era — the focus period for observations analyzed in this thesis.

1.1. Comets in Ancient European Philosophy

In Europe, no single influence had a greater impact on cometary thought over more centuries than did Aristotle, who viewed comets as part of the terrestrial atmosphere and thus placed his discussion of them in his *Meteorologica*, together with shooting stars, aurora borealis (*cf.* Heath 1966, p. 243), and the Milky Way. Aristotle reviewed the theories of those who preceeded him, including Anaxagoras, Democritus, the Pythagoreans, Aeschylus, and Hippocrates of Chios — the last three of whom viewed comets as "one of the planets" (*Met.* I.VI, Lee 1952, p. 41). Aristotle objected to this planetary theory on the grounds that comets are seen to move far from the ecliptic, the path of the planets.

Aristotle visualized an "outer part of the terrestrial world, that is, of all that lies beneath the celestial revolutions, . . . composed of a hot dry exhalation", and it is from this region that a comet is born:

> *Now when as a result of the upper motion there impinges upon a suitable condensation a fiery principle which is neither so very strong as to cause a rapid and widespread conflagration, nor so feeble as to be quickly extinguished, but which is yet strong enough and widespread enough; and when besides there coincides with it an exhalation from below of suitable consistency; then a comet is produced, its exact form*

depending on the form taken by the exhalation — if it extends equally in all directions it is called a comet or long-haired star, if it extends lengthwise only it is called a bearded star.[2]

Aristotle talked much about the fire of a comet, a theme that would continue for many centuries thereafter in discussions on comets:

> *. . . for the course of a shooting star is similar in that because the fuel is suitable [the fire] runs quickly along it. But if the fire were not to run through the fuel and burn itself out, but were to stand still at a point where the fuel-supply was densest, then this point at which the fire stops would be the beginning of the orbit of a comet. So we may define a comet as a shooting star that contains its beginning and end in itself.*

Aristotle links comets, via their dry exhalations, to wind and drought (Lee 1952, p. 55): "*We may regard as a proof that their constitution is fiery the fact that their appearance in any number is a sign of coming wind and drought.*" The air becomes drier, he continues, because "*the moist evaporation is disintegrated and dissolved by the quantity of the hot exhalation so that it will not readily condense into water.*"

Schechner Genuth (1988, p. 29) states that the poem *Astronomica* by Marcus Manilius, originally written between 9 and 15 AD, was "an agent for transmitting classical views on comets to the west", being "widely read throughout the Middle Ages and Renaissance". While adhering to Aristotle's placement of comets in the terrestrial atmosphere, Manilius modified that view:

> *For there are fires born at infrequent intervals and forthwith swept away. In times of great upheaval rare ages have seen the sudden glow of flame through the clear air and comets blaze into life and perish. Maybe the earth breathes forth an inborn vapor, and this damper breath is overpowered by an arid air; when clouds are banished for long periods of clear weather so that the air grows hot and dry under the rays of the sun, fire then descends and seizes its apt sustenance and a flame takes hold of the matter that suits its nature; and since there is no solid body, but only the wandering elements of the breezes, tenuous and most like to drifting smoke, the action is short-lived and the fires last no longer than the moment of their beginning: the comets perish as they blaze.*[3]

As Goold notes here in a footnote, Manilius seemingly "confuses comets, which are not of momentary duration, and shooting stars, which are." This is despite the fact that, later (*Astron.*

[2] *Met.* I.VII, as translated by Lee 1952, p. 51.

[3] *Astronomica*, 1.813*ff*; quoted from Manilius and Goold 1977, p. 71.

1.847-851), the poet relates: *"There are also shooting stars, which hurl long trails of slender fire and are seen flying everywhere, when wandering lights flash through the clear sky, and dart afar like winged arrows, tracing the slender line of a path on high"* — after which he likens the fire of comets and meteors to that of lightning and *"the [volcanic] flames of Etna"* (Manilius and Goold 1977, p. 73).

In view of what was known about comets, contemporary observers must have wondered what their eyes were showing them; as Hahm (1978) says, "we know that there was hardly a philosopher or scientist during [the century after the death of Aristotle] who did not write one or more treatises on vision, the senses, mirrors, or some other aspect of the science of vision." Smith (1990) notes that there was a distinction between "philosophical vision" ("rooted primarily in Platonic, Aristotelian, and Stoic doctrine"), "medical vision", and "mathematical vision" in Hellenistic times. This distinction in vision may be important for understanding how the ancients perceived comets, and why. Comets did not seem to do as the planets and other celestial objects did, so were they mirages (as implied by one associated Babylonian word[4]) or mirror images of something? Their mysterious nature contributed to their occult qualities.

Lucius Annaeus Seneca (*ca.* 4 BC-65 AD) wrote a book on comets in his *Natural Questions* that provided scathing criticisms of the comet theories of the preceding centuries. He begins,

> *It will be worth while in this investigation to inquire whether comets have the same nature as the planets and stars . . . A comet seems to have certain things in common with them: rising and setting, the same appearance, although a comet is scattered and extends farther. It is also fiery and bright. And so, if all planets are earthy bodies, comets will also have the same condition.*[5]

Seneca thus elevates comets from the terrestrial atmosphere into the celestial realm. Attacking Aristotle, he says:

> *For I do not think that a comet is just a sudden fire but that it is among the eternal works of nature. First of all, all things the atmosphere creates are short-lived, for they are produced in an unstable and changeable element. How can anything remain the same for long in atmosphere when atmosphere itself never remains the same for very long? . . .*
>
> *Furthermore, fire either goes where its own nature leads it, that is, upwards, or in the direction that its fuel attracts it, to which it clings and on which it feeds. None of the ordinary fires in the sky has a curved*

[4] the Assyrian word *sallummû*, which may refer to a mirage, a comet, a meteor, a meteorite, or a fireball; cf. Hunger 1992, p. 335; Reiner and Pingree 1981, p. 19

[5] *N.Q.* VII, 2.1, via Corcoran 1972, p. 231.

> *path. It is characteristics of a planet to follow a curve. And yet did other comets do this? I do not know. The two in our time did.*[6]

Natural Questions also disputes that comets are related to "a Torch", "lightning bolt", or "a shooting star" (Book VII, 23.3). Seneca disagrees with Aristotle's assessment on cometary influence, but does not disagree that comets are omens: "*. . . the rising of a comet does not immediately threaten wind or rain, as Aristotle says it does, but makes the entire year suspect.*"

Again following Aristotle, Ptolemy (*ca.* 100-175 AD) clearly viewed comets as being part of the earth's atmosphere, and declined to even mention them in his *Almagest.* In his *Tetrabiblos*, Ptolemy provides a bit of a "recipe" for dealing with comets in astrological predictions:

> *Of occasional phenomena in the upper atmosphere, comets generally foretell droughts or winds, and the larger the number of parts that are found in their heads and the greater their size, the more severe the winds. . . We must observe, further, for the prediction of general conditions, the comets which appear either at the time of the eclipse or at any time whatever; for instance, the so-called 'beams', 'trumpets', 'jars', and the like, for these naturally produce the effects peculiar to Mars and to Mercury — wars, hot weather, disturbed conditions, and the accompaniments of these; and they show, through the parts of the zodiac in which their heads appear and through the directions in which the shapes of their tails point, the regions upon which the misfortunes impend. Through the formations, as it were, of their heads they indicate the kind of the event and the class upon which the misfortune will take effect; through the time which they last, the duration of the events; and through their position relative to the sun likewise their beginning; for in general their appearance in the orient betokens rapidly approaching events and in the occident those that approach more slowly.*[7]

Robbins (1940, p. 193, n. 4) observes: "Other astrologers and . . . writers classified the comets much more elaborately by their shapes and their associations with the planets, of which they were supposed to be the fiery missiles; Ptolemy is much more conservative in what he says." Robbins also notes (p. *x*) that "the *Tetrabiblos* enjoyed almost the authority of a Bible among the astrological writers of a thousand years or more"; given the link between astronomy and astrology through ancient and medieval times, and the powerful longevity of Aristotle's and Ptolemy's writings, it should not be surprising that Tycho had to work hard to convince his readers that the bright comet of 1577 was further away than the Moon (Hellman 1944).

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[6] *N.Q.* VII, 22.1 and 23.1, via Corcoran 1972, p. 273.

[7] *Tetrabiblos* II.9.90-91, II.13.102; quoted from Robbins 1940, pp. 193-195, 217.

1.2. Some Recent Naked-Eye Comets: Understanding What the Ancients Saw

Seneca wrote: *"Apollonius says that the Chaldaeans place comets in the category of planets and have determined their orbits"* (*Natural Questions* VII, 4.1, via Corcoran 1972, pp. 233-235). Though some ancient observers evidently considered comets to be like planets in their nature and motion, it is easy to see why they would not be so considered. The recent comet C/1996 B2 (Hyakutake) shone with a brilliance rivaling the brightest stars (total visual magnitude, $m_1 \simeq 0$) for northern-hemisphere observers around 1996 March 25, when it passed some 0.10 Astronomical Unit[8] from the earth, but the comet rose quite rapidly in brightness in the preceeding two weeks from faint naked-eye visibility, a factor of nearly a hundred in brightness (see Figure 1.1).

An even more rapid increase in brightness in a naked-eye comet occurred in May 1983, when comet C/1983 H1 (IRAS-Araki-Alcock) rose by about the same brightness factor (from the limit of naked-eye visibility to total visual magnitude $m_1 \simeq 1.5$, or slightly brighter than the second-magnitude stars of the Big Dipper) in the span of only a week (Marsden and Green 1983). Comets that go quite close to the sun tend to have highly elliptical orbits that translate into such comets becoming visible quite suddenly from the solar glare or twilight, then fading quite rapidly due to faint absolute brightness and/or to disruption or disintegration of the cometary nucleus. In ancient and medieval times, without optical aid and without ephemerides for projecting future movements of comets, a period of several cloudy days followed by clear skies in such a case as C/1983 H1 would have the effect of a "sudden" appearance of a comet.

But one does not need the close approaches to the earth — as happened with both comets C/1983 H1 and C/1996 B2 noted here — for a "sudden appearance". Comets are known, for unexplained reasons, to have significant outbursts (and decreases!) in brightness over 1-2 days, on the order of 1 to even 5 magnitudes. Comet 41P/Tuttle-Giacobini-Kresák rose some 10 magnitudes in total brightness in less than one week in late May 1973, reaching visual mag ~ 4 (Marsden 1973). The distant comet 29P/Schwassmann-Wachmann (which never now reaches naked-eye visibility), has many significant outbursts on a frequent basis — as many as 2-3 times per year.[9] Also, moonlight can have an effect that causes comets to appear to suddenly brighten when a bright moon suddenly moves out of the sky (*e.g.*, Morris 1980), with the coma (and possibly tail) that was hidden by a bright sky background coming into "sudden" view. Comets that go very near the sun, such as 96P/Machholz (*e.g.*, Green *et al.* 1990) or the Kreutz family of sungrazing comets (which, as members of at least one very large original comet that broke apart, have been appearing occasionally as extremely bright objects — sometimes rivalling the moon in apparent brightness — for at least a millennium or two; Marsden 1967, 1989), are known to undergo very rapid increases in brightness when near the sun — as is readily visible in even a cursory perusal of my recent publication of SOHO spacecraft data (Beisecker and Green 2002). And from data gained via wide-field photographic searches for comets in the past few decades, there is a strong

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[8] or about 15 million km

[9] The exact physical mechanisms leading to outbursts are not clear (*e.g.*, Sekanina 1991, p. 792; Hughes 1991).

suggestion that many comets brighten 1-3 magnitudes (or more) in the several days immediately prior to discovery.

The splitting of comets into two or more pieces is now known to be rather common (see reviews by Sekanina 1982, 1997; Whipple and Green 1985, pp. 171ff; Kresák 1986, 1987). The general tendency in such cases is for an initial brightening and then a fading to below the original brightness level for the primary (or largest) component (*e.g.*, Meech *et al.* 1995), with secondary components usually disappearing after one or two returns to perihelion in the case of short-period comets. Comet C/1975 V1 (West) is a famous recent example of a comet that broke into four notable fragments that caused a 2-magnitude increase in brightness, producing one of the most impressive comets of the past century visually (*e.g.*, Milon 1976). But comets are also very prone to fading, sometimes very rapidly — and sometimes completely falling apart or disappearing (*e.g.*, Whipple and Green 1985, pp. 82ff). Even rather bright comets have been seen to fall apart rapidly and fade away in a matter of just a few days.[10]

This partially explains why ancient and medieval astronomers had a difficult time following the progression of cometary apparitions with their limited naked-eye viewing, which resulted in 'stunted' overall observational arcs for many (if not most) comets, leading to inferences of sudden appearance in such statements as this one by Manilius:

> *So wonder not that torches suddenly burst forth from the skies; and that the air is kindled and shines with flickering flames after embracing the dry seeds exhaled by the earth, seeds which the swift fire, as it feeds, both pursues and shuns, for you see the lightning hurl its quivering flash from the midst of a rainstorm and the heavens rent with the thunderbolt. Possibly it is the principle of earth supplying seed for fleet fire which has given birth to comets; or perhaps in those torches nature has created dim stars that shine in heaven with meagre flames .* . .[11]

Comets reach $m_1 = 0$ a few times each century, but when comets do become that bright, they are usually rather close to the sun in the sky (elongations generally $\epsilon < 40°$ from the sun, where $\epsilon \lesssim 30°$ essentially represents a twilight object[12]). Comet C/1996 B2 (Hyakutake) was unusual in its reaching peak brightness around $m_1 = 0$ while visible nearly overhead for observers in middle-northern-hemisphere latitudes (see Figure 1.1). The ancient astronomers noted the propensity of

[10] Recent examples of fairly bright comets disintegrating include comets C/1999 S4 (*e.g.*, Sekanina 2000; Kidger 2000a, 2000b; Weaver 2000) and C/2002 O4 (*e.g.*, Sekanina 2002).

[11] *Astronomica* 1.859-868, quoted in Manilius and Goold 1977, p. 73.

[12] Actually, astronomical twilight begins when the sun is 18° below the observer's horizon, but atmospheric extinction at sea level for an object within 12° of the horizon rises rapidly from 1 magnitude at 12° to 5 magnitudes at 2° (*cf.* Green 1992a). Thus, a comet of mag 0 that is 5° above the horizon in a dark sky will not necessarily appear conspicuous to the naked eye.

observed comets 'statistically' to be near the sun in the sky, as exemplified by Manilius' remark:

> *. . . but the Sun with its consuming heat attracts the blazing comets to itself, absorbs them in its own fire, and then releases them; just so do the orb of Mercury and the planet Venus, when she kindles her evening lamp and brings on night, oft disappear and elude our gaze and oft visit us again.*[13]

And we read in Seneca:

> *We do not see many comets because they are obscured by the rays of the sun. Posidonius reports that once during an eclipse a comet appeared which the nearness of the sun had concealed. Moreover, often when the sun has set, scattered fires are seen not far from it. Obviously the comet itself is blanketed by the light of the sun and so cannot be seen, but the tail escapes the sun's rays.*[14]

[13] *Astronomica* 1.869-873, quoted in Manilius and Goold 1977, pp. 73-74.

[14] *Natural Questions* VII, 20.4, as quoted in Corcoran 1972, p. 269.

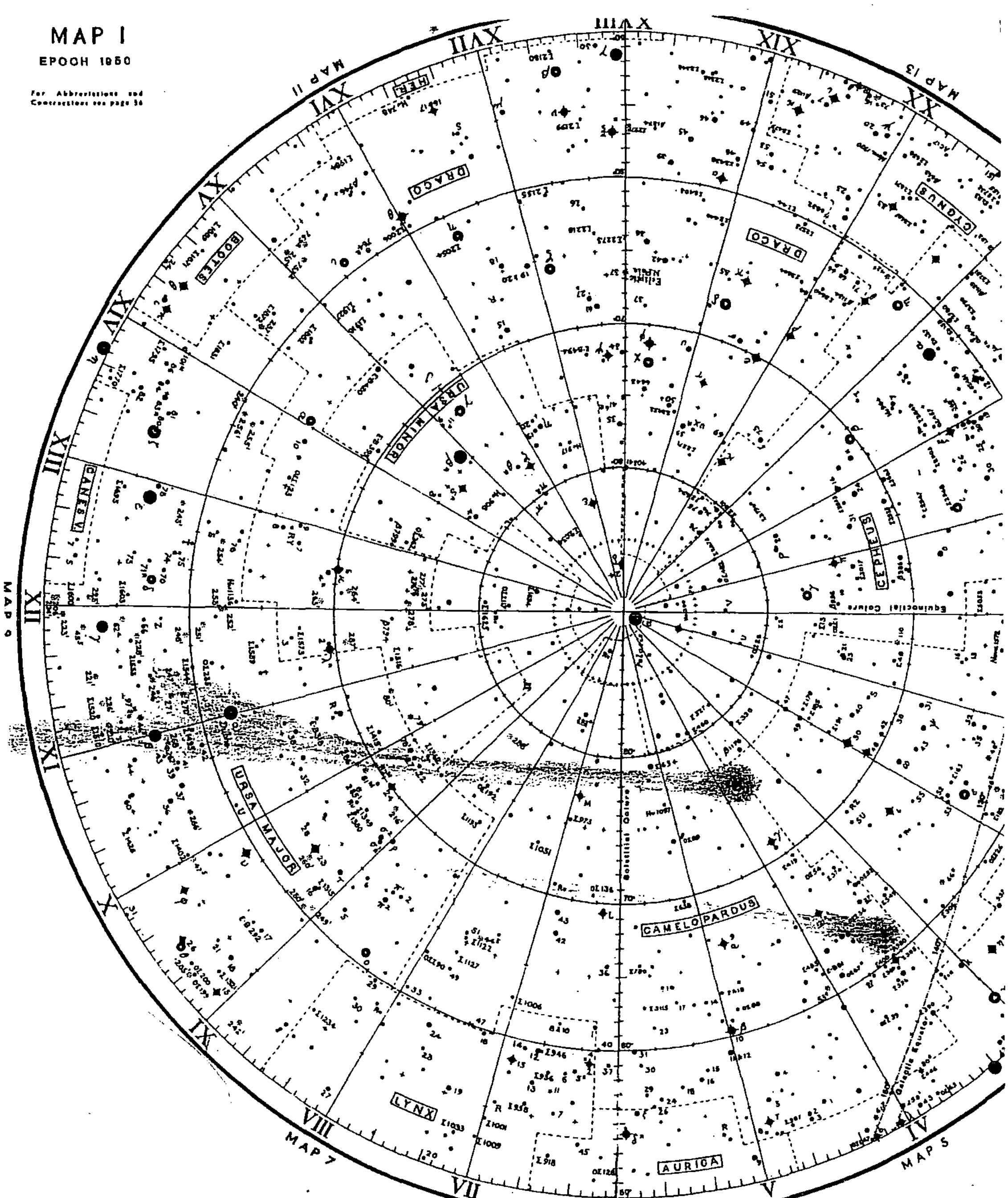

Figure 1.1. Figures of comet C/1996 B2 drawn by Dan Green (onto photocopies of an old Norton's Star Atlas), showing its naked-eye appearance and motion on 1996 Mar. 28.25 UT (longer tail) and again a couple of nights later (with short tail). Compare with Figure 8.9.

1.3. Ancient Influence Through the Middle Ages

The view of comets as fiery exhalations in the earth's atmosphere was to predominate in Western thought from ancient times well into the sixteenth century. Understanding this ideology is important for understanding the mindset of observers who reported observational data on the subjects of this thesis (comets and supernovae) and for understanding the context and sources of uncertainty in the measurements. Observers apparently saw no reason to make observations of comets, in terms of positions on the sky as a function of time, because there was no valid point in expending such effort on mere short-lived atmospheric phenomena. After all, what useful purpose could any positional measurements of these atmospheric comets possibly have? When Edmond Halley later found that most historical observations were unsuitable for orbit computation, he remarked that "the observations were made neither with sufficient instruments, nor due care, and on that account are disagreeing with themselves, and can by no means be reconciled with a regular computus" (Halley 1752, p. Oooo2) — adding that "no body thought it worth while to take notice of, or write about, the wandering uncertain motions" of comets (*op.cit.*, p. Llll3).

This manner of thinking extended to the "new stars" that occasionally appear as naked-eye objects in our skies — mostly objects that we now call novae or supernovae. In the Aristotelian ideology, the heavens were perceived as perfect while terrestrial matter was not, so that unpredictable apparitions such as comets, novae, and supernovae had to be associated with the earth's atmosphere — and novae and supernovae tended to be considered as types of comets by many Europeans in late medieval and even early-modern times. Comets and novae thus "fit in" with fireballs, meteors, and aurorae as parts of the atmosphere, and they were all treated similarly by observers and chroniclers of the skies throughout the Middle Age — indeed with the distinctions between the various categories of object being often blurred, so that modern researchers are not always sure of what type of object was being discussed. As Barry Hetherington (1996) has perceptively stated, medieval observers did not understand exactly what it was that they were observing when they saw a comet or a bright meteor or the northern lights, so it can be difficult to know how to describe such an event, especially without a firm grasp of defined nomenclature. How many monastic chroniclers, for example, really knew the terms for these phenonomena and how to differentiate between them — and where/how would they have learned this information? Even in modern society today, people often confuse comets with meteors. Indeed, I was contacted a few years ago by a large U.S. advertising agency because they were producing a television commercial in which two people facing each other were conversing at night, during which time a meteor flashed behind the person facing the camera. The person facing the meteor, upon seeing it flash by in a second or two, exclaimed that his companion had just missed seeing Halley's comet and would have to wait another 75 years. Somebody at the ad agency had expressed concern that this might not be an appropriate portrayal of Halley's comet, and so I was called. Though I explained that this was indeed an inappropriate way to depict a comet, the agency wanted a big "name" like 'Halley's comet' to catch the audience's attention, and they eventually went with the original idea!

Although several bright novae or supernovae were recorded in the millennium or two prior to 1572 — mostly in east-Asian annals — European records of such "new stars" are rather scarce, despite a relatively large number of eclipse and comet records from Europe through the Middle Ages (Clark and Stephenson 1977, 16*ff*). This fact can probably be explained largely by noting that east-Asian astronomers were more regularly observing the sky, while Europeans evidently had ceased doing so after Antiquity; thus, unless a nova or supernova was exceptionally bright (that is, approaching or exceeding the visual brightness of the brightest planets, Jupiter and Venus), a stellar object can easily go unnoticed to those who do not regularly look at the stars at night. Astronomy was largely lost to Europeans during the early to middle medieval period — with the exception of the important task of maintaining the calendar, including especially the tabulation of the dates of Easter — so that regular observation of the heavens fell into oblivion for centuries. The chief astronomical records in Europe during most of the middle ages (certainly until about the 12th or 13th century) were the monastic chronicles, in which eclipses, comets, and sometimes aurorae and meteoric fireballs were semi-regularly recorded (though usually with very little detail).

As Stephenson and Clark (1978, pp. 6*ff*) have remarked, little was done in the way of actual astronomical observations by medieval writers of tracts regarding *any* celestial phenomena; such writers tended to be speculative or cosmological in their scope. One must generally turn to the monastic and town chronicles after about 1000 AD in order to find potentially useful qualitative reports of celestial events such as eclipses and comets (and, to a lesser extent, bright meteors).[15] We thus see a very large gap of about a millennium between the work of Ptolemy and the sources where other Europeans set down qualitative celestial observations (with limited exceptions, such as a record of the solar eclipse of 733 August 14 from northern England; *cf.* Stephenson 1997, p. 422). One interesting aspect regarding the existence of medieval chronicles, as noted by Stephenson and Clark (*op.cit.*), is that "most of the records come from England, France, Germany, and Italy, where the concentration of monasteries was highest"; it would be these same countries where the scientific revolution would begin as the medieval era gave way to the early-modern era, and these same countries would also be the sites of the first scientific academies — probably not a coincidence.

The Milky Way supernova of 1054 was visible in broad daylight, as bright as Venus at peak brightness, according to the Chinese annals, but there are no extant European records of this object. The brighter supernova of 1006 was recorded in two European monastic chronicles, Benevento and St. Gallen, but knowledge of this seems not to have been available to the sixteenth-century astronomers who viewed the new star in Cassiopeia. Thus, nothing definitely perceived as being beyond the moon was ever seen to "suddenly appear", in the traditional knowledge of European society in 1572. The "highest" objects above the earth perceived as suddenly appearing and disappearing were comets. Indeed, many people who saw the new star in 1572-1573 did not even

[15] See also Vyssotsky 1949 and Kronk 1999 on the problems of astronomical records associated with old European manuscripts.

think to compare it to any other class of celestial bodies other than comets (Dreyer 1890, p. 43).

It is most interesting that the 1577 comet, which was intrinsically one of the brightest seen in the past millennium,[16] appeared only five years after one of the few Milky Way supernovae visible in the past thousand years. That brilliant new star appeared in Cassiopeia in November of 1572, remaining visible to the naked eye for 18 months. Tycho Brahe reported that the new star was as bright as the planet Venus for about three weeks from his first sighting of it on November 11 (Dreyer 1890, p. 41), after which time it slowly faded. Philip Apian (son of Peter) and many others who saw this star considered it to be a comet (*e.g.*, Hellman 1944, p. 111), but its comparison to comets can hardly be considered surprising.[17]

Tycho and many other contemporaries did note that the new star of 1572 could not be a comet because it had neither the appearance nor motion exhibited by comets. In the twentieth century, the new star of 1572 has been recognized as a supernova in our own Milky Way galaxy (*e.g.*, Clark and Stephenson 1977, pp. 172*ff*). Indeed, Tycho was unusual in that he became "appalled by the general incompetence of the accounts and distressed by assertions that the star [of 1572] was a comet as close as twelve to fifteen earth radii away" (Thoren 1990, pp. 63, 69). This supernova certainly served to prepare astronomers for the bright comet five years hence. In England, Thomas Digges published a 1573 tract on the new star (titled *Alae seu Scalae Mathematicae*) that included "a plea for the use of the experimental method in astronomy". In this tract, he emphasized the importance of compiling large bodies of careful observational data of various celestial bodies "in order to determine experimentally a true system of the universe, or to verify or correct the Copernican theory" (Hellman 1944, pp. 112-113); Digges thus foreshadowed similar general scientific pleas by Francis Bacon a few years later. As we shall see, observers such as Maestlin and Tycho drew on their experiences in measuring the position of the 1572 supernova.

Though very rough positional measurements of comets were recorded in Asian annals[18] through the European Middle Ages, many comets appear to have been largely ignored by Western scribes from the end of ancient times up to the fifteenth century (as a perusal of Kronk 1999 will show). Certainly there were some comets mentioned in Western medieval records, but such sources tend to lean towards astrological speculation, yielding little in the way of qualitative measurement or serious contemplation about the physical nature of comets. Prior to the fourteenth and fifteenth centuries, for example, observations of comets had been primarily limited to discerning that various comets merely differed in their appearances, leading to various attempts either to confirm or revise ancient classifications of comets according to type of tail and perhaps to coma

[16] as ascertained from the listing of "absolute" magnitudes by Vsekhsvyatskij (1964).

[17] And, indeed, the first two sun-orbiting planets to be discovered after the invention of the telescope — Uranus in 1781 and (1) Ceres in 1801 — were both initially considered to be comets in the absence of other obvious possibilities for new moving objects (*e.g.* Forbes 1971; Green 1995b).

[18] See the catalogues of Kronk (1999), Ho (1962), and Hasegawa (1980) as illustrations of this. Yau (1988, Appendix III) provides a useful "Catalogue of Possible Novae and Supernovae from Far Eastern Sources" that also shows the rough locations given for celestial objects in ancient and even "early-modern" Asian records.

size and degree of condensation. The classification was often (if not generally) tied in to determining astrological influences that a given comet might portend. Comets' celestial positions were only given in the vaguest terms — sometimes visible from a given geographical location, sometimes in a certain direction in the sky (*e.g.*, "in the west"), in a given month and/or year, sometimes with a duration given in days or months. Though Geoffrey of Meaux recorded positional observations of the comets of 1315 and 1337 (Thorndike 1950, pp. 208, 219; Jervis 1985, p. 31), few other attempts were taken to improve available information on comets for another century or two. Halley (1705a, b) was able to compute an orbit for the comet of 1337 from the observations — the earliest comet for which he had enough qualitative data to enable such a calculation.

1.4. Late Middle Ages

Medieval European thinkers were preconditioned to their view of comets from the accepted Aristotelian and scholastic mindframe. Without some sort of systematic manner of observing and recording cometary phenomena, astronomers could not much advance their knowledge of these objects. Medieval and early-modern observers were necessarily affected by the Aristotelian concept of comets as atmospheric phenomena. As Ludwig Fleck (1979) has said, "even the simplest observation is conditioned by thought style and is thus tied to a community of thought"; one had to apply radical approaches to observation and thought to view comets in a different way than had been done for so many centuries. As we saw, the vocabulary and prevailing thought style would cause many to view the supernova of 1572 as a comet. But a new thought style was being introduced in the 16th century, based on the work by Regiomontanus and others in the previous century (as outlined by Jervis 1985). Some standardization of observing procedures was being established, based on Regiomontanus's recommendations, and astronomers were thinking more in terms of measuring the size and positions of comets as celestial objects (not as Aristotelian exhalations). This more serious approach to observation was also reflected in the increasing frequency of published catalogues, observations, and star charts graphically depicting the motions of comets.

As the Aristotelian hold on natural philosophy in western Europe weakened in the late medieval period under increasing criticism of scholastic scholars (*e.g.*, Kuhn 1957, Chapter 4), the "beginning of the end" for acceptance of Aristotle's atmospheric view of comets was emerging for about a century prior to the appearance of the great comet of 1577. A new way of perceiving comets arose from observing methods that were more data-oriented, from challenges to accepted "theory", and from more original ideas about what the observations might represent. The bright comet of 1456 (which would much later be identified as an apparition of Halley's comet) might be seen as a key turning point in the science of astronomy in general, and in the observation of comets in particular. Fairly accurate positional observations of the comet of 1456 were attempted by Georg Peurbach, by Regiomontanus (Johannes Müller), and by Paolo dal Toscanelli, and in the discussions surrounding this comet, the idea was formulated of attempting to measure a comet's parallax to determine its distance. Regiomontanus wrote an important treatise on comets that

went through numerous published editions well after his death in 1476, into the following century. For the comet of 1472, he used a cross-staff for measurements of positions on the sky (both in terms of ecliptic and altitude/azimuth coordinates) and of its head and tail dimensions, and this particular treatise encouraged other observers to do the same. Regiomontanus also made an impact by refusing to mix his astrological material with his comet discussions, stressing observation to arrive at meaningful conclusions (Hellman 1944, p. 82), and rather stating a list of observational problems and proposing procedures to better determine a comet's position and possible parallax (Jervis 1985, pp. 93*ff*). Again, Halley was able to compute an orbit for the 1472 comet.

Girolamo Fracastoro also observed the comet of 1472, though he still held that comets were sublunar. Some 60 years later, Fracastoro and Peter Apian published their observations that comet tails always remain pointed away from the sun (*e.g.*, Hellman 1944, p. 88), and this "fact" was widely assimilated and acknowledged by numerous observers of comets seen in the decades up to and including 1577 (*e.g.*, Gemma Frisius 1545, p. 33a; Maestlin 1578, p. 2; Christianson 1979, p. 135).[19] Indeed, this anti-solar-tail trait in comets was used by various sixteenth-century writers, including Tycho, to attack Aristotle's atmospheric paradigm (Schechner Genuth 1988, p. 257), under the argument that fiery exhalations in the atmosphere should not be aligned with the sun. Apian used both a quadrant and a cross-staff in efforts to produce good positions of comets from night to night, and he is particularly known for his work on Halley's comet at its 1531 apparition. Kokott (1981) observes that the observations compiled by Apian were "crucial for Halley's identification" of the 1531 comet with its apparitions in 1607 and 1682. Joannes Vögelin (or Vogelinus) attempted to determine the parallax of the comet of 1532, following the procedures of Regiomontanus (Jervis 1985, p. 123); despite poor results, he was cited for his efforts by various writers later in the century, including Tycho Brahe (cf. Hellman 1944, pp. 96*ff*). The 1532 comet's orbit was the fourth in Halley's 1705 catalogue.

Phillip Melanchthon, the influential 16th-century German innovater of university education, was also a fan of Regiomontanus (*e.g.*, Thorndike 1941a, p. 368), who had embraced Aristotle and Ptolemy in their original forms (without including misleading medieval commentaries), and who also had encouraged the new astronomical quest to improve observational data. It is interesting to note that late in his life, Georg Joachim Rheticus (Copernicus' first significant follower) wrote "that it was his ambition to free astronomy from hypotheses and to be able to be content with observations alone"; in 1557, Rheticus wrote of Peurbach and Regiomontanus as being the rescuers of astronomy from barbarism (*ibid.*, pp. 347, 416). Though appreciating the work of earlier men such as Regiomontanus, Tycho did not hesitate to criticize his contemporaries (including Michael Maestlin) for putting too much faith in their predecessors (cf. Thorndike 1941a, p. 376). Tycho's careful observations of the planets revealed discrepancies in the work of Copernicus, which he had

[19] In the 7th century AD, the Chinese recorded their knowledge of the anti-solar nature of comet tails (e.g., Needham *et al.* 1957; Ho 1966, p. 130; Xi 1984), but it is virtually certain that Europeans could not have known of this in the sixteenth century.

embraced early in his career; this disappointment with Copernicus and the Prutenic tables led Tycho to a career of collecting increasingly more precise astronomical observations.

As Kuhn (1957, p. 140) has remarked, "Many of the data inherited by Copernicus and his colleagues were bad data which placed the planets and stars in positions that they had never occupied." Some of these bad data came from poor observers, or "had been miscopied or misconstrued during the process of transmission" through the centuries. The advent of printing, of course, greatly helped to reduce the problem of miscopied data. While 16th-century astronomers were well aware of the discrepancy between observation and theory, it was Tycho who realized most deeply that better instruments had to be built to overcome the problems. Chapman (1990, p. 16) reflects that "Tycho established a practical tradition that introduced the philosophical community for the first time to the concepts of precision measurement, regularity, and system in the making of observations", claiming that his publications "*Mechanica* and *Progymnasmata* contained a method for the conduct of science that was no less important than Galileo's *New Sciences* or Bacon's *Novum Organum*". In fact, Bacon thought that "an understanding of the operations of comets would throw light on larger scientific problems", and he suggested "that a history of comets be prepared as part of the groundwork needed to establish a future philosophy" (Schechner Genuth 1997).

Because the medieval observations were so poor, both Regiomontanus and Copernicus were "inclined to put greater trust in the recorded astronomical observations of the ancients, and to question medieval observations [that] were not in agreement with these" (Thorndike 1941a, p. 337). Chapman (1990, pp. 11*ff*) observes that the primitive state of astrometry and astrometrical instrumentation hindered research by maintaining strict barriers to the obtaining of accurate data. He criticizes historians of science over the years for regularly putting philosophical barriers over technological barriers in explaining the slow development of science through the medieval and early-modern periods. There may be some validity to Chapman's criticism, but I would argue that the mindframe with which astronomers of medieval and early-modern times looked at the sky was integral — a product of both philosophical outlook and technological capability. In a recent detailed history of the development of measuring comet brightness in the nineteenth and twentieth centuries, I have found that — though comets were fairly well observed astrometrically beginning with Tycho, and particularly after the eighteenth century (due to increasing improvement and standardization regarding star catalogues, instrumentation, etc.) — observers rarely attempted to measure a comet's brightness (Green 1996c). This was partly because the ancient crude magnitude scale of Hipparchus and Ptolemy had not been improved upon, but it was also because astronomers did not know how to quantify brightness in terms of extended, diffuse objects like comets. A new set of ideas had to be developed first. Only after a good magnitude scale and a concept of integrated brightness were developed could a new set of data be regularly obtained — data that could allow a new way of looking at potentially unknown physical processes.

In the years immediately preceding 1577, some attempts had been made by various individuals to place comets beyond the moon. Jerome (Girolamo) Cardan, who taught medicine at the

University of Pavia from 1543 to 1560, asserted that comets were supralunar because they moved more slowly than did the moon with respect to the background stars — drawing analogy from the common assumption that those planets furthest from the earth are those that move the slowest, and *vice versa* (Hellman 1944, pp. 92*ff*; Schechner Genuth 1988, p. 227). Cardan wrote in 1550 that the comet of 1532 moved slower than the moon, and he wrestled with the traditional notion of comets, concluding that they are globes somehow formed in the sky, with the sun's rays shining through the globe to form the tail (perhaps in a manner like sunbeams, which are sometimes seen as distinct rays of sunlight jutting through thick clouds). Cardan still considered comets as astrological portents, a trend that was even slower to die than the atmospheric paradigm.

The widely-observed comet of 1556 yielded many tracts — some of which included relatively accurate positional measurements (and the observations permitted Halley to compute the comet's orbit).[20] Paul Fabricius (1529-1588) made perhaps the best observations of this comet, and he leaned towards Seneca's view of comets as stars made by God to announce future events. Flock (1557) also recorded positional observations of this comet, saying that it was first observed on 1556 Mar. 3; he followed it until the morning of April 6, noting its rough positions with respect to some stars and giving some ecliptic coordinates to the nearest degree. The published tracts on the comet of 1556 are important for the study of comets, and ultimately for advances in observation and thought leading to the acceptance of heliocentrism, for the following reasons: (1) the material added attention, discussion, and debate to more rapidly evolve the thought process regarding comets, producing a growing body of objective data on comets; (2) they indicate increased interest and illustrate a growing tendency of writing in the vernacular; and (3) they reflect the increased use of printing. This escalating attention, discussion, and debate served to rapidly push issues regarding comets, reaching a peak with the comet of 1577. Patterns and trends were being established that served as fertilizer for an "atmosphere" of more reflective, creative, and critical appraisals of cometary observations.

Later, Tycho Brahe became aware of Cardan's thoughts on comets, as mentioned in the former's major treatise on the comet of 1577 (Dreyer, IV, p. 137)[21]. Indeed, Cardan's view of comets may have played a key role in Tycho's geo-heliocentric system that placed the comet of 1577 in orbit about the sun outside of Venus' orbit. Numerous fifteenth- and sixteenth-century writers noted that comets are visible mainly near the sun; combined with the fact that naked-eye comets are generally visible once every few years (on average), this may also have contributed to the forthcoming posturing by Tycho and Maestlin that the comet of 1577 orbited the sun near the circular orbit of Venus (with that planet, of course, only visible near the sun). Ruffner (1971) has observed that "Tycho established the principle that the apparent motions of comets follow

[20] Observations of the 1556 comet from various original sources were collected and published by Jahn (1856).

[21] Note that throughout this thesis, I frequently use the convention "Dreyer, (volume number), (page number)" to denote his *Tychonis Brahe Dani opera omnia* (published during 1913-1929). Additionally, references in the text to the English notes manuscript of various volumes in Dreyer's *Opera omnia* shall henceforth be given in the form "Dreyer, volume number, MS" (see section 8.1).

the arcs of great circles on the celestial sphere, particularly near the middle of their appearance (or more specifically, near perigee), and that they exhibit minor deviations from such arcs only near the beginning and end of their apparent tracks".

Some "rumblings" against the atmospheric-comet paradigm of Aristotle were certainly beginning in the decades prior to 1577, but even Tycho Brahe subscribed to the Aristotelian idea of comets when he wrote his 1573 tract on the new star of 1572 (cf. Dreyer 1890, p. 47). In the 1570s, improved positional observations of the bright supernova in 1572 and the bright comet in 1577 led to the argument (against Aristotle) that these were indeed new celestial objects beyond the earth's atmosphere. However, the dogma of Aristotle was so firmly entrenched in astronomical thought of the fifteenth and sixteenth centuries that it was only natural that a fair amount of time was needed to convince all scholars of both the validity of the new observations and of the new theories stemming from these observations. But the Aristotelian hold on comets was weakening, partly aided by a more general attack in the mid-sixteenth century on Aristotle from many different philosophical angles (Thorndike 1941b, p. 363).

The fiery-nature paradigm of comets that formed Aristotle's philosophy of these objects would survive astronomical analysis beyond Isaac Newton and Edmond Halley into the eighteenth century, but those who championed Aristotle's placement of comets as atmospheric exhalations steadily declined in numbers during the century after the great comet of 1577. Those who worked hard to obtain more careful, accurate observations of comets — and who made these observations and their subsequent speculations generally available through the rising media of printed books and booklets — gradually drew respect from an increasingly wide audience, thereby leading to increased serious discussion on comets and other matters astronomical. For example, Tycho rapidly gained respect across Europe for his excellent positional observations made with well-constructed instruments, and even though he expounded views on comets within a geo-heliocentric model that would not survive long, his "authority" demanded that he be taken seriously; in the late sixteenth and early seventeenth centuries, his precision was widely accepted, allowing his influence to "pave the way for a new astronomy" (Hellman 1944, p. 121).

1.5. The Beginnings of Standardization

Following no real advances in cometary astronomy for more than 14 centuries after the writings of Seneca in the first century (*Naturales Quaestiones*, Book VII), the introduction and spread of printing in Europe finally served as the catalyst for revolutionizing how comets were observed and discussed. The printed book encouraged more and more observers in the sixteenth century to publish their results, allowing many more people to analyze and discuss comets than ever before. This process gradually introduced standardization into astronomical observation, which in turn gradually but steadily changed the way comets would be perceived and studied.

The era of change began with the late-15th-century and early-16th-century work of Regiomontanus, Peurbach, Bernard Walther, Gemma Frisius, and others at encouraging a more rigorous approach to measuring celestial positions. The changing thought process continued with the pub-

lication of Copernicus' *De revolutionibus* and many tracts on comets observed in the early- to mid-16th century, leading to the analyses of better observations by Tycho Brahe and Michael Maestlin, leading into Johannes Kepler's defining work with positional data.[22]

Kokott (1984) boldly states that five conspicuous comets, seen in a span of only eight years, 1531-1539, "mark the beginning of systematic observations of these celestial objects". A most remarkable series of observations of the 1530s comets was published by Peter Apian. Near the end of his *Astronomicum Caesareum*, Apian included a 20-page section on the comets, wherein he produced his own observations along with a series of steps for reducing the observed quantities to positions on the celestial sphere, including some discussion of tail orientation and length. He included careful drawings of the comets' motions and tail directions with respect to the sun, together with measurements of the comets' positions in the sky from night to night. This 1540 folio volume represents the lion's share of the decade's observations that Kokott deals with in his own thesis, as Apian's recounting of observational data and procedure is more impressive than that of any other observer. Apian effectively applied and extended the earlier 15th-century work on observational techniques by Regiomontanus. By amplifying the concept of standardized astrometric measurements of celestial objects in order to learn more about them, Apian's publications helped to jumpstart the new revolution in astronomy. Kokott shows in detail that numerous other contemporary observers contributed to this development. But Apian uniquely demonstrated, not only by measurement of position but also through schematic diagrams, that comet tails tend to point anti-sunward.

Medieval European chroniclers generally became more and more "observational" regarding many astronomical events as the centuries progressed. That is, more and more details of celestial events came to be recorded of such events as solar eclipses (Thorndike 1941a, p. 366), in which the details of the sun's disappearance or the effects upon animals and people of the loss of daylight were carefully described (*e.g.*, Stephenson 1997). Cometary apparitions, in which drawings of their apparent location and their tails with respect to the background stars and the sun began to appear in the fifteenth and early sixteenth centuries — notably from such observers as Paolo dal Toscanelli and Peter Apian (*e.g.*, Jervis 1985).

David Turnbull (1993) has argued that "the introduction of perspective geometry in Renaissance Europe had a revolutionary impact", and this impact may be involved here in our discussion of comets and astronomy. Turnbull cites James Burke, who noted the importance of being able to measure from this new geometry perspective, making the world "available to standardization" in terms of scale and mathematics instead of philosophical quality. I think this gets very much at the root of the problem. Perhaps the drawings of the orbits of the planets (and comets) in books by Copernicus and Tycho helped spur thinking on the topic of proper placement via enhanced

[22] While researching literature for this thesis, I agreed to write biographical sketches for Peurbach, Regiomontanus, Walther, and Maestlin for the forthcoming *Biographical Encyclopedia of Astronomers* (Green 2004c, 2004d, 2004e, 2004g).

visualization. Other illustrated astronomy publications in the sixteenth century were likely to be quite inspiring for the imagination. These included a book with the collected works of Peter Apian and Gemma Frisius (Beller 1584) and the impressive *Astronomicum Caesareum* that was complete with hand-coloured moving parts showing the moving planets. The increase in finely illustrated books in 1500s and 1600s may have even been encouragement for some observers to put more effort into observations.

And yet, Apian was a medieval astronomer who necessarily had an Aristotelian mindframe. We see in his *Astronomicum Caesareum* that his observations were made with respect to the local horizon via altitudes and azimuths (comets conventionally being considered as objects in the earth's upper atmosphere), even though Apian published therein not only the comet's celestial longitude and latitude, but also right ascension and declination — revealing an emerging opinion that considered comets more in terms of celestial objects further separated from the earth. Kokott documents well the attempts of these astronomers in the 1530s to make measurements of comets more carefully than had been customary in the past, including their efforts to calculate the comets' distances from the earth (soon after the publication of Regiomontanus' influential tract on comets). Not until the the supernova of 1572 and the comet of 1577 would astronomers routinely measure the new objects with respect to the positions of stars, leading to new catalogues and thereby pushing the new revolution in astronomy. The 1532 comet is specifically addressed in Chapter 7 of this thesis, for illustration.

Reiner Gemma Frisius (1508-1555) was well known in the sixteenth century as the author of astronomical books on the measurement of astronomical positions, or what we today call astrometry, and he was involved in the design of globes and astronomical instruments that were "much sought after throughout Europe" (Kish 1972). In his 1545 treatise on the astronomical radius, Gemma Frisius writes[23] in his Chapters 19 and 21 of noting when stars are in a straight line with a planet or comet. Such a procedure had been published the previous year by Johannes Schöner (1544, p. 43a), a noted Nuremberg astronomer and astronomical editor/publisher[24] who had apparently been aware of the usage of such a method by Regiomontanus and Bernard Walther decades earlier, having recorded alignments of Halley's comet with reference stars (Schöner 1531a). (The noting of alignments of stars with planets or the moon dates back to antiquity, as Ptolemy discussed such procedures in his *Almagest*; *e.g.*, Ptolemy and Toomer 1998, pp. 322-327, 336.) Noting alignments of comets and (super)novae with various reference stars became a rather common record in the printed literature of the century beginning with Halley's comet in 1531, and recording such alignments might be considered one of the early "standard" observing procedures used by astronomers.

The supernova of 1572, also known as B Cassiopeiae, was noted by many observers of the comet of 1577. In fact, any serious look at evaluating the impact of the 1577 comet upon astronomers and astronomy must necessarily include the context involving the new star of 1572.

[23] Gemma Frisius 1545, pp. 32b, 37a; Beller 1584, pp. 313, 318

[24] born 1477, died 1547 (Zinner 1934, p. 99)

Though supernovae and comets today are considered to be extremely different sorts of objects and are not usually studied by the same astronomers, they were seen in the sixteenth century as puzzling new objects similar to comets, in need of explanation due to conflict with Aristotelian theory. The "Renaissance" of astronomical observation had really begun in the previous century, with applications in rather crude form being given in particular to those bright comets that had appeared in 1531, 1532, 1533, and 1556 (Hellman 1944, Kokott 1984, Kronk 1999). The observers of those comets had continued to think in terms of measuring the size and position of each object, following from the work of the previous century by Peurbach, Regiomontanus, and Walther (*e.g.*, Jervis 1985, Beaver 1970). Recording observations and publishing them became increasingly the norm, and we find observers of the comets of the mid-16th century recording such data as (a) positions as a function of celestial longitude and latitude, (b) distance in degrees from specified stars, and (c) straight-line alignments with pairs of stars.

Maestlin modified this third procedure already with his observations of the supernova of 1572 by finding pairs of stars whose interconnected lines intersected at the supernova.[25] As discussed in my chapter on the 1572 supernova, Thomas Digges also used the alignment method (with an instrument such as a cross-staff) of using pairs of stars in measuring the position of the supernova. Maestlin (1578, p. 22) actually refers to the 21st chapter of Gemma Frisius' tract on the radius as inspiration for his use of a string — which Maestlin evidently felt would lead to better results than using a radius or cross-staff (though he probably could not afford any better instrument early in his career; cf. Jarrell 1971, p. 105). Tycho also mentions Gemma Frisius and his books on astronomical instruments (*e.g.*, Ræder *et al.* 1946, p. 97), and early in his career, Tycho recorded observations of the planets as being in straight lines with pairs of specified stars (Dreyer 1890, p. 32).

The noted alignment of new stars and comets with reference stars and the measuring of distances from new objects from reference stars was not a new concept; Peter Apian, Gemma Frisius, and others had published such methods in earlier decades. But the concerted use of these methods for the 1572 supernova and then the 1577 comet by numerous observers marked a change in the way astronomy was performed. As will be seen in the remarks concerning individual observers below, some observers took more care than others, and some probably had superior instruments compared with those of other observers. Constructive criticism (and some not-so-constructive!), regarding observational procedures and data, erupted as never before — both in personal letters and in published tracts on the supernova. This criticism continued with the comet of 1577 and helped lead astronomers in this new scientific revolution to better observing procedures and instruments (including better star catalogues), with Tycho taking the lead.

The publication and discussion of this information obviously influenced observers of the 1572 supernova and the 1577 comet, as the treatises on these objects frequently refer to earlier measurements of celestial objects in the previous century. Some observers of the comet of 1556, including

[25] Maestlin 1573; Dreyer, III, 61; Clark and Stephenson 1977, p. 186.

Cornelius Gemma and Thaddaeus Hagecius, were also influential observers of the 1572 supernova and the 1577 comet. Unlike comets, which are usually not visible for longer than several weeks (even for brighter comets), the supernova of 1572 remained visible for well over a year. Furthermore, the new star in Cassiopeia was circumpolar for all European observers, being visible all night long whenever the sky was free of clouds. Comets, on the other hand, are almost always relatively close to the sun in the sky when they are bright, and as such they generally either set within a couple of hours of sunset or rise within a couple of hours of sunrise; their window of naked-eye visibility is generally much more constrained than was that for the 1572 supernova.

All of these factors must have played into the response of the observers of the 1572 supernova, because it was observed both more seriously and analytically than earlier objects had been. Many tracts were published on the new star,[26] and they showed that the degree of measuring for this object increased significantly as compared to earlier astronomical apparitions. At the forefront of this renewed enthusiasm for measurement was Tycho Brahe, who measured distances of the supernova to numerous other stars and devoted a large book (his *Progymnasmata*) to the observations and analysis of this new star. But such distances were also carefully measured by Jerónimo Muñoz, Thomas Digges, and Hagecius (cf. Brotóns 1981, p. 45; Clark and Stephenson 1977, Ch. 10). Alignments of the supernova with other stars were noted by Michael Maestlin (1573) and several of the other observers. The observers of the 1572 supernova not only published their results individually, but they wrote to each other extensively, informally starting what might well be considered the first astronomical society, a highly influential international collaboration without a name. As we have seen, this informal society would continue to progress, thereby aiding the development of observational astronomy through the apparition of the 1577 comet and on into the era of the telescope in the next century.

The 1572 supernova burst into the night sky only a little more than a century after the introduction of printing in Europe. Printing was one of the most important factors in stimulating a revolution in astronomy in the sixteenth century (e.g., Eisenstein 1980), and the 1572 supernova became really the fifth astronomical event in history that led to a large number of published tracts (the first four being the bright comets of 1531, 1532, 1556, and 1558; cf. Zinner 1964), though more tracts appeared on the new star of 1572 than on any of those earlier comets (Hellman 1944; de la Lande 1970, pp. 96ff; Grassi 1989). This supernova was viewed by what might be thought of as the first loose association of astronomers in Europe, brought together largely by the printing press (which encouraged the dissemination of new astronomical observations and analyses, and discussion of new ideas, by allowing broad transmission of data that were not possible previously). While the observing methods may seem crude by today's standards (it would be another 36 years or so before Galileo first pointed a telescope at the night sky), there was a slow logical progression building up during the sixteenth century, in terms of astrometry and overall thinking in terms of astronomy (e.g., see Hellman 1968a). Those bright comets earlier in the century had played a

[26] *e.g.*, Hellman 1944, 1960, 1968a; de la Lande 1970, pp. 96*ff*; Grassi 1989

part, in which astronomers struggled to place them and their positions via a gradual modification of the ancient astronomical theory that had survived the Middle Ages.

The discussion of how observations were being made of astronomical objects up through the 1572 supernova, which included how to use various instruments to obtain astrometric positions and even the suggestion of trying to use the very imperfect clocks then available, was clearly yielding new results. Astronomers were now noting that comet's tails tend to point anti-sunward, and the 1572 supernova was determined by some observers (including Tycho) to have such little parallax that it could be assumed to be as distant as the stars, in the outermost Aristotelian "sphere". And star maps were appearing in print, including published charts showing the paths of comets with respect to the stars. In line with the questioning of Aristotelian dogma that had been slowly but steadily developing in the preceding centures (cf. Kuhn 1957), observers during the years leading up to the comet of 1577 had tended to treat comets (including the "comet" of 1572) as astronomical objects, rather than as the atmospheric exhalations that Aristotle had claimed. And the serious astrometry that was being undertaken for these "transient" celestial objects was a sure sign that the astronomers of the 16th century believed that more could be learned if one used a more careful, serious, and systematic approach to observing anything astronomical. The new highly-debated Copernican thesis also undoubtedly factored in on this new approach to observing — by emphasizing that better observations were needed — with the growing feeling (culminating with Tycho's observing program) that perhaps more careful, systematic observations could determine which model of the sun, planets, and stars was correct. Paralleling this 16th-century interest in improving upon celestial-position measurements (astrometry) was work in geographical surveying techniques, and it is perhaps not surprising that Haasbroek (1968) has shown that three of the foremost people involved in serious terrestrial surveying were also involved in promoting celestial surveying: Gemma Frisius, Tycho Brahe, and Willibrod Snell.

It is obvious that both Cornelius Gemma and Hagecius made great efforts to measure high-quality positional data for the comet of 1577, and their instrumentation and ability permitted them to obtain data nearly as good as those of Tycho. That said, Tycho did go noticeably further in making many more observations than the other observers and in recording more details regarding the clock time, possible problems with the recorded time, the weather conditions, and details on the comet's visibility, tail, etc. In other words, Tycho was "pushing the limit" on astronomical observation with the naked eye and the available instruments, and as such he was recognizing the various limitations that had to be contended with — imperfect clocks, weather conditions, and a comet that became fainter and much harder to see as the weeks progressed. This attention to observational details was rather novel, and it indicated to other astronomers that a serious approach to observation included attention to such details as well as improving instrumentation.

Tycho himself noted that he needed the experience of many years of observing from his teenage years into middle-age to enhance and improve the accuracy of his observing (Ræder *et al.* 1946, p. 110) — perhaps one of the first explicit remarks in history about how good astronomical observation is the product of experience, not mere glancing at the sky. Peter Dear (1987, p. 160) has

pointed out differences between observation and experience, where "it was not a straightforward matter for anyone to reproduce for himself the experiences claimed by astronomers." In the eyes of the Jesuit Blancanus, a contemporary of Galileo, "it is the process of construction, as well as the specialized nature of the data which itself must be 'manufactured' using instrumental techniques, that sets 'observations' apart from 'phenomena'" (*ibid.*, p. 150). Also, most late-medieval and early-modern celestial observers and chroniclers were basically unaware, to varying degrees, of the potential value of good time-keeping for such astronomical observations. It is curious, however, that 16th-century astrologers (who were largely inseparable then from the concept of astronomer) *were* focused on precise hours in terms of people's birth for the purposes of casting horoscopes.[27] The presence of times of the day, often given to the minute, in horoscope production during the sixteenth century is evident in the genitures that were widely published in books on astrology in general (*e.g.*, see the figures of Grafton 1999) and on many comets in particular (as mentioned in this thesis' chapter on the role of cometary illustrations). Even Tycho Brahe took care about the hour of the day for astrological discussion (Dreyer 1890, p. 77).

Manuals for observing celestial objects astrometrically began with posthumous publications of works by Regiomontanus (notably edited by Schöner in 1531 and 1544), encompassed by important astronomical treatises written by Peter Apian and Gemma Frisius in the mid-sixteenth century that went into multiple printings (e.g., Gemma Frisius 1545; Apian and Gemma Frisius 1550, 1584); many of these editions included observations of the location of comets on the sky. Regiomontanus, subsequently highlighted by Gemma Frisius, made an important impact by promoting the acquisition of distance measures between a comet and two background stars (Regiomontanus and Schöner 1531; Schöner 1544; Jervis 1985) — and their methods would be widely cited by observers who made such measures for the new star of 1572 and the comet of 1577. The instrument of choice that Regiomontanus promoted for such celestial distance measures (or astrometry) was the 'Jacob staff' or cross-staff, later in the sixteenth century termed "astronomical radius" by astronomers (cf. Haasbroek 1968; Zinner and Brown 1990) — and this instrument was still used by numerous astronomers while observing the 1572 supernova. Nonetheless, published positional information for new celestial objects like comets tended, however, for decades to be mostly altitude-above-horizon measures or already-reduced coordinates (usually ecliptic longitude and latitude) — which generally prohibit modern researchers from refining positions further.

The measurement of a comet with respect to two reference stars had been undertaken by Regiomontanus (Schöner 1544, p. 43a) and Walther (cf. Hellman 1968a), who observed together at Nuremberg in the early 1570s. The naked-eye procedures used by Tycho and Maestlin for obtaining a comet's position — measuring the distances between the comet and selected stars, and also noting alignments of the comet in a straight line with two other stars — were continued

[27] See, *e.g.*, Thorndike (1941a), pp. 302 and 315. Already in the fourteenth century, the French critic of astrology Nicolas Oresme had objected to the astrological stance that a given hour of a day is "ruled" by a certain planet (Thorndike 1934, p. 415).

by other observers into the following century. For example, Willebrord Snell (1619) used both procedures for his observations of a comet seen in November 1618.

Brahe represents an important catalyst in the changing astronomy: the development of astronomy beyond classical studies of Hipparchus and Ptolemy. This development was only beginning with observers such as Toscanelli, Regiomontanus, and Peurbach in the fifteenth century. Though ideas were implemented and added to by Copernicus and others in the first half of the 16th century (cf. Kuhn 1957), Tycho's work represented an immense jump in the changes that were only beginning. Of course, he was not alone: Tycho was strongly affected by the work of his contemporaries — possibly as much by Michael Maestlin as anyone. Tycho rightly realized that the basis of any advance in astronomy would be dependent upon much better measures of celestial positions than had been accomplished prior to his time, and that a good astrometric star catalogue would be a prerequisite for learning about everything from precession to planetary, solar, lunar, and cometary motions to cosmological models.

The idea of more care employed in measuring the positions of astronomical objects was not new, but necessary technological advances in the instrumentation were very slow to occur, thereby impeding what could be done. This had not stopped some, such as Regiomontanus, from attempting to search for parallax in comets (among other celestial objects). Tycho's difference was in insisting on vastly improving the technology of observing instruments, and he was among the few astronomers who had the financial resources and energy to accomplish this task. Tycho placed tremendous emphasis on the instruments needed to make good positional measurements, and worked hard to improve his instruments by building new and larger instruments that benefited from experience with the older ones employed by the Dane. No other astronomer from the late-medieval or early-modern era described his instruments in such detail (and with such candor) as did Tycho,[28] and his 1598 publication *Astronomiae instauratae mechanica* gives details (and diagrams) on most of his instruments (though we lack what would have been a most useful detailed description of his clocks). As an example, here are some descriptive remarks by Tycho on his steel sextant, used for determining star/comet distances for the comet of 1577 (Ræder *et al.* 1946, p. 78):

> *The use of the instrument is for measuring angular distance of the stars up to one-sixth of the circumference of the circle, and that with one observer who, having placed his eye near the centre at A, and having adjusted the whole sextant according to the plane of the stars with the aid of the screws of the base, then turns the screw GH towards one side or the other, thus increasing or diminishing the angle BAC, until the two stars are distinguised with perfect accuracy through the pinnules BC. The division of the arc BD will then indicate the required distance between them. To begin with the circumference had in addition to*

[28] at least until Johannes Hevelius (1673) nearly a century after Tycho.

> *the usual division a Nonnian division, but when experience taught me that another method of division, namely the one that makes use of transversal points, is much more convenient and accurate, I gave up the methods previously used and applied the latter.*

Tycho took a problem with the available instrumentation that had been recognized by those before him, such as Gemma Frisius (*e.g.*, Lammens 2002, pp. 45-46), and sought to improve the instrumental technology. Error in Tycho's celestial positions was minimized by the huge size of his instruments and "by the graduations carefully marked on them to facilitate angular measurements on the celestial sphere, altitudes, and azimuths. Tycho checked instruments against each other and corrected for instrumental errors" (Hellman 1970, p. 405). Tycho's star catalogue of positions meticulously measured at Hven was transformed into the famous *Uranometria* of 1603 — Johann Bayer's landmark atlas of the heavens, which was the first really detailed engraved star atlas, and which made a major impact upon astronomy because of its relative precision and pragmatic character (Whitfield 1995, p. 85; Ashbrook 1984). The result was an encouragement for astronomers to locate celestial objects more carefully with respect to the background stars, putting more emphasis therefore on measurement in astronomy. But Tycho's observations were far from perfect.

It is often thought (and generally taught) that Tycho was the only observer worth mentioning in the half-century before Galileo pointed his telescope skyward. But many of Tycho's contemporaries were not only quite serious about observing and discussing the implications of the observational data in terms of cosmogonical models, but they influenced each other (including Tycho) significantly — including especially Hagecius, Maestlin, Cornelius Gemma, and the Landgrave of Hesse. Tycho gained much during his observational career from his correspondence with, and visits to/by, those other observers throughout Europe. Previous historians have not explored very extensively an intercomparison of observational data by late-16th-century astronomers, and there is likely to be a good deal that can be learned about the community of thought underlying this loose association of astronomers from analyzing their approaches to observation.

Not only was the 1577 comet a crucial factor for the development of Tycho Brahe's observational program and for his astronomical theories, but the interaction that occurred amongst astronomers regarding both that comet and the bright supernova of 1572 were to have far-reaching impacts on astronomy and on science. This important semi-formal discussion between astronomers, much of which was published and survives today for historians of astronomy to analyze, can well be seen as the first astronomical society for the critical review of observational procedure, acquisition, and reduction/analysis. The considerable correspondence that occurred between most of the top observers of the comet of 1577, some of it even during the two-month interval that the comet was being observed (Nov. 1577-Jan. 1578), and the large amount of referencing by 1577 observers regarding positional measurements of the 1572 supernova (and to other astrometric work on comets, planets, and stars in the previous century), all show that none of

these observers were acting in a vacuum. Astronomers were reading each others' published tracts carefully, and one sometimes finds an important 16th-century astronomy publication that is heavily annotated by some reader. Gingerich (2002a) has shown the importance of such annotating in copies of Copernicus' *De revolutionibus*.

Much of the correspondence between late-medieval and early-modern astronomers regarding comets and novae — and also manuscripts containing observations of these objects not published (for whatever reasons) by the original authors — would be published by various leaders in the community, such as Brahe (1596),[29] Hagecius (1574, 1576), Lubienietz (1667), and others. And yet additional authors would compile observations of observers without publishing whole written letters (*e.g.*, Snell 1618, 1619; Chiaramonti 1628). This would all lead to the eventual development of published European periodical "journals" in the late 17th century and 18th century — devoted to publishing astronomical observations, correspondence, and analyses of data — thereby further encouraging standardization of reporting format (and of observing procedures).

Some notable examples that I have come across include copies of Tycho's *De mundi*[30] and *Progymnasmata*[31] The section on comets in the copy of Newton's *Principia* in Oxford's Hertford College Library is also extensively and critically annotated in dark-brown ink in the page margins — the unknown reader jotting down numerous corrections throughout the volume.

We have seen thus far that one must very much consider the observational program of Tycho Brahe and the programs of his contemporary observers as products of their predecessors and the current state of astronomy with regard to comets, of their exchange of observations and theories with each other, and of the instruments (and star catalogues) available to them. All these factors helped to determine what data were obtained and how they were measured. Though Gemma died of the plague in 1579 at age 44 (Hellman 1944, p. 181), and so did not observe any further comets, other major observers of the comet of 1577 did observe the comet of 1580 and later comets. Maestlin (1581), for example, observed the comet of 1580 in detail, and he was evidently persuaded by Gemma, Hagecius, Tycho, and others that the string-alignment method that he had used for the 1572 supernova and the 1577 comet was not a "state-of-the-art" observing technique; consequently, he acquired and used an astronomical radius for the comet of 1580.

Maestlin's presentation of his observations for both the 1577 and 1580 comets was more "professional" and orderly, in that he neatly tabulated his measurements. Hagecius (1581) also

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[29] and very notably also in his books on the 1572 supernova and the 1577 comet

[30] Maestln's heavily annotated copy is in the British Library; another quite serious unknown annotater spent many hours marking up the copy located in the Bodleian Library — both of these being 1588 editions. Of the three Hven-printed editions of *De mundi*, I have seen 33 copies (ten of the 1588 edition, eight of the 1603 edition, and fifteen of the 1610 edition).

[31] A heavily annotated copy of the 1602 edition now resides in the Royal Library, Copenhagen. Rather extensively annotated copies of the 1602 edition were located both at Wolfenbüttel and again at the Royal Library, Copenhagen. Of the three Hven-printed editions of *Progymnasmata*, I have seen nineteen copies (six of the 1602 edition, two of the 1603 edition, and eleven of the 1610 edition).

published comet-star distance measures for the comet of 1580, but as he (and most other astronomers) had done in his treatise the 1577 comet, he presented his results in paragraph form. Additional research on the observation programs for the comets of the 1580s and 1590s will build on this historical analysis of work undertaken by astronomers in the 1570s to explore how this area of astronomy and was developing in terms of the participants, their efforts, and their perceptions of what might be useful to promote their own views and/or to work towards some standardization of methodology. More numerical approaches in astronomical studies were now being employed, and these numerical approaches would continue to increase significantly in the work of Kepler and Newton in the following century.

Chapter 2: Accessing the Original Astronomical Data: Sources and Problems

As noted in Chapter 1, many comets appear suddenly when already bright, and this is still true today. (This is certainly true for supernovae and novae, which by their very nature erupt catastrophically into bright outburst in a matter of hours or days.) Naked-eye comets will brighten and fade from view rather rapidly in most cases (in a matter of days or weeks). Prior to the existence of "passable" optics in telescopes (meaning the late-17th or early-to-mid-18th centuries in Europe), the observability of comets was restricted to the time spans in which they were visible to the naked eye.[32] Because comets were unpredictable in terms of their appearances, they would generally not be detected when they first rose above the limit of naked-eye visibility. There were probably never any astronomers who regularly scanned their entire night skies for unusual objects like comets in pre-telescopic times; there were no real published star charts until the 16th century, so one would have to have memorized large swaths of the sky (and we have no records that anybody ever attempted this in pre-telescopic Europe). So, with few observers regularly even *looking* at the night sky in a serious way (noting and sometimes recording the visibility of planets, the moon, and atmospheric effects such as aurorae and meteors), it is hardly surprising that most observed cometary apparitions — in the extant library materials available to us today — are relatively short in duration. And when comets *were* seen, medieval European observers did not have an appreciation or capability to know what information might later be useful to others.

In addition to there being relatively few medieval and early-modern observers with a "useful", intimate knowledge of the night sky, and to comets appearing suddenly, there are a couple of additional factors that contribute to the dearth of qualitative records on comets in medieval manuscripts and books: (1) much of Europe is often cloudy, limiting the number of useful nights for viewing the night sky; and (2) the motion of comets was unpredictable to observers — so that if the comet was relatively faint and/or it was not observed for some days (or weeks) due to clouds, bright moonlight, etc., it would be nearly impossible for naked-eye observers to definitively identify at a later date.

Therefore, it is prudent for modern astronomers who are collecting old data for analysis to look for as many possible sources as possible to add to the often-meager collection of astronomical observations. The situation changed dramatically in the 16th century because of the ascension of printing in Europe, permitting much more data to be moved from the more-transient form of

[32] The term "naked eye" is used here to indicate observations without magnified-optical aid.

handwritten manuscripts into many copies of the exact-same texts, and therefore permitting more dialogue and discussion (and encouragement to standardize and report more data, as noted in Chapter 1 of this thesis).

2.1. Late-medieval and Early-Modern Observational Sources

Numerous bibliographies (none of them complete) of astronomy tracts published in the sixteenth and seventeenth centuries show how printing created an explosion of interest in the observation of 'transient' celestial objects such as novae and comets (*e.g.*, Hellman 1944; de la Lande 1970; Zinner 1964; Grassi 1989; Brüning 2000). From my own visits to dozens of rare-book libraries for researching this thesis, I was surprised to learn not only how many old tracts existed with usuable observational material on comets and eruptive stars, but also how incomplete the various bibliographies are concerning these early printed books. At some point it would be useful for a researcher to combine the contents of all of the available bibliographies (including now also those referenced in this thesis), and additional European library research that I plan in the coming years will surely add to this growing list.

There are many manuscripts scattered in rare-book libraries, mainly in Europe, that contain information on astronomical events including eclipses, comets, "new stars", aurorae, fireballs, meteor showers, etc. (e.g., Zinner 1925; Hellman 1968b). However, most medieval handwritten manuscripts containing astronomical observations that were never published are extant only as single copies, and when visits to libraries are made to view them (or photocopies acquired via postal mail from the libraries), they can be virtually impossible to read to the eye that is untrained in such manuscript writing (usually in Latin). Fortunately, much such manuscript material on comets and the 1572 and 1604 supernovae has been transcribed by experts into print — whether in specialized journal articles (e.g., Hellman 1960), books on a specific topic (e.g., Thorndike 1950), or the collected works of various astronomers (e.g., Dreyer 1923). Nonetheless, few medieval manuscripts contain anything more than the most cursory information on comets (*i.e.*, usually no positional or physical measurements — generally, at best, a range of dates and sometimes a rough direction in the sky). But even with the late-medieval and early-modern printed books, which do often contain useful (to modern astronomers) positional and physical data on comets, much of the older astronomical data has escaped modern use and analysis. This emphasizes the fact that observers who took their measurements seriously sought earnestly to put them into print for wide reading by others — an action that greatly benefits us today.

But many printed late-medieval and early-modern astronomical tracts contain much interesting and even useful data for modern astronomy — and much of this has been untapped. An interesting example is something that I found recently in Johann Baptista Cysat's important 1619 comet tract. On page 72, Cysat reports that the last of the three 1618 comets was observed by himself on Dec. 1 and 4 with an "optical tube", or telescope. It hadn't even been ten years since Galileo first turned his telescope skyward, and only a couple of months earlier had the first known

telescopic observation made of a comet — by Kepler, of the first 1618 comet. Until recently, it was evidently unknown that there were any telescopic comet observations by any other observers until much later in the 17th century.[33] Cysat speaks of the comet's head and mentions the comet's "nucleus" (what we would now refer to as the nuclear condensation) — in what is the first such use of that word in this context, to my knowledge. But even more interesting are the presence, on page 74 in his tract, of drawings of the inner coma made by Cysat from his telescopic observations — which are apparently the first known illustrations from telescopic observations of a comet (reproduced here as Figure 2.0, below). The next astronomer to publish telescopic drawings of comets evidently was Hevelius (1668, p. 414, Figure F), half a century later.[34] Additionally, John Bainbridge (1619) says that he observed the comet about 1 a.m. on Dec. 3 at altitude $< 10°$ with "The Telescopium or Trunke-spectacle". Hevelius (1668, p. 878) also remarked that Gottfried Wendelinus observed the comet telescopically during 1618 Nov. 29-1619 Jan. 10.

[33] Kronk (1999) also noted Cysat's telescopic observation but did not note the significance of Cysat's drawings; it is known that Kronk had limited access to library materials and did not see very much original literature (Green 2002d, 2004f).

[34] After 1618, the next comet in Hevelius' catalogue that is noted to have been observed with a telescope was the 1652 comet — seen by Cornelius Malvaeticus Bononiae on Dec. 21 and by himself beginning six days later (Hevelius 1668, p. 889).

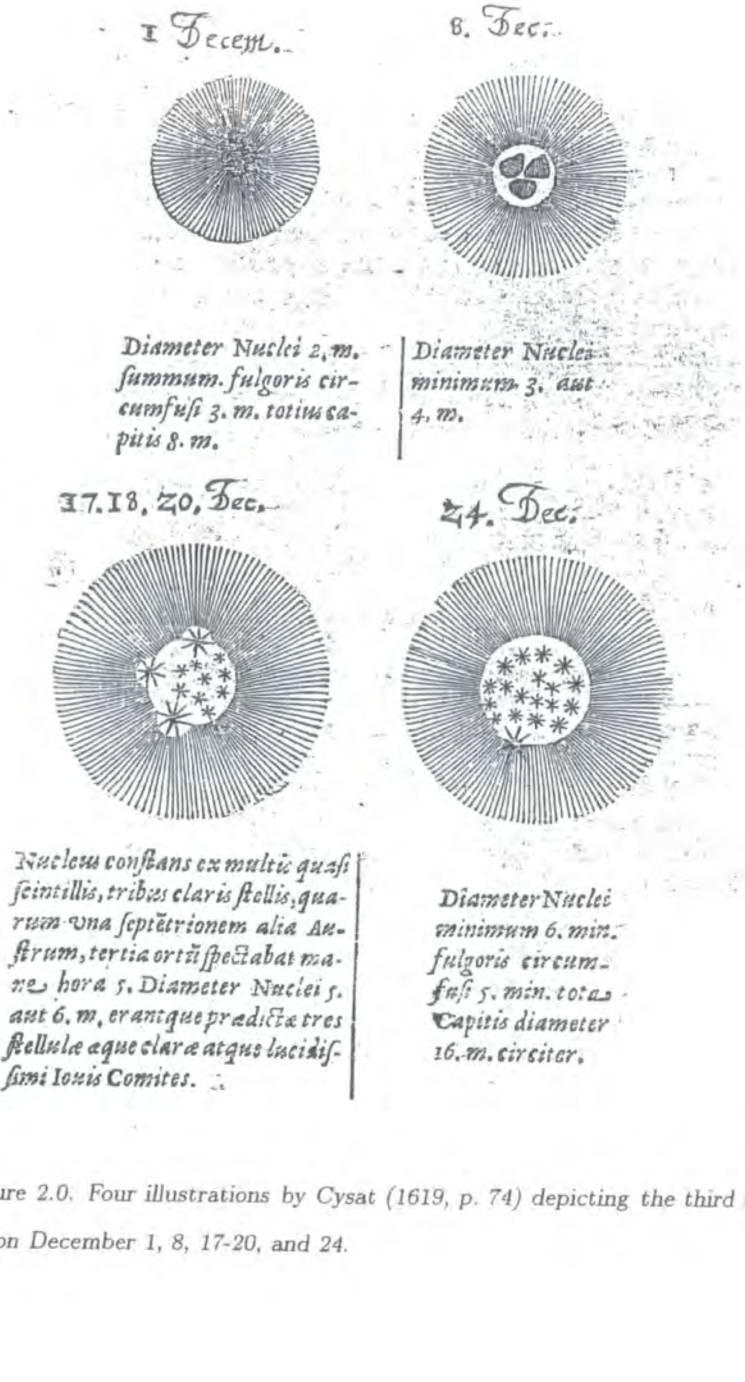

Figure 2.0. Four illustrations by Cysat (1619, p. 74) depicting the third comet of 1618 on December 1, 8, 17-20, and 24.

In some rare-book libraries (*e.g.*, Oxford, Vienna, and Wolfenbüttel), readers are asked to sign when using a book, giving the date and sometimes soliciting remarks by the reader. During my research on late-medieval and early-modern books on comets, I found that most such tracts had not been looked at in quite a long time (generally quite a few decades). The Cysat example just noted, as well as many of the observations covered in the remainder of this thesis, illustrate well how little these tracts have been looked at in the last couple of centuries, showing how much future potential there is beyond this thesis.

There are various types of printed books from the target era with potentially useful observational material on comets and novae. The chronicles of the middle ages contained general topics of local importance in manuscripts that were often maintained in monastic communities, though sometimes there was royal sanction for chronicles. One 12th-century chronicler, Gervase of Canterbury, even wrote about the proper function of a chronicler, namely to briefly describe "the actions of kings and princes which occurred at those times . . . [and also to commemorate] events, portents and wonders" (Clanchy 1993). But the chronicles tended only to mention that a comet (or new star) was visible in a given month, possibly for a rough duration (days, weeks, or months), and occasionally in a general direction of the sky. A great percentage of European chronicles with any useful information at all have been transcribed into type and published over the last few centuries, and many of these contain mentions of cometary apparitions that represent — in many cases — virtually the only information that we have on comets in the European middle ages.[35] The *Nuremberg Chronicle*, published in 1493 in both Latin and German editions, was an early example of a chronological history that was designed specifically for print; the German edition of the *Nuremberg Chronicle* has just recently been republished in a beautiful folio facsimile (Schedel and Füssel 2001). Occasionally short manuscripts were written in the European middle ages on a particularly interesting comet, some of which have appeared in print in the last century or two (*e.g.*, Thorndike 1950; Jervis 1985). But there are many late-medieval manuscripts on comets that have yet to be put into print.

Some of the earliest printed books in European history — just a few years after the first printing presses began churning out books in Mainz and in urban areas beyond the Rhineland (*e.g.*, Schottenloher *et al.* 1989, pp. 73ff; Eisenstein 1983, p. 13) — were tracts on the bright comet of 1472 (Hellman 1971, pp. 76ff; Jervis 1985). Numerous manuscripts were written on this comet (cf. Kronk 1999, p. 285), now designated C/1471 Y1 (due to its apparent first observation having been made in December 1471) — several of which made their way to print in the years and decades following the comet's appearance.[36] In these early days of printing, authorship was

[35] Representative examples of such published chronicles include Stubbs 1868; Luard 1872; Gregory of Tours and Dalton 1927; Wallace-Hadrill 1960; Campbell 1962; Colgrave and Mynors 1969; Garmonsway 1972; Turtledove 1982; Davis 1989; Anderson 1990; Stokes 1993.

[36] I located two unpublished manuscripts, written in very difficult Latin handwriting, in the manuscript library of the Universitäts Bibliothek at Jena, reported by Zinner (1925, pp. 118, 363) to have material on the 1472 comet: one by Johann von Glogau (shelfmark El 2° 70., sheets 62-65′), and another by Valentin von Zatkov (shelfmark El

often not very conspicuous — sometimes given at the end of a tract, sometimes not at all. For example, an observational tract on the 1471-1472 comet attributed to Regiomontanus, published a century later by Hagecius (1574, pp. 146-149), is argued by Jarvis to have been written instead by a colleague of Regiomontanus — namely Eberhard Schleusinger. Another single observation of the 1472 comet — published by Schöner [1544, p. 43(a)] and again by Snell (1618), in a collection of observations by Regiomontanus and his colleagues and/or students — was evidently made by Walther and/or Regiomontanus at Nuremberg.[37] Other published tracts written on comet C/1471 Y1 include one or more by Angelo Cato Supinas (1472)[38] and a tract published in 1474, which is present in many rare-book libraries, by an anonymous physician in Zurich.[39] C/1471 Y1 also evidently caused enough interest to have a printing made of a tract on the 1402 comet by Jacobus Angelus of Ulm.[40]

Although there are a few European tracts listed in bibliographies for comets observed in 1500 and 1506 (*e.g.*, Brüning 2000), in my research I have only located a single tract on any comet observed between 1472 and 1531 — that by Virdung (1507), notable for his having also later published on the 1532 comet. This is despite the fact that there are numerous east-Asian reports of at least eight comets seen in this six-decade span (Kronk 1999).[41] This places emphasis on

73 2°, sheets 56, 56′, 45′). Brüning (2000, pp. 6-7) also lists numerous unpublished manuscripts on C/1471 Y1.

[37] Both were apparently observing from Nuremberg in 1472 (Zinner 1934, p. 66).

[38] I first saw this 62-page volume in the John Rylands Library. In addition to the "standard" 1472 Supinas tract listed in my reference list, the Bibliotheque Nationale de France in Paris has, under shelfmark PV 118, a single bound volume containing the main 1472 tract followed by a 13-page printed tract (in a different typeface) from Rome, which begins "Cum huius diei magni & horrẽ di Comete recens apparitio mortalium corda porterreat." This shorter incunabulum concentrates on the astrological meaning of the comet in six chapters with emphasis on the comet's tail.

[39] The anonymous author may have been Eberhard Schleusinger (Zinner 1934, p. 98). I learned from my library research that several typesettings and printings of this 53-page tract occurred, beginning in 1474 (Anonymous 1474). I have viewed six copies of the early editions in the Bodleian Library, the British Library, the Crawford Library, the Bibliotheque Nationale de France, and the New York Public Library. I viewed copies of the later edition (Anonymous 1556) at the Danmarks Natur- og Laegevidenskabelige Bibliothek and at the Crawford Library (and the Royal Astronomical Society Library also lists a copy).

[40] Also known as Jakob Engelhart (Brüning 2000, p. 9). See Jarvis (1985), p. 37, who also provides a complete facsimile copy of the 31-page tract (pp. 131-161). She notes the uncertainty in the date of publication (evidently sometime between 1475 and 1490). A fair number of copies seem to have been circulated: I have looked at copies of this incunabulum, entitled *Tractatus de cometis*, in the Crawford Library at Edinburgh, in the British Library, in the Bodleian Library, and at the manuscript library of the Universitäts Bibliothek at Jena.

[41] By "at least eight comets", I mean cases where comets were most likely what was seen. Kronk has inconsistencies in his catalogue, in which some comets were missed and others that are probably not comets were included (as I have noted in my reviews: Green 2002d, 2004f). Kronk missed a 1527 object widely referred to as a comet, both in several tracts published then (*e.g.*, Anonymous 1527?; Creutzer 1527?; see also Brüning 2000, who mentions two tracts by Vogelin, who made notable observations of the 1532 comet, discussed in Chapter 7, below)

the fact that the comets of the 1530s really caught the interest of European astronomers, so that Europeans began in the sixteenth century to assume the role over Asian observers as the primary observers of both comets and novae. By the 1530s, title pages were becoming standard for printed comet tracts, and illustrations began to play a key role in the presentation of observations.

There are certainly later unpublished comet manuscripts buried in books that are still awaiting publication. One such handwritten segment is situated at the end of the copy of Scultetus' printed tract on the 1577 comet that is located in the Crawford Library.[42] The unnamed author writes in Latin that a comet was observed with a nautical radius from London on Nov. 2, 3, 9, 13, 15, 25, and 25 — with reference-star/comet distance measures given for all but the first night. Different shades of ink suggest that the entries were made in real time, but I have not yet identified the year in which the observations were made (not evidently a comet observed between 1556 and 1620).[43]

Numerous copies of late-medieval and early-modern books will have been lost over the years due to fire, water damage, etc., and certainly a fair number of comet tracts are in private hands. Stephan Füssel estimates that around 1400 Latin copies and around 700 German copies of the *Nuremberg Chronicle* — which contains medieval-type short descriptions of bright comets over the centuries — were published in 1493 (Schedel and Füssel 2001, p. 32). As for purely astronomical texts, Owen Gingerich (1995) has estimated that perhaps 135 copies of Apian's *Astronomicum Caesareum* are extant today,[44] and he has shown that just over 600 copies are known today of the 1543 and 1566 editions Copernicus' *De revolutionibus* — out of supposed print runs of roughly 500-600 for each edition (Gingerich 2002a, p. xiv). Gingerich adds that 400 copies of Galileo's *Sidereus nuncius* were printed in 1610. Somewhat remarkably, Tycho Brahe's two long books on the comet of 1577 (465 pages) and the supernova of 1572 (850 pages) were each printed in much larger quantities of about 1500 copies (Dreyer 1890, p. 369; Thoren 1990, pp. 366, 421; Christianson 2000, p. 377). It is difficult to estimate how many copies of a typical late-medieval comet tract (which were usually under a hundred pages in length, and often under 50 pages) were printed, but given the availability of some titles in rare-book libraries (and on the open market) today, one might guess that such tracts may have had print runs of not more than a few hundred

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and in catalogues for 1-2 centuries afterward, but which has been now largely accepted as an appearance of aurora borealis.

[42] Scultetus' tract is the third item in a volume with shelfmark CR.C2.6 (1-10). The table of contents to the whole volume has an insert that states that Dreyer bought the book in Copenhagen in 1882, evidently acquired by Lord Crawford in Armagh during the eclipse expedition of 1887.

[43] I plan to reduce the astrometry and compute an orbit to determine the year of this comet (by comparison of orbital elements in a modern comet catalogue), and hope to publish the entire transcript and reduction soon.

[44] Even Edmond Halley (1752, p. Rrrr2) remarked that it was difficult finding a copy of the *Astronomicum Caesareum* early in the 18th century, as he was trying to compile comet astrometry for his orbital calculations. In addition to the 111 copies that Gingerich had seen to that point, Röttel and Kaunzner (1995) list several copies not seen by Gingerich, but the list may be older, and it certainly contains some errors. I recently viewed a copy in Oxford's New College Library that is not listed in either of these two censuses.

copies. However, it is conceivable that higher quantities of the many comet tracts written by lesser-known authors (which were often printed on lower-quality paper, with fewer eye-catching diagrams, and with less-crisp typesetting) are likely to have been discarded over the years by heirs of the books' owners (and maybe even the original owners themselves), as simply "uninteresting".

2.2. Catalogues of Cometary Apparitions and Observations

Catalogues of comets were increasingly perceived as useful ways to study comets, and Antoine Mizauld (or Mizaldus) published such a work in Paris in 1549, listing comets seen up to 1540. Several comet catalogues appeared within two years after the comet of 1556 (cf. Hellman 1944, pp. 109-111), including those compiled by Benedict Marti von Bätterkinden (also known as Aretius), by Ludwig Lavater (1556?), and by Erasmus Flock (1557). Paul Eber (b. 1511; d. 1569), who was a pupil both of Philip Melanchthon and Martin Luther (and later professor at Wittenberg), also compiled a catalogue of comets in the 1530s (a manuscript copy of which resides in the Gotha Schloss Forschungsbibliothek[45]). The first edition of Lavater's catalogue is quite a lengthy catalogue — the actual text on comet apparitions covering some 60 pages, including (for example) six pages from various sources on the 1472 comet alone; a revised edition was edited by Johann Jacob Wagner over a century later (Lavater and Wagner 1681). Lavater's citing of earlier authors makes the book quite possibly the best comet catalogue prior to those of Lubienietz and Hevelius, a century later. Markus Frytsch (1563a) produced a comet catalogue about twice the length of Lavater's. Georgio Caesius (1579a, b) of Leutershausen (and also Rotenburg) published two comet catalogues — his second tract being a historical catalogue of comets (citing earlier chronicles, cometographies, etc., for each apparition) that spans 120 pages. Andreas Angel (1597) included a 20-page historical catalogue of comets in a 307-page "book of wonders".

As the seventeen century opened, Abraham Rockenbach (1602) of Frankfurt wrote a descriptive comet catalogue about as long as that of Frytsch's, covering comets through 1596. Rockenbach's catalogue was also highly cited in the following century. (Five years later, Rockenbach published an astrological tract on comet 1P/Halley, which appeared that year.) Thomas Hartmann (1605) compiled a catalogue that was fairly extensive after 1300 AD. Johann Sifard of Zwickau published an extensive 1605 catalogue of comets that was basically astrological (listing comets in history and their effects on mankind). Heinrich Eckstorm (1621) produced a comet catalogue somewhat longer than Lavater's that was heavily cited in the 17th century. A 258-page historical catalogue of comets by constellation and astrological significance was authored by Johann Praetorius (1665) along with tracts on the 1665 comet.

Mention is appropriate, in this context, of the two magnificent seventeenth-century catalogues published only a year apart by Lubienietz (1667) and by Hevelius (1668). There were some notable attempts by Hevelius in his catalogue to order comets by appearance, and the lavish illustrations of both catalogues certainly made an impression on those who perused the books. We know

[45] This was evidently intended for a published book, but I have not found such a book. Pingré (1783, p. 181) suggested that Mizauld's (rather strangely arranged) 1549 comet catalogue was based on Eber.

that Halley was familiar with these works in compiling observations for his 1705 work. Newton was likely also to have had familiarity with the catalogues of Lubienietz and Hevelius, possibly affecting his own comet work that was to appear in gradually revised form in his three editions of *Principia*. But neither Hevilius nor Lubienietz gave anywhere near the details that would appear a century later in Pingré's *Cometography* in terms of detailed discussions of earlier comets. Rather, the significance of the textual portions of both of their catalogues lay in the authors' own observations and published correspondence with other astronomers. Hevelius and Lubienietz themselves relied on published compilations by earlier authors such as Eber, Mizauld, Aretius, Lavater, Flock, Francesco Giuntini (1573), Christopher Ireneus (1578), Caesius, Hartmann, Elias Ehinger (1618), and Giovanni Battista Riccioli (1651) — to name a few.

Johann Zahn (1696) included a 52-page catalogue of comets observed through 1683 in his larger book that also included eclipses and novae. Zahn made extensive references in individual entries to authors of earlier cometographies. Where full catalogues were not published, authors often would give some partial lists (some rather extensive) of past comets for illustration of various points in the given tracts; examples of such "mini-catalogues" were included by Johannes Hebenstreit, Jr. (1556), Giuntini (1573), Ireneus (1578), Johann Richter Praetorius[46] (1578), Matthaeus Zeysius (1578), Caesius (1582?), Sebastian Koestner (1607?), Riccioli (1651), and Erhard Weigel (1661). But catalogues of comets would evidently not really advance the knowledge of comets — via critical comparison of one comet to another — until the appearance of Halley's orbit catalogue in 1705. Yet Halley (and likely also Newton) were influenced constructively by these earlier comet catalogues, which encouraged discussion and contemplation.

2.3. Late-Medieval and Early-Modern Star Catalogues

Prior to 1603, there were no convenient Bayer designations for the reference stars, and observers referred to the often-ambiguous catalogue attributed to the ancient Alexandrian astronomer Ptolemy (1515, the first printed edition; see also Peters and Knobel 1915) and/or the catalogue provided by Copernicus (1543) that was based on Ptolemy. The catalogues of Ptolemy and Copernicus both listed stars within each constellation by their location envisioned in a given part of that constellation — but without the benefit of accompanying illustrations. The first printed celestial star charts with constellation figures were those by Albrecht Dürer in 1515 (in which Johann Stabius and Conrad Heinfogel plotted the star positions); though additional constellation/star charts were printed in the following six decades — including those in 1540-1541 by Peter Apian in his *Astronomicum Caesareum* and elsewhere, by Johannes Honter, and by Alessandro Piccolomini in his *De le Stelle Fisse* (Wattenberg 1967, pp. 52-53; Warner 1979; Kunitzsch 1995; Whitfield 1995) — and elaborate celestial globes were being produced by Johann Schöner, Gemma Frisius, and Gerard Mercator around this same time (Lammens 2002, pp. 57-58, 126-131;

[46] This Praetorius lived from 1537 to 1616 (Thorndike 1941b, p. 59), compared to the author of the large 1665 catalogue, Johann Praetorius, who lived from 1630 to 1680 (Thorndike 1958b, p. 490).

Crane 2003; Short 2004).

The relatively poor star catalogues available to medieval and early-modern astronomers were part of the hindrance to acquiring useful data (and hindrance to standardization). Prior to the first printings of Ptolemy's star catalogue in the late fifteenth century,[47] star catalogues were only available in manuscript form, with all the incessant problems involved with typographical errors due to copying mistakes. One of the problems with star catalogues was the remarkable lack of a simple identifying scheme for the visible (naked-eye) stars. Ptolemy's famous catalogue in the *Almagest* was copied down through the Middle Ages, suffering from many transcription errors over the centuries. In his catalogue, stars are referred to simply according to their place in the perceived mythological images, projected onto the sky by way of named constellations. Thus, we have "the northernmost of the two stars in the right knee" of Pegasus, or "the star on the left upper arm" of Cassiopeia (Ptolemy and Toomer 1998, pp. 358 and 351). However, problems arose because there were no rules defining constellation boundaries or how figures were to be pictured on the sky. Though Schroeder had copied the star catalogue of Ptolemy (and Copernicus) with some precessional changes for 1550 and with a numbering scheme for each star within a constellation (Swerdlow 1986), Tycho and others did not follow Schroeder's scheme.

A good example of the problems that can arise concerns α Aur (Capella). Cornelius Gemma (1575, p. 115) gives this star as "clara in Hyrco", which Brahe (1602, p. 558) then lists as "claram Hirci" in his discussion of Gemma's observations (where the star's distance to B Cas is given). One might look in a dictionary and find the Latin word *hircus (hirci)*, meaning a goat (animal), but Capricornus is much too far away for the 42° distances reported by Gemma and Tycho. Johann Bayer's *Uranometria* (1603) is a good resource for alternate Latin and Greek names of constellations and stars. A quick look at a star atlas might cause one to check Cygnus, for which Bayer gives an alternate name as "Hirezim", but Deneb (the brightest star of Cyg) is only $\approx$ 36° from B Cas. Capella looks closer to the correct distance, and indeed Bayer gives "Hircus" as an alternate name for Capella. Copernicus (1543, p. 50) describes Capella as "in sinistro humero fulges qua uocant capella" — "the brilliant star on the left shoulder [of Auriga], which is called Capella" (Copernicus and Wallis 1995, p. 94) — which is similar to the descriptions in Ptolemy's *Almagest* (Peters and Knobel 1915) and in Tycho's *Progymnasmata* (Tycho 1610, p. 267; Dreyer 1916, p. 363). So only recourse to a source such as Bayer (or Allen 1963) would have made this obvious. Bayer himself likely made some use of Schöner's edition of Copernicus' star catalogue, published in the middle of the sixteenth century (Schöner 1551), for his star descriptions (Swerdlow

[47] The first printing of his *Almagest* was in Venice in 1515, but the star catalogue itself was extracted from the *Almagest* and published in Book XVII of a 1501 tome by Giorgio Valla, entitled *De expetendis et fugiendis rebus* and published in Venice (Swerdlow and Neugebauer 1984). Even earlier printed versions of the star catalogue were included with the Alfonsine Tables (Isaac ben Sid and Judah ben Moses ha-Cohen 1483, 1492; see Chabás and Goldstein 2003 for details). The available versions of Ptolemy's star catalogues prior to the late 16th century are listed by Truffa (2002).

1986).

A common method utilized occasionally by Maestlin, in which observers would refer to the stars of either the Ptolemaic or Copernican star catalogues, was to state the ordinal number of the star within a given constellation, so that the specific catalogue had to be (and still must be!) consulted. In his own copy of Tycho's 1588 *De mundi*, where there are tables of reference stars used by Tycho in his observations of the 1577 comet, Maestlin carefully inscribed two additional tables with the corresponding star numbers within the given constellation as provided in the star catalogues of Ptolemy and Copernicus — showing that even extra effort was needed then to keep the stars "straight". Maestlin was quite a serious astronomical observer, as attested by the fact that his copy of Copernicus' *De revolutionibus* is heavily annotated on the star-catalogue pages, with corrections to positions and even star descriptions.[48] Not unexpectedly, then, Maestlin can be found referring to the nth star of a constellation in his own treatise on the comet of 1577, possibly following Schroeder (though referring to Copernicus, who did not order his stars the same as did Ptolemy), while Tycho went on with his own variation of the Latin descriptions of where each star was imagined to be in a given constellation. He even varied his description in citing the stars used in his astrometry for the comet of 1577; for example, the star ϵ Pegasi is noted sometimes as the mouth/muzzle of Pegasus (os Pegasi) and sometimes as the nose (narem Pegasi). The mere fact that such a cumbersome system existed for star designations reflects the low state and lack of astronomical observations.

Neither was Tycho very consistent in how he referred to stars, and in fact he was quite sloppy and careless in many places (Dreyer, III, MS). This is a problem even when sifting through his observations of comets, as he tended to abbreviate many of his star references/designations and even use different words for the same star (nose *vs.* mouth, for example, as noted above). Even Bayer's famous *Uranometria* star atlas, published in 1603 — which was evidently based on Tycho's new star catalogue that had appeared in *Progymnasmata* the previous year [49] — is often difficult to correlate in connection with star references to parts of constellations by the observers of that time. And most observers, even if aware of Bayer's atlas, did not use Bayer's convenient Greek-letter designation system for stars for many decades after its publication — indicating how hard it can be to replace an old, established (even if awkward) way of doing things. And, as revolutionary and useful as Bayer's atlas was for observers, it still contained numerous mistakes and some very confusing placements of stars (brighter stars missed, fainter stars included).

[48] Maestlin's heavily annotated copy of the 1588 tract is located in the British Library under shelfmark C.61.C.6. Maestlin was evidently one of the most careful readers of astronomy texts of that era, having also heavily annotated his copy of Copernicus' *De revolutionibus* (Gingerich 2002a). See also footnote 30.

[49] The *Progymnasmata* contained only 777 stars, but Bayer is thought to have used Tycho's expanded catalogue of 1004 or 1005 stars, which was only available in manuscript form until its full publication in 1627 via Kepler's *Tabulae Rudolphinae*. For discussion on this, see Dreyer (1890, p. 266) and Thoren (1990, p. 299) and references therein. Truffa (2002) has noted that the catalogue of 1004 stars was printed in 1604 in a little-known commentary on the Sphere of Sacrobosco by Francesco Pifferi.

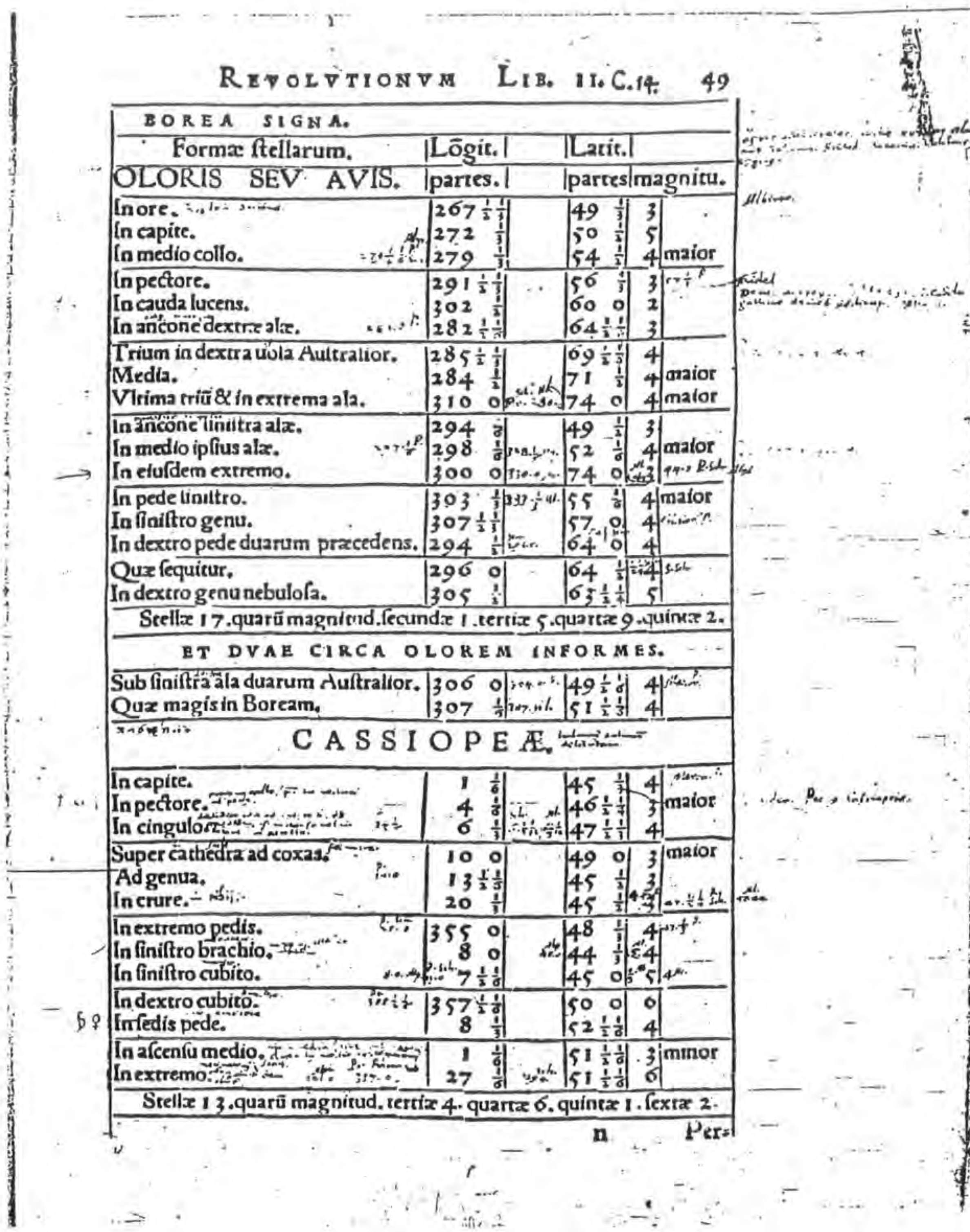
To illustrate the confusion that must have also been sometime confronted by early-modern observers with the available catalogues, Bayer's assignment of the designations h and χ Per in the vicinity of the double open cluster, for example, was taken through most of the last century by astronomers (*e.g.*, Alter *et al.* 1970) to be those two clusters (NGC 869 as h Per, and NGC 884 as χ Per). However, it has recently been shown by Steve O'Meara and me that χ Per was likely to have been taken by Bayer to be the combined light of both open clusters (NGC 869 and NGC 884), while h Per seems likely to have been a sixth-magnitude combination of two stars (that blend as one to the naked eye) located 20′ to the west of the center of NGC 869, on the fringe of the cluster's halo of unresolved starlight (O'Meara and Green 2003). The "nebulous mass on the right hand" of Perseus had been catalogued at the location of the double cluster since antiquity, by way of Ptolemy (Jones 1968; Ptolemy and Toomer 1998, p. 352). But pre-telescopic astronomers did not understand why a "star" would be "nebulous" or diffuse (though some may have guessed that a grouping of faint stars would do the trick). The point here is that problems were introduced regularly that would cause identification problems for both observers and later analysts in terms of star identification, and the problems became more acute for fainter stars, as emphasized by Baily (1835, p. 401): "Indeed it would have been much better had Bayer himself limited his notation to a few of the first letters of the Greek alphabet, so as to have excluded all stars below the 4th or 5th magnitude; since the smaller stars were very likely, especially in his day, to be mistaken one for the other: even as we now find to be the case when we attempt to identify some of his stars."

Figures 2.1a and 2.1b show pages for the stars of the constellation Cygnus from Copernicus' and Tycho's star catalogues, respectively; Tycho has remeasured all of the star positions and precessed the longitudes forward to 1600. But notice how different the descriptions of the individual stars are between the two catalogues. Flamsteed even later got in a heated dispute with Halley over the proper classical references to the naked-eye stars (Baily 1835, pp. 286-288).

Another problem with Copernicus' star catalogue, of which users need to be wary, is that Copernicus simply subtracted 6°40′ from the longitudes of all of the already-precessed values,[50] so that the first star in Aries lies at longitude 0°00′ rather than at 6°40′. Tycho adopted a point for the vernal equinox, rather than a star; he found the first star in Aries "to be too faint to be conveniently observed by moonlight" anyway (Dreyer 1890, p. 350). Thus, positions from most observers in the late sixteenth century (other than Tycho, who was preparing his own astrometric star catalogue) cannot be mixed with the observations of Tycho's without correction for longitudes (and, of course, there were other sources of error involved). It is thus best to work with pure distance measures from stars if one wants to derive useful positions in modern assessments of the sixteenth-century data.

[50] The precession amount was 27°35′ from Ptolemy's catalogue; cf. Swerdlow and Neugebauer 1984, and Swerdow 1986.

Figure 2.1a. Page 49 from Copernicus' 1543 De revolutionibus*, showing the section of his star catalogue for Cygnus ("Oloris sev avis"). This taken from Maestlin's annotated copy of the book*



REVOLUTIONUM LIB. II. C.14. 49

BOREA SIGNA.

Formæ ſtellarum. OLORIS SEV AVIS.	Lõgit. partes.	Latit. partes	magnitu.	
In ore.	267 ½ ⅓	49 ⅓	3	
In capite.	272 ⅓	50 ½	5	
In medio collo.	279 ⅓	54 ½	4	maior
In pectore.	291 ½ ⅓	56 ⅓	3	
In cauda lucens.	302 ½	60 0	2	
In ancone dextræ alæ.	282 ½ ⅓	64 ½ ⅓	3	
Trium in dextra uola Auſtralior.	285 ½ ⅓	69 ½ ⅓	4	
Media.	284 ½	71 ½	4	maior
Vltima triũ & in extrema ala.	310 0	74 0	4	maior
In ancone ſiniſtra alæ.	294 ⅙	49 ½	3	
In medio ipſius alæ.	298 ⅙	52 ⅙	4	maior
In eiuſdem extremo.	300 0	74 0	3	
In pede ſiniſtro.	303 ⅓	55 ⅙	4	maior
In ſiniſtro genu.	307 ½ ⅓	57 0	4	
In dextro pede duarum præcedens.	294 ½	64 0	4	
Quæ ſequitur.	296 0	64 ½	4	
In dextro genu nebuloſa.	305 ½	63 ½ ¼	5	

Stellæ 17. quarũ magnitud. ſecundæ 1. tertiæ 5. quartæ 9. quintæ 2.

ET DVAE CIRCA OLOREM INFORMES.

Sub ſiniſtra ala duarum Auſtralior.	306 0	49 ½ ⅙	4	
Quæ magis in Boream.	307 ⅓	51 ½ ⅓	4	

CASSIOPEÆ.

In capite.	1 ⅙	45 ⅓	4	
In pectore.	4 ⅙	46 ½ ¼	3	maior
In cingulo.	6 ⅓	47 ½ ⅓	4	
Super cathedra ad coxas.	10 0	49 0	3	maior
Ad genua.	13 ½ ⅓	45 ½	3	
In crure.	20 ⅓	45 ½	4	
In extremo pedis.	355 0	48 ⅓	4	
In ſiniſtro brachio.	8 0	44 ⅓	4	
In ſiniſtro cubito.	7 ½ ⅙	45 0	5	
In dextro cubito.	357 ½ ⅙	50 0	6	
In ſedis pede.	8 ⅓	52 ½ ⅙	4	
In aſcenſu medio.	1 ⅙	51 ½ ⅙	3	minor
In extremo.	27 ⅙	51 ½ ⅙	6	

Stellæ 13. quarũ magnitud. tertiæ 4. quartæ 6. quintæ 1. ſextæ 2.

n Per-

Figure 2.1b. The stars of Cygnus from Tycho Brahe's star catalogue (taken from Dreyer, III, 360).

FLAM-STEED	BAY-ER	DENOMINATIO STELLARUM	Longitud. S.	Longitud. G.	Longitud. M.	Latitud. G.	Latitud. M.		Mag.	
		CYGNVS.								
6	β	In rostro	♑	25	44	49	2	B	3	
12	φ	In capite	♑	29	20	50	42	B	5	18v
21	η	In medio colli	♒	7	33	54	19	B	4	
37	γ	In pectore	♒	19	25	57	9½	B	3	
50	α	In cauda	♒	29	53½	59	56½	B	2	
18	δ	Prima et lucidiſ. in ancone super. alæ	♒	10	53	64	28	B	3	
13	ϑ	Trium in ſuperiori uola, auſtralis	♒	13	21	69	42	B	4	
10	ι^2	Penultima superioris alæ	♒	12	39½	71	31	B	4	
1	κ	Extrema superioris alæ	♒	9	36⅓	73	50½	B	4	
53	ε	Quæ in ancone inferioris alæ	♒	22	9½	49	26	B	3	
54	λ	In medio ipsius	♒	24	18	51	41⅓	B	4	
64	ζ	Extrema inferioris alæ	♒	27	43	43	44	B	3	†
58	ν	Præcedens in infimo pede	♓	0	32	54	59	B	4	
62	ξ	Quæ sequitur in infimo genu	♓	5	21½	56	36	B	4	
30	o^1	Auſt. et præc. duar. contig. in ſup. pede	♒	22	50	63	37	B	4	
32		Sequens earundem et borealior	♒	24	34½	64	17½	B	4	
65	τ	Inferior duar. infor. dex. alam sequens	♓	3	3½	50	33	B	4	
67	σ	Superior earundem	♓	4	53½	51	31	B	4	
78	μ	In extrema dextra ala Cygni	♓	4	33	38	39	B	4	†
13 Lyræ		Infer. præc. duar. infor. int. ly. et sup. alam Cygni	♑	19	57	66	15	B	4	
16 Lyræ		Superior earundem	♑	24	49½	68	52	B	4	
		INFORMES STELLULÆ CIRCA HUNC ASTERISMUM.								
16	c	Trium in superior. alâ Cygni infima	♒	13	31	69	35	B	6	
		Prima in infer. alâ Cygni	♒	28	44	25	11	B	6	
2 Pegasi		Quæ in inferior. eius femore	♒	28	22	35	35	B	6	†
42		Vltima in inf. alâ Cygni	♒	18	15	53	12	B	6	
16	c	Quæ in ſuper. alâ Cygni	♒	13	18	69	42	B	6	†
		CASSIOPEA.								
17	ζ	In capite	♈	29	35	44	40½	B	4	
18	α	In pectore, Schedir	♉	2	17½	46	35½	B	3	
24	η	In cingulo	♉	4	38	47	5	B	4	
27	γ	In flexura ad coxas	♉	8	27½	48	46	B	3	

Ad

2.4. Issues Involving Time and Clocks

The whole issue of timekeeping is a problem with medieval and early-modern astronomical observations: not only was clock time problematical, but dates were also a problem. Observers of astronomical phenomena through the European middle ages were often careless about recording dates of observation, and in the sixteenth century we still find vague references to dates concerning observations of comets. For example, Gemma Frisius observed the comet of 1533, but we have limited information such as "about the beginning of July, in the 5th degree of Gemini . . ." (Kokott 1981, p. 100). And the orbit computer working with observations of comets in the late-sixteenth and seventeenth centuries must be aware of the change from Julian to Gregorian calendar, which was undertaken much later in Protestant countries (and in rather haphazard manner) than in Roman Catholic countries (where the introduction theoretically began in Oct. 1582).

The issue of typographical errors is constantly an issue that the astronomical analyst must consider — whether dealing with observations of centuries ago or with observers today. Late-medieval and early-modern astronomers certainly made their share of mistakes, both in manuscript logbooks or paper at the telescope and in printed, typeset form later. Frequent mistakes are noticeable to the reader of books from that era. While astrometric mistakes are more common in pre-electronic-computer records than they are today, date and time errors seem to transcend all time and place. The date was more of an issue in late-medieval and early-modern times because of such issues as a lack of standardization regarding clock time — whether days were counted from midnight or noon or sunset — and because of the introduction of the Gregorian calendar (which was accepted in different countries in different years).

Clocks in the sixteenth century were still in a fairly primitive state. Early in the century, Bernard Walther was evidently the first astronomical observer to make note of using "a well regulated clock" for his observations (Beaver 1970). We now know that Regiomontanus (observing a couple of decades prior to Walther) obtained timings of eclipses that were good to within ± 15 min, while Walther's timings were good to within ± 18 min (Steele 1998, 2000). Several decades later, Tycho Brahe was very concerned about clocks and proper time. The installation of mechanical astronomical clocks had become fairly widespread by the sixteenth century, particularly in large city churches and cathedrals. In Tycho's travels as a student, he no doubt came into contact with such astronomical clocks and probably contemplated their function. For example, a very notable two-story astronomical clock (with two clock faces, one portraying a perpetual calendar) was constructed in 1472 at the Marienkirche in Rostock (*e.g.*, Dehio 1968), a city where Tycho spent some considerable time as a student (*cf.* Thoren 1990, 22-29). The inaccuracy of clocks even in later medieval times was underscored by the fact that the division of clock faces to minutes was not to become commonplace until after the introduction of the pendulum clock, ca. 1657 (Andrews 1994). David Landes (1983, pp. 103-105) provides some discussion and useful references regarding clock problems facing Tycho and his observing contemporaries.

The Landgrave of Hesse, Wilhelm IV, an observer much respected by Tycho, was in frequent

correspondence with the Dane in the 1570s and 1580s regarding assessments of observations of all objects celestial, including especially comets. Following a 1575 visit by Tycho to the Landgrave's private observatory, Wilhelm was persuaded to hire some assistants, and he got two very capable men in Christoph Rothmann and Jost Bürgi. Prior to this, Wilhelm had actually devised and constructed a mechanical astronomical clock (Herrmann 1976), and his positional measurements of the comet of 1577 are accompanied by time measurements that are sometimes given to a quarter of a minute (Dreyer, IV, 183).

Bürgi (1552-1632) became well known for his good craftsmanship in constructing clocks as well as other astronomical instruments (Nový 1970). Baillie *et al.* (1956) suggest that Bürgi was the foremost among clockmakers prior to the application of the pendulum to clocks in the mid-17th century, as he "invented a most ingenious form of cross-beat escapement with two cross-beating foliots, which attained an accuracy of time-keeping within a minute a day", and "he achieved standards of accuracy in tooth-cutting and general finish which were hardly surpassed for the next two hundred years". The accuracy of his clocks is borne out in Wilhelm's observations, as I show in Chapter 8 for the comet of 1577. An example of one of Bürgi's clocks is pictured in Figure 13 of Landes (1983). Despite a statement made in a 1680 publication that Tycho had one or more clocks made by Bürgi, Dreyer (1890, p. 324) disputes this, saying that "he would not have neglected to describe so important an addition to his stock of instruments". However, Baillie *et al.* not only suggest that Tycho used Bürgi clocks, they claim that "an unaltered specimen survives in the Danish National Museum at Copenhagen". It is possible that Tycho obtained one or more Bürgi clocks in the 1580s or 1590s, but it seems true that he did not have such a clock when the comet of 1577 made its appearance. Tycho only briefly discusses his clocks in his *Mechanica*: "One of these [four clocks], the largest, manages the whole business with the aid of three wheels, of which the largest, cast from solid pure brass, has 1200 teeth. The diameter of this wheel is [78 cm], from which the rest can be calculated. The three other clocks are smaller, and need more wheels" (Ræder *et al.* 1946, p. 30). Tycho states that he had clocks at his mural quadrant that gave "not only the single minutes, but also the seconds, with the greatest possible accuracy" (Ræder *et al.* 1946, p. 29); he was obviously in bragging mode in *Mechanica*, to the point of exaggeration.

But Tycho knew that he had significant problems with his clocks — though that did not stop him from working with the clocks and recording times of observations diligently. Dreyer (1890, p. 324) notes that Tycho owned three or four clocks, saying "he does not anywhere describe them in detail, while he in several places remarks that he did not depend on them, as their rate varied considerably even during short intervals". Tycho often made corrections to the clocks before observing in the evening, by resetting the clock to the setting sun — whose time of setting was ascertained from ephemerides, quite possibly those of Johannes Stadius (1560), whose volumes Tycho is known to have owned (Norlind 1970, p. 363).

Though Thoren (1990, p. 123) says that Tycho obtained a clock in the spring of 1577 that displayed hours, minutes, and seconds, such a clock evidently did not keep very good time; Thoren

adds that the first clock was inadequate, and Tycho acquired three more clocks in the next four years. The errors sometimes accumulated into hours in only a few days, and "it soon became part of Tycho's routine to reset the clocks by the noon sun and record the error every day" (*ibid.*, p. 158). Even after the clocks were adjusted to better rates, the daily drift might be as little as a few minutes, though frequent 20-minute gains or losses were common. Dreyer (IV, MS, p. 5) observes that in 1578,

> *[Tycho had not yet] realized that his clocks were not good enough to allow him to measure differences of Right Ascension by observing the time of transit over the meridian. In the autumn of 1581 he gave the method a thorough trial, observing the transits of the 12 stars used with the comet [of 1577] and some others over the meridian, by means of two different clocks (cf. T. X, pp. 110 sqq), but after that he abandoned this method altogether.*

Tycho probably realized, then, that distance measures using reference stars were *the* most reliable method of doing astrometry for obtaining positions of comets, "new stars", and planets — as well as for star positions in his new catalogue. He knew that altitude/azimuth (or 'altaz') measures were too dependent on clock time, and thus not "absolute". John Steele (1998, 2000) has shown that Tycho's eclipse timings during 1577-1600 were sometimes off by as much as ± 13 min — only a slight improvement in a century's time over what Regiomontanus had accomplished. Tycho kept building and refining his instruments, but by the time of the 1580 comet's appearance, astrometric measurements were still being made with both an astronomical radius and a sextant — the typical difference in celestial positions ranging from 10′ to 30′!

When European astronomers first observed the comet of 1577, it was moving particularly rapidly across the sky: around 4°/day, or 8′-10′ per hour in the first few days that he viewed it. Note the large residuals in Wilhelm's ecliptical measurements of the comet on Nov. 11 in Table 8.1. Also, when Tycho's assistants were measuring star positions for his catalogue (to be published eventually in Tycho's *Progymnasmata*), they got to the point where they could obtain something like one sextant distance measure for every five minutes (or twelve per hour), and this was when numerous assistants were available to make the sighting, to read the angles and clock(s), and to record the results in the logbook (cf. Thoren 1990, pp. 201, 296). The length of time needed to obtain comet/star distance measures for the comet of 1577 may also have been a factor in properly (or improperly) recording the clock times. A lone observer had to observe, use a lantern to read angles, and record times and distances all by himself. One can imagine the increased potential for errors involved in doing all this without assistants to help.

Maestlin used a weight-driven clock for his observations in 1577; Jarrell (1971, p. 90) states that while "the accuracy of his clock is impossible to assess, . . . [Maestlin] seems to have been pleased enough with it as it was employed for a great number of observations after 1577, particularly for eclipses". One must still assume that his clocks were not more accurate than were

Tycho's, and Maestlin surely could not afford Bürgi clocks. In his treatise on that comet, Maestlin provides quite a number of comet-star distance measures, together with careful noting of all times of observation (he being one of the few who had adopted time recording as important with the comet of 1577).

Until the late 18th century, local mean time appears not to have been used much in Europe — with local solar time used and adjusted as needed during the year. The British astronomer Flamsteed did produce tables around 1670 for conversion of clock time to mean solar time (Griffiths 1994), but it seems that even astronomers generally recorded local solar clock times for their celestial observations during much of the following century. Indeed, apparent solar time continued to be used as long as accurate time could only be obtained by direct astronomical observation (*i.e.*, due to the insufficient precision of mechanical clocks), with determinations of local apparent time being commonly made by observing the altitudes of stars or the sun. Until early in the nineteenth century, the various annual national ephemerides published the apparent solar time data, and mean time could be computed by applying the equation of time to the apparent time (Seidelmann *et al.* 1992). Geneva introduced the first formal adoption of mean civil time in 1780 (Macey 1994, p. 443). Note also that astronomers frequently (but not always) counted their days from noon — particularly in the 18th and 19th centuries — until the practice was changed in 1925 to starting at midnight.

Figure 2.2. Drawing of Peter Flemløse showing himself using the steel sextant at Hven (from Dreyer, X, 67).

Chapter 3: Morphological and Photometric Information on Comets

3.1. Basic Anatomy of a Comet

Comets continue to be distinguished from asteroids upon discovery due to their display of a *coma*, or atmosphere, and possibly a *tail* (or streamers or jets, which are typically small tails) that points generally (but not always) in the anti-solar direction (in fact, jets — which are small features close to the comet's nucleus — protrude from the nuclear region in almost any direction, especially the solar direction). Comets also usually show an increasing density of light toward the center of the coma (which is also the location from which tails appear to emanate); sometimes this condensation will appear disklike or even starlike, and it is this appearance that gave rise to the term "nucleus" already hundreds of years ago, when it was thought that this condensation might refer to a planetary object that underlies the comet's activity. Already in 1687, Isaac Newton suggested in his *Principia* that *"the bodies of comets are solid, compact, fixed, and durable, like the bodies of planets. For if comets were nothing other than vapors or exhalations of the earth, the sun, and the planets, this one [the comet of 1682] ought to have been dissipated at once during its passage through the vicinity of the sun"* (Newton *et al.* 1999). But due to the intense presense of inner coma dust and gas near the true comet nucleus, the actual nucleus of a comet is rarely (if ever) detected from the earth (A'Hearn 1988; Jewitt 1991, and references therein); this concept has been discussed for more than a century (*e.g.*, Boss 1882, *p.* 3). The usually-central condensation is sometimes referred as a "false nucleus". This "false nucleus" is extremely variable in appearance as viewed through different instrumentation — as one goes from large apertures and/or focal ratios to lower apertures and/or focal ratios in the observing telescopes (Steavenson 1956; Green 1996b). Comet C/1983 H1 (IRAS-Araki-Alcock) passed within 4×10^6 km of the earth in May 1983; though radar bouncing off the comet's nucleus suggested a size of only around 1 km, the highest-resolution optical images showed only a "planetary disk" of size $\sim$ 25 km, without the phase effect normal seen in planetary disks — and thus showing that we were seeing only an optically-thick sphere of solid particles close to the nucleus (A'Hearn and Festou 1990).

The actual nucleus is quite small with respect to the coma, the former being evidently only one or a few kilometers across in most cases, and the latter being anywhere from thousands to millions of kilometers across (depending on distances from the sun and earth, on the size of nucleus and number of active areas on the nucleus, and on observed wavelength). One can rightly think

of a comet as a small (or minor) planet in its own right, with the coma being a generally quasi-temporary atmosphere. Several cometary nuclei have been imaged and resolved in recent years, beginning with 1P/Halley during the March 1986 flybys of the *Giotto* and *Vega* spacecraft (*e.g.*, Keller 1990a). The nucleus of Halley's comet was larger ($\approx$ 8 km $\times$ 8 km $\times$ 15 km in size, sort of shaped like a peanut or potato) and darker (albedo $\simeq$ 0.04) than expected, and it contained many visible features in the *Giotto* imagery, including a "crater", "chain of hills", "mountain", and bright jets of dust and gas emanating from localized vents generally in the solar direction (Keller 1990b). Rotation also appears to play an important role in cometary nuclei, but such motion may be quite irregular for non-spherical nuclei (see the review by Sekanina 1990). *Giotto* scientists studying visible-light images identified 17 separate dust filaments emanating from various sites on the comet's nucleus, the vast majority of activity occurring on the sunward side of the nucleus (as expected), but only about 10 percent of the total surface seemed to be active — suggesting that a non-volatile mantle of material covers most of 1P/Halley's nucleus. The overall density of the cometary nucleus is unknown, but it is thought to be between $\approx$ 0.2 and 1.0 g/cm^3 (where the density of water ice is 1 g/cm^3). A large fraction of cometary astronomers believe that the average comet has a density in the range 0.2-0.6 g/cm^3, and Fred Whipple has likened this density to that of a "popcorn ball". However, there are comets that may well have overall densities $\geq$ 1.0 g/cm^3, and it is likely that comets actually span a rather wide range in overall densities — with actual densities in a single comet nucleus perhaps varying throughout the nucleus, due to the collection of various sorts of ices, rock, and dust (see Klinger *et al.* 1996).

As a comet approaches the sun, the increasing effect of the solar radiation causes the comet's ices to sublimate and be spewn outward from the nucleus at velocities around 1 km/s; this material is composed of gases and accompanying dust and small "rocks" being sent directly into the expanding atmosphere, or cloud, surrounding the nucleus and known as the coma. Observations have yielded an overall gaseous "production rate" for 1P/Halley-type comets (at 1 AU from the sun) of $Q \sim 3 \times 10^{29}$ molecules per second, and a comparable rate of dust (corresponding to $\sim$ 10,000 kg per second). The density of the gas close to the comet's nucleus is estimated in this case to be near 3×10^{12} molecules per cubic centimeter (compared with $\sim 10^{19}$ molecules/cm^3 in the terrestrial atmosphere near the earth's surface), dropping to $\sim 10^6$ molecules/cm^3 at 5000 km from the nucleus; the temperatures of this material ranges from $\sim$ 20 to 200 K ($-250°$ to $-75°$ C, or $-425°$ to $-100°$ F; Arpigny 1994; Shimizu 1991; see also A'Hearn and Festou 1990). The size of a comet's coma at visual wavelengths may exceed 100,000 or even 1,000,000 km in size; comet C/1995 O1 (Hale-Bopp) sported a 3-million-km coma at visual wavelengths in late October 1996. In addition, when a comet is within 1 AU of the sun, there is a large hydrogen coma (presumably from dissociated water molecules) visible at ultraviolet wavelengths that may extend to as much as 1-10 million km from the comet's nucleus (Feldman 1991).

As with any astronomical object, a comet appears different at different observed wavelengths, because different aspects of the comet (gas and dust) are responsible for its appearance at any given wavelength. It is thought that the majority of visible radiation detected by the human eye

is due to emissions in the comet's coma that come from dust (as reflected sunlight) and from the fluorescence of certain gaseous molecules, chiefly C_2 (diatomic carbon), but also C_3, CN, and CH (Bobrovnikoff 1951; see the spectra of 1P/Halley in the visible wavelength range by, *e.g.*, Rettig *et al.* 1986 and Moreels *et al.* 1987); the well-known Swan-band series of C_2 lines ($d^3\Pi_g$ — $a^3\Pi_u$ transition, in the terminology of molecular spectroscopists) occurs in the range 434-676 nm (Arpigny 1995). Both reflected sunlight off of comet dust and fluoresced emission from comet molecules represent what the eye sees in a comet's coma, and there is no definite edge to the coma; rather, the coma drops off gradually into the sky background, with the dust component usually dropping off more rapidly than the gaseous component (Swings and Haser 1956, p. 9). In fact, it is the intense Swan bands of diatomic carbon that determine the visual diameter of the coma when a comet is within a heliocentric distance of ~ 1-2 AU. The continuum (or dust-reflected solar spectrum) is very strong in the region of the Swan bands, and as Swings and Haser (1956, p. 17) note, "depending on the relative intensities of the solar continuum and of the Swan bands, the color of the comet [to the human eye] will be from blue-green to yellow". Ralph Copeland and J. G. Lohse found from comet spectra that the human eye could only detect spectral features from 419 to 670 nm (4190-6700 Å), giving an idea of the limit of spectral sensitivity of the human eye. Spectroscopy shows that the strong CN emission in comets seen near 3800 Å generally extends the furthest of any species from the nucleus in the optical range. The dust component (continuum) generally remains quite close to the nucleus in spatial extent, with emission from gaseous CH and C_3 extending a little further out.

The comet's tail, formed mostly as a result of the coma material meeting the solar wind particles and being swept anti-sunward by magnetic and dynamic pressures, may also be found present around other planets (large and small) in the solar system, though not so obviously present at visible wavelengths. Dust particles released from the comet's nucleus do not always lag anti-sunward, because they are not affected by the magnetic properties of the solar wind in the manner that the gaseous particles are so affected, and they move much more slowly (on the order of 1 km/s or less). Gaseous tails tend to be more straight, with abrupt kinks often visible due to sudden changes in local properties of the solar wind with respect to the cometary material (see Figure 3.1); such material in the so-called plasma tails moves away from the comet's nucleus at velocities in the range 20-250 km/s (*e.g.*, Niedner 1981; Wyckoff 1982; Brandt 1990).

Figure 3.1. Photograph of comet C/1893 U1 (Brooks) taken by E. E. Barnard at Lick Observatory with the 6-inch Willard lens on 1893 Oct. 21-22 (Barnard 1913, Publ. Lick Obs. **11***). North is up and east to the left. The image shows a prominent kink in the comet's ion tail due to interaction with the solar wind.*

Figure 3.2. Photograph of the bright comet C/1975 V1 (West), taken by Thomas L. Rokokse (in my presence!) from Deep Gap, North Carolina, through thin clouds on the morning of 1976 March 4. The 25°-long tail seen here was not very dissimilar to the naked-eye view. Synchronic bands are visible in the original photograph.

At the time of closest approach to the earth, comet C/1996 B2 (see Figures 1.1, 8.8, and 8.9) showed to the naked eye (for an observer far from artifical light pollution, thus more what ancient and medieval observers would have experienced in terms of observing conditions) a bright, starlike nucleus surrounded by a concentric tenuous, "vapory halo" or coma that extended to a diameter of some 2° or more (several times the apparent diameter of the moon), and this in turn was accompanied by a southward tail that extended a third or more of the distance across the sky (tail length $> 65°$). Records suggest that such long observed comet tails are very rare, occurring not more than once or twice a century at best.

Dust tails tend to be more or less strongly curved, with the motions of the dust-tail particles moving as a result of the comet nucleus' orbital motion about the sun, of the manner and degree of release from the cometary nucleus, of collisions with other cometary particles, and of momenta imparted to the dust particles by solar radiation pressure; such tails seldom show any structure, but there are prominent exceptions — such as comet C/1975 V1 West; O.S. 1976 VI = 1975n (see Figure 3.2) — that have contributed much to our knowledge of dust tails through such features as striae — up to two dozen practically-straight bands of light stretching across the tail background, which may be due to fragmentation of grains in the tail (Sekanina 1976, 1981). Larger dust particles move slower and remain closer to the comet's nucleus longer; they appear in more highly curved dust tails and can form such visible features as the so-called "anti-tail", which is visible in many comets generally when the earth passes through the orbital plane of the comet (*e.g.*, Sekanina 1976a), and so one views the dusty material in the plane of the comet's orbit edge-on (see Figure 3.3). This occurs around the time when the ecliptic longitude of the earth[51] is the same as either the ascending or descending node of the comet (these terms are defined in the next section); for a comet with high orbital inclination, this may restrict the visibility of an anti-tail to a few days on either side of comet-plane passage, though a comet with low orbital inclination can theoretically exhibit an anti-tail for a much longer period of time (as the earth lingers longer near the comet's plane). The anti-tail is composed of heavy dust particles as large as 0.1-1.0 mm that evidently left the nucleus 2-3 months prior to observation, whereas the "normal" dust tail is composed of small particles that left the comet's nucleus recently (Grün and Jessberger 1990).

[51] One can ascertain the earth's longitude from the tables of solar longitude in the annual *Astronomical Almanac*, published by the U.S. Government Printing Office and by HMSO, London; the earth's ecliptic longitude is 180° more or less than the solar longitude.

Figure 3.3. Photograph of comet C/1962 C1 (Seki-Lines) taken by Alan McClure from Frazier Mountain, California, with a 5.5-inch f/5 Zeiss triplet aerial lens and panchromatic plates; 15-min exposure beginning 1962 Apr. 23.18 UT. Note the ion tail pointing to upper left, the more diffuse dust tail pointing straight up, and the expansive, stubby anti-tail pointing downward.

Figure 3.4. Photograph of comet 17P/Holmes taken in Nov. 1892 by E. E. Barnard (1913, Publ. Lick Obs. **11***, Plate 104). The 4th-magnitude galaxy is at the bottom. The comet is the roundish dense object near the top. There are a couple of streaks emanating from the bottom of the comet and the top of M31 that are plate defects.*

Not all comets show tails. And some comets show noticeable tails at large heliocentric distances; comet C/1987 H1 (Shoemaker) showed a tail longer than 1,200,000 km at $r = 7.65$ AU, and numerous other comets have exhibited tails beyond $r = 9$ AU (Meech 1991). When within 1 AU of the sun, comets can exhibit tails as long as 1 AU or more (hundreds of millions of kilometers), but such comets are rare (Biermann and Lüst 1963). Comets occasionally show tails longer than 20° across the sky to earth-based observers, but this also is rare (about one comet every 10-15 years). In principle, a comet's tail on the sky cannot exceed its phase angle (see section 2.5.1). Dust "trails" extending up to 48° of the sky have been observed trailing some short-period comets at infrared wavelengths (25-60 μm); these trails are thought to be large dust particles that may last in their narrow trails of debris for hundreds of years (Grün and Jessberger 1990).

We know from the spacecraft flybys of Halley's comet in 1986 that dust particles ranging from 100 nm (about the size of the wavelength of visible light) to several millimeters are present in the comet's inner coma, and it is anticipated that dust "clumps" or "rocks" up to tens of centimeters are ejected from the comet's nucleus via the gas jets (Grün and Jessberger 1990). The instruments on the *Vega* and *Giotto* spacecraft detected two principle particle types: (1) those rich in the elements H, C, N, and O; and (2) those rich in silicates (Mg, Si, and Fe). From the earth, it is difficult (but not impossible) to detect the "parent" molecules (those assumed to be present in the actual nucleus prior to sublimation) in the coma, because solar radiation breaks such parent molecules very quickly into "daughter" molecules; the parent molecules have spectral signatures that show up at infrared and radio wavelengths, but not at visible wavelengths (Arpigny 1995). The metals observed in comets include Na, K, Ca, V, Cr, Mn, Fe, Co, Ni, and Cu; other atoms seen in cometary spectra include sulphur. Diatomic molecules in comets include CH, CO, CN, C_2, CS, OH, NH, S_2, $^{12}C^{13}C$, and ^{13}CN; those molecules with three or more atoms include H_2O, CO_2, NH_2, HCN, C_3, H_2CO, HDO, CH_3OH, HNC, CH_3CN, H_2S, OCS, and NH_3 (A'Hearn and Festou 1990; Arpigny 1994).

The gas tail of a comet has ionized atoms and molecules — OH^+, H_2O^+, and H_3O^+ being seen closer to the comets nucleus, and H^+, O^+, and C^+ being seen further away (as photodissociation and photoionization of the molecules and atoms continues as each species moves further away from the inner coma to increased interactions with the solar wind). For example, the C^+ observed in comet tails may come from the photodissociation of CH, CH_2, CO, and CO_2 neutral molecules in the coma (Ip and Axford 1990). A tricky problem for cometary astronomers is determining which are parent molecules, which are daughter molecules, and how each observed species is formed. In the 1990s, it is thought that most comets have their "parent" nuclear ices dominated by water (constituting some 80 percent of all volatile ices), followed by CO_2 and CH_3OH around the 1- to 10-percent level, and thereafter in much smaller quantities by CH_4, NH_3, HCN, N_2, and some sulfur-based molecules; CO and H_2CO are present roughly the 1- to 15-percent level in the inner coma and have been considered as parent molecules, but observations suggest that they are in fact released from the CHON particles after leaving the cometary nucleus (Arpigny 1994). It is clear that comets vary markedly in their dust-to-gas-production ratios, and while comets appear

generally to share the same constituent molecules, the abundances in those molecules seem to vary widely from comet to comet. Much discussion in recent years has surrounded the suspicion that CO or CO_2 may be a dominant factor in driving the activity in many comets, particularly at large heliocentric distances where it is thought that water ice cannot sublimate (but where many comets show 'active' comae).

The Swan-band emission of C_2, which generally defines the visual (naked-eye) coma when comets are at $r < 1$ AU, extends well beyond that of C_3, but not as far from the nucleus as that of CN (Swings and Haser 1956). Towards the blue, the solar continuum drops off steadily in strength, allowing one to clearly see the strong OH emission at 300-314 nm and the NH emsssion near 335.8 nm. The strongest features in the optical spectra of comets are the emissions due to OH, CN, and the Swan band of C_2 (Arpigny 1994).

3.2. The Human Eye as a Light Detector

The human eye is a remarkable detector, superior to any artificial light-detection instrument in terms of dynamic range of spectrum and light intensity combined. Visual observers today opt for direct viewing because of the low monetary costs involved; the simplicity of transport, set-up, and storage of supporting small-aperture instrumentation; and/or the fun and challenge of observing comets directly, whether for making serious scientific measurements or not. But prior to the 19th-century invention of photography, the visual observation of comets was the only way to obtain direct information on them. While this is not the appropriate place for a detailed discussion of the human eye as an instrument, a brief overview is offered here because of the importance in understanding the detection mechanism behind viewing comets.

The retina is that inner part of the eye that converts incoming light into chemical energy that activates nerves, which in turn conduct messages to the brain for interpretation (Davson 1985). The human eye has four types of cells that serve as photoreceptors: rods, which are "color-blind" detectors of low-light levels (as used in astronomy at night); and three types of "cones" (blue, green, and red) that give us our color vision in brighter light (Dartnall *et al.* 1983; Schnapf *et al.* 1988). Use of the rods is known as scotopic vision, and use of the cones is known as photopic vision (Stabell and Stabell 1980a; Miller 1985). There is a notable shift in the spectral responses of the rods *vs.* the cones: the rods peak around 495 nm (Kraft *et al.* 1993, Dartnall *et al.* 1983; Stabell and Stabell 1980b; Brown 1979; Alpern 1978), which is some 35 nm blueward of the green cones' peak. The red cones peak around 558 nm; interestingly, the blue cones (of which there are very few compared to green and red cones, so that the contribution is complex) peak well to the blue of the green cones, at 419 nm (Schnapf *et al.* 1988; Dartnall *et al.* 1983). While it is assumed that the rods are principally used by visual observers of comets, it is highly possible that cones become involved when viewing brighter (especially naked-eye) comets, thereby complicating the concept of what is being measured in estimating the brightness (and size) of the visible coma of the comet in terms of varied spectral response of the observer's eye (Green and Arshavsky 1996). The

sensitivities of rods and cones differ from observer to observer, and there are times when rods and cones are working together under low-light levels (Reitner *et al.* 1991; Stabell and Stabell 1981; Drum 1981). The eye's spectral response is known to degrade at the blue end of the spectrum as we age (*e.g.*, Sagawa and Takahashi 2001). More study is needed to determine how much differing color sensitivities from observer to observer (*cf.* Sterken and Manfroid 1992b, pp. 26*ff*; Padgham and Saunders 1975) actually affect comet observations, because total-visual-magnitude, coma-diameter, and tail-length data may be strongly affected by such factors. Sterken and Manfroid (1992a) have recently addressed this problem in the light of visual magnitude estimates of variable stars.

3.3. The Brightness of Comets

The total magnitude (m_1) of a comet is taken here to mean the total, integrated brightness of the comet's coma or head. There has been much debate in recent years as to whether the tail should be considered part of m_1: tail brightness usually is not a factor in the overall brightness, as the surface brightness of the tail tends to be well below that of the comet's head in most cases. But for some comets (particularly bright comets with very bright tails), it becomes a problem since most m_1 data in existence refer to visual estimates[52], and it is nearly impossible for the visual observer to disentangle the inner tail from the comet's coma when making total-brightness estimates.[53]

Planets in the solar system, which usually do not change intrinsic size or albedo, are observed to vary in brightness as a function of distance from the observer, according to the inverse-square law of physics, and also to some degree according to what is usually called the "phase effect" — where the object's Earth-facing "hemisphere" is generally not fully lit due to varying sun-comet-Earth angles. This sun-comet-Earth "phase angle", β, is given by

$$\cos\beta = \frac{r^2 + \Delta^2 - r_\oplus^2}{2r\Delta} \tag{3.1}$$

(*e.g.*, Müller 1897, p. 58; Meeus 1991, p. 216), where the comet's geocentric (Δ) and heliocentric (r) distances, and the earth's heliocentric distance ($r_\oplus$), are usually given in AU. Thus, when we

[52] Photographic total magnitudes of bright comets were never taken seriously and good such data do not exist; nowadays the only alternatives to optical non-visual total-magnitude data on comets are photomultiplier tubes (still in use, but being phased out) and CCD detectors. Only a few amateur astronomers have made sporadic attempts at measuring the total brightness — with or without the inner tail being considered — of bright comets (i.e., those brighter than apparent $m_1 \approx 4$).

[53] Comet total brightness is estimated in magnitudes — a system dating back to the ancients (used, for example, by Manilius and in Ptolemy's 18-century-old star catalogue; cf. Manilius and Goold 1977, p. c) but quantified by Pogson (1856) at Oxford, who devised the quantitative definition still in use — namely, that 5 magnitudes represents exactly a 100-fold change in brightness, though still with small numbers representing brighter objects. This made the brightest star in the sky, Sirius (α CMa), not visual magnitude 1 (as given in catalogues from Ptolemy through the middle ages), but now mag -1.5.

see a comet at opposition, its phase angle will be near 0°; when we see a comet at small solar elongations (say, within 30° of the sun in the sky), $\beta \rightarrow 180°$. The angular elongation of a comet from the sun can be found from

$$\cos\epsilon = \frac{\Delta^2 - r^2 + r_\oplus^2}{2r_\oplus\Delta}. \qquad (3.2)$$

In the case of small objects, in particular, shapes of asteroids and comets will not be very round — and as they rotate, their lightcurves will be noticeably affected (*e.g.*, Lagerkvist *et al.* 1989), but it has been difficult to discern unambiguous rotation periods for a cometary nucleus due to coma contamination (Jewitt 1991; Belton 1991).

More simply, a planet's brightness can be expressed generally as

$$J = J_0 f(\Delta)F(r)\phi(\Delta, r) \qquad (3.3a)$$

where the functions f and F are given in terms of the "absolute magnitude" (J_0) at normalized (unit) distance, and ϕ is the phase function. This form of the equation was given by N. T. Bobrovnikoff (1951), who also cautioned that even for the major planets, the formula does not account for all of the observed contributions to brightness variation. The phase term is generally deleted for comets in terms of visual brightness because the phase effect is assumed to be small, though in the case of dust particles (continuum sunlight scattered off of dust grains), it has been shown that there is a peak in brightness (of as much as a factor of 2) within 10° of opposition (*i.e.*, where $\beta < 10°$).[54]

The standard so-called "power-law formula" also derives from the inverse-square relationships for light intensity *vs.* distance. Öpik proposed in 1963 that the geocentric term may vary at some power other than Δ^{-2}, but there is not enough supporting evidence to take this seriously (*e.g.*, Meisel 1970; Meisel and Morris 1976), though some have recently warned that the issue is not solved (*e.g.*, Marcus 1986; Jewitt 1991). This proposed factor is sometimes called the "Delta effect", but several recent close-approaching comets with good sets of observed magnitudes have failed to show any such effect (*e.g.*, Green and Morris 1987; Green 1991, 1996a). Thus, still retaining the phase function, we are left with

$$J = J_0\Delta^{-2}F(r)\phi(\Delta, r), \qquad (3.3b)$$

which, when applying the laws of logarithms, leads to

$$\log(J/J_0) = \log[\Delta^{-2}F(r)\phi(\Delta, r)] \qquad (3.3c)$$

and then to

$$\log(J/J_0) = -2\log\Delta + \log[F(r)] + \log[\phi(\Delta, r)], \qquad (3.3d)$$

and dropping the phase term, we get

$$\log(J/J_0) = -2\log\Delta + \log[F(r)]. \qquad (3.3e)$$

[54] *cf.* Kiselev and Chernova 1981; Ney 1982; Millis *et al.* 1982; A'Hearn *et al.* 1984; Jewitt 1991.

Now, late in the nineteenth century, the heliocentric term for comets was also assumed to vary as an inverse-square power (*e.g.*, Payne 1892; Deichmüller 1892; Holetschek 1896; Müller 1897), leading to $F(r) = r^{-2}$ and to

$$\log(J/J_0) = -2\log\Delta - 2\log r. \tag{3.3f}$$

For many years (spanning the turn of the century), comet ephemerides would give predicted brightnesses in terms of a unit brightness determined at the time of discovery, say B_o (Payne 1892). If B_o is taken as unity (1.0), with r_o and Δ_o taken to be the comet's heliocentric and geocentric distances at the time of discovery, then the relative brightness on any other date is simply

$$B = \frac{r_o^2\Delta_o^2}{r^2\Delta^2}. \tag{3.4}$$

However, it was rapidly noted in the early twentieth century that comets did not generally follow an inverse-square law in terms of the comets' heliocentric distances, and an r^{-n} relationship was proposed (*e.g.*, Orlow 1911), with $n = 4$ found as an average value (*e.g.*, Vsekhsvyatskii 1928). This use of the "power-law exponent", n, yields

$$\log(J/J_0) = -2\log\Delta + \log[r^{-n}] \tag{3.5a}$$

and

$$\log(J/J_0) = -2\log\Delta - n\log r. \tag{3.5b}$$

Thus, for a comet at any given distances, Δ and r, one might expect a rough brightness J, assuming values for the brightness J_0 at unit distance and for the parameter n, a value that determines how rapidly the comet's brightness will increase or decrease with decreasing or increasing (respectively) heliocentric distance.

As noted in footnote 53, Pogson defined five magnitudes to be a difference of 100 in brightness. Thus, for a difference of 1 magnitude, there is a difference of $100^{1/5} = 10^{2/5} \doteq 2.512$ times in brightness. This means that a difference in luminous flux from two objects (or flux from one object at two different times), F_a and F_b, is given as

$$F_a/F_b = (10^{2/5})^{m_b - m_a}, \tag{3.6a}$$

where m_a and m_b are the respective magnitudes (*e.g.*, Henden and Kaitchuck 1982), which (again using laws of logarithms) can be rewritten as

$$\log(F_a/F_b) = \frac{2}{5}(m_b - m_a). \tag{3.6b}$$

Now, returning to equations (3.3) and (3.5), and substituting H_0 (as a comet's "absolute magnitude" at unit distance) and m_1 (as a comet's observed total magnitude) in place of magnitudes m_a and m_b, respectively, we get

$$\log(J/J_0) = \frac{2}{5}(H_0 - m_1), \tag{3.7a}$$

and, combining with equation (3.5*b*), we get

$$\log(J/J_0) = \frac{2}{5}(H_0 - m_1) = -2\log\Delta - n\log r. \tag{3.7b}$$

Re-arranging equation (3.7*b*), we get

$$H_0 - m_1 = -5\log\Delta - 2.5n\log r, \tag{3.7c}$$

and finally ending up with the usual form of the power-law equation,

$$m_1 = H_0 + 5\log\Delta + 2.5n\log r. \tag{3.8}$$

One can then take $m_1 - 5\log\Delta$ as the "reduced brightness" or "heliocentric magnitude" of the comet (*cf.* Bobrovnikoff 1951), often denoted H_Δ. Since H_Δ is linearly correlated with log r, analysts of comet light curves often perform least-squares calculations of the equation

$$H_\Delta = H_0 + 2.5n\log r \tag{3.9}$$

and produce graphical plots of H_Δ *vs.* log r.

However, a straight-line relationship between brightness and heliocentric distance does not always hold up for comets, though it does for many over fairly large ranges in r. It has also been found that comets with longer orbital periods tend to have lower values of n than do comets with shorter periods; thus, for example, a typical long-period comet tends to have $n \sim 3$, whereas a typical short-period comet tends to have $n > 4$ (*cf.* Green 1995). Because the overall average of n in the power-law equation has long been known to be near 4 for all comets (*e.g.*, Vsekhsvyatskij 1933), it is customary to assume $n = 4$ for a newly-discovered comet when producing ephemerides; when $2.5n = 10$ is so assumed, the absolute magnitude is often denoted H_{10} (and such data are sometimes put together for larger numbers of comets into "H_{10} catalogues" of photometric parameters to compare one comet with another; *e.g.*, Vsekhsvyatskij 1958, 1964). But, especially due to short-term, temporary fluctuations in total brightness (and especially to the fact that many newly-discovered comets probably had significant steep outbursts of brightness just prior to discovery), it can be quite difficult to know for some time if a comet is following a power-law formula reasonably well (and, if so, what the general value of n might be). Also, comets frequently will increase/decrease for weeks or even months according to one value of n, and then abruptly change to a higher or lower value of n; furthermore, it is common for comets to exhibit significant pre- and post-perihelion asymmetries in brightness — comet 1P/Halley being quite famous in this respect (*cf.* Green and Morris 1987). And significant fractions of comets either will split into two or more sizeable chunks of the original nucleus or will fall apart completely with little or no advance warning, and these two not-uncommon events generally mean temporary sharp increases and permanent rapid decreases, respectively, in overall coma brightness.

For over 25 years now, I have been compiling the *International Comet Quarterly* (*ICQ*) archive of photometric data on comets, which concentrates on collecting total visual magnitude (m_1) data

rather than so-called "nuclear" (m_2) data — the latter being much more difficult to define and interpret (see historical reviews by Green, Rokoske, and Morris 1986; Morris and Green 1992; Marsden *et al.* 1994). A valuable base of data not previously available has been steadily compiled in this manner, largely improved by the introduction of standard observing and collecting procedures.

In my work with Syuichi Nakano to produce annual *Comet Handbooks* of ephemerides and orbital elements, I have sifted through all of the archival comet-magnitude data each year, updating the light curves of comets based on recent observations (Green 1996b). In this process, I have been compiling power-law magnitude parameters (H, n) for the total "visual" magnitude, m_1, for both long-period and short-period comets. These parameters have been published in the annual issues for comets deemed observable in the year of publication (*e.g.*, Nakano and Green 2003), but they have never been published *in toto* in one place. I am now in the process of preparing just such a catalogue of short-period-comet magnitude parameters for publication. But I have collected these parameters together for plotting in Figure 3.5, which shows the value $2.5n$ as a function of the comet's orbital period, and in which larger symbols indicate multiple comets with the same integer period and log-r parameter. One can see from this that short-period comets with $P < 20$ yr have a distribution that extends into steep values of n; in fact, the average value of n is certainly > 4.

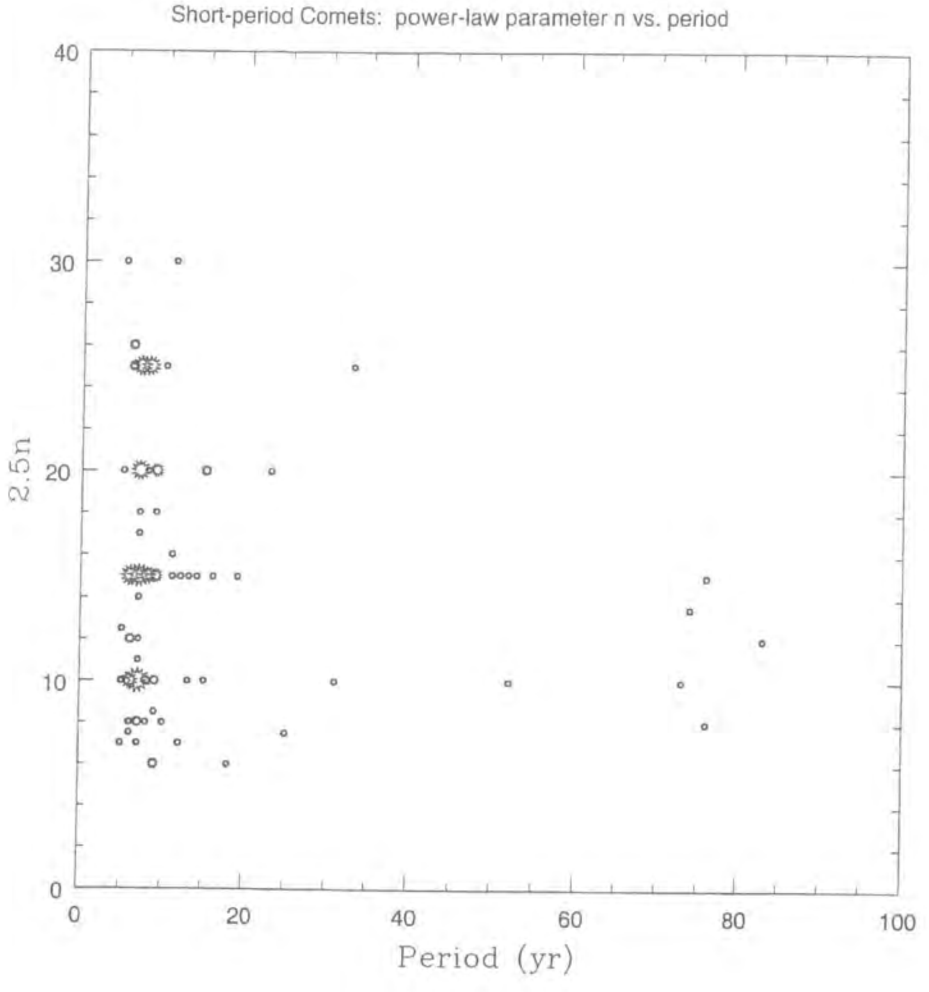


Figure 3.5. Plot of orbital period, P, vs. the power-law coefficient term, 2.5n, for 107 short-period comets, from my on-going study of comet lightcurves.

In 1995, I undertook a study of bright long-period comets, which is quite pertinent for the naked-eye comets studied for this Ph.D. research programme. Using the *ICQ* database, m_1 values were analyzed for 42 long-period comets observed in the past 40 years, with the so-called Kreutz sungrazers excluded (due to their unique nature). The chosen comets had perihelion distances in the range 0.14-1.95 AU, with four exceptions: C/1962 C1 (Seki-Lines) had $q = 0.03$ AU; C/1991 B1 (Shoemaker-Levy) had $q = 2.26$ AU; C/1983 O1 had $q = 3.32$ AU; and C/1980 E1 had $q = 3.36$ AU. In general, the comets that were chosen were visible over several (if not many) months and had a fair amount of reliable magnitude data available. Forty-one of the 42 comets were observed with binoculars (C/1980 E1 was the only comet in the group that was not so observed, reaching $m_1 \sim 11$ at maximum brightness), and 22 were observed with the naked eye. Unfortunately, there is an inevitable overall availability of more post-perihelion than pre-perihelion data for the average long-period comet, due to unpredictable discovery circumstances.

The solutions that were found (Table 2 of Green 1995) are generally such that $2.5n$ falls in the range 7-15 (meaning n in the range 2.8-6.0). This was not a new result, as numerous efforts have been made in the past to catalogue power-law parameters of comets (see p. 415 of the review by Meisel and Morris 1982). Oort and Schmidt (1951) proposed a correlation between a comet's brightness behavior and its orbital "age", in which a "new" comet (possibly on its first visit to the inner solar system from the so-called Oort cloud of comets) varies differently in brightness than does an "old" comet that has a smaller orbit (and thus has made many more trips around the sun). A comet is generally considered to be dynamically "new" when the "original" value of its orbital semi-major axis, $a_{\rm orig}$, is $>$ 10,000 AU (Oort and Schmidt 1951; Marsden and Roemer 1982; "original" means running the comet's orbit back with the inclusion of planetary perturbations to outside 30 AU — the heliocentric distance of Neptune — and referring it to the center of mass of the solar system); thus, it is considered probable that comets with $a_{\rm orig} >$ 10,000 AU are passing through the inner solar system for the first time (see also Fernández 1980). However, it is more certain that a comet with $a_{\rm orig} <$ 10,000 AU is "old" than it is that a comet with $a_{\rm orig} >$ 10,000 AU is "new", in that some "old" comets are perturbed by the planets back into larger orbits. Eleven of the comets selected for this study would thus be tentatively classified as "new" — the remaining 31 comets have likely passed through the inner solar system at some time in the past (some having done so many times). Whipple (1978) noted earlier remarks by Marsden and Sekanina that nongravitational forces could further cause some comets with apparent $a_{\rm orig} <$ 10,000 AU actually to be entering the inner solar system for the first time.

Oort and Schmidt (1951) found that "new" comets rose less steeply in brightness with decreasing heliocentric distance than do "old" comets. Meisel and Morris (1976) noted that Oort and Schmidt were using the old magnitude formula derived by B. Levin (cf. Schmidt 1951); they therefore provided a more extensive look at correlations of magnitude (using the standard power-law formula) *vs.* orbital characteristics, finding that a correlation with perihelion distance (q) was more notable than was any correlation with the "age" of the comet. Meisel and Morris reported an average value of $2.5n = 8.0$ for "new" comets and 10.5 for "old" comets (from solutions repre-

senting 141 cometary apparitions), though some assignments of "old" and "new" to comets were found by the present author to be different (by comparison with the extensive set of original $1/a$ values compiled by Marsden 1994).

Three of the 42 long-period comets in my own study had post-perihelion photometric data only, leaving 39 long-period comets having pre-perihelion data of varying quantity and quality. Despite attempts to select the best comets for the 1995 study, fully 25 of the 39 comets had pre-perihelion arcs of data that constitute $\leq$ 1.0 AU in the range of heliocentric distance; six comets had a range of 1.0-2.0 AU, and eight comets had a range of > 2.0 AU. [For comparison, Whipple (1978) looked at > 100 comets, only 15 of which had pre-perihelion r ranges > 1.0 AU.]

Because of this difference in the range of heliocentric distance, the weighted arithmetic means of the photometric index, $\langle 2.5n \rangle_{\rm w}$, were obtained by weighting the derived parameters according to three different schemes intended to give emphasis to the range in r or $\log r$ for which each set of (H, n) parameters were found to be valid. The small pre-perihelion range of r for numerous comets in the 1995 study cautions one to infer that power-law parameters derived over such short periods are not likely to be as reliable, and the weighting was done to compensate for this. Weighting based on range in r alone suffers from a failure to compensate for a larger gradient in cometary brightness variation over unit heliocentric ranges at different mean r — *e.g.*, a heliocentric range of 1 AU, centered on $r = 1.0$ AU (or 0.5-1.5 AU) *vs.* $r = 5.0$ AU (or 4.5-5.5 AU). So the weighting included incorporation of the the smallest comet-sun distance for which magnitude data were used to derive a given set of (H, n) parameters.

The results of determining these weighted mean values, and the unweighted means with standard deviations, were given in Tables 4, 5, and 6 of my 1995 paper for pre-perihelion, post-perihelion, and combined mean values of $2.5n$, respectively. That study suggested that the data for the ten "new" comets that have pre-perihelion data might indicate a clumping around $2.5n$ (unweighted) ≈ 7.5, though $\langle 2.5n \rangle_{\rm w} \approx 8.3$ for the examined sample. The 14 comets with $1000 < a_{\rm orig} < 10000$ show a less-prominent peak around $2.5n$ (unweighted) ≈ 9.5, with $\langle 2.5n \rangle_{\rm w} \approx 9.0$ for this sample. In the case of long-period comets with $a_{\rm orig} < 1000$ AU, there is an apparent double peak around $2.5n$ (unweighted) ≈ 7.5 and 9.5, but the mean weighted value of the sample of 15 comets is $\langle 2.5n \rangle_{\rm w} \approx 10.8$. The mean for all 29 "old" comets considered in the 1995 study is $\langle 2.5n \rangle_{\rm w} \approx 9.9$. The differences in $\langle 2.5n \rangle_{\rm w}$ for the three different weighting schemes are rather small, though there are rather larger differences between the weighted and the unweighted means (not unexpected, considering that in the unweighted case, a comet with an observed range of 0.05 AU in r is treated the same as one with a range of 4 AU). There does seem to be a trend toward increasing n as $a_{\rm orig}$ decreases, though it should be noted that the standard deviations are not as small as one would like; ultimately, there is a need to extend this sample to many more comets — preferably with better magnitudes and better ranges in r obtained from future cometary apparitions. These results generally support conclusions drawn by the previous researchers (noted above), although there is no definite correlation between n and q in the data of my 1995 study.

Two "short-period" comets were included — 1P/1982 U1 (Halley) and 109P/1992 S2 (Swift-

Tuttle) — as representative examples of such "Halley-type" comets, both having observations over a wide range in r. The $2.5n$ values for both comets are rather high for pre-perihelion behavior, compared to most long-period comets in the same study. I remarked then that the (unweighted) mean pre-perihelion value for 129 short-period comets — from parameters derived by me during the previous decade of preparing the annual *ICQ Comet Handbook* — is $\langle 2.5n \rangle \sim 17.0$. There very clearly is an increase in the average value of n as a comet progresses from a "new" comet to one that has experienced many passes through the inner solar system. [However, neither of these two short-period comets was included in the statistical analyses of long-period comets in the 1995 study.]

There are 39 solutions from the 1995 study that contain parameters representing at least part of both pre- and post-perihelion brightness data. Of these 39 solutions, 24 sets of parameters represent the entire range of observed m_1 values for those 24 comets. Nearly two-thirds of the comets can be represented by a single set of power-law parameters, but it should be noted that in only four cases out of 39 comets are there reliable m_1 data spanning more than 2.0 AU in r for *both* pre- and post-perihelion portions of the comets' orbits; in these four cases, two comets have a single set of power-law parameters, and the other two comets each have one set of pre-perihelion parameters and one set of post-perihelion parameters. Fully two-thirds of the comets (26) have observed ranges in $r \leq 1.0$ AU. Still, only seven or eight comets out of the 39 showed a definite change in the power-law exponent, n, during either the pre-perihelion portion or the post-perihelion portion of observability (as opposed to, say, a change quite close to the time of perihelion). Eight comets can be represented by two sets of separate pre- and post-perihelion parameters, suggesting a change in the brightness behavior around the time of perihelion.

Of the eight comets showing an apparent brightness change around the time of perihelion, three comets showed a decrease in n from pre- to post-perihelion and three comets showed an increase in n — the other two comets showing a slight increase in H only. No correlations can be seen between such brightness changes and dynamical ages. Of the remaining six comets with multiple sets of (H, n), two show decreases in n and four show increases in n (again, no obvious correlation with dynamical age). Thus, post-perihelion brightness behavior in long-period comets generally parallels the pre-perihelion behavior, but there are frequent exceptions in both directions (more- and less-rapid post-perihelion fading).

As for the post-perihelion data of 42 comets, $\langle 2.5n \rangle_{\rm w} \sim 8.2$ for comets with $a_{\rm orig} > 10^4$ AU, ~ 9.2 for comets with $10^3 < a_{\rm orig} < 10^4$, and ~ 9.7 for comets with $a_{\rm orig} < 10^3$ AU. While $\langle 2.5n \rangle_{\rm w}$ is similar for both pre- and post-perihelion parameters of comets with $a_{\rm orig} > 1000$ AU, there is a noticeably-higher pre-perihelion $\langle 2.5n \rangle_{\rm w}$ for comets with $a_{\rm orig} < 1000$ AU than post-perihelion $\langle 2.5n \rangle_{\rm w}$; whether this is significant or not is uncertain from the data.

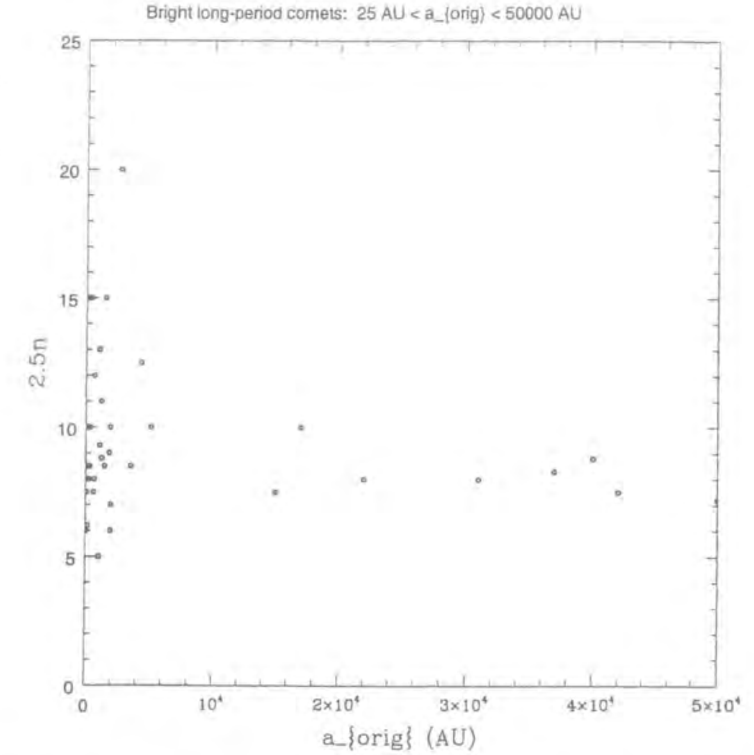
Because there is so much overall similarity in $\langle 2.5n \rangle_{\rm w}$ for pre- and post-perihelion activity, and because so many solutions continue across perihelion, it seemed logical to look at the combined data in the tables of my 1995 paper, in which the trend of increasing n for decreasing dynamical age is still visible. But unlike the marked conclusions of Whipple (1978), who found that $\langle 2.5n \rangle$

increased from pre- to post-perihelion for "newer" comets and that $\langle 2.5n \rangle$ decreased from pre- to post-perihelion for "older" comets, this study yields no clear difference in the average values of n before *vs.* after perihelion other than a possible slight decrease for all categories of dynamical ages with that higher decrease noted above for comets with $a_{\rm orig} < 1000$.

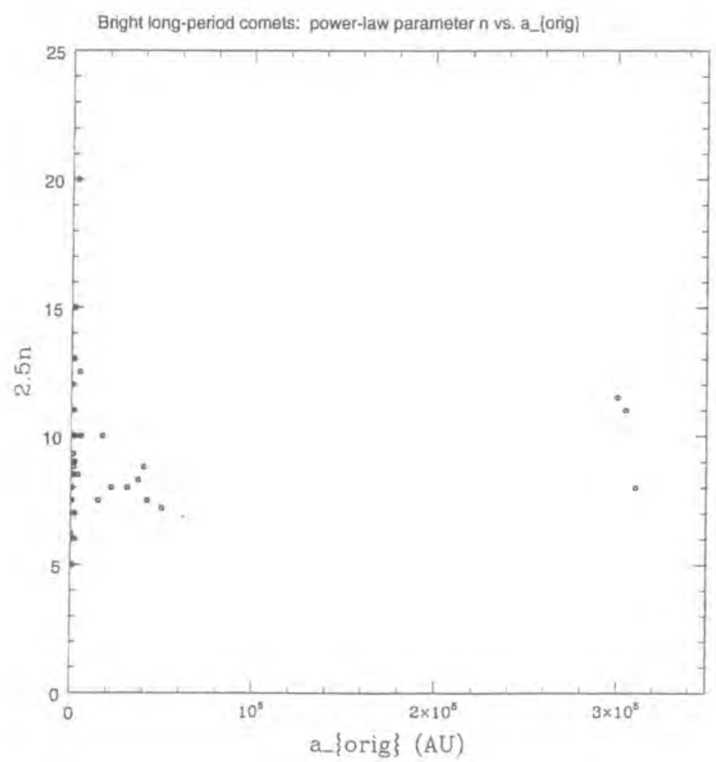
Figure 3.6a of this thesis shows the results from the 1995 study, drawn in the same manner as Figure 3.5 (see above), but with the original semi-major axis plotted instead of the orbital period (with $a_{\rm orig} = 0$ to 50000 AU). Added here (not included in the original study) is the point for comet C/1995 O1 (Hale-Bopp) — intrinsically the brightest comet since 1995 and the comet with the longest naked-eye arc of observation in history. For C/1995 O1, which has $a_{\rm orig} \approx 261$ AU (Nakano 1997),[55] I adopt $H = -1.0$ and $2.5n = 8.5$, which represents the light curve well during 1995-2001, although the comet has dropped off a bit more steeply during the last couple of years. From Figure 3.6a, we see that the concentration of high-n parameters visible for the short-period comets is missing for the long-period comets. Indeed, as expected from the results presented in the tables of my 1995 paper, one can see how the clustering actually peaks at $n < 4$. Notable are the comets with $a_{\rm orig} > 10000$ AU (that is, comets with orbital periods $\geq 10^6$ yr). Figure 3.6b shows the extension of this plot out to 300000 AU, though there are only three additional points that distance.

I presented these results last year at the General Assembly of the International Astronomical Union in Sydney, Australia, where my recommendations based on this study as Chairman of the Subcommittee on Comet Brightness was adopted by Commission 20. One of those recommendations is to use $n = 3$ for ephemerides of newly discovered long-period comets for which little is known about their brightness (*e.g.*, Green *et al.* 2001). (The standard for nearly a century has been to use $n = 4$ in such cases, leading to many problems where comets were predicted to become brighter than they actually did.) The thinking has been that dynamically "newer" comets (*i.e.*, those that have apparently spent much less time, if any, in the solar system than those with shorter orbital periods) have some "pristine" material (amorphous ices) on the surfaces of their nuclei that are lost after an initial passage through the inner solar system. In looking at the comet observations from centuries ago, I shall generally adopt this new standard of assuming $n = 3$ in the absence of much qualitative brightness data.

[55] though later Nakano (2001) has found the need to invoke nongravitational forces for this large, very active comet — making the determination of original semi-major axis more uncertain



Above: Figure 3.6a. Plot of 'original' semi-major axis, $a_{\rm orig}$, vs. the power-law coefficient term, 2.5n, for 45 bright comets with long-observed arcs in the last half-century. Below: Figure 3.6b. Same as for Figure 3.6a, but with extension out to 300000 AU.



3.4. Types of Comets in the Ancient Sense

Aristotle postulated two classes — "comets" (or "long-haired star") and "bearded star" — but he proposed that comets and shooting stars are the same type of object, one moving and the other stationary (*Met.* I.VII, quoted from Lee 1952, p. 51). Pliny (*ca.* 62-113 AD) lists no fewer than 10 categories of comets (*Natural History* II.XII), a book read through the European middle ages, even though other Greek texts having material concerning comets may have been not readily available in Europe until the 12th or 13th century (*e.g.*, McCluskey 1998). Pliny's list was copied in European texts mentioning comets over many centuries — still published sixteen centuries later in an English treatise by the astrologer John Gadbury (1665): "hairy comet", "bearded star", "javelin", "sword" or "dagger", "horse's mane" (Gadbury, pp. 6-8), and Epigenes' "Blazing star" or Boetheus' "*apparitions* of the *Air*" (*ibid.*, pp. 10-11). Interestingly, though Pliny includes the categories of 'Torch-star' and 'Goat comets' (Rackham 1938, p. 233), Lee (1952, pp. 28-29) infers that Aristotle specifically lists "goats" and "torches" as meteoric phenomena dealing with "shooting stars". As we noted earlier, Aristotle essentially classified shooting stars as swiftly-moving comets. But Pliny *seems* to make more of a clear distinction between meteors and comets, when — regarding the former — he speaks of 'torches' (*lampades*), 'missiles' (*bolides*), and 'beams' (Greek *dokoi*).[56]

In section 1.1, we noted other attempts by ancient writers to classify comets according to their visual morphology and appearance. In the fourth century AD, the astrologer Hephaestion of Thebes was influenced heavily by Ptolemy's *Tetrabiblos* and "believed in seven kinds of comets, five of which were named after the planets, color being the basis of comparison" (Hellman 1944, p. 42). The actual number of categories, into which any given writer placed comets, was not as significant as the numerology of planets (for example), but it was an issue that was argued nonetheless. Clearly, the widely-differing appearances and morphologies between different comets were at least somewhat perplexing to ancient observers.

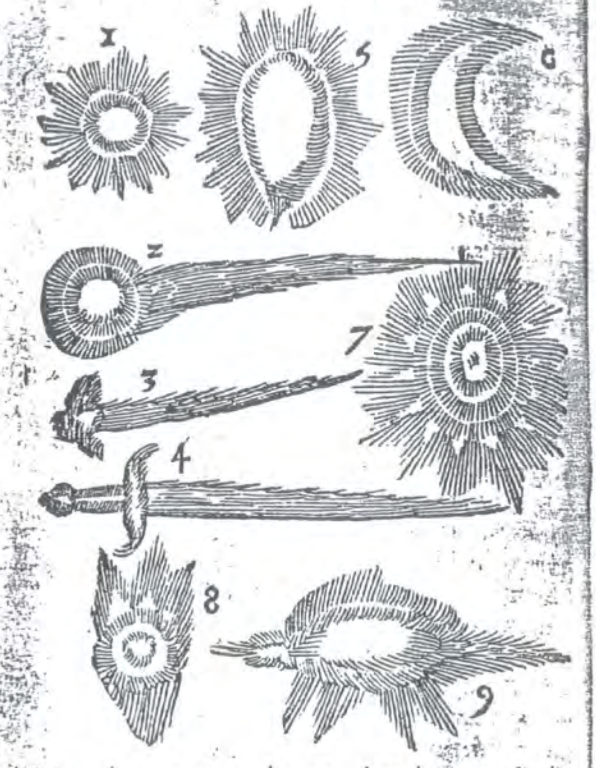
It is noteworthy to mention that as early as the second century BC, Chinese astronomers had compiled an illustrated catalogue of cometary types (Xi 1984; Stephenson and Yau 1985), depicting 29 different morphologies regarding coma and tail appearances. So naked-eye comets appeared frequently enough not only to warrant notice, but to encourage rather close scrutiny by some observers in terms of the general appearance of (a) its coma's degree of condensation, brightness gradient, and size and (b) its tail's length, shape, and even surface brightness. Present in the Chinese drawings are clear evidence for narrow gas tails in some comets, broad dust tails in other comets, and both types of tails in yet further comets. While medieval European observers lagged behind ancient observers in exploring the different apparent types of comets, by the 16th century, printing in Europe encouraged a new look at the topic through visualization — via the use of semi-realistic drawings of comets in the observers' own published books.

Dasypodius [1578a, p. Aiv(b); 1578b, pp. Bii(b)-Biii(a)] included diagrams of three ancient

[56] *N.H.* II.XXV-XXVI, as quoted in Rackham 1938, pp. 239-241.

types of comets: "Stella Comata" had a coma but no tail; "Barbata" had a concave-shaped tail, narrower after leaving the comet's head but then expanding outward (indicative of a dust tail); and "Caudata" had a tail that started as wide as the coma but rapidly diminished in width as it faded virtually to a point some distance away (indicative of a gas tail). Three similar diagrams were produced by Angelo Rocca (1578?) of Camerino, without the images being labelled with ancient type-names — his illustration depicting an obvious ion tail showing a narrow tail curving back and forth. In Chapter 4 of his German tract, Scultetus [1578b, p. Eiv(a)] tries to categorize the 1577 comet based on its appearance from the categories of Pliny. Matthew Zeysius (1578) discusses the different types of comets, giving examples of each, including "Comata seu crinita stella", 1470 Jan.; "Xiphias, altenuata forma ensis", 1095 Oct. 7; "mit einem Pfawenschwantz", Aug. 1506; "wie ein Drach", 1541 Aug. 21; "wie ein brennender Balck", 1017. For the 1577 comet, Zeysius says [p. Biii(a)] that it had a tail that may permit it to be categorized in the ancient system as "Xiphias" or "Lampadias" or "Acontias" or "Pauonis cauda". In addition to his comet catalogue, Frytsch (1563b) published a book on meteorological phenomena (in the Aristotelian sense) that includes dozens of pages on comets (and meteors), including discussion on the ancient types of comets.

Figure 3.7, taken from Cornelius Gemma's 1575 tract (Book 1, p. 196), shows one late-medieval artist's depiction of different types of comets via his interpretation of the ancient Greek classification system. Gemma depicted *kometis* as a round comet with no tail (his object labelled '1'), for example, and *pogonias* as a comet with a narrow, tapering tail (his number '2'). Whether the differing lengths of the rays in the coma of these two images has any meaning is unknown. Gemma's object '7', *pithetis,* appears a slightly elongated, tailless version of *kometis* but with several more apparent layers to the coma; does this refer to the haloes or shells that are sometimes seen in bright comets today (especially in comets that come relatively close to the earth)? Perhaps the last serious attempt to assign ancient comet types to actual illustrations of comets was that by Hevelius (1668, pp. 442ff), whose *Cometographia* is known for its many full-page illustrations of comets.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COMETARVM GENERA 9.

1. κομήτης. 2. πωγωνίας. 3. ἀκοντίας. 4. ξιφίας. 5. δισκεύς. 6. κερατίας. 7. πιθέτης. 8. λαμπαδίας. 9. ἱππίτευς.

nimè operæpretium duxi: quòd figurarum non ita definitus numerus videatur, quin ex antè relatis pleraq; ad vnũ pertineant genus, vt solis & clypei similitudo, præter easdem quoque

Above: Figure 3.7. The ancient Greek classification of comets as interpreted by one sixteenth-century comet observer (Gemma 1575); see text.

3.5. Medieval and Early-Modern Comet Illustrations

The earliest images of comets known to me are the 29 drawings depicting different types of comets from their appearances in a Chinese silk book dated to 168 B.C. (Xi 1984). These Chinese drawings are absolutely amazing, for they depict features that are readily recogizable to a modern cometary astronomer — such as a comet seen near opposition with a short tail on all sides of the coma, and various versions of dusty and gaseous tails, including even apparent disconnection events. The earliest European images of comets of which I am aware are the depiction of Halley's comet in 1066 on the Bayeux Tapestry (*e.g.*, Rud 2001; see Figure 3.8) and a colored drawing of a comet from a manuscript that dates to ca. 1350 (Page 2002). The 1066 image also shows what may be a disconnection event — and, at any rate, an appearance to comet 1P/Halley that was rather similar to its appearance in April 1986 when near its closest approach to the earth. There are few other known European illustrations of comets prior to the appearance of Halley's comet in 1531.

◇ ◇ ◇

Figure 3.8. Detail of Bayeux Tapestry showing Halley's comet at the time of the Battle of Hastings in 1066 AD.

Published 16th-century diagrams depicting large-scale or distant natural features have been shown elsewhere besides astronomy to have great potential where one might be tempted at first to simply assume "artistic licence". For example, a map by Olaus Magnus in 1539 showing swirls in the northeast Atlantic Ocean may in fact represent real eddies created by the interaction of the warm Gulf Stream and cold Artic waters (Rossby *et al.* 2004). In my viewing of hundreds of comet tracts from the 16th and 17th centuries, I have come to realize that what appear initially to be simple stylistic (or generalized) drawings of comets can and do, in fact, show something of the physical nature of comets in some — and perhaps many — cases. While this topic is envisioned by me as a worthy subject for an entire book, replete with hundreds of illustrations of comets from these early printed tracts, along with some interpretation of them, it is a topic worthy of some initial discussion here. Time and space does not permit me to provide more than a few representative examples of the more interesting illustrations that I have come across in my library research, but some examples appear on the following pages.

I have mentioned Apian's 1540 masterpiece *Astronomicum Caesareum* a few times already. While I have seen only about ten percent of the known extant copies of this folio book (see footnote 44, above), in looking for possible annotations in the comets section, I began to notice some differences in the way that the comet tails are depicted with paint. As Gingerich (1995) has stated, most (if not all) of the elaborate coloring was apparently done in the print shop (unusal for books of that time, which tended to be colored later by their owners). Apian evidently had great control over the production of the book, produced as it was in his own shop in Ingolstadt. It is therefore of some potential interest that I noted some copy-to-copy differences in how the paint was applied to the comet diagrams. While there was a general tendency for the print shop to color all of the large figures, including the volvelle (moving circular disks) pages, not all of the copies have the pages with smaller figures (which include those with the comet diagrams and observations) colored. But where there is coloring of the comet diagrams, the painting is interesting.

First, all of the tails in the Leipzig printed facsimile (Wattenberg 1967) of the *Astronomicum Caesareum* are painted the same color of yellow, though the colors for the comae in the different comets vary from light pink to brown-red to the gray-blue noted here. A short streamer is also depicted in hand-painted (not machine-printed) gray-blue — the same paint color used for the coma, but unlike the yellow coloring of the main tail — coming off the main tail of the 1538 comet, in this facsimile (see Figure 3.9, below). This uniform, full-tail coloring is seen also in other copies, such as that at the Old Library of Oxford's Magdalen College and at Oxford's St. John's College Library. In the original copy of *Astronomicum Caesareum* at the Bibliotheque Nationale de France in Paris, I found an even more curious hand-coloring of the comet: they appear with red/brown comae and green/yellow tails, but there appears to be an intential bifurcation in the tail, in which part of the tail (along the entire length) is colored green, and the other part of the tail (again, along the entire length) is colored yellow. The copy at Oxford's Bodleian Library also has this color bifurcation along the length of each tail of the comet figures, with half to two-thirds of each tail being green, the rest being yellow — but there is more of a "wavy" (non-uniform) border

separating the two colors in this copy than in other copies I have seen.

The British Library copy of the same book (while only having half to a third of the comet images hand colored) also shows the colored tails split — again down their axes — between a darker green paint and a light yellow paint, and also between yellow and no coloring at all. The copy of *Astronomicum Caesareum* at Oxford's New College Library shows a different twist to this theme: half to two-thirds of each comet tail is painted green with an uneven border along the length of the tail, but some figures have the rest of the tail left unpainted — the remaining comet illustrations have that portion of the tail painted yellow. Curiously, the coloring of the last comet figure on page OII(b) of the New College copy has a "shingled" appearance to the tail, as if the "green" side of the tail was significantly shorter than the "yellow" side (the actual black-and-white outlines of each comet tail are rather generic, the tails' widths being similar in size to the coma diameter, and the length of the tails being pretty much the same on other side).

It might be relevant that we know that often bright comets have comae that are seen to be bluish-green, due to the strong Swan C_2 emission at visible wavelengths. Also, the dust tails in bright comets are often seen to be yellowish, and the ion tails to be bluish. These colors are also borne out in photographs and CCD images. So were Apian and his printer making an attempt to portray the actual colors of the comet? Apian's careful attention to the placement of the comet in his drawings — concerning their lengths and also with respect to the sun's position and his local horizon (and sometimes also to background stars), noting the above-mentioned streamer shown for the 1538 comet — suggests that perhaps there is meaning to the coloring. The small streamer of the 1538 comet in the Leipzig copy is not present in other copies that I have seen, apparently, but the main tail is colored in such a way as to almost suggest a varying intensity down the length of the tail.

Regarding handwritten marginal annotations by early owners of the *Astronomicum Caesareum*, it stands to reason that there would not be much such writing due to the expensive and grand nature of the book — being prepared more for wealthy individuals such as royalty than for scientists. As noted in footnote 44, above, even Halley had difficulty locating a copy for his orbital work on comets. However, Gingerich (2002b) has located Tycho's copy of *Astronomicum Caesareum* (now owned by a private collector in the United States), which contains numerous marginal annotations in Tycho's hand and only in the comets section of the book.

QVARTVS in ordine Cometa anno 1538 menſe Ianuario conſpectus eſt, à 17 vſq; in 21 menſis eiuſdem poſt occaſum, verſus Zenith caudam erigens rectiſſimè. Locus in ecliptica ipſius erat verus, gra. 5 ♓ Latitudo Sept. gra. 17, in ipſo pegaſi collo cō putata. Cauda 30 gradus propè in longitudine complexa eſt, anguſtiori tamen latitudine. Mane nemini viſus eſt ante Solem aſcendētem, à quo diſtabat gra. 32 mi. 30, quam rem præſens imago depingit.

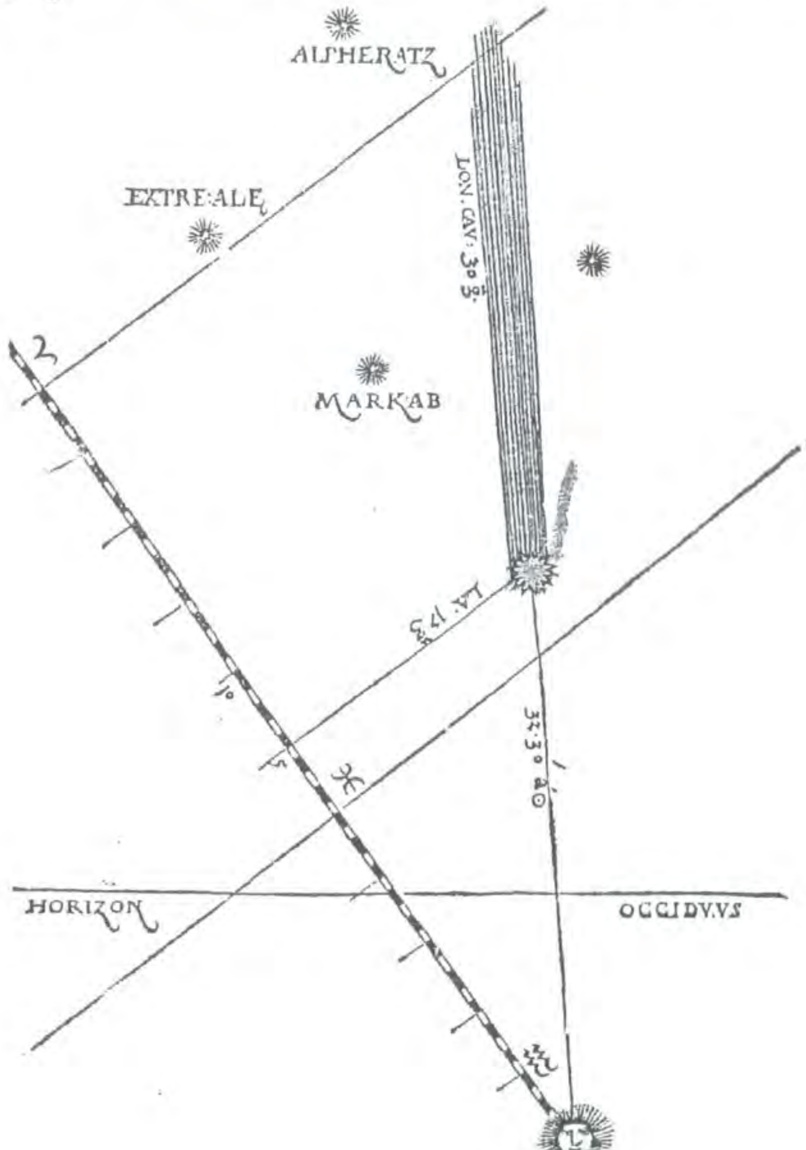

Figure 3.9. Apian's drawing of the 1538 comet, showing an apparent small tail streamer beside the main tail.

Flock (1557) includes, on page Aiv(a) of his tract, woodcut diagrams depicting different-looking tails for each of the five comets of the 1530s. The 1531 comet has a slightly curved shortish tail, in which the width of the tail when leaving the coma is nearly equal to the coma diameter — indicative of a dusty comet. The 1532 comet is shown with a short, quickly tapering, straight tail. The comet of 1533 is illustrated with the longest tail of the bunch — a straight tail that expands a bit towards its end (and with a width only half the coma size at the coma) — with white space (no drawn lines) in the middle of the tail out to about two-thirds of the distance from the coma to the termination of the tail. This suggests an ion tail that may have had a disconnection event, causing part of the tail to "tear away" due to magnetic-field disruption from high-speed solar particles. Flock's image of the 1538 comet shows the second-longest tail of the five comets, appearing much like that of his 1533 comet, except that rays are shown curving outward and the tail expands a bit more as its gets further from the coma — all suggestive of a very dusty tail with possible striations, like those in the recent bright comet C/1975 V1 (West). The 1539 comet, by contrast, is drawn by Flock as only a large round coma, with no tail — often seen in comets with a high gas-to-dust ratio that are intrinsically faint, as with the close-approaching comet C/1983 H1 (IRAS-Araki-Alcock).

The comet of 1556 seems to have caused an explosion of printed illustrations of the comet and its tail. Some such diagrams show the comet as a star embedded in a large coma with a relatively narrow tail leaving the coma and expanding outward before tapering to a point at the end. While the comets of 1531 and 1532 started a minor increase in printed comet illustrations, there was some factor that caused this marked increase — perhaps the comet's brightness and wide visibility; perhaps the movement in the printing industry during the intervening 25 years toward the inclusion of better and more refined illustrations.

Petro à Probossczovvice, an astrologer at Cracow, wrote a 23-page tract on the 1556 comet that contains a title-page woodcut depicting two comet images, both with a rather narrow tail emanating from the coma — but one with a longer tail that quickly expands in width from the coma outward, and eventually remains constant in width, and a second showing a shorter tail continually expanding in width. He states that the comet was first observed on "our horizon" on 1556 March 3 and disappeared on March 17, so the two comet images in his tract may depict its appearance to him on two dates in this two-week period. His description is suggestive of tail foreshortening due to viewing the comet along the line-of-sight with the sun — and indeed an ephemeris indicates that the comet passed close to the earth in the second week of March 1556 and just outside the earth's orbit in opposition to the sun.[57]

While observers reporting a comet's celestial position might be presumed to have generally reported the position of the comet's head, it was also common practice to note the length of the tail or where in the sky the tail ended; also, the tail of a comet is noticeably fainter than

[57] I used the parabolic orbital elements of Hoek (1861, *A.N.* **55**, 216), as precessed by Marsden and Williams (2003).

the comet's head, and most early observers would probably have realized that the head is the source of the tail and thus the most important part of the comet. Tycho had come to realize the importance of diagrams for explaining comets and supernovae (both in his observing logbooks and in his printed books), as did many other authors — whether encouraged by their publishers to do so or on their own insistance. There are many examples of this with the 1577 comet, and I am considering the idea of writing a detailed survey in the coming several years that illustrates how the many diagrams played an important part in the development of this area of astronomy — some showing what astronomers can now see as actual physical processes in the comet's coma and tail. Roeslin (1578) published a big foldout diagram (folded three times) at the end of his tract on the 1577 comet that shows various stylized comet images (1577, 1556, 1532, 1533, "1572 Stella") against a celestial-sphere grid (with the zodiac; Milky Way, as "Galaxia"; Germany horizon; etc.) — some with paths and other comets with one position only (no tracks/paths). Busch (1577) included nice diagrams with the comet against the background constellations in his tract on the 1577 comet. Paul Fabricius (1578?) published a wonderful "two-sheet" (broadside) picture of the constellations with the 1577 comet's path and depicting its long, curved tail as it moved away from the earth over two months.[58]

Maestlin (1578) had his printer use red ink to depict the moving comet/tail against the black-inked constellations on the title-page diagram of his well-known tract on the 1577 comet; he also made extensive use of geometrical diagrams in his very serious treatment of the position of the comet within the text. In his tract, Cornelius Gemma (1578) has two of the most interesting figures of the 1577 comet, from a scientific perspective; a nice foldout diagram (labelled Fig. I) shows the earth at centre of the celestial sphere, the zodiac, celestial "aeqvator", "via Lactea", Aql, Del, Peg, Cyg, lines of ecliptic longitude, the sun, planets, the comet's track, and the comet with a long dust tail for Nov. 14 at 5 p.m. A two-page diagram facing page 19 shows the comet in Sagittarius with two tails (which we now know to be a dust tail and a gas tail). Figures 3.10 and 3.11 depict the 1577 comet against the stellar background as a 'star' (the comet's head or coma) with a long tail streaming outward from that main 'star'; this depiction as a 'star" suggests that it was indeed this bright condensation that was being measured, and at the level of precision accorded by these naked-eye astrometric measures, it is unlikely that very large astrometric errors were induced by uncertainty regarding *what* to measure.

Figure 3.10 shows the path of the comet of 1577 against the background of the constellations as given by Hagecius (1578, p. 11). Compare this with an independent plot of the comet's path by Gemma in Figure 3.11 (from Gemma 1578, p. 19). While both Hagecius and Gemma draw the brighter stars with their semi-standard constellation pictures, and both show the basic celes-

[58] I have not seen this in person, but have a slide of it, courtesy of Owen Gingerich. Both copies that I have seen of Fabricius' 18-page tract on the comet (Fabricius 1578) have hand-coloured title pages (Royal Astronomical Society Library, shelfmark GH 5 E 44, item 15; Houghton Library shelfmark *GC5.F1149.577i), but this is different from the apparent broadside.

tial equatorial coordinate lines with the ecliptic superimposed, Hagecius seems more interested in showing the comet's changing physical appearance and Gemma seems more concerned with carefully showing its motion across the sky (note Gemma's carefully-marked numbers displaying the ecliptic coordinates). But Gemma's one image of the comet in Figure 3.11 is spectacular (unlike those in Hagecius' figure).

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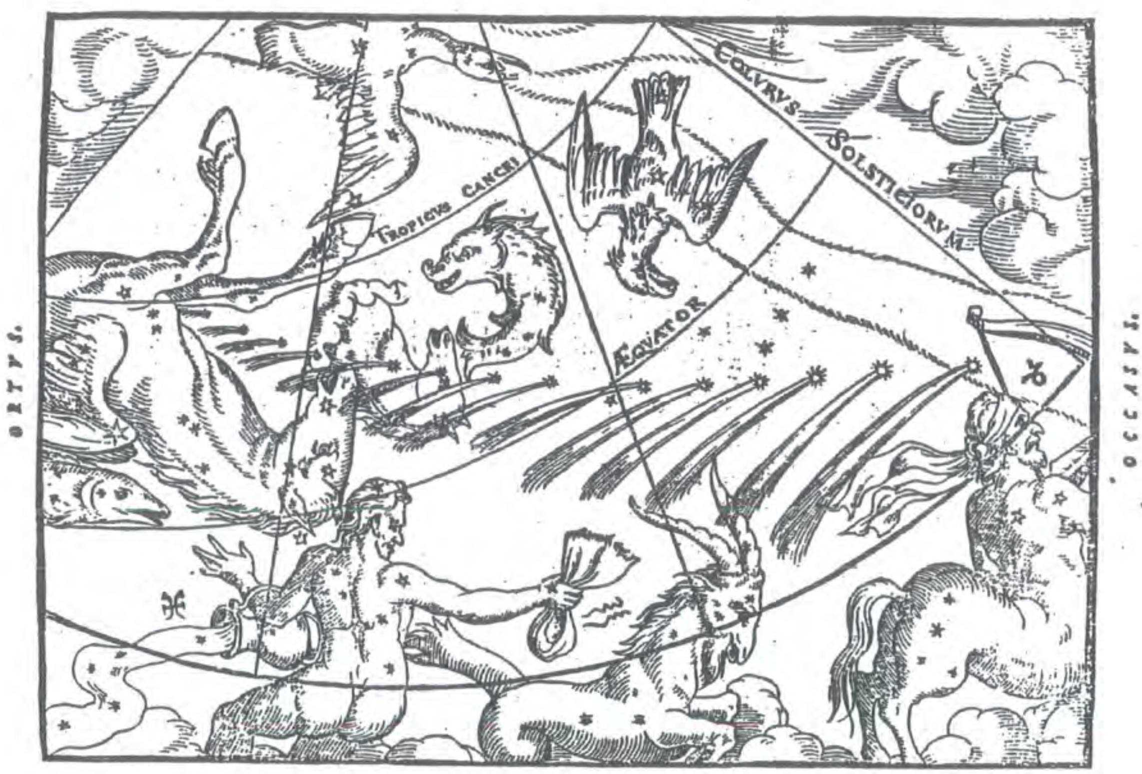


Figure 3.10. The path of comet C/1577 V1 as depicted by Hagecius (1578).

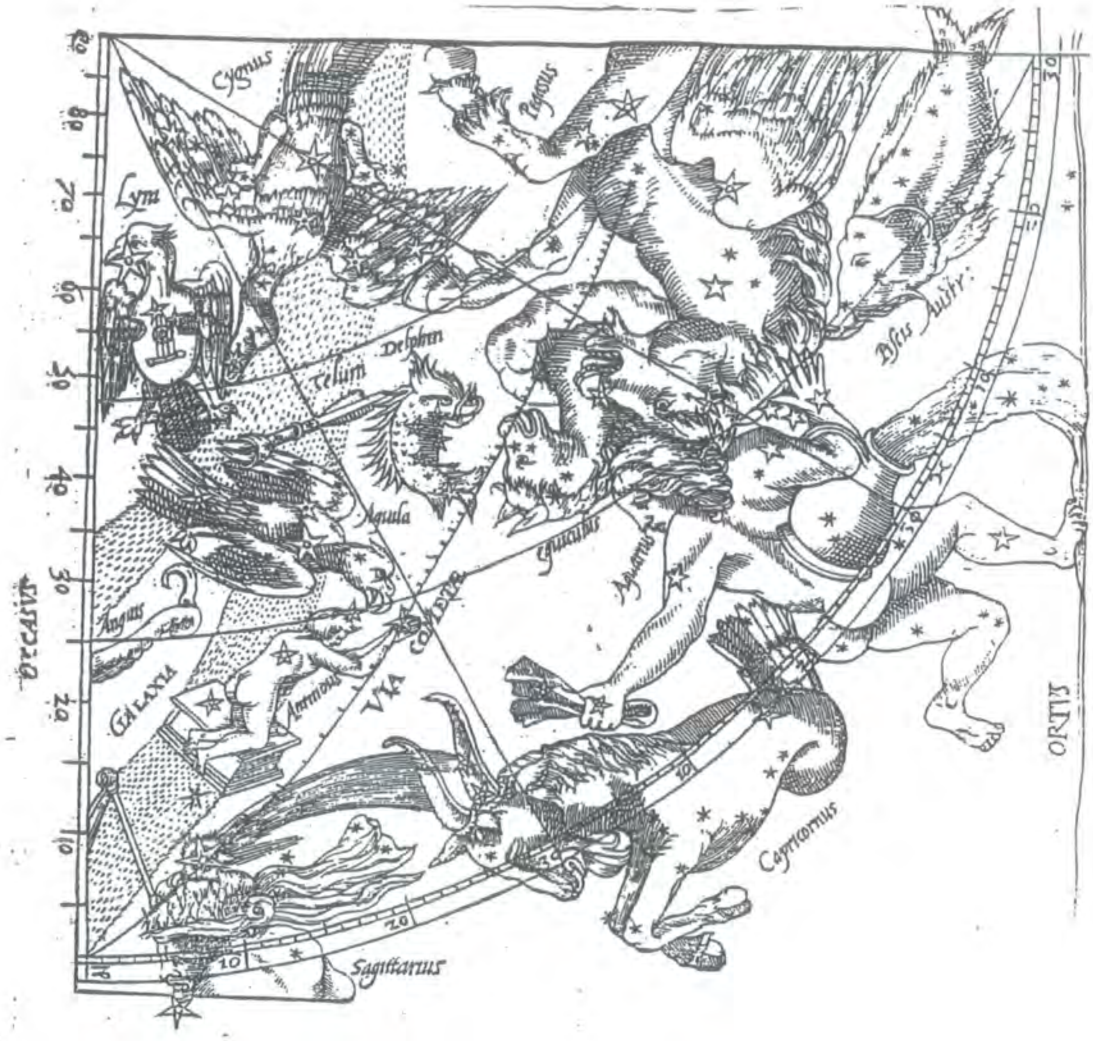


Figure 3.11. The path of comet C/1577 V1 as depicted by Gemma (1578).

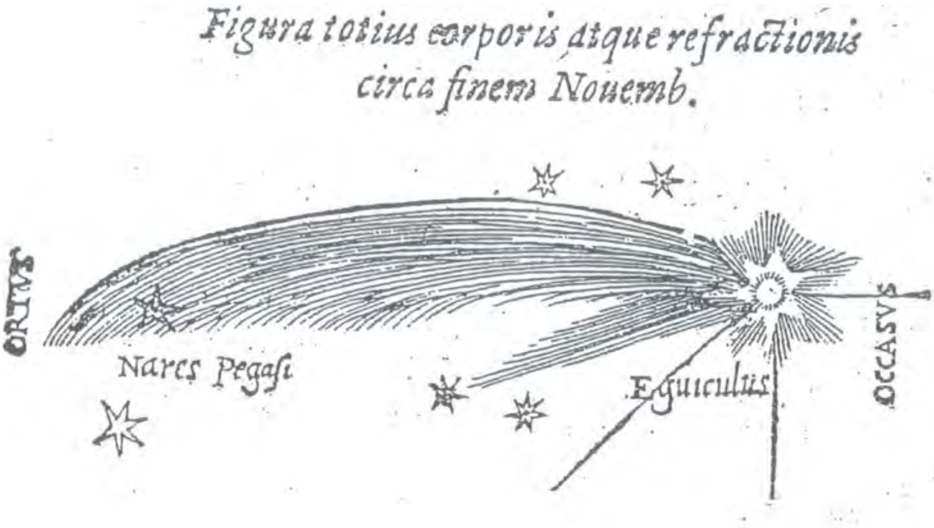
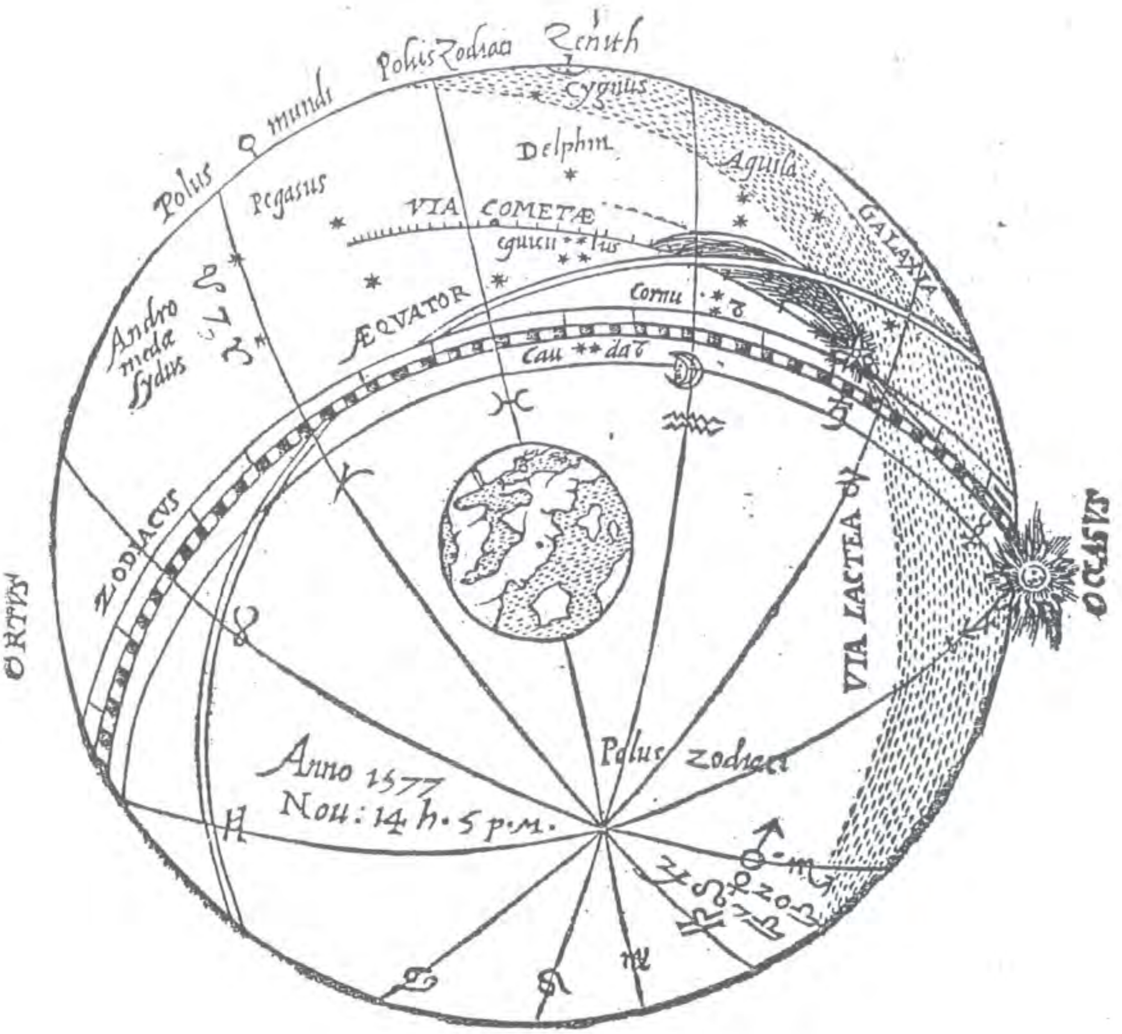


Figure 3.12. Detail of comet C/1577 V1 as depicted by Gemma (1578) as seen on 1577 Nov. 28. This remarkable drawing shows the straight shorter gas tail below the long, curving dust tail.

Figure 3.12 shows an illustration of the comet on November 28 (from Gemma 1578, p. 26); it is thought-provoking in its detail: it shows the comet and its tail with respect to the brighter nearby stars of Equuleus and Pegasus, but particularly notable is the bifurcated tail. This may be one of the earliest drawings of a comet showing its curving dust tail and its straight gas tail — today recognized as a normal aspect to the anatomy of the larger and brighter comets. Given the attempt at detail, we may also assume that the layers in the coma might also have been real features, at least to some extent — that is, there was probably a faint outer coma disappearing gradually into the background, though a sketch by Tycho from November 13 that shows no apparent gas tail shows the tail as wide as the coma when leaving it. Figure 3.13 shows an additional interesting aspect of Gemma's thinking (from Gemma 1578, p. 4), by depicting the comet against the celestial sphere and apparently well away from the earth (and thus, far beyond the earth's atmosphere). That Gemma showed the blue ion tail may result from something noted in modern observations, as well: some observers are more blue-sensitive than others (as noted in section 3.2, above), and faint ion tails can be difficult to see — especially if one is not expecting to see a fainter tail pointing in a different direction from the brighter dust tail (in the case of a dust-rich comet).

Figure 3.13. The placement of the 1577 comet in space, as visualized by Gemma (1578).



Scultetus [1578b, p. B1(a)] published a diagram of the comet, apparently for 1577 Nov. 10, showing a relatively narrow but long tail with slight broadening as it extends from the coma, but with two slight curves (first downward and then upward a little further down the length of the tail) — suggestive of an ion tail with "kinks" due to interaction of the tail particles with the solar magnetic-field lines — but it is hard to say whether this had anything to do with reality or if it was simply "artistic licence" (a problem that must be considered in some manner with most comet drawings from this period).

Many 1577 tracts simply had crude or stylized title-page drawings of a comet (e.g., Fiornouelli 1578; Schinbain 1578; Steinmetz 1577; Vergeri 1578). Pachymerius (1577) and Praetorius (1578) had the same publisher for their tracts, whose title pages with stylized comets and three men looking at the comet/tail against the background stars (with one man pointing to the comet) appear identical.[59] But even some of these may indicate something truly physical about the comet. For example, Thomas Twyne (1578) wrote a 24-page tract on the comet whose title page shows what appears to be simply a stylized comet, but at closer examination it shows a rayed star as the head, surrounded by lines that may indicate a fainter outer coma, and with a tail emanating from the coma that at first is less than the diameter of the coma but then expands outward as it gets further away from the coma.[60] Similar examples can be seen in two diagrams of a tract by Portantius (1577), where page Aii(a) has an interesting diagram that seems suggestive of two comet tails, even though the comet is rather stylized in appearance. Another example of an apparently simple, stylized comet title-page woodcut that may have something deeper can be found in a tract by David Chytraeus (1577); a seemingly crude diagram of a stylized comet with long tail amidst background stars has what appears to be an interesting coma. Another interesting coma appears in the title-page woodcut of the French pamphlet by de Mauden (1578), in which a two-"shelled" coma is depicted — possibly indicating a brighter inner coma and a fainter outer coma (often reported by visual observers today); de Mauden also showed the comet's shortening tail with time as a series of images representing the comet's path among the background constellations — with the early images showing a long tail and a feathered appearance to the tail's boundaries, indicative of striations or synchrones in the dust tail.

Johannes Huernius (1578) published a tract with a title-page diagram depicting a comet that again is somewhat stylized, but it also shows what appear to be different "layers" to the coma (suggesting a fainter outer coma — perhaps even hoods or dust shells?), with the tail again narrower than the coma diameter at the comet's head but expanding its width greatly some distance from the coma. A rather unique and curious series of diagrams accompanied various editions on the 1577 comet by Hannibal Raimondo (1577, 1578) showing six arching comet paths

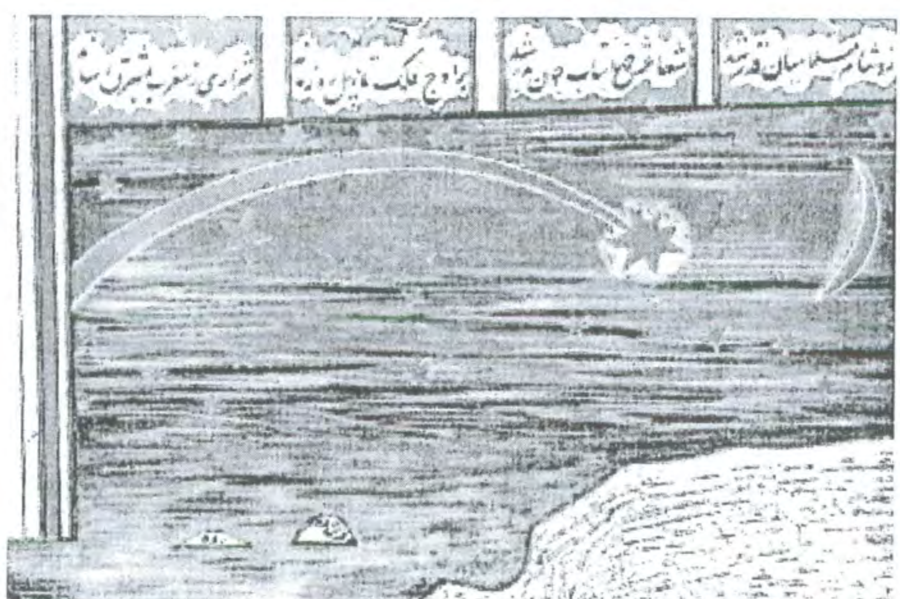
[59] Indeed, the similarity of the titles and tracts suggest that Pachymerius and Praetorius may be the same person.

[60] This particular tract, found in the British Library under shelfmark 1395.c.3 1578, says simply "Written by T.T. this 28. of Nouember, 1578" on the title page in terms of authorship, but Hellman (1971, p. 423) says "probably Thomas Twyne".

curving down into the horizon with tails flowing after them. Graminaeus (1578) even published, as his title-page diagram for his treatise on the 1577 comet, a woodcut from a tract on the *1556 comet* depicting that earlier comet's path against the constellations (perhaps he thought nobody would notice!).

One author even collected drawings of other observers and published them (Squarcialupi 1580) — five of the six examples showing curved tails for the 1577 comet. A different set of five illustrations depict only a star for the coma (the sixth having no star but a round coma and an long, outwardly expanding tail with a strong curve) — indicating that, when the comet was bright, it had a very small, almost-starlike coma (typical of bright comets, particularly when then are near perihelion well inside the earth's orbit — the high velocities of the comet and the impending solar radiation stripping away the coma particles too rapidly for them to remain in a relatively "quiet", sizeable coma). Two paintings from Istanbul (Figures 3.14a, b) are highly stylized but clearly show the definitive curved dust tail (cf. Menali and Ünver 2004). So it is obvious that artistically stylized images of comets in these old sources at least sometimes show real features that were visible to the observers.

Figures 3.14a and 3.14b. Two paintings of the 1577 comet from Ottoman manuscripts in Istanbul (described fully in Menali and Ünver 2004). The originals are in color.



The astrological placement of the comet of 1577 in horoscope diagrams became a commonplace occurrence in tracts, the prevailing thinking being that comets such as this had some influence on the events of mankind. Conrad Dasypodius (1578a, b) included a nice title-page horoscope diagram with the comet in the upper-right corner and the middle of the diagram giving 1577 Nov. 11 at 6 hours, 0 minutes p.m., evidently taken to be the birth time of the comet (as so many observers appear to have first seen the comet then, coming rapidly up over the southern horizon then as it moved northward in the sky). Gropler's (1578) title-page has a square horoscope woodcut that shows a stylized comet/tail in the lower central triangle, with the centre box reading "A.D. 1577. Noũmbris. 9 D. 12 H. 26 M.". Gropler, a mathematician at Brandenburg, wrote in his third chapter that the brighter a comet is, the more significant it is. Blaise de Vigenére (1578) wrote a tract containing nice diagram on page 2 with an eagle (presumably for Aquila) and stars, with a comet showing its tail and its head/coma in the mouth of the eagle; the book also contains three horoscope diagrams, one of which has at its centre "A six heures 41. minutes du soir: auquel temps presque s'apparut la Comete. 48. Degr. 42. minut." A horoscope diagram with the comet by Peter Sordi (1578) gives the "birth" times as 4:40 on 1577 Nov. 9. Nicolas Bazelius (1578) of Bergen published a tract with a title-page diagram depicting the comet in between signs for Saturn and zodiacal constellations, another fascinating woodcut showing a comet with horrific scenes on earth. Scultetus' extensive tracts on the 1577 comet (Scultetus 1578a, b) have an unusual fan-tailed comet depicted on the title page, with the fan hand-coloured orange or red on most of the copies that I have seen; horoscope diagrams on pages inside his Latin tract (only) have red/brown-coloured comets that appear to have been "stamped" onto the pages by the printer (see Figure 3.15). Other horoscope diagrams with the 1577 comet were published in tracts by Winckler (1578), Henisch (1578), Meyne (1578), Raxo (1578), and Montelli (1578?).

Figure 3.16 shows the title page of a book on the third 1618 comet from Thurnman (1619), in which short lines form a halo around the star that obviously represents the nuclear condensation (in some form) within that fainter outer coma. It is not clear where the line is drawn between artistic license and reality, but probably many cases of simple comet diagrams have a basis in depicting real features. But many apparent features can be explained by direct comparison to a modern atlas of cometary photographs — such as those for the well-documented 1910 and 1986 returns to perihelion of comet 1P/Halley (Donn *et al.* 1986; Brandt *et al.* 1992). These atlases show an amazing amount of diversity in the appearance of a single comet over time, from a tailless, circular coma to a complex tail spread over large position angles of sky with both dust and ionized-gas components of varying widths, lengths, and intensities.

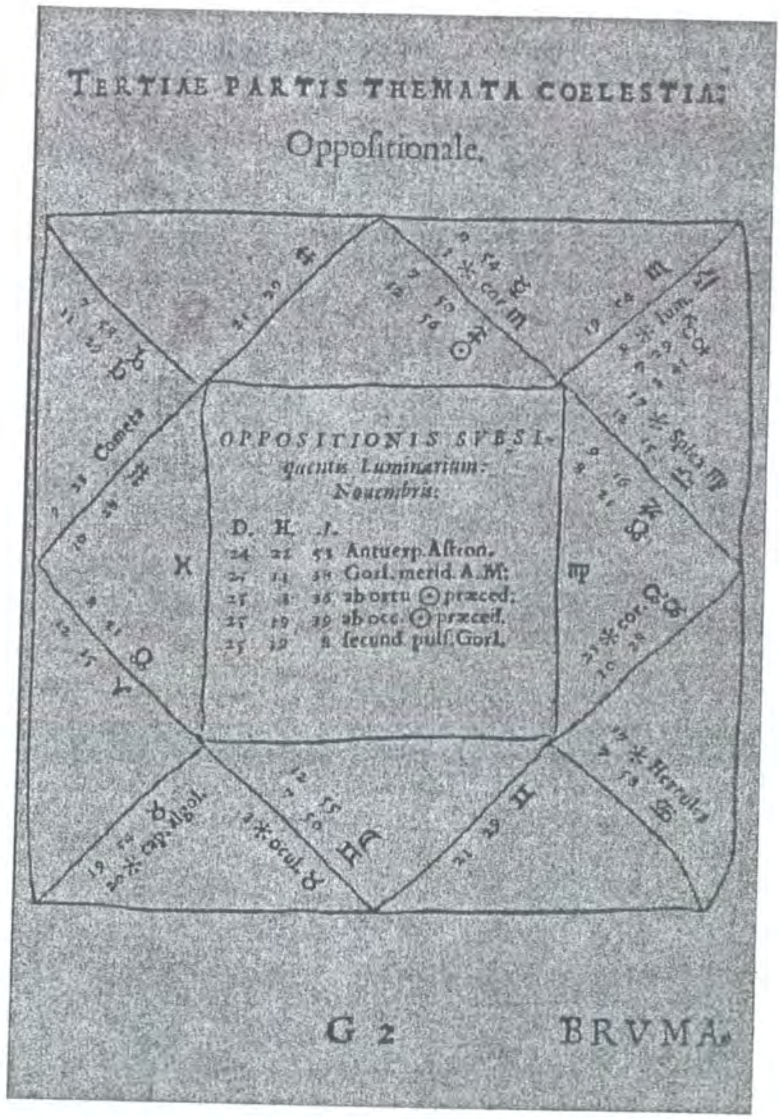


Figure 3.15. Horoscope diagram from Scultetus (1578b), p. G2(a). The comet, colored red in all of the original printed copies, is in the triangle at upper left, with the tail curving(!) downward through two more triangles.

STELLA COMANS

Oder

Gründliche vnd Warhafftige

Beschreibung/

Von dem newen Comet- vnd WunderStern / Auch Conjunctionen der Obern Planeten / so im November vnd December des 1618. Jahrs/ für dem Auffgang so wol als Nidergang der Sonnen / *juxta calculum Prutenicum sub elevatione Poli Maurimontani* 51. *Grad.* in der Lufft vnter dem Himmel erschienen vnd gesehen/ sampt desselben Bedeutungen.

Jederman zu getrewer Warnung/ mit besondern Fleiß observirt vnd beschrieben.

Durch

JOHANNEM ThurnMan / Maurimontanum, *Sax. Astronomiæ Studiosum.*

Gedruckt zu Erffurd/ bey Tobias Fritzschen/ Im Jahr Christi / M. DC. XIX.

Figure 3.16. Title page of book on 1618 comet depicting a comet with different levels of coma, from Thurnman (1619). See text.

Chapter 4:
Procedures of Reduction and Analysis of Old Astrometry

4.1. Distance Measures from Two Stars: Reduction Procedures for Naked-Eye Astrometry

In order to obtain better positional data with which to compute new orbital elements of comets observed in early-modern times, I wrote computer Fortran [61] programs to obtain right ascension (α) and declination (δ) coordinates for equinox J2000.0 from sixteenth-century star-comet (and star-supernova) visual distance measures. The basic problem of getting celestial coordinates from two sets of (reference star)-(supernova) distance measures is not readily available in the modern astronomical literature, including even basic texts on spherical astronomy, probably because few astronomers are now concerned with re-assessing old astrometric data. I was forced therefore to derive procedures for this purpose and to write computer programs to make these reductions much easier (and I am including a basic description of the procedures here for the benefit of those who may wish to pursue similar analyses).

Various spherical-trigonometric theorems and formulae were adapted for this purpose, beginning with the standard distance formula (*e.g.*, Meeus 1991), used for computing the distance, D, between two celestial objects when the coordinates for objects 1 (at position α_1, δ_1) and 2 (at position α_2, δ_2) are known:

$$\cos D = \sin\delta_1 \sin\delta_2 + \cos\delta_1 \cos\delta_2 \cos(\alpha_1 - \alpha_2). \tag{4.1}$$

If D_1 is taken as the measured distance between star 1 and the supernova (or other celestial object such as a comet), and D_2 is taken as the measured distance between star 2 and the supernova, we have two equations that can be combined to search iteratively for the supernova's declination by slowly varying the (assumed) supernova's right ascension:

$$\sin\delta_2 \cos D_1 - \sin\delta_1 \cos D_2 = \sin\delta_2 \cos\delta_1 \cos\delta_c \cos(\alpha_1 - \alpha_c) - \sin\delta_1 \cos\delta_2 \cos\delta_c \cos(\alpha_2 - \alpha_c), \tag{4.2}$$

where α_c and δ_c are the supernova's (or comet's) coordinates on the sky. This leads to

$$\cos\delta_c = \frac{x_0}{y_1 - y_2}, \tag{4.3}$$

where

$$x_0 = \sin\delta_2 \cos D_1 - \sin\delta_1 \cos D_2, \tag{4.3a}$$

[61] Examples of good Fortran manuals are Adams *et al.* 1997 and Chapman 1998.

is a constant for a given triangle. If we also take constants $x_1 = \sin\delta_2 \cos\delta_1$ and $x_2 = \sin\delta_1 \cos\delta_2$, then

$$y_n = x_n(\alpha_n - \alpha_c). \tag{4.3b}$$

There are potential problems that arise in this procedure when objects are near the celestial equator, and also when all three objects are nearly in a straight line, and some coding is necessary to handle these problem cases.

For any pair of star-supernova (or star-comet) distance measures, there are two general solutions on the celestial sphere that can be derived through a series of spherical triangles and their associated trigonometric equations. One works with four basic spherical triangles: (1) one containing the two reference stars and the supernova as the corners, (2) one containing the two reference stars and the north celestial pole (NCP) as the corners, (3) and two containing the supernova, one of the two reference stars, and the NCP. One must determine the right ascension of the supernova, α_c, by first determining the angle of the large spherical triangle that includes the NCP, the supernova, and one of the two catalogue stars. The supernova's declination, δ_c, comes from determining the length of side a in the same large spherical triangle. One first takes a spherical triangle connecting the NCP (at coordinates $\alpha = 0$, $\delta = +90°$) with stars 1 and 2, as the three distances between the points can be easily calculated with the distance equation, and the three included angles can then be calculated with the Sine Theorem (*e.g.*, Rektorys 1969; Woolard and Clemence 1966; Duncombe 1992).

The latter two triangles, each visualized like the one depicted in Figure 4.1 are needed for the two different solutions (each supernova-star-NCP triangle will produce a unique solution); one solution will be derived from the specific triangle set-up depicted in Figure 4.1 (with the supernova at $\alpha_c > \alpha_1$ and $\alpha_c > \alpha_2$), and the second solution comes from reversing the locations of star 1 and the supernova.

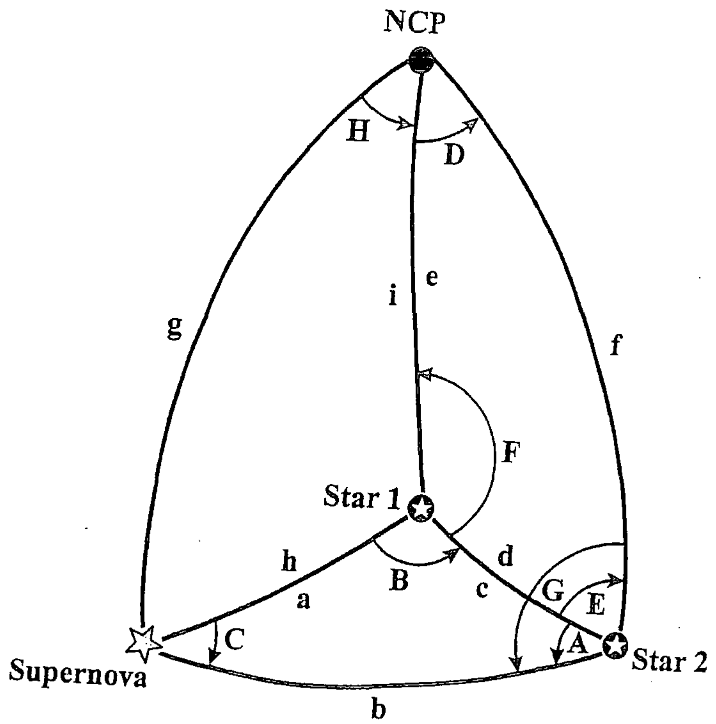


Figure 4.1. Series of nested spherical triangles illustrating explanation in section 4.1.

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One of the two formulae that are useful here is the cosine theorem for the sides (*e.g.*, Rektorys 1969, p. 123):

$$\cos A = \frac{\cos a - \cos b \cos c}{\sin b \sin c}, \tag{4.4}$$

where a, b, and c are the lengths of the sides, and A is the angle corresponding to a point at α_1, δ_1 (with a representing the side opposite to angle A in the spherical triangle). Once two sides and an angle are known, other angles can be determined from the sine theorem (*ibid.*):

$$\frac{\sin a}{\sin A} = \frac{\sin b}{\sin B} = \frac{\sin c}{\sin C}, \tag{4.5}$$

where angles B and C are opposite sides of length b and c, respectively.

In Figure 4.1, for example, one knows sides d, e, and f, and therefore the included angles of the triangle including the two catalogued stars and the NCP, by way of the distance formula (equation 4.1, above) and the sine theorem. One can determine the angle G of the large triangle (having the supernova, star 2, and the NCP as corners) by adding angles E (determined via the sine theorem as just noted) and A (determined via the cosine theorem for the sides, equation 4.4, from knowledge of the lengths of the three sides a, c, and b, which represent the two measured star-supernova distances and the distance between the two catalogued stars). With two sides (f and b) and one angle (G) of the large triangle known, the remaining side, g, can now be computed from

the same equation 4.4. This third side of the large triangle represents the supernova's declination, δ_c. The angles H and $H + D$ now represent the difference in the supernova's right ascension and that of stars 1 and 2, respectively, and $H + D$ can be calculated from the sine theorem.

4.2. Refraction

Any standard set of equations used to correct for refraction will suffer from uncertainties in the local observing conditions, so the best that one can do is to approximate some corrections for differential refraction effects; the complexities involving refraction errors were discussed by Ramsayer (1967). It is difficult enough solving for refraction if good data are available regarding the exact time and topographical location for the observations. But the observations of the 1604 supernova lack good timing information, and this puts strong constraints on what can be done in terms of refraction. For example, for an observer in northern Europe (latitude $\approx 50°$ N) viewing an object situated near the celestial equator at an altitude of $h \approx 5°$ over 15 minutes of time, the change in the amount of refraction is on the order of $\sim 2'.5$; at $h \approx 10°$, there is still a change of $\approx 1'$ in the refraction correction in 15 minutes of clock time. Medieval and early-modern observers generally did not state the time that they made astronomical observations, often because clock time was not very accurate, but also because they did not perceive a need to record accurate times.

If we take α and δ to be the actual right ascension and declination of a celestial object, and α' and δ' to be the observed values, we can determine the so-called parallactic angle, η, from

$$\cos\eta = \frac{\cos(90° - \phi) - [\cos(90° - \delta)\cos z]}{\sin(90° - \delta)\sin z}, \tag{4.4}$$

in which the zenith distance, z, can be found from

$$\cos z = [\cos(90° - \delta)\cos(90° - \phi)] + [\sin(90° - \delta)\sin(90° - \phi)]\cos H, \tag{4.5}$$

where ϕ is the observer's geographical latitude and H is the hour angle (cf. Green 1985, fig. 4.2; Rektorys 1969, equation 2). The observed values of the reference stars and planets are then determined from the first-order equations

$$\delta' = R(\cos\eta) + \delta \tag{4.6a}$$

$$\alpha' = \alpha + R(\sec\delta')\sin\eta \tag{4.6b}$$

where R is the amount of refraction (e.g., Hohenkerk *et al.* 1992, equations 3.283-3; Smart 1949, equations 39 and 40). For the calculations presented in this thesis, the value R was determined from

$$R = \frac{a}{\tan X}, \tag{4.7a}$$

with

$$X = h + \frac{b}{h + c}, \tag{4.7b}$$

and where h is the altitude of the object above the local horizon, $a = 1$, $b = 7.31$, and $c = 4.4$ (Meeus 1991, equation 15.3). In this manner, the differential refraction is determined for the reference objects, and then the supernova or comet position is calculated from this using the method outlined in section 4.1 (or Appendix A of Green 2004). Then, equation 15.4 of Meeus (or equations 4.7, above, with $a = 1.02$, $b = 10.3$, $c = 5.11$) is employed to subtract the effect of refraction to obtain a final supernova position (using the now-given values of α' and δ' and solving for α and δ via equations 4.6a and 4.6b, above).

4.3. Recorded Alignments of Comet with Star Pairs

Of the three naked-eye methods mentioned in Chapter 1 for determining a comet's position, one might think that the observing of alignments between pairs of stars and the comet might be the easiest. By way of a backyard experiment, I learned that finding bright, naked-eye celestial objects in precisely a straight line is difficult to accomplish: searching the sky over a couple of hours yielded only 11 sets of three stars that appeared to be reasonably in a straight line. Such a simple backyard test with a white string will show that parallax is definitely a problem, particularly when the three aligned stars are more than a few degrees apart. The observer must keep his/her head steady, moving only a single eye (and this must be done with single-eye vision) back and forth quickly while attempting the difficult feat of holding the string steady, which presumably would have some simple holder (rather than just holding the string up with fingers) to hold the string taut for increasing the accuracy. (Indeed, we read that Digges used such a holder, and we can suppose that Maestlin probably did also.) Fainter stars are, of course, much more difficult to align than are brighter stars. It is also rather difficult to find pairs of fairly bright naked-eye stars that have a common fifth star at their centre.

A couple of hours of evening searching of the northern autumn/winter sky for sets of stars along a projected taut (straight) string yielded nine sets of three stars in a line, but only two sets of crossing lines that intersected fairly close (to the naked-eye view) to a single star. I was curious to see how far each central star (in each set of three stars deemed, via naked eye and taut string, to be in a fairly respectable straight line) is from a straight line connecting the outermost two stars. So I selected J2000.0 positions from the PPM Catalogue (Röser and Bastian 1991), inserting α_1, δ_1, α_2, α_3, and δ_3 into equation (4.8), below, and solving for δ_2 (the declination of the middle star). For three objects (or points) along the same great-circle "straight line" on the celestial sphere, the following spherical trigonometric formula relates the three sets of α_n, δ_n (*e.g.*, Meeus 1991):

$$\tan\delta_1 \sin(\alpha_2 - \alpha_3) + \tan\delta_2 \sin(\alpha_3 - \alpha_1) + \tan\delta_3 \sin(\alpha_1 - \alpha_2) = 0. \tag{4.8}$$

The results showed deviations that ranged from arc-minute to worse-than-1° precision; the fact that fainter stars become much more difficult to use in naked-eye sightings of this nature was quite evident (the better results employed brighter stars). The results suggest that very careful measurements may yield positions that are within an order of magnitude of Tycho's instrumental accuracy, at best. The average deviation of the central star from a straight line constitutes the better part of 1°. This simple test shows that, even when one thinks there is a good alignment, there can be considerable error. Tycho was aware of this fact and expressed his concern to Maestlin, who had concentrated on alignments for his astrometry of the 1572 supernova and 1577 comet, as I noted earlier.

Re-arranging the terms of equation 4.8 to solve for an unknown declination value, δ_2 — assuming a particular right ascension (α_2) — we get:

$$\arctan \frac{[-\tan\delta_1 \sin(\alpha_2 - \alpha_3) - \tan\delta_3 \sin(\alpha_1 - \alpha_2)]}{\sin(\alpha_3 - \alpha_1)} = \delta_2. \tag{4.9}$$

For example, one can search over a range of $\pm$ 1° in α from the centre of a modern-day supernova remnant at 1″ intervals to look for the best fit. The solutions are sets of α_2 and δ_2 determined from the corresponding sets of straight lines. But for a comet, where one knows less clearly where it "ought to be", straight-line alignments including the comet and two more-distant objects are more problematical, giving inherent uncertainties that tend to greatly exceed those of distance measures from the comet to known celestial objects. For comets, then, one can take two intersecting lines of solutions of alignments with two sets of reference objects for use where better forms of astrometrical measurement are not available — but this is actually rather rare in practice.

Nonetheless, most of the serious observers of the comet of 1577 reported at least some alignments or near-alignments. My test shows that, even when one thinks there is a good alignment, there can be considerable error. For this reason, it is not very productive to consider cases where the comet was only determined to be in alignment with one pair of stars at one time; unfortunately, this situation occurs in most cases. Grynaeus (1580, pp. 78-81) reported six such alignments from November 22 to December 15; Nolthius [1578, pp. Ci(b)-Cii(b)] noted three such alignments on November 24 and on December 1 and 2; Gemma recorded two such alignments, on November 29 and December 26; Hagecius reported two such alignments, on November 24 and January 3; and Tycho recorded at least six such alignments.

Maestlin appears to have given the most thought to comet-star alignments, as it forms a major part of his argument on his 1578 treatise on this comet, even though he seems largely to have abandoned it due to "peer" pressure by the time of the 1580 comet apparition. Maestlin seems to understand the need for observing the alignment of the comet with more than one star pair, but just as I found in my tests, Maestlin found it exceedingly difficult to find multiple alignments of the comet with star pairs on a single night, and he resorted to other very awkward observations — for example, noting where the line between the comet and one star bisects the line connecting two other stars. Still, Maestlin reported alignments of the 1577 comet with two different star pairs on three different nights (November 12 and 17, and December 15). Figure 4.2 is from Maestlin's

1578 treatise, showing pairs of stars aligned with the comet (at position 'A') on the sky. Other observers who noted single-night alignments of the comet with two or more pairs of stars include Gemma (Jan. 6), Grynaeus (Dec. 14, 28, and 31), Hagecius (Dec. 1), and Tycho (Nov. 30). Some of the star identifications in these "alignment-pair" situations, however, are highly ambiguous.

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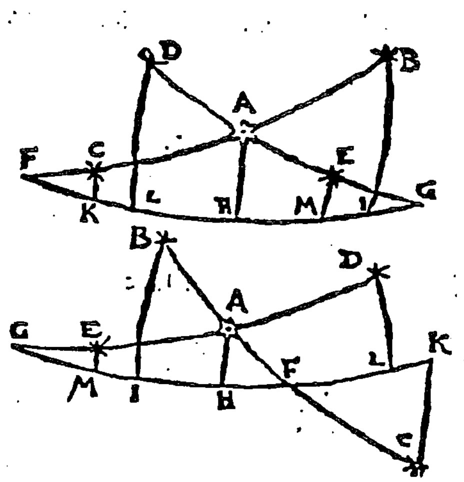

Figure 4.2. Michael Maestlin's sketches showing the comet (point A) at the intersection of great-circle lines connecting two pairs of stars (from Maestlin 1578, page 28).

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4.4. Orbital Characteristics of Comets

The comets that we see (at least initially) orbit the sun, though we see that some become ejected from the solar system due to close approaches of one of the planets, as comet C/1980 E1 (Bowell) was in the early 1980s (Green and Marsden 1982). This sun-orbiting feature of comets was unknown — though sometimes postulated without benefit of proof in the hundred years prior to the 1687 publication of Isaac Newton's *Principia*, by such men as Tycho Brahe, Michael Maestlin, William Lower, and Henry Percy (Bailey *et al.* 1990, *p.* 96) — until Edmond Halley (1705) used newly-developed concepts of physics and mathematics developed by Isaac Newton to show that positional measurements can be used to derive "variables" known as orbital "elements".

It is not known when Halley performed all of his calculations for the 24 orbits that appeared in his *Synopsis of the Astronomy of Comets*, which first appeared in 1705,[62] but it is known that he

[62] Halley's *Synopsis* was published in numerous places from 1705 to 1752, with some editorial changes by the author being made from one edition to the next. For example, Latin and English editions both appeared in

did some extensive work in 1695, because we have correspondence from that year between Halley and Newton on this very topic (see Scott 1967, pp. 165-190; MacPike 1932, pp. 91*ff*). There is, frustratingly, not much indication of the specific sources or data that Halley used for those comets seen before his day — though he specifically mentions observers' names for 16 of the 24 comets: "Nicephorus Gregoras, a Constantinopolitan Historian and Astronomer" (comet of 1337), Regiomontanus (comet of 1472), Peter Apian (comets of 1531 and 1532), Fabricius (1556), Tycho Brahe (comet of 1577), Michael Mæstlin (comets of 1580, 1596), Kepler and Longomontanus (1607, 1618), Hook (1664/5), "Mrs. Cassini" at Paris and Flamsteed at Greenwich (1680), and himself (1682 and 1683).[63]

Good accounts of the historical development of orbit computing of comets are given in numerous articles by the premier computer of comet orbits in the twentieth century, Brian G. Marsden (1974b, 1979, 1985a, 1985b, 1989, 1991, 1995c).[64] Basically, six "elements" or values are needed to determine the nature of a preliminary (two-body) orbit of a comet about the sun. Three positions at appropriately-spaced times (say, on three separate nights, or possibly fewer than this if the comet is moving rapidly in celestial coordinates α, δ) will then provide six data values (α, δ) are needed to compute a preliminary orbit, which is done assuming that the comet has no mass and the sun is considered as the only other object in the solar system; refined orbital elements (accounting for gravitational perturbations by the major planets) can be undertaken later (*e.g.*, Cunningham 1946); see Figure 4.3.

It was customary in eighteenth-century comet-orbit catalogues to list the comet's perihelion distance (now usually denoted q), which is its point of closest approach to the sun, in astronomical units (AU); the comet's time of perihelion (now usually denoted T); and angles representing the comet's orbital "longitude of perihelion" ($\tilde{\omega}$, or sometimes π), longitude of the "ascending node" (Ω), and inclination (i) with respect to the ecliptic. The "ascending node" is the point where the comet's inclined orbit passes northward through the plane of the ecliptic (which is the earth's orbit about the sun), and Ω represents the angle (usually given in degrees) between the directions to the vernal equinox and the ascending node as seen from the sun (see Fig. 2.1); likewise, the object's "descending node" is the point where the comet's orbit passes southward through the ecliptic plane, which is situated 180° from the ascending node (with respect to the sun in the plane of the ecliptic). All eight major planets (Mercury-Neptune), and most asteroids in the "asteroid belt" between Mars and Jupiter, have low-inclination orbits that stay within a few degrees of the ecliptic.

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[63] Halley 1752, pp. L4 and O2; Halley 1708, pp. 2-4. He mentions only Tycho with regard to the comet of 1577. Halley was also frustratingly vague about his reductions, and there are no known surviving manscripts of his orbital calculations or observation reduction.

[64] Other useful sources with historical information on the computation of orbits of comets (and planets) include Cunningham 1946; Herget 1948; Brouwer and Clemence 1961; Danby 1988; Yeomans 1991.

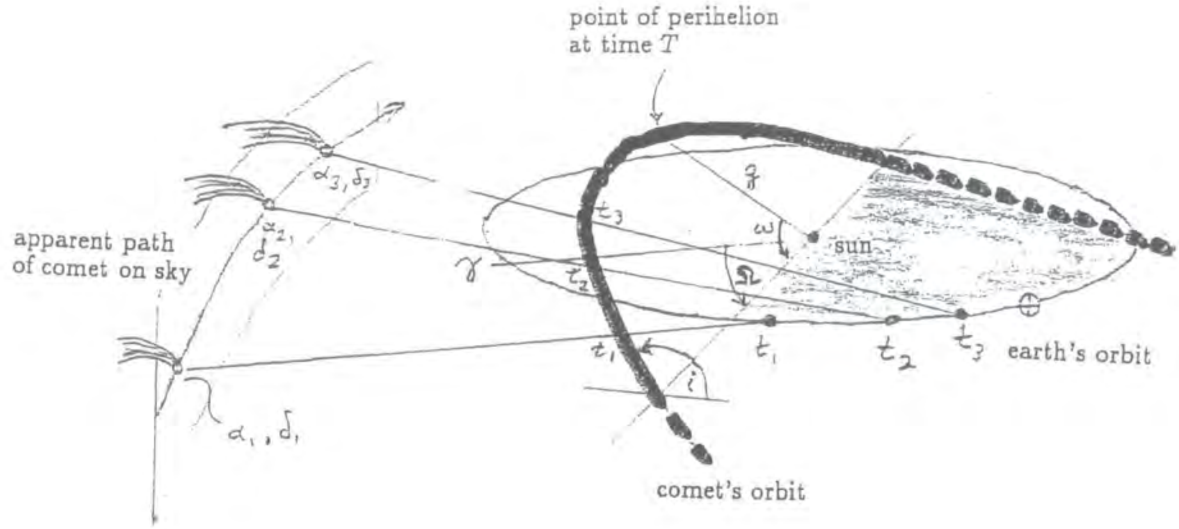

Figure 4.3. Diagram showing the key elements of a comet's orbit, as ascertained from positions on the background sky for times t_1, t_2, t_3, etc.; at the time of perihelion (T), the comet's heliocentric distance is denoted q.

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Prior to catalogues containing orbital elements that were compiled by Alexandre Pingré in 1783-1784 and by Wilhelm Olbers in 1797, comets were assumed in most orbital calculations to travel on parabolic orbits, but Pingré and Olbers added information concerning the semi-major axis[65] (a) and revolution period (P) for comets' orbits (Marsden 1979) — though for a long time, only Halley's comet was conclusively known as a comet returning to perihelion (and being so observed), with a period of revolution about the sun of some 75-76 years.

The "eccentricity", or shape, of the comet's orbit, is nowadays denoted e, with $e = 0$ representing a circular orbit and $e = 1$ representing a parabolic orbit (orbits with $e > 1$ are hyperbolic, and not bound to the sun). One sometimes finds (in old publications) an angle ϕ, where $e = \sin \phi$. Olbers began cataloguing values of e in his 1823 catalogue of cometary orbits, which included 125 orbit entries (Marsden 1979). We have the convenient relationship

$$q = a(1 - e), \qquad (4.10a)$$

[65] Most comets appear to travel in elliptical orbits, in which half of the longest axis through the ellipse (basically connecting the points of perihelion and aphelion) is termed the "semi-major axis". Note that the sun is generally considered to be at the center of this focus as the dominant gravitational force of the solar system, but the masses of the planets cause the center of mass of the solar system — its barycenter — to be offset somewhat from the center of the sun. This barycenter is used chiefly for considering orbits before and after long-period comets are well outside the orbit of Neptune.

and for a comet's furthest point from the sun (known as its "aphelion"), we have

$$Q = a(1 + e) = 2a - q. \tag{4.10b}$$

Orbits with aphelion distances < 7 AU from the sun are generally known as being in the "Jupiter family" of comets, due to their strong gravitational control from Jupiter's massive grip (*e.g.*, Marsden 1974a; Kresák 1982a). The orbital period of a comet is the time that it takes for the comet to make a complete revolution about the sun; this is given by

$$P = a^{3/2} \tag{4.10c}$$

in "Gaussian" years of 365.256898 days (Porter 1952). Another convenient relationship defines the line perpendicular to the semi-major axis (in the comet's orbit) from the sun's focus, known as the *semi-latus rectum*, p:

$$p = a(1 - e^2). \tag{4.10d}$$

Today a comet's orbit is usually given via the following six elements: q, T, e, and the three angles usually given in degrees that require specification of "mean equinox date" — i, Ω, and ω, the "argument of perihelion", which is the angle from the comet's perihelion point to the ascending node. Note that $\omega = \tilde{\omega} - \Omega$. The three angles describe the orientation of the comet's orbit with respect to the ecliptic (and, by correlation, also with respect to the celestial sphere); as such, they refer to a specific equinox epoch (though standard mean equinoxes were not employed until the mid-1800s) and must be stated along with the specified equinox epoch; the location of the vernal equinox changes due to the earth's precession. For many years until 1992, orbit computations (and astrometric positions) of comets referred to (mean) equinox B1950.0, but since 1992 the convention has been to use (mean) equinox J2000.0. Two quantities used to look at similarities of comet orbits are the ecliptic longitude of perihelion,

$$L = \Omega + \arctan(\tan\omega\cos i), \tag{4.10e}$$

and the ecliptic latitude of perihelion,

$$B = \arcsin(\sin\omega\sin i). \tag{4.10f}$$

Alternatively, instead of T, one can give the comet's position in terms of an angle known as an 'anomaly' at a specific epoch; the *mean anomaly*, denoted M, is usually found in orbital elements of major and minor planets:

$$M = n(t - T) = E - e\sin E, \tag{4.10g}$$

where t is the epoch (date), E is the *eccentric anomaly*, defined by $r = a(1 - e\cos E)$, and n is the *mean daily motion* (usually expressed in degrees). Equation (2.4g) is known as *Kepler's equation*, and is valid for elliptical (but not parabolic) orbits. A useful form of the mean motion can be found in the equation

$$n = ka^{-3/2} = 0^\circ\!.985\ 607\ 668\ 6/P, \tag{4.10h}$$

where k is Gauss' constant, defined as 0.017 202 098 95 AU/day, as $0^\circ\!.985\ 607\ 668\ 6\ \text{day}^{-1}$, or as 29.80 km/s (Porter 1952). A comet's velocity, v, with respect to the sun can be determined from the equation

$$v^2 = k^2\left(\frac{2}{r} - \frac{1}{a}\right), \tag{4.10i}$$

if the orbital elements are elliptical (*i.e.*, $e < 1.0$), where r is the comet's computed heliocentric distance (in AU) for the particular moment in question. In the case of a parabolic orbit (where $e \equiv 1.0$ and $a \equiv \infty$),

$$v^2 = 2k^2/r. \tag{4.10j}$$

Initial orbit determinations are made considering only two bodies: the comet and the sun (with the observed coordinates from earth reduced to a heliocentric system of coordinates). After a sufficient number of astrometric observations are available over a significant period of time (generally several weeks), a refined orbit that accounts for the perturbations of the major planets will be necessary. In this case, a seventh "element" is included with the six key orbital elements — the epoch of the "osculating" orbit, which is a time for which the orbit is valid. (Due to continual gravitational perturbations on the comet by the various planets and the sun, and to nongravitational forces caused by jetting action on smaller comet nuclei, a comet's orbit is constantly changing as it moves through the solar system. Because of the unstable nature of comet orbits, which carry comets closer to major planets of the solar system than do the orbits of more stable minor bodies (such as main-belt asteroids), they change rapidly with time and the epoch of the osculating orbit becomes therefore even more significant. Porter (1952) gives one of the best clear, technical introductions to orbital elements of comets.

It was well known that Halley's comet returned some 3-4 days late (Whipple 1950; Yeomans 1985) at each return to perihelion, with respect to the purely-gravitational orbital solution, when Fred L. Whipple investigated a similar problem with the orbit of Encke's comet. Whipple (1950) introduced a new icy-conglomerate model for the cometary nucleus that was acted upon by jets of material sent outward from the cometary nucleus as a result of solar radiation warming the nuclear ices. In the 1960s, Brian G. Marsden (1985a) was the first to model empirically these nongravitational forces (NGF) in a manner so that they could be well represented in orbital calculations. In Marsden's system, the accelerations due to NGF are inserted into the comet's equations of motion as three-dimensional parameters, A_1, A_2, and A_3. The first parameter represents the rocket-like radial acceleration that acts on the comet's nucleus in the sun-comet direction (at r = 1 AU); the A_2 parameter represents the transverse component of the NGF — the corresponding acceleration acting perpendicular to A_1 and in the plane of the comet's orbit (the corresponding component being parallel to the line from the sun to the point in the instantaneous orbit 90° ahead of the comet); and A_3 represents the normal to this plane but is generally ignored (as its average effect has been found to be rather negligible). The transverse component is the best-determined of the

three components of the NGF. The NGF affecting the motion of comet 1P/Halley has evidently not changed much in many centuries (Yeomans 1985).

As noted in section 1.2 and above, comets are inherently in unstable orbits because of their planet-crossing nature, and as such, comet orbits are constantly changing on scales that are generally much greater than can be seen in the orbits of the major planets and main-belt asteroids (for example). The orbital elements of long-period comets (customarily denoted as those comet having orbital periods $P > 200$ yr) with good arcs of astrometric observation are integrated backwards and forwards to give "original" and "future" orbits with respect to the solar system's barycenter — that is, orbits as they would appear prior to and following the "recent" observed apparition of the comet in the inner solar system; as noted before, such "original" and "future" orbits are different from the near-perihelion osculating elements in that they show the comet's orbit before and after extensive perturbations by each of the major planets. It is from these "original" orbits that we see a clustering of semi-major axes around $a = 10^4$-10^5 AU, representing the Oort Cloud. Curiously, no definite cases of "original" hyperbolic orbits of comets have been observed, meaning that we have not yet definitely seen an interstellar comet (that is, one that was not originally orbiting the sun); those original slightly-hyperbolic orbits that are present in catalogues of cometary orbits can be explained by uncertainties in the astrometric positions, orbital computations, and other issues such as nongravitational forces acting on the comets (*e.g.*, Porter 1963; Weissman 1996).

Some comets are seen to be ejected from the solar system in their "future" orbits; an unusual such case was comet C/1980 E1 (Bowell), which had a low-inclination orbit of only $1\overset{\circ}{.}7$ and passed 0.24 AU from Jupiter in December 1980, throwing the comet into a hyperbolic orbit that is carrying it permanently out of the solar system (Green and Marsden 1982). Comet D/1993 F2 (Shoemaker-Levy 9) was actually in orbit about Jupiter for some decades before a close pass in 1992 pulled the comet into many individual nuclei, later pulling the comet into a spectacular predicted collision with the jovian planet in July 1994 (Marsden 1995b; Spencer and Mitton 1995). Close encounters with Jupiter frequently cause comets to undergo perihelion-distance changes of > 1 AU (Belyaev *et al.* 1986, p. 371), and some short-period comets are also rendered invisible by greatly-increased perihelion distances, such as 39P/Oterma. Short-period comets (those with sun-orbiting periods $P < 200$ yr) are generally divided into those with "Jupiter-family" orbits, with $P < 20$ yr, and those with "Halley-type" orbits, with $P > 20$ yr (*e.g.*, Kresák 1982b); the Jupiter-family comets generally spend much time in the vicinity of Jupiter's orbit and thus have significant changes visible in orbital elements on time scales much shorter than for Halley-type orbits. Halley-type comets (named after the prototype comet 1P/Halley) have orbits that can evolve into Jupiter-family orbits, and short-period comet orbits can evolve into Halley-type orbits, but the evidence suggests that the two types of comets have different dynamical origins (Chambers 1994). Theoretical studies have shown (*op.cit.*) that comets in a variety of Halley-type orbits will over a million years see about a fourth of its candidates ejected from the solar system, another fourth evolve into sungrazing comets, and most of the remaining half evolve into

long-period orbits. One interesting comet that evades close planetary encounters for long periods of time, 96P/Machholz, is steadily spiraling in toward the sun in a matter of centuries (Green *et al.* 1990).

4.5. Preliminary Orbit Determination and Differential Correction

Ever since Newton and Halley, it has been customary to calculate parabolic orbits for newly discovered comets, as their motion can usually be well represented over at least a short arc by a parabola (and this reduces the six unknown orbital elements to five, by assuming the eccentricity to be 1.0). Later, when more observations have sufficiently extended the available arc, the orbit usually becomes obviously elliptical (and occasionally hyperbolic). But for the less-precise observations that we deal with, in terms of pre-telescopic astrometry of comets, there is but little choice than to assume parabolic motion. The orbit of a comet can generally be computed given three celestial positions at three known times, along with the observers' topocentric coordinates. In practice, there are problems of indeterminacy that arise when the arc of observation is short — particularly with older observations whose accuracy is not very good.

At the Smithsonian Astrophysical Observatory, I have worked as a staff member of the Minor Planet Center for some 25 years. Under the direction of its long-time Director, Brian Marsden, the MPC and SAO staff have developed a battery of Fortran computer programs that deal with observations of minor planets and comets in many different ways — depending upon what is available in the way of the observations themselves. For shorter arcs (hours, days), where a standard preliminary-orbit-determination procedure may fail, a form of the method developed by Väisälä (1939; Väisälä and Oterma 1951) is used — in which a family of orbits can be produced for a pair of observations in which the object itself is presumed to be at perihelion. One, two, or more elements can then be held "fixed" to solve for the remaining elements. For longer arcs, a method based on a 1946 Harvard Ph.D. thesis by Leland Cunningham was developed by Marsden and colleagues into extensive Fortran programs.

Cunningham's method guesses the object's distance from the observer at the middle of three dates/times as an initial approximation, and the goal is to "determine the coordinates and velocities at the middle date so as to fit exactly as many as possible of the six observed" sets of α, δ (Cunningham 1946, p. 64); this procedures uses the f and g functions, and it uses coordinates and velocities to compute orbital elements. The expressions for the f and g functions can be taken as:

$$f_i = 1 - [C(t_i - t_0)^2/2r_0^3] \tag{4.11a}$$

$$g_i = (t_i - t_0) - [C(t_i - t_0)^3/6r_0^3] \tag{4.11b}$$

where t_0 is the specific time at which x_0, y_0, and z_0 is the position of the comet *with respect to the sun* in three-dimensional coordinates and $\dot{x}_0$, $\dot{y}_0$, and $\dot{z}_0$ represents the comet's velocity; likewise,

other times, positions, and velocities are to be determined for the ith observations (*op.cit.*, p. 9):

$$x_i = f_i x_o + g_i \dot{x}_o \tag{4.12a}$$

$$y_i = f_i y_o + g_i \dot{y}_o \tag{4.12b}$$

$$z_i = f_i z_o + g_i \dot{z}_o \tag{4.12c}$$

The distance is given by

$$r_0 = (x_0^2 + y_0^2 + z_0^2)^{1/2}, \tag{4.12d}$$

and the constant $C = 0.01720209895$, with distances measured in AU and times in days. The direction cosines can be determined from the equatorial coordinates (being the geocentric or topocentric positions of the comet):

$$\lambda_i = \cos\delta_i \cos\alpha_i \tag{4.13a}$$

$$\mu_i = \cos\delta_i \sin\alpha_i \tag{4.13b}$$

$$\nu_i = \sin\delta_i . \tag{4.13c}$$

Also, the distance of the comet from the observer, ρ_i, is related to the sun's topocentric coordinates (X_i, Y_i, Z_i) by

$$\rho_i \lambda_i = x_i + X_i \tag{4.14a}$$

$$\rho_i \mu_i = y_i + Y_i \tag{4.14b}$$

$$\rho_i \nu_i = z_i + Z_i . \tag{4.14c}$$

After correction for light travel time between the comet and the observer (dividing the distance by the speed of light), one sets down nine equations with nine unknown variables and does iterative solving:

$$\rho_i \lambda_i - g_i \dot{x}_0 - [(f_i x_0) + X_i] = 0 \tag{4.15a}$$

$$\rho_i \mu_i - g_i \dot{y}_0 - [(f_i y_0) + Y_i] = 0 \tag{4.15a}$$

$$\rho_i \nu_i - g_i \dot{z}_0 - [(f_i z_0) + Z_i] = 0 \tag{4.15a}$$

(Cunningham 1946, p. 65). One begins by assu;ming a distance to the comet through a series of iterative solving of several sets of equations at a time. The positions (x, y, z) and the velocities ($\dot{x}$, $\dot{y}$, $\dot{z}$) of the comet are then related by quantities known as P and Q vectors to the standard six orbital elements (*e.g.*, Cunningham 1946, p. 41; Brouwer and Clemence 1961, pp. 31ff).

After preliminary orbit determination, a differential orbit correction is made numerically via least squares, in which each of the six orbital elements is successively changed by a small amount

and comparison made to the actual observations — yielding residuals in α and δ that have a bearing on the magnitude and direction of change in the individual elements (cf. Brouwer and Clemence 1961, pp. 233ff). Gauss in 1799 and Legendre in 1806 were apparently the first to use least-squares methods for differential orbit corrections of solar-system bodies (Marsden 1991, 1995c). Marsden (1995c) notes that, while "the 'standard' least-squares differential-correction development is nowadays considered to be that of Eckert and Brouwer (1937)",[66] "it is often convenient simply to revert to Legendre's procedure and approximate *all* the partial derivatives used in an orbital differential correction" for programs used with modern computers.

Obviously, the quality of observations are very important for the results of orbital calculations. As we shall see, with observations made prior to the last century or two — when observing procedures were crude or in their infancy — the accuracy of the positions (and, in many cases, the recorded times of observation also) put much greater constraints on our knowledge of the orbit than is true for most comets observed today. Thus, only two-body (comet/sun) calculations are warranted for most older comets with highly imprecise astrometry, where only an arc of some weeks is available. In the case of multiple apparitions for returning comets, particularly where modern precise observations are compared with older observations to explore possible identifications, orbital calculations must include allowance for perturbations by the major planets (and nowadays it is also customary to allow for the masses of the largest minor planets in the main asteroid belt, as their masses are fairly well known).

However, it should be noted that, where there are no identifications with more-recently-observed comets, the astrometry of comets goes down rapidly in quality as one goes back in time. The period of time covered in this thesis (in terms of the objects analyzed at length) spans basically the 16th through the 18th centuries, during which time the uncertainty in the astrometry decreases from $\approx$ 20′-40′ at best in the 1530s to $\approx$ 5′-8′ at best in the 1570s, and from $\approx$ 3′-4′ in the mid-1600s to $\approx$ 1′-2′ in the 1700s. Prior to the sixteenth century, the state of positional information on comets is so poor that orbital calculations drop significantly in determinancy — and many such older orbital solutions need to be treated with great caution.

[66] *A.J.* **46**, 125

Chapter 5:
Astrometry of the 1572 Supernova (B Cassiopeiae)

5.1. Introduction

The appearance of the Milky Way supernova of 1572 was perhaps one of the two or three most important events in the history of astronomy. The "new star" helped to shatter stale, ancient models of the heavens and to inaugurate a tremendous revolution in astronomy that began with the realized need to produce better astrometric star catalogues (and thus the need for more precise astronomical observing instruments). The supernova of 1572 is often called "Tycho's supernova", because of the extensive work that Tycho Brahe (1573, 1602, 1610) did in both observing the new star and in analyzing his own observations and those of many other observers. But Tycho was not even close to being the first to observe the 1572 supernova, although he was apparently the most accurate observer of the object (though not by much over some of his European colleagues). The supernova itself was given the designation "B Cassiopeiae" by Bayer in his 1603 atlas,[67] and I will hereafter refer to the supernova as "B Cas". With the on-going high interest in the supernova remnant 3C 10 (obvious from the numerous papers on this object published in the literature during the last two decades), it is appropriate to again look at the supernova and its position on the sky.

My own work in re-reducing astrometric data on the comet of 1577 showed that Tycho's positional measures for that object were not much better than much of the astrometry performed by his fellow European observers, notably Thaddeaus Hagecius of Prague and Cornelius Gemma of Louvain (see Chapter 8). Tycho did not have his best instruments available in the 1570s, as this was early in his observing career (see, e.g. Dreyer 1890; Thoren 1990). I was naturally drawn therefore to look at the new star of 1572, which these and other observers of the 1577 comet had also diligently followed — publishing data concerning the nova's brightness, colour, and position within Cassiopeia. Knowing that previous research on the supernova's position had concentrated on Tycho's own observations (with the notable exception of the work by F. R. Stephenson and D. H. Clark), I was curious to analyze data uncovered in my own research by various 1572-1573 supernova observers via some new computer programs that I had compiled to analyze the 1577 comet. Indeed, it is hard to not find considerable mention of the 1572 supernova in any tracts on the 1577 comet!

[67] on page K; even though the star had been invisible for three decades, Bayer gave a long description of the supernova and depicts B Cas as the brightest star in Cassiopeia on his map of the constellation.

The more reliable contemporary reports state that the new star itself burst forth sometime between 1572 November 2 and 6 (Dreyer 1914, **2**, 18-20), when it rivalled Venus in brightness. The supernova remained visible to the naked eye into 1574, gradually fading until it disappeared from view. Numerous other researchers have published their analyses of the supernova's brightness and colour, and only reference to some of the key citations is given here for the benefit of readers: Baade (1945); Clark and Stephenson (1977, pp. 177-180); Doggett and Branch (1985); van den Bergh (1993); Schaefer (1996). English translations of relevant passages in Brahe (1573, 1602, 1610) concerning the supernova's brightness and colour can be found also in Dreyer (1890, pp. 41-42) and in Thoren (1990, p. 68).

The search for a supernova remnant was negative until fifty years ago, when Hanbury Brown and Hazard (1952) reported a radio detection at 158.5 MHz. This was confirmed at wavelength 1.9 m by Baldwin and Edge (1957), and the remnant was also identified tentatively in the second Cambridge radio-source catalogue as object 2C 34 and identified more firmly as 3C 10 in the third Cambridge list (Edge et al. 1959). There is no dispute that 3C 10 is the remnant of the supernova observed in 1572-1573. Following the review article by Minkowski (1968), the designation 3C 10 appears to be that most commonly used in the literature when referring to the radio remnant of B Cas (though some authors use the tabulated Galactic designation G120.7+2.1 of Green 1984, and many authors commonly refer to it as "Tycho's supernova remnant" — somewhat of a misnomer, as Tycho saw the pointlike supernova, not the expansive radio remnant). Because the radio remnant was reported before the optical supernova-remnant wisps were discovered (see the historical account on this by van den Bergh 1971, footnote 1), the designation 3C 10 is used by some to signify the remnant at all wavelengths, and I'll adopt that convention here.

5.2. The Sixteenth-Century Observers and Their Data

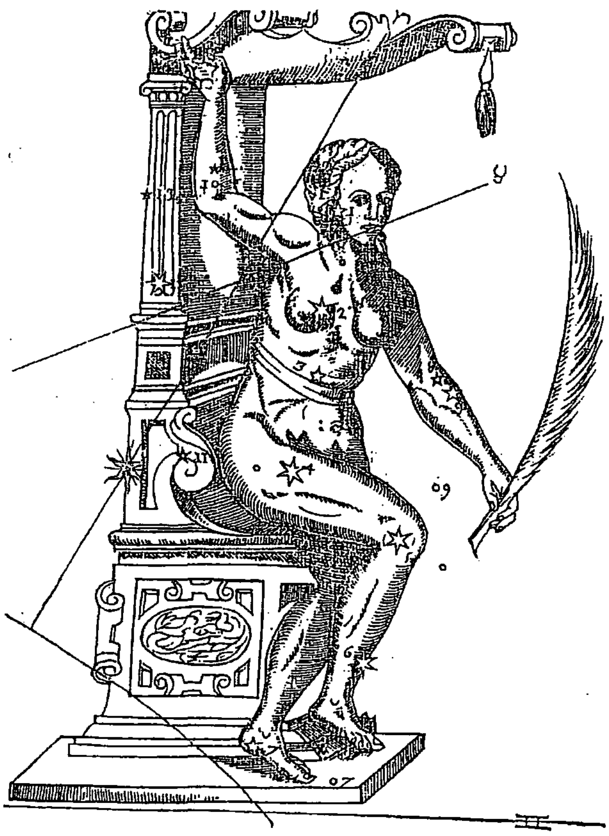
As noted earlier, a standard method of astronomical observation was beginning to develop during the sixteenth century, but standardization took on new meaning with the supernova of 1572 and the comet of 1577. Communication between astronomers in Europe was slow then, compared to today. But in the case of B Cas, which was visible for well over a year, there was time for initial tracts on the supernova to appear in print and letters to be exchanged between astronomers while observing was still possible. Most of the tracts on B Cas were published in late 1572 or in 1573, but a few important publications occurred some years later — most notably those by Cornelius Gemma (1575) and posthumously by Tycho Brahe (1602, 1610). The majority of tracts on the 1572 supernova had some astrological speculation in them, as that was considered a normal aspect of astronomy in sixteenth-century Europe.

A large percentage of the tracts (probably most of them) on the new star contained at least some positional information from observations: usually at least a rough attempt at (and some employing considerable effort to get) the object's celestial coordinates in terms of ecliptic longitude and latitude, and sometimes some measured altitudes of the supernova with respect to the

local horizon. Several serious observers concentrated on reporting altitude measures and celestial coordinates for B Cas, which are of little use for modern attempts at improving upon the position of the supernova (altitude measures would have the same or worse uncertainty as/than distance measures between stars, and they would need very accurate clock timings to have any value, another impossibility given the state of technology in 1572). However, their contributions were important in the progression of the state of astrometry in the years to come, even if we can do little now with their data to improve upon our knowledge of the position of B Cas. So it is useful to mention some of the key individual observers (and some of their work cited parenthetically): George Busch (1573); John Dee (Brahe 1602); Paul Fabricius (Hagecius 1574); Paul Hainzel (Brahe 1602); Cyprian Leovitius (1573); Francesco Maurolyco (1572); Andreas Nolthius (1573); Annibale Raimondo (1573); Erasmus Reinhold, Jr. (Brahe 1602); Helisaeo Roeslin (1578); Wolfgang Schuler (Brahe 1602); Wilhelm, Landgrave of Hesse (Brahe 1602). Brahe (1602, 1610) devoted most of the third part of his *Progymnasmata* (pages 489-786) to detailed discussion of many other observers, one by one, including most of those just cited; Tycho even included large-scale transcriptions of the text and data of many published tracts and unpublished manuscripts of these other observers (text republished via Dreyer 1916).

A few observers noted the alignment of the new star with pairs of other visible stars, using a straight-edge of some sort (or even a taut string or thread) held up between the stars and the observer's eye. Also, several observers recorded measurements of the new star's distance in degrees and minutes of arc from nearby reference stars, mostly those in Cassiopeia but also Polaris and a few other bright stars. As discussed in Chapter 2 of this thesis, despite the advent of the printed star chart, it was not always clear which catalogue description of a star within a constellation belonged to which star on the sky. Thus we have the chair, head, or knee of Cassiopeia. While observers tended to identify these stars correctly, some observers did have problems identifying the stars of neighboring constellations (see the remarks about Digges' observations in section 5.2.5, below). The reference stars in Cassiopeia are shown in Table 5.1 (listed there in the order that they appear in Ptolemy and Copernicus), together with the Latin descriptions from various catalogues in use within a few decades of the appearance of B Cas (see Figure 5.1). Catalogues by Ptolemy, by Copernicus, and by Schöner (1551) were used by the observers of the supernova. Star descriptions from the later catalogue of Tycho (which was laboriously produced over many years of observation, spurred by the appearance of the 1572 supernova) and from the 1603 atlas of Bayer are included in Table 5.1 for comparison.

Figure 5.1. Figure of Cassiopeia (with B Cas located below the centre on the back part of the throne at left) and tables of reference stars and distances to B Cas, from Thomas Digges' 1573 tract on the supernova, pages Ai(b) and Aii(a).



[illegible]

CASSIOPEÆ

Stellarum.

Nomina.	Longitudines. Gr.	Mi.	Latitudines. Gr.	Mi.	Magn.
1 In Capite.	1	10	45	20	4
2 In Pectore.	4	10	46	45	3
3 In Cingulo.	6	20	47	50	4
4 In Coxa.	10	0	49	0	3
5 In Genu.	12	40	45	30	3
6 In Crure.	20	20	45	30	3
7 In Extremo pedis.	25	0	48	20	4
8 In Sinistro brachio.	7	40	45	0	5
9 In Sinistro Cubito.	8	0	44	20	4
10 In Dextro Cubito.	357	40	50	0	6
11 In Sedis pede.	8	30	52	40	4
12 In Ascensu medio Cath.	1	10	51	40	3
13 In Extremo.	357	0	51	40	6

Phaenomeni caelestis insoliti, Distantia à stellis in Cassiopea.

	Gradus.	Scrupuli.
Pectore	7	47
Coxa	4	58
Genu	8	5
Crure	9	45
Sedis pede	1	28 1/2
Ascensu medio	5	15

A.ij.

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TABLE 5.1. Identification of reference stars in Cassiopeia

Bayer Desig.	*Ptolemy (Peters/Knobel)*	*Copernicus/ Schöner*	*Tycho*	*Bayer (text)*
ζ Cas	in capite	in capite	in capite	in capite supra nasum
α Cas	in pectore	in pectore (Schedar)	in pectore, Schedir	in pectore, Seder, perparam Scheder
η Cas	borealior ipsa et est in cingulo	in cingulo	in cingulo	in corde
γ Cas	supra sedem in cruribus	super cathedra ad coxas	ad ilia; in flexura ad coxas	ad ventrem, seu ilia
δ Cas	in genibus	ad genua	in poplite ad genu	in dextro femore, iuxta genu
ε Cas	in tibia	in crure	in crure	in crure sinistro
ι Cas	in extremitate pedis	in extremo pedis	estrema pedis	in extremo pedis sinistri
κ Cas	supra pedem sedis	in sedis pede	in erectione sedis	in medio sedis, id est reclinatorio
β Cas	in media sede seu cathedra	in ascensu medio medio	in medio cathed.; Lucida cathedrae	in summâ feré cathedrâ propoer brachium dextrum

◇ ◇ ◇

My discussion of the data of the primary observers naturally begins with Tycho.

5.2.1. Tycho Brahe (Copenhagen)

Tycho had been observing astronomical objects half-seriously for about ten years when (with Tycho at age 26) the 1572 supernova burst forth. In addition to Tycho's own discussions of his astrometric instruments and his assessment of errors in his measurements (Brahe 1598, 1602), good accounts of the evolving observing astrometric precision over several decades in his observing program have been given by Dreyer (1890), Thoren (1973, 1990), and Wesley (1978). While sixteenth-century astronomers were well aware of the discrepancy between observation and theory, it was Tycho who realized most deeply that better instruments had to be built to overcome the problems. Tycho perceived that the new star in Cassiopeia was something that was very important to understanding astronomy, and he realized that the existing star catalogues needed vast improvement if anything was to be learned about the 1572 nova (a realization enforced with the appearance only five years later of one of the brightest comets of the millennium).

Tycho's precision got better after 1572, as he constructed bigger and better instruments that produced smaller errors in measurement. I have found in my research on the comet of 1577 that Tycho changed the distances measured from the comet to numerous stars from what was written in his observing logbooks (Friis 1867) for the final publication in his monumental book on the comet (Brahe 1588). Whether he was doing this as part of his determined instrumental corrections, to correct clock error (as sometimes noted by Tycho) for the fast-moving comet, or for some other reason, he showed early in his observing career that he was determined to be critical of his own

observations. Dreyer (1890, p. 387) showed Tycho's measured star positions to be generally within $\sim 1'$ of catalogued positions from the second half of the nineteenth century; I have verified that Tycho's positions for (bright) stars are generally around $1'$ in accuracy when compared with 20th-century catalogues. But these measures between reference stars were largely made well after 1572, when Tycho had his better instruments, so they are not overly helpful in assessing the accuracy of his measures for B Cas — for which he mainly used a sextant with arms made of "very dry walnut wood" and its 30° arc made of metal (Ræder et al. 1946). This "enhanced" astronomical radius (like a giant compass) was apparently built by Tycho's craftsmen after the appearance of the supernova, when he realized that he quickly needed something to provide more accuracy than the old cross-staff that he had purchased a few years earlier.

Tycho published an initial tract on the supernova in 1573, while it was still visible, containing only preliminary distance measurements between B Cas and three reference stars in Cassiopeia. Much of Tycho's observing logs are missing from the time around the appearance of B Cas, but a couple of entries are still available to us in a manuscript logbook from 1573. Around 1914, Dreyer wrote in his manuscript notes for the background information to *Tychonis Brahe Dani opera omnia*, "Among Tycho's manuscript observations, there are none from 1572, and from 1573 only these of the new star", which he published in at least three places (Dreyer 1890, p. 41; Dreyer 1915, p. 455; Dreyer 1923). In Dreyer's final version (1923), which has the complete extant text from the manuscript observing book for 1573, Tycho corrects the original distances for B Cas to γ Cas (5°08′), β Cas (5°28′), and α Cas (8°05′) to 5°00′, 5°20′, and 7°52′, respectively, due to the instrumental parallax caused by the eye being a little distance behind the first slit. (These corrections were based on empirical correction and were possibly established at some later date — cf. Brahe 1602, pp. 340ff; Dreyer 1923, pp. 19-20; Ræder et al. 1946, p. 82.) These observations were made on May 10 of that year. The next entry in the logbook is for August 14, giving the distance of the nova to Polaris as 25°09′, and there are no additional entries for the new star. Given that Tycho's 1573 book — which contains only distance measures from the nova to α, β, and γ Cas, as 7°55′, 5°21′, and 5°01′, respectively — was finished in late April of that year (Thoren 1990, p. 72), it seems likely that Tycho did not measure distances to other stars until later in 1573, as the new star was fading to second or third magnitude.

Tycho spent much of the rest of his career working on his impressive mammoth Latin-text *Progymnasmata* (republished via Dreyer 1915, 1916), which was mainly about the supernova. Distance measures by Tycho from several additional stars to B Cas appear in a table in his *Progymnasmata* (Brahe 1610, pp. 344; Dreyer 1915, p. 336): Tycho made corrections to his original raw distance measurements (made with the sextant) for the final publication therein; the corrections are based on instrumental-parallax problems inherent in the sighting mechanism on his sextant (Brahe 1602, p. 342; Dreyer 1890, p. 47; Thoren 1973), and the corrections increased with larger measured distances. For example, Brahe (1602, pp. 593-596) states that the correction amounted to $4'.5$ for α Cas, $1'$ for γ Cas, and $2'$ for β Cas, which agrees with the difference between the distances given for these three stars in Tycho's publications of 1573 and 1602.

In the third part of *Progymnasmata* (p. 558), when he gives a table comparing the distances measured by Gemma and himself between the supernova and the various reference stars, Tycho adds his own measures for α Per and α Aur (Capella) that did not appear earlier. The inclusion of these two additional stars to Tycho's own measures bring the position of B Cas closer to the centre of 3C 10, so I have included a solution in Table 5.4 that includes the measures to Capella and to α Per.

5.2.2. Thaddeaus Hagecius (Prague)

Thaddeaus Hagecius ab Hayck was a friend and regular correspondent of Tycho's and one of the premier astronomical observers of the late sixteenth century (Green 2004h). His Latin-text *Dialexis* (Hagecius 1574) is perhaps the most impressive tract on the 1572 supernova after Tycho's own work. Horský (1967) published a facsimile edition of *Dialexis*, along with a short biography of Hagecius. Prior to *Dialexis*, Hagecius published some positional information on B Cas in a 7-page essay that appeared as part of Reisacher's 1573 tract on the new star.

Like Tycho, Hagecius published a table of distance measures between the supernova and nearby stars in Cassiopeia (and also of distances between the reference stars; Hagecius 1574, p. 18). Tycho published his discussion of Hagecius' observations on pages 505-528 of *Progymnasmata* (corresponding to Dreyer 1916, pp. 19-43). Hagecius was heavily involved in discussion and correspondence regarding B Cas with other observers for some years to come, and his 1574 book included observations by other observers by way of short tracts written by Gemma and Fabricius. Horský notes (p. 14) that Hagecius rewrote part of his *Dialexis* after criticism that came from Tycho and others, though the modified version of that revision apparently was not preserved; the modified text was sent to Tycho, where parts are evident in the *Progymnasmata*, including two revised distance measures that are given in Table 5.2, below. As noted in Chapter 2, Hagecius later published books on the 1577 and 1580 comets with useful astrometry; Horský adds that Hagecius published a Czech tract on the comet of 1556.

5.2.3. Cornelius Gemma (Louvain)

After publishing a shorter tract (Gemma 1573) that was also partly included in Hagecius (1574), Cornelius Gemma put more work concerning his observations of the 1572 supernova into a 1575 book (*De Natvrae divinis Characterismus*, Book 2, pp. 115-116) that encompassed many other unusual natural phenomena. Fewer (supernova)-(reference star) distance measures appeared in Gemma's earlier work, *De Peregrina Stella* (p. A2) — all of which (except the distance to Polaris: "almost 23°48′") are listed in Table 5.2, below. Tycho published his discussion of Gemma's observations on pages 553-564 of *Progymnasmata* (corresponding to Dreyer 1916, pp. 67-80). Though one of the most respected astronomers of his day, and the son of a leading instructor in astronomical observation (Gemma Frisius), and though his observations of the comet of 1577 were evidently better (perhaps improved following discussions of observations of the 1572 supernova with other astronomers), the residuals of Cornelius Gemma's observations of B Cas are not as self-

consistent as those of some other observers. Gemma earlier had also made positional observations of the 1556 comet.

5.2.4. Jeronimo Muñoz (Valencia)

Muñoz (1573, 1574) made only four distance measures between the supernova and reference stars (listed in Table 5.2), but his measurements were fairly accurate, obviously undertaken with care. Muñoz's 1573 tract was republished in facsimile, with translation and background material, by Brotóns (1981). Tycho published his discussion of Muñoz's observations on pages 565ff of *Progymnasmata* (corresponding to Dreyer 1916, pp. 80-87).

5.2.5. Thomas Digges (London)

Digges (1573) made some of the more accurate distance measures between the 1572 supernova and neighboring reference stars (see Table 5.2) and published them in his tract *Alae sev scalae Mathematicae* on page Aij (see Figure 5.1). He also noted the alignment of the supernova with two pairs of stars (the identification of which were confused and had to be corrected by Tycho). This is discussed further in the section concerning Maestlin, below. Tycho published his discussion of Digges' observations on pages 653ff of *Progymnasmata* (corresponding to Dreyer 1916, pp. 167-203).

5.2.6. Michael Maestlin (Tübingen)

Maestlin (1573) wrote a short tract that is very rare today, but which was published again in Tycho's *Progymnasmata*, on pages 544-548. It was originally printed and bound as pages 27-32 of a tract on the supernova by Nicodemus Frischlin (1573). Maestlin made no distance measures between B Cas and reference stars, but he did note the straight-line alignment of the supernova with pairs of other stars, using a thread or string held to the sky. [Maestlin (1578) also used this method for the comet of 1577, but following discussion with Tycho and other observers, he changed to measuring comet-star distances for the comet of 1580.] Maestlin's results for B Cas, together with the straight-line alignments noted by Digges (corrected by Tycho), were analyzed by Stephenson and Clark (1977), who found amazing agreement in the position, which precessed to equinox 2000.0 is $\alpha = 0^h26^m01^s$, $\delta = +64°07'.2$, lying just outside the current southeastern boundary of 3C 10 (see Figure 5.2).

5.2.7. Bartholomew Reisacher (Vienna)

Reisacher (1573) only made one measure of the distance between B Cas and another star, κ Cas: 1°25′ — a value too small to be usable. But Reisacher's observations were repeated with discussion by Muñoz (1573) and by Brahe (1602, 1610). As noted above, Reisacher included Hagecius' first essay on the supernova in his own tract.

TABLE 5.2. Distance measures (in degrees and minutes of arc) for various observers between reference stars and the 1572 supernova.

Ref. star / *Observer:*	*Tycho* (1602)	*Hagecius* (1574)	*Muñoz* (1573)	*Gemma* (1575)	*Digges* (1573)	*Computed**
α Cas	7°50′.5 7 52 **	7°47′	7°50′	7°24′ 6 58 #	7°47′	7°49′.2
β Cas	5 19 5 20 **	5 15	5 20	5 04 4 40 #	5 15	5 20.3
γ Cas	5 02 5 00 **	4 51 5 03 ***	5 10	4 36 4 28 #	4 58	4 58.9
δ Cas	8 03.5				8 05	8 00.3
ϵ Cas	9 48				9 45	9 45.3
ζ Cas	10 22			9 36		10 20.7
η Cas	6 53	7 00		6 36		6 50.0
ι Cas	12 58.5					12 57.9
κ Cas	1 31	1 24 1 26 ***		1 24	1 28.5	1 28.7
α UMi	25 14 25 09 **	25 30	26 40	24 40		25 14.4
α Per	27 22 ##			27 07		27 25.4
α Aur	42 28 ##			42 04		42 30.6

NOTES:

*Distance computed from modern reference-star positions to default position taken for centre of supernova remnant given as the last entry of Table 5.4 (see text).

**Surviving measurement from Tycho's observing logbook (Dreyer 1923; see text).

***Correction proposed by Hagecius to Tycho (see text).

#From Gemma (1573).

##Possibly calculated, as opposed to measured (from Tycho 1602, p. 558).

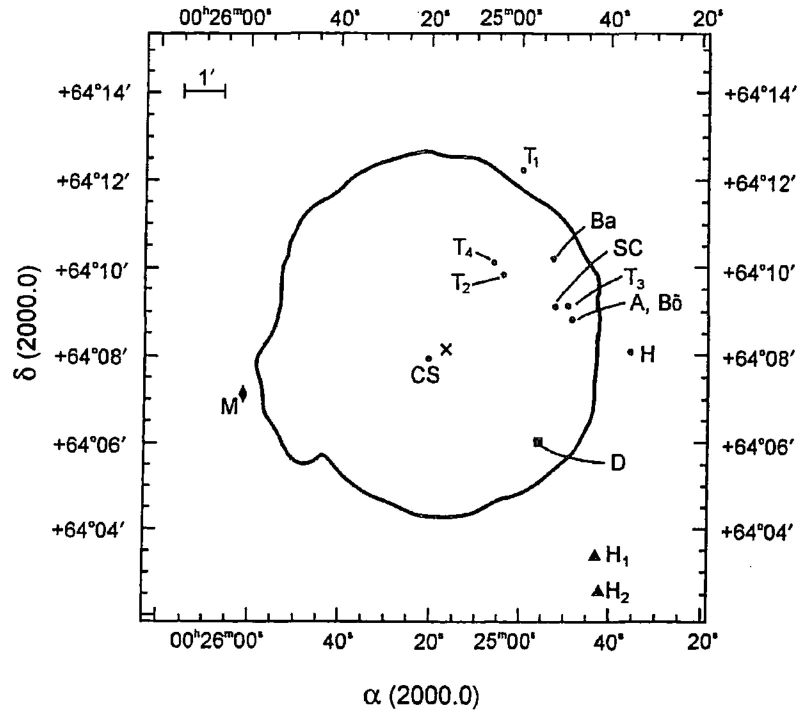

Figure 5.2. Locations of the various reduced positions for the 1572 supernova (B Cas) with respect to today's supernova remnant, 3C 10 (see section 5.4 of text). The centre of 3C 10 is marked with a cross (×). Seven newly reduced positions from Table 5.4 are plotted, four from Tycho (T_1, T_2, T_3, and T_4 being, respectively, the first four positions listed in Table 5.4), one from Digges (D), and two from Hagecius (H_1, H_2). The point (CS) closest to the centre of 3C 10 is that from Clark and Stephenson (1977, p. 184), which was derived after a correction of $2\rlap{.}'6$ was applied to all of Tycho's measurements. Other points plotted from Table 5.5 represent other previous reductions of Tycho's measurements: A = Argelander (1864); Ba = Baade (1945); Bö = Böhme (1937); H = Hind (1861); M = combined Maestlin/Digges measures with thread, from Clark and Stephenson (1977, p. 186); SC = Stephenson and Clark (1977).

5.3. New Analysis of the Historical Data

Besides the varying degrees of care used by individual observers, and besides the fact that some measuring instruments were surely superior to others, what factors might be considered in determining the accuracy of the astrometry for B Cas? One issue must concern that of the supernova's brightness; as with large images of bright objects (stars, comets, planets) that appear on photographs or electronic images, it is more difficult to determine the true centre of an object and thus its true position. This may have been a factor when B Cas rivalled Venus and Jupiter in brightness in the first couple of months. Observers were generally not very clear about the time that their astrometric measurements were made for the new star. Furthermore, some observers are known to have changed earlier measurements following the discussions that ensued in print and via personal letter in the months and years afterwards, and it is not entirely clear what basis was taken for the revised positions, though we know that some observers widely criticized the observations of others (in print and personal letter).

The 1572-1573 measurements of the supernova's distance from nearby reference stars have been reduced to modern equinox-2000.0 coordinates (right ascension, α; and declination, δ), employing modern reference-star positions. Table 5.3 shows the derived positions (α, δ) and proper motions (μ_α, μ_δ) of the relevant reference stars (for equinox J2000.0, epoch 1991.25) from the Hipparcos-satellite star catalogue (Perryman et al. 1997). Most of the proper motions are quite small, but two stars (β Cas and Polaris) have proper motions over 418 years of $\mu \sim 1'.5$, while that for Capella exceeds $3'$, and that for η Cas exceeds $4'$. Reductions were also made using the PPM catalogue (Röser and Bastian 1991), which contains positions for equinox and epoch J2000.0, as a check; the results (as expected) are very similar to those found with the Hipparcos data — so that the reduced 1572-1573 supernova PPM-based positions are within a couple of arcsec of the Hipparcos-based positions in all cases (despite some small differences in star positions and proper motions).

The position of the supernova for the sets of measures obtained by contemporary observers (given in Table 5.2) was then obtained using a computer program that is based on the procedure outlined in section 4.1 of this thesis. The astrometric results are given (ordered by observer) in Table 5.4, with the centre of the supernova remnant (3C 10) included for reference. All the visual astrometry except for that of Gemma place the supernova westward of the centre of 3C 10 by $\sim$ $1'$-$15'$. The observations of Tycho and Muñoz yield a declination within an arcmin or so of the 3C 10 centre, but those of the other visual observers yield positions noticeably south of the radio centre.

TABLE 5.3. My working positions for reference stars (equinox J2000.0, epoch 1573.0).

Derived from epoch-1991.25 positions and proper-motion values (μ) in the Hipparcos catalogue.*

Star	α	μ_α	δ	μ_δ
α Cas	$0^h40^m27^s.90$	$-2^s.55$	$+56°32'27''.8$	$+13''.4$
β Cas	0 08 42.25	−28.45	+59 10 14.9	+75.4
γ Cas	0 56 41.06	−1.46	+60 43 01.8	+1.6
δ Cas	1 25 32.28	−16.68	+60 14 27.7	+20.7
ϵ Cas	1 54 21.70	−2.01	+63 40 20.0	+7.8
ζ Cas	0 36 57.45	−0.84	+53 53 52.7	+3.8
η Cas	0 48 09.64	−56.88	+57 52 50.4	+234.0
ι Cas	2 29 04.99	+2.03	+67 23 53.2	−15.5
κ Cas	0 32 59.74	−0.24	+62 55 55.3	+0.9
α UMi	2 30 25.23	−95.95	+89 15 57.0	+4.9
α Per	3 24 18.31	−1.04	+49 51 51.4	+10.9
α Aur	5 16 38.27	−3.03	+46 02 55.0	+178.5

NOTE:

*μ = proper motion over 418 years, given in seconds of time for right ascension (μ_α) and seconds of arc for declination (μ_δ), listed here as the correction applied to the epoch-1991.25 positions

Table 5.5 provides the derived equinox-2000.0 positions for previous determinations of the position of Cas B by various authors (which were given originally for equinox 1865.0 or 1950.0) — all using only Tycho's measurements from the supernova to various reference stars. Hind (1861) used only the preliminary data from Brahe (1573), while the other authors evidently concentrated entirely on the data given by Tycho in his *Progymnasmata* (Brahe 1602, pp. 336-337). Some earlier analysts have eliminated ι Cas from the solution of Tycho's measurements, finding it to be more errant than his other measurements, but this is not borne out from an inspection of Table 5.2 (and elimination does little to the final figures, anyway). One can see from this that the new calculations of this thesis unfortunately do not improve upon earlier work because of the necessary uncertainty in the naked-eye measurements of 1572-1573.

Clark and Stephenson (1977) assumed a correction to Tycho's own refined distance measures found in his *Progymnasmata*, yielding the final listed position of Table 5.5. It could well be that such a correction is needed, though one can see from Table 5.3 that some of the distance measures from the supernova to reference stars that were made by other contemporary observers — particularly Muñoz and Digges — are as good or better than those of Tycho. We are probably at about the limit of what can be accomplished with the visual astrometry performed in 1572 and 1573.

◇ ◇ ◇

TABLE 5.4. New determinations of the position* of B Cas (for this thesis)

α	δ	*Observer's data*	*Stars used***
$0^h24^m.59$	$+64°12'.2$	Brahe (1573)	α, β, γ Cas
0 25 04	+64 09.8	Tycho (manuscript; text in Dreyer 1923)	α, β, γ Cas
0 24 $49^s.5$	+64 09 04″	Brahe (1602, 344)	nine stars in Cas; Polaris
0 25 06.1	+64 10 08	Brahe (1602, pp. 344 and 558)	all in Table 5.2
0 24 55.7	+64 06 02	Digges (1573)	all in Table 5.2
0 23 45	+64 08.2	Muñoz (1573)	α, β, γ Cas
0 26 00	+63 18.0	Gemma (1573)	α, β, γ Cas
0 27 03	+63 51.1	Gemma (1575)	all in Table 5.2
0 24 43	+64 03.4	Hagecius (1574)	all in Table 5.2
0 24 42	+64 02.5	Hagecius (1574), with corrections in Brahe (1602)	all in Table 5.2 (but using corrected values for γ, κ Cas)
0 25 17.5	+64 08 08	(see section 5.4 of text)	average position for centre of 3C 10

NOTES:

*equinox J2000.0; epoch 1573.0 for the supernova positions, epoch ca. 1986 for the supernova remnant centre

**as listed by observer in Table 5.2

◇ ◇ ◇

TABLE 5.5. Earlier modern determinations of the supernova position

(equinox 2000.0, epoch 1573.0)

from Tycho's distance measures between B Cas and reference stars

α	δ	*Author(s)*
$0^h24^m35^s.3$	+64°08′01″	Hind (1861)
0 24 48.4	+64 08 51	Argelander (1864)
0 24 52.4	+64 10 08	Böhme (1937)
0 24 47.9	+64 08 50	Baade (1945)
0 24 51.5	+64 09 03	Stephenson and Clark (1977)
0 25 20.3	+64 07 55	Clark and Stephenson (1977)

◇ ◇ ◇

5.4. Comparison with the Supernova Remnant

Optical, radio, infrared, and x-ray aspects of 3C 10 overlap well, with the few visible optical wisps corresponding to the outer rim of 3C 10. No stellar remnant of B Cas has been found within 3C 10, which itself is still highly circular in shape and $\approx 8'$ in diameter (e.g., Henbest 1980; Reynoso et al. 1997). Several papers have discussed the position of the centre of 3C 10. Several authors have suggested that the geometric centre of 3C 10 may not be the true location of the original supernova (with the outflow velocities being somewhat asymmetrical). The eastern edge of the remnant appears to be impacting higher-density gas than the western edge (e.g., Hwang et al. 2002). But given the close-to-circular appearance of the remnant, it is unlikely that B Cas would have been more than several *arcsec* from the geometric centre. For the purposes of comparing the derived positions for the optical 1572 supernova (B Cas), I have elected to take the equinox-2000.0 average of derived geometric-centre values for the ROSAT x-ray J2000.0 position of Hughes (2000) and the B1950.0 radio positions published by Duin and Strom (1975), by Henbest (1980), and by Reynoso et al. (1997). This average is shown in Table 5.4.

Figure 5.2 shows the respective locations of the various reduced optical positions for B Cas with respect to 3C 10; the boundary of 3C 10 is derived from radio observations (cf. Dickel et al. 1991; Hwang and Gotthelf 1997; Reynoso *et al.* 1997), which is similar to the x-ray boundary. From this, one can see a scattering of the reduced positions around the general perimeter of the remnant's current boundary — i.e., several arcmin from the centre of 3C 10. What inferences can be made from this, and what conclusions can be drawn? It is immediately obvious that Tycho's observations were not much better than those of his contemporaries — at least if we assume that the supernova appeared at the centre of today's remnant. One can also see that the outer boundary of the visible remnant material has expanded $\approx 4'$ from the point of explosion.

It is assumed that there is no perceptible proper motion for 3C 10 (and thus for Cas B over four centuries) — and that proper motion cannot therefore contribute to the disparity between the position of Cas B and the centre of 3C 10 — even though the absolute magnitude of Cas B at maximum brightness and the distance for Cas B/3C 10 remain highly uncertain; estimated distances for 3C 10 are generally in the range 1500-4500 pc (e.g., Kamper and van den Bergh 1978; Chevalier et al. 1980; Henbest 1980; Green 1984; Strom 1988; Lozinskaya 1992; van den Bergh 1993; Schwarz et al. 1995; Schaefer 1996; Hughes 2000). (Supernovae are assumed to have absolute magnitudes in the general range -16 to -20, and for the Cas B/3C 10 position problem to be explained by proper motion, Cas B would have needed an absolute magnitude closer to -5, which would be rather faint even for classical novae.) Refraction was ignored here for analyzing the astrometry of B Cas (as it was by earlier authors), because Cassiopeia (being circumpolar) was high in the sky, and contemporary writers did not give much useful information concerning altitude when the distance measures between the supernova and reference stars were made; it is assumed that refraction, therefore, also would not contribute to the discrepancy between the calculated position of B Cas and the centre of 3C 10.

Given the inherent problems with the observing instruments in 1572-1573, it is perhaps not realistic to consider formal error analysis. It is presumed that all of the observed distances in Table 5.2 (except for those by Tycho) were made with cross-staffs (or astronomical radii), and it is perhaps remarkable that the results are in as much agreement as they are. Clark and Stephenson (1977) applied a correction of $2'.6$ to all of Tycho's measurements to derive the position plotted closest to the centre of 3C 10 in Figure 5.2, suggesting that a systematic correction might give some explanation. But there are problems within Tycho's measurements, due to the inherent instrumental problems that he often acknowledged in his writings, that simply cannot be corrected. The discrepancies in the various optical positions, compared to the centre of 3C 10, must be assumed as due to the observational errors that have no straightforward correction — unless additional observational material surfaces in libraries, possibly in manuscripts. But this study has introduced new contemporary positional measurements for B Cas that have not been discussed in the modern literature previously.

Chapter 6:
Astrometry of the 1604 Supernova (V843 Ophiuchi)

6.1. Introduction

Exactly 400 years ago on October 9, a new star burst forth in the southwest evening sky amidst a rare clustering of the planets Jupiter, Saturn, and Mars that had daily called astronomers' attention to that part of the sky. Indeed, the 'nova stella' in Ophiuchus may not have been so widely noticed, had the conjunction of these planets not drawn so much attention to the southwestern sky at this time. The supernova of 1604 was discovered independently by numerous observers in Asia and Europe — including Ilario Altobelli in Verona, Raffael Gulaterotti in Florence, Baldesar Capra and Simon Mayr in Milan, and Johannes Brunowsky in Prague on October 9 and 10 (Gregorian calendar). But the 1604 supernova event was not as extensively observed as B Cas (the 1572 supernova), because it was much lower in the sky, setting within a couple of hours after the sun in October — and becoming lost in the solar glare soon thereafter (this difference in visibility for observers of the two supernovae was remarked on by Kepler; cf. Kepler *et al.* 1977). Again, Asian observers recorded useful brightness information but did not approach the precision of their European counterparts in terms of positional accuracy (Clark and Stephenson 1977, pp. 191ff; Stephenson and Green 2002).

Earlier work on what might be considered as "modern" reductions of the position of V843 Oph was published mostly in the *Astronomische Nachrichten* (Winnecke 1857; Schönfeld 1865; Schlier 1935; Böhme 1937), with discussion of that earlier work undertaken by Baade (1943). This chapter takes a new look at the astrometric measurements of the two chief astrometric observers — Johannes Kepler (with his Prague colleagues, Franz Gansneb Tengnagel and Jost Bürgi) and David Fabricius (in Osteel, East Frisia) — that were investigated by previous modern researchers. I also investigate several other notable observers who were ignored during the past 150 years. Numerous observations of planet-nova distances and nova alignments made by several observers (including Kepler *et al.* and Fabricius), which apparently have not been analyzed in the last two centuries, are addressed here, as well.

As variable stars in the Milky Way traditionally get star designations assigned to their particular constellation (not the year/letter designations that are assigned to extra-Galactic supernovae), the official IAU designation for the 1604 supernova, V843 Oph (cf. Kukarkin *et al.* 1971), is used in this thesis. The object is sometimes referred to as 'Kepler's supernova', but (a) Kepler did not

discover the new star, (b) his observations of it ironically have been assumed to have been poorer than those of Fabricius, and (c) Kepler was not nearly as interested in it as Tycho Brahe was in the 1572 supernova (or, possibly, as Fabricius was of the 1604 event) — so any reference to V843 Oph as "Kepler's" is rather misinformed. Variable stars of any sort were a novelty in that era, and Fabricius had already discovered one in 1596 — *o* Ceti, or Mira (e.g., Rosen 1967).

6.2. Original Observations

Just as with B Cas and the comet of 1577, quite a few tracts were published on the new star in Ophiuchus of 1604-1605; bibliographies of the many such tracts can be found in de La Lande (1970, pp. 141ff) and Zinner (1964). My detailed search of rare-book libraries over several years for contemporary observational material on the 1604 supernova revealed actual distance measures between the new star and surrounding stars (and planets) only from three European locations — a curious step backward from the observational efforts of astronomers during the previous few decades in Europe — though other types of positional measurements were made elsewhere, as discussed below. Tycho Brahe and other leading astronomical observers of the sixteenth century had rather established a standard astrometric procedure of measuring (and then publishing) the distances determined from new objects to various surrounding catalogued stars, a procedure continued by Fabricius (1605), by Brengger (1607), and by Kepler (1606) and his colleagues. Indeed, all but one of the five known distance measurers of V843 Oph had either observed with Brahe or had observational correspondence with him prior to his death in 1601.

However, a majority of contemporary authors writing on V843 Oph seemed to lack the understanding that such distance data could be really useful for future reference (or perhaps they lacked the instruments needed for such measures) — most authors taking some effort to place the new object's place within a zodiacal band of longitude (and also often giving the zodiacal latitude), thereby diluting their work (because the employed coordinate system was then not very accurately determined). A very common procedure among these early-seventeenth-century observers was to publish their measured angular altitudes (and sometimes also azimuths) of the supernova and other notable objects; even if times were given, clock time could not be very accurately determined, so such 'altaz' data cannot now be converted to useful celestial coordinates. Also typical was the effort made by some observers to try and determine whether parallax was detectable in the supernova's position. Of course, this was a few years before Galileo first turned his telescope to the sky, so all observations of V843 Oph were made without optical aid for the eye (generally using instruments such as sextants and quadrants to determine on-sky distances and zodiacal or altaz coordinates) — though it should be noted that the telescope did not replace the naked eye for astrometric purposes for another century, due to the very poor optical glass then available, so it is unlikely that we'd have any better measurements of the supernova's position if it had been observed even in the mid- or late-seventeeth century.

The 1605 tract by Fabricius and the 1606 book by Kepler are the two most detailed contem-

porary publications on V843 Oph. A curious 56-page treatise by Capra (1605) appears to rival what Kepler and Fabricius wrote on the star, discussing his own observations together with those of other Italian observers including especially Galileo. One of the typical aspects of Capra's book is that the author speaks of his use of astronomical sextants for measuring the distances from the supernova to various stars (including two stars close to the ecliptic in Oph — apparently ρ Oph and either Bayer's A or d Oph), but he does not actually give those distances (rather, he simply gives his own reductions of the supernova's position as ecliptic longitude and latitude). One interesting piece of positional information that Capra provides (p. 19a) is from Galileo's public lectures on the new star (cf. Drake 1976): Galileo reported that his own observations with "his instrument" showed that V843 Oph was in a straight line with the stars α Cyg and α CrB — the fact that the star never moved from this line showed that it had no motion (and ultimately no parallax). Actually, no star in Cygnus lines up with α CrB in a manner that comes close to the position of V843 Oph, but η Oph and α CrB line up quite well. Galileo was so perturbed about Capra's tract that he published his own tract in 1607, entitled "Defense of Galileo Galilei . . . Against the Libel and Deceit of Baldessar Capra of Milan" (transcribed in Galilei and Favaro 1890-1909 and 1968), in which he vehemently argues that Capra gave the incorrect stars (the correct alignment is given in Table 6.3). Perhaps Capra misunderstood the stars that Galileo mentioned. It is curious that Galileo denounced Capra in 1607 as a plagiarist and had the young man kicked out of the University at Padua (cf. Drake 1976); if Galileo's accusations were at all true, it is possible that Capra did not himself make the distance measures that he refers to in his tract on the supernova (thus perhaps explaining the absence of the actual data in his book), but sloppily mentions measures made by somebody else that he knew (such as Mayr) — though Capra's book is written in a manner that suggests that he was quite knowledgeable about astronomical matters.

Capra does give some extensive discussion on the brightness and colour of V843 Oph over time (used by Baade 1943), as do some other contemporary writers to a lesser extent (e.g., Koestner 1605; Lorenzini 1605; Nagel 1605; Molerius 1606; and authors of contemporary letters published by Caspar in 1951 and 1954) — including much data apparently unknown to 20th-century astronomers looking at the light curve of this particular supernova (Baade 1943; Clark and Stephenson 1977, pp. 191ff), which at some point could be incorporated into a comprehensive light curve for V843 Oph.

In addition to the published tracts, there are various letters and manuscripts extant in library collections regarding the 1604 supernova. There are fragments of a manuscript of Galileo's well-known public lectures on the new star that Favaro published in the late 19th century (Galilei and Favaro 1890-1909 and 1968, pp. 276ff). An unpublished manuscript by Michael Maestlin, located in the Württembergische Landesbibliothek Stuttgart, contains alignment data used below. Numerous contemporary letters that are transcribed in Caspar's *Gesammelte Werke* of Kepler also contain much positional data on V843 Oph. One manuscript by Kepler is listed in the catalogue of the Austrian National Library, in Vienna, entitled "'Pro vero loco Novae stellae a. 1604 mense Octobri exortae investagando' calculi et observationes" (Royal Academy of Vienna 1871, p. 225).

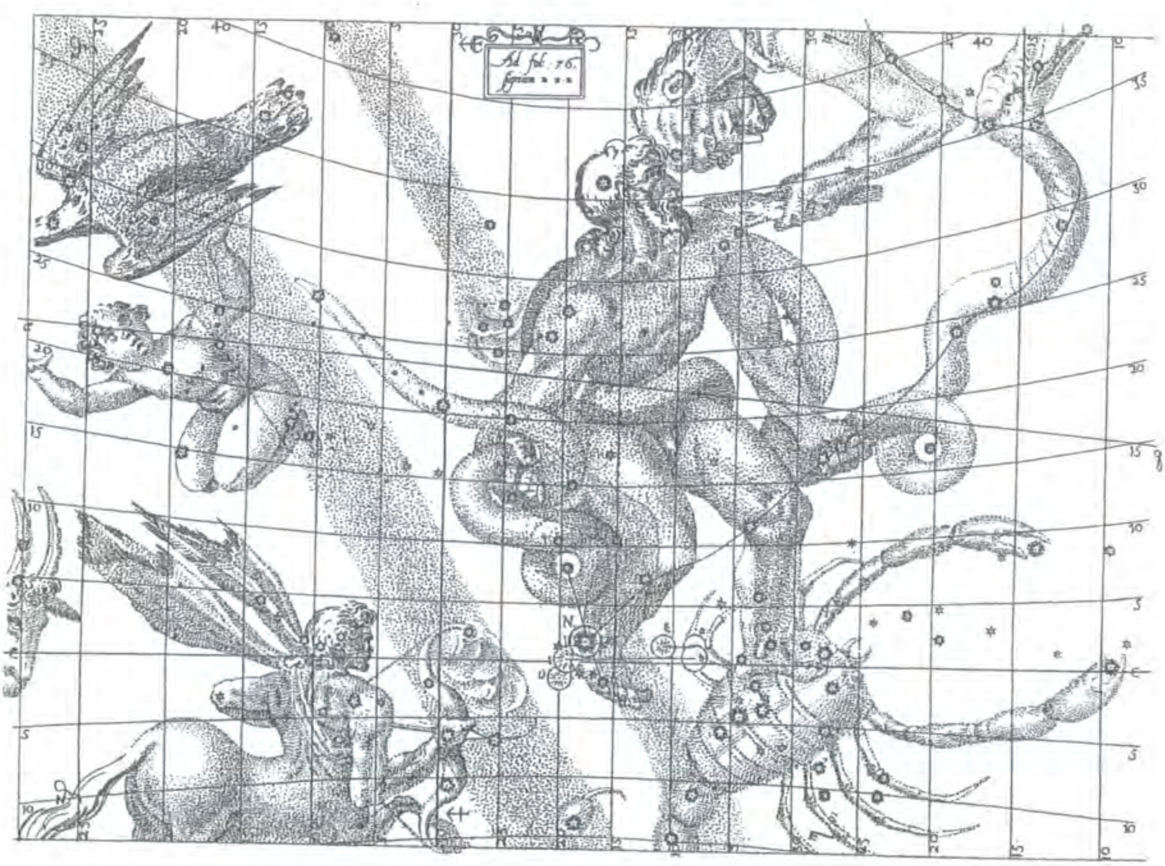

Figure 6.1. The fold-out illustration of the constellations surrounding the 1604 supernova that appears in Kepler's 1606 tract. The coordinates are ecliptic, and the "nova stella" is denoted by the letter 'N' (below centre). To the right of the supernova is Saturn's moving position, represented by α and ϵ at each end. Below this is the moving position of Jupiter, represented at each end by ι and η. To the lower left of the supernova is the position of Mars on 1604 Oct. 10, when V843 Oph was first observed at Prague. The other stars are all unlabelled; ζ Oph is the star immediately to the right of the new star.

6.3. Distance Measures of V843 Oph with respect to Other Celestial Objects

There are numerous available measures from the contemporary literature of the distances between V843 Oph and surrounding stars and planets. The two main sources of such data are Kepler and Fabricius, both from their published tracts on the supernova and from letters to each other that were published in the 20th century by Max Caspar. Kepler, in Prague, made some astrometric observations of the new star with a 3.5-foot iron sextant that had been given to him by Baron Johann Friedrich Hoffmann; Kepler was not allowed by Tycho Brahe's heirs to use Tycho's instruments (cf. Caspar *et al.* 1993, p. 160). Kepler observed also with Bürgi (one of the most acclaimed clockmakers of Europe), who evidently used his own sextent, and Tengnagel (Tycho Brahe's son-in-law), who used Tycho's instruments, with Kepler looking on (Kepler 1606, p. 58; Caspar 1938, pp. 209-210; Caspar 1951, p. 78). It is not entirely clear who made the distance measures from the supernova on 1604 Oct. 27 at Prague (whether Bürgi, Tengnagel, Kepler, or a combination of these men). Fabricius also used a sextant for his distance measures (Caspar 1951, p. 116), two of which were given incorrectly by Kepler (1606) but which were corrected by Caspar (1938, p. 211). Fabricius was based in the town of Osteel, which is northwest of Bremen and just southeast of Norden, near the present-day German border with The Netherlands.

Johann Georg Brengger (of Kaufbeuren), a regular correspondent with Kepler, wrote letters to Kepler giving some distance measures that he evidently made with an astronomical radius (Caspar 1954, pp. 36ff). Though Kepler stated in his 1606 tract (Caspar 1938, p. 211) that Brengger was in Alsace (where no Kaufbeuren is obvious), it is clear (from other remarks in the contemporary correspondence about the location of Kaufbeuren) that it is the city of that name in Bavaria, southwest of Augsburg and southeast of Memmingen; perhaps Brengger was temporarily in Alsace on 1605 Jan. 29, the date given by Kepler. Although Bayer's 1603 *Uranometria* had been in print for a year when the supernova first appeared, the Greek-letter designation system for naked-eye stars had not yet been accepted, and all observers used the customary Ptolemaic/Copernican-catalogue designations, in which stars were identified by their location within the actual figure of a constellation (see Table 6.1). This identification involved some considerable effort in a few cases, in which distances were actually computed to rule out some reference stars (notably, the stars in Sgr for Kepler, and stars used by Galileo and Maestlin in the star/supernova alignments discussed in section 5, below).

The extant books and manuscripts containing distance measurements between V843 Oph and reference stars by these five observers indicate numerous cases where multiple measures were obtained by the same observer on a single night or on multiple nights. The averages of these measures were generally used for the Prague observers and Brengger in Table 6.2a, as there was no clear value to be used in these cases, but the published book measures were taken for Fabricius (where he clearly gives one set of values for each specified distance, despite the fact that he gave multiple measures for some pairs in earlier letters to Kepler). In cases where multiple measures

were recorded, the notes to Table 6.2a give the available sets of measures.

Melchior Jöstel wrote from Dresden on 1604 Dec. 12 (old-style) to Kepler, saying that on Oct. 21 (new-style) he noted that the distance of the new star from Jupiter appeared to be like "distantia caudae et pectoris Cygni" (Caspar 1951, p. 81). The stars in the tail and breast of Cygnus (as known in the catalogues from Ptolemy to Tycho) have Bayer designations α Cyg and γ Cyg, and we can compute their separation as 6°08′, but the nominal distance of Jupiter from the centre of the 1604 supernova remnant on 1604 Oct. 21.7 was 4°01′. If the seeming conflict regarding new- and old-style dates in the same letter can be resolved by assuming that the observation date, Oct. 21, was given via the Julian calendar, the distance between Jupiter and the centre of 3C 358 on Oct. 31.7 UT was 5°46′ — a value much closer to Jöstel's reported distance. But the indication is that this was simply an unaided-eye observation (no visual aids — that is, without an astronomical radius or other graded instrument), and nothing more will be considered of Jöstel's record.

The distances of V843 Oph to the various stars (Table 6.2a) and to the planets (Table 6.2b) are as given by the original observers, in degrees and minutes of arc. The calculated distances are also provided in the right columns, neglecting refraction (though for three of the stars in Table 6.2a, examples of what typical refraction effects would have on shortening the measured distances are given for illustrative purposes; see section 4 of this chapter). From the calculated distances based on the modern values of the star positions, it is seen that (contrary to what Schönfeld and Schlier claimed in their discarding of Kepler's data) Fabricius' measurements were no better than those of the Prague observers.

The times given in Table 6.2b were those chosen for obtaining the planet's positions; the decimals of a day were selected based on the respective altitudes of the nova and the planet, with evening times generally $\geq$ 45 min after sunset and morning times $\geq$ 45 min before sunrise (the given times correspond to the calculated distances). The planetary positions were calculated using the Jet Propulsion Laboratory's 'Horizons' ephemeris program (Giorgini *et al.* 1996). Note that, due to uncertainty in the clock time, there is uncertainty of up to 1′-2′ in the positions of the planets (most notably Mars) due to their motions with respect to the background stars over an hour or two.

Table 6.1. Positions of stars used to estimate the position* of V843 Oph (equinox 2000.0, epoch 1604.8)

Modern Desig.	*Star description(s) given by the observer(s)*	α	δ	V	μ_α	μ_δ
α Aql	Aquila	$19^h50^m32^s.68$	$+08°49'33''.6$	0.8	$-14^s.00$	$-149''.0$
α Boo	Arcturus	14 16 10.27	+19 24 05.8	0.1	+29.92	+771.6
ϵ Boo	in femori Bootis	14 45 00.72	+27 04 19.3	2.4	+1.47	−7.7
α CrB	Lucida Coronae	15 34 37.69	+26 43 28.1	2.2	−3.52	+34.4
α Lib	lance australi	14 50 55.61	−16 02 03.1	2.8	+2.83	+26.7
β Lib	lance boreali	15 17 02.99	−09 22 50.3	2.6	+2.52	+8.0
α Oph	capite Oph	17 34 53.09	+12 35 04.1	2.1	−2.91	+86.0
ζ Oph	sinistro genu Oph/Serp.; femore sinistro Ophiuchi	16 37 09.21	−10 34 07.1	2.6	−0.32	−8.8
η Oph	per dextrum latus Serp.; genu (dextro) Oph	17 10 21.62	−15 44 06.9	2.4	−1.03	−36.3
72 Oph	quinta inter informes circa Oph.	18 07 22.68	+ 9 33 18.1	3.7	+1.66	−31.1
ζ Sgr	posterior in trapezio Sag.	19 02 37.57	−29 52 48.8	2.6	+0.86	−0.4
σ Sgr	humerum Sgr, quae est clara quadrilateri sive Trapezii	18 55 15.52	−26 17 27.4	2.0	−0.40	+20.3
α Sco	seu corde Sco; antares	16 29 24.76	−26 25 46.0	1.1	+0.29	+9.0
β Sco	Bor. 3 in front. Sco	16 05 26.41	−19 48 09.8	2.6	+0.18	+9.6
o Ser	decima quinta Serpentis	17 41 26.87	−12 52 09.7	4.2	+1.95	+20.9
ϵ UMa	la prima stella delle tre nella code dell'Orsa Maggiore	12 53 56.58	+55 57 38.3	1.8	−5.05	+2.9

NOTES:

* from Hipparcos/Tycho satellite data, with stated proper motions given in seconds of time for right ascension (μ_α) and seconds of arc for declination (μ_δ), listed here as the correction applied to the epoch-1991.25 positions used to convert to the 1604.8 positions that are given in columns 3 and 4 above. The V magnitudes are given in the last column.

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Table 6.2a. Distance measures between reference stars and V843 Oph

Ref. star	*Kepler et al.** (1606)	*Fabricius*** (1605)	*Brengger* (1607)	*Calculated**** $h = 90°$	$h = 9.°2$	$h = 4.°3$
σ Sgr	19°59.′4 [1]			19°53.′5	19°53.′2	19°52.′0
η Oph	7 34.2 [2]	7°30′ [5]	7°29′	7 30.3	7 30.1	7 29.3
α Oph	34 02.0 [3]	34 00		34 05.6	34 01.3	33 57.1
ζ Oph	16 52.0	16 46	16 49#	16 51.3		
α Aql	45 46.2 [4]	45 45 [6]		45 47.4		
α Sco	14 55.0	14 50.5 [7]	14 44.5##	14 49.8		
β Sco		19 59		20 00.0		
α Lib		38 04		38 06.5		
β Lib		34 14		34 18.4		

NOTES:

*The Kepler/Tengnagel/Bürgi figures are generally averages of several measurements, though he did not clearly specify which were to be preferred over others: [1] 20°00′, 20°01′, 20°02.′5, 19°54′ [this latter value corrected from Kepler's original 19°34′ by Caspar (1938, pp. 209 and 475)]; [2] 7°39′, 7°35′, 7°31′, 7°32′; [3] 34°02.′5, 34°00′, 34°01.′5; [4)]45°43′, 45°51′, 45°45′, 45°44′, 45°45′.

**Fabricius also gave different measures from different observations, but these are in letters to Kepler that predate Fabricius' book (and thus were omitted from the calculations done for this thesis): [5] average of two positions — 7°32′ (Kepler 1606, p. 60) and 7°28′ (Caspar 1951, p. 151); [6] 45°46′ (Caspar 1951, p. 116); [7] 14°50′ (Caspar 1951, p. 151).

***Distance computed from modern reference-star positions to default position taken for centre of supernova remnant given as the last entry of Table 6.4 (see section 6). The calculated positions are given for Prague on 1604 Oct. 17, for three different supernova altitudes, h (in degrees), with $h = 90°$ corresponding to the zenith (the case of no refraction). The refraction values for three stars are given here merely for illustration (see section 4 for discussion on refraction).

average of three distances: 16°56′, 16°46′, 16°45′

average of two distances: 14°46′, 14°43′

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Table 6.2b. **Distance measures between the planets and V843 Oph**

Planet	*Date (UT)**	*Observer*	*Reference***	Measured	*Calculated****
Venus	1605 Jan. 5.292	Fabricius	C1951/116	17°43′	17°44′.9
Venus	1605 Jan. 7.267	Brengger	C1954/37	15°26′	15°30′.3
Venus	1605 Jan. 23.285	Fabricius	C1951/116	3°06′	3°04′.7
Venus	1605 Feb. 13.25	Fabricius	C1951/151	27°54′	27°59′.3
Mars	1604 Oct. 17.729	Kepler	K1606/57	8°31′	8°20′.1
Jupiter	1604 Oct. 13.747	Fabricius	C1951/58	2°51′#	2°50′.1
Jupiter	1604 Oct. 17.72	Kepler	K1606/57	3°28′.5	3°23′.5
Jupiter	1604 Oct. 18.72	Kepler	K1606/57	3°40′	3°32′.5
Jupiter	1604 Oct. 21.719	Tengnagel	C1938/209	4°01′.5##	4°00′.8
Jupiter	1604 Oct. 27.70	Bürgi or Tengnagel	K1606/57	4°59′.5	5°01′.8
Jupiter	1604 Nov. 9.701	Brengger	C1954/36	7°35′	7°29′.4
Jupiter	1605 Feb. 13.253	Fabricius	C1951/151	28°34′	28°40′.7
Saturn	1604 Oct. 17.729	Kepler	K1606/57	6°13′###	6°07′.1
Saturn	1605 Jan. 23.27	Fabricius	C1951/117	4°41′	4°41′.1
Saturn	1605 Feb. 13.25	Fabricius	C1951/151	6°32′	6°30′.4
Saturn	1605 Mar. 27.16	Brengger	C1954/38	8°28′	8°26′.7

NOTES:

*The observers usually did not specify exact times; see section 2 of text.

**References are given in the sense *source/page*, where the sources are as follows: C[year] = Caspar ([year]); K1606 = Kepler (1606)

***Distance computed from modern reference-star positions to default position taken for centre of supernova remnant given as the last entry of Table 6.4 (see section 6). Refraction is neglected here.

Frisch (1859) transcribed this as 2°57′.

This corrected value is by Caspar, from a Pulkovo manuscript (see Caspar, p. 475); the original value from Kepler (1606, p. 58) was 4°07′.5.

Average of two positions: 6°12′ and 6°14′.

6.4. Refraction and V843 Oph

Because the 1604 supernova was quite low in the southwestern evening sky in October when observers followed it, one might naturally consider an analysis of the effects of refraction upon both astrometric and photometric measures. Indeed, this was addressed by some of the previous *A.N.* authors who wrote about the position of the 1604 event (Winnecke 1857; Schönfeld 1865; Böhme 1937), though the details of what they did were not given. The observers generally did not state the time of observation. Occasionally a mention was made such as "hora 1 post occasum" (1 hour past sunset at Osteel, 1604 Oct. 3 old-style; Fabricius, via Caspar 1951, p. 58) or "manè hora 7. juxta horologium" (7 a.m. local clock time at Kaufbeuren on 1605 Jan. 7 new-style; Brengger, via Caspar 1954, p. 37), but such cases are unusual, and they generally are not very useful for a couple of reasons.

First, one can generally constrain the observations of the supernova in early evening and late-night skies to within an hour or two anyway (due to setting soon after sunset in the evening in late 1604 and to rising soon before sunrise in the morning in early 1605). The times stated upon occasion cannot be taken as absolutely correct, due to problems with the clocks of that era. Second, as noted earlier, numerous positional observations were generally made by each observer on a given night with a sextant (astronomical radius), and it would probably have taken a few minutes per measurement, and then a few minutes in between measurements of different objects. Probably because observers were not aware of how the field of astrometry would develop in the centuries to come, it is understandable that they would not seriously worry that refraction might be a problem for later reduction of positional measurements of celestial objects near the horizon, and they would not have understood the need therefore to record the times for each observation. This despite the fact that some observers of the 1604 supernova may have been aware of the problem of refraction in general astronomical terms from Brahe's (1602, p. 280) notes in his tome on the 1572 supernova. Without the important quantity of clock time being supplied for their observations, we are left to speculate on reasonable times for observations in order to assess any applicable refraction effects, and then compare this with the unrefracted cases.

Occasionally there is a record containing only a rough assessment of the supernova's altitude when the measurements were made. As noted above, one must usually assume a time that is generally constrained to within about an hour or so by twilight and rising/setting times. One should perhaps assume that, for an observer at geographical latitude $+50°$ in mid-October, the second-magnitude comparison stars would not become readily visible for distance determinations until well past the end of nautical twilight, or not prior to $\approx$ 75-80 minutes after sunset. Such stars do become visible well away from the sunset point in the sky around 50-70 minutes after sunset, but stars in the much brighter southwest twilight take notably longer to become visible, and longer yet for their visibility to enable their use in distance determinations.

The supernova became lost in the twilight in November, as it moved toward conjunction with the sun, and was observed again by observers in the morning sky in January. Thus, I chose times

for the brightest planets (as noted in section 3, above) and stars that were generally 45-90 minutes after sunset when observed in the evening sky, and 45-90 minutes before sunrise when observed in the morning sky (nautical or astronomical twilight). For fainter stars, times were generally picked that were either in the darker half of astronomical twilight or outside of twilight altogether (i.e., 1.5-2.5 hours from sunrise). Indeed, sometimes there is an obvious difference between the stars used and the planets used for determining the supernova's position, as the planets were often at smaller solar elongations and thus had to be sometimes observed in a brighter sky wherein some of the fainter references stars would not have been easily visible.

As we have seen, even on the one or two occasions where local clock time was specified by an observer, it is well known from Tycho Brahe that clocks were notoriously prone to errors of many minutes by evening, even after having been set by the sun at noon that same day (e.g., Thoren 1990, pp. 157-158). In his book, Fabricius [1605, p. Biii(v)] did not even give dates for most of his measurements, though he noted that the nova was once 8°-9° from the horizon when he made his observations with an astronomical sextant, and dates are available for his planetary-supernova distance measurements from his correspondence with Kepler. Kepler (1606; Caspar 1938) only once noted the supernova's altitude (roughly): for the evening of 1604 Oct. 17, concerning his distance measures from the supernova to σ Sgr and to η Oph, Kepler noted that the supernova descended from altitude (h) 9° to 4°. We can now calculate that this corresponds to a time span of 1604 Oct. 17.72-17.75 UT[68] for Prague. (The supernova was at h = 10°-11° in the southwest sky about an hour after sunset, so the observers were obviously making their measurements about the time that it was getting dark enough to do so.)

Ultimately, one cannot really correct for refraction because of the many variables, which include local atmospheric uncertainties due to the general low altitude of the supernova ($< 10°$) and numerous reference objects when measurements were made. It likely took several minutes for a single distance measure, D, between the supernova and a single reference star, during which time the supernova was sinking toward the horizon at a rate of about 1° every 9 minutes. Thus, even using standard, "generic" refraction formulae, we cannot know how much refraction to allow for because the observers did not provide definitive values of h at the times of observations. It is unlikely, as might be inferred from a couple of remarks in the contemporary literature, that all distance measures on a given night were made only when the supernova was between h = 8° and 9° — not only because it would be unreasonable to get several good D measurements for different reference stars in a span of nine minutes, but because one must be suspicious of the accuracy of any stated altitudes without some expressed details as to how such altitudes would have been

[68] This decimal-date form (used in formal International Astronomical Union publications containing observations of celestial objects) is equivalent, in this particular case, to $17^h 16^m.8$ UT on Oct. 17. Note that a decimal point used anywhere in this thesis is just that: strictly a decimal point (not to be confused with the common-but-questionable European practice of using a decimal point instead of a colon to distinguish hours from minutes in clock time).

accurately determined.

Our problem is compounded by the fact that it is the supernova position that we are seeking, and the supernova was lower in the sky than the reference stars (generally by 3°-4°, but sometimes by sometimes by tens of degrees). One can determine a "generic" amount of refraction from standard formulae for the stars in question during the time that the supernova was between, say, 9° and 4° above the horizon, and I have done that for three reference stars to illustrate what sort of effects the refraction may *reasonably* be assumed to have had on the position of the supernova (see Table 6.2a). In this process, we can compare the difference between the distances from the centre of the supernova remnant (3C 358) to the reference stars for the "general refraction" case and the non-refraction case.

Taking the case of 1604 Oct. 17, Kepler measured D = 20°00′ to σ Sgr, and D = 7°39′ and 7°35′ to η Oph. The supernova was at the following altitudes, h, at the following 0.01-day intervals: Oct. 17.72, 9°.2; 17.73, 7°.6; 17.74, 6°.0; 17.75, 4°.3. Standard refraction formulae (e.g., Meeus 1991) yield refraction amounts, R, of 5′.8, 6′.9, 8′.5, and 11′.1, respectively, for the supernova at these four times — meaning that the supernova appeared that much higher in the sky than it really was due to atmospheric extinction. Using standard equations to determine the change in right ascension and declination due to such refraction (e.g., Chauvenet 1960; Smart 1949; Green 1985), one can redetermine the distances, D', between the centre of 3C 358 and the reference stars, using modern catalogue positions. The results indicate a general shortening of D' on the order of 0.02-0.04 percent when the supernova was at h = 7°.6 and 0.13-0.4 percent when the supernova was at h = 4°.3. This figure tends to be 1′.5 or less even for D < 20°, though for α Oph (at D ≈ 34°), the difference $D' - D'(h)$ can approach 10′. (Though Kepler measured D for α Oph and ζ Oph on Oct. 21, for reference I computed the refraction for these stars also on Oct. 17.7 (only four days earlier, so the comparison should be relevant). The range in h for α Oph was 40°.1-36°.1 (with the refraction increasing from R = 1′.2 to 1′.5) while the supernova sunk from h = 9°.2 to 4°.3. On Oct. 21.72 UT at Prague, V843 Oph was setting at the rate of ≈ 1°.6 every 14.4 minutes (0.01 day).

Table 6.2a gives the relevant distance measures, D and D', between the supernova/3C 358 and three reference stars (at h = 90°, 9°.2, and 4°.3). Given that the measurements by Kepler and Fabricius tend to have average errors as much as 2′-4′, and sometimes much higher, it makes sense only to say that the closeness of the non-refraction supernova position to the centre of 3C 358 can be wholly satisfied by a combination of the visual sighting errors (which appear to be on the order of a few arcmin) and what small refraction contribution was present (on the order of 0′.1-1′.5 for small D) during the measurements of D. While one could, in practice, assume default altitudes for the supernova and reference stars and apply standard refraction formulae to obtain a "revised" average position for the observed supernova, such an exercise would not guarantee an answer closer than the non-refraction calculation for the reasons stated above. Nonetheless, rather than just dismissing allowance for refraction on the above arguments, general refraction effects were computed for all measurements in this study, using the procedure outline below, to

compare the results with the unrefracted calculations.

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6.5. Observed Three-body Alignments with V843 Oph

Several sets of straight-line alignments were noted by contemporary observers including V843 Oph and two other celestial objects (stars and/or planets). As noted elsewhere (e.g., Brahe 1588; Dreyer 1890; Green 2004), even when a straight-edged instrument is securely fixed (i.e., not hand-held), such alignments are fraught with problems due to parallax inherent by the eye moving along the edge connecting the celestial objects and due to the constant diurnal motion of the sky. The only hope to get some reasonable convergence to the true location of the unknown object (V843 Oph, in this case) is to have as many different alignments as possible to look for a mean position. This sort of analysis evidently has not been performed by modern astronomers — though an attempt was made by Stephenson and Clark (1977, pp. 191ff) to determine the position of the 1572 supernova from various published visual alignments. Table 6.3 lists the alignments found in the literature. The date/time (Universal Time) is given where planets are involved — except for the observation by Helisius Roeslin, who evidently observed from Hagenow in north-central Germany without providing a time — as there can be considerable motion over an hour or less (particularly with Mars, where the motion in right ascension was $\approx 2'$/hr in mid-October 1604).

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Table 6.3. Reported straight-line alignments of V843 Oph with other celestial objects

Other two objects	*Date UT**	*Observer/Reference*
Jupiter, Mars	1604 Oct. 12	Roeslin (1605)
Jupiter, Mars	1604 Oct. 13.74	Fabricius (1604; Caspar 1951)
Mars, ζ Sgr	1604 Oct. 17.72	Kepler (1606; Caspar 1938)
ϵ Boo, η Oph		Maestlin (1605)
o Ser, 72 Oph		Maestlin (1605)
α CrB, ϵ UMa		Galileo (1607; Galileo and Favaro 1968, pp. 526ff)

NOTES:

*The times given above are uncertain by perhaps ± 30 min, and are based on circumstantial descriptions (not actual clock times) given by the observers.

From an analysis of the data in Table 6.3 (see section 4.3 of this thesis for details), the solution from Galileo's data comes no closer than $\approx 17'$ from the centre of 3C 358. Maestlin's first alignment in Table 6.3 comes no closer than $\approx 5\farcm8$, while his other alignment approaches to within $\approx 1\farcm2$ of the remnant centre. Fabricius' alignment comes within $\approx 1\farcm6$ of the remnant centre, and Kepler's alignment comes no closer than $\approx 6\farcm3$. The errors from this form of measurement, combined with the poor distribution of alignments on the celestial sphere, result in corresponding lines that do not intersect very close to the supernova. Clearly these data are greatly inferior to the distance measures discussed in previous sections of this chapter, and nothing more can be done with them.

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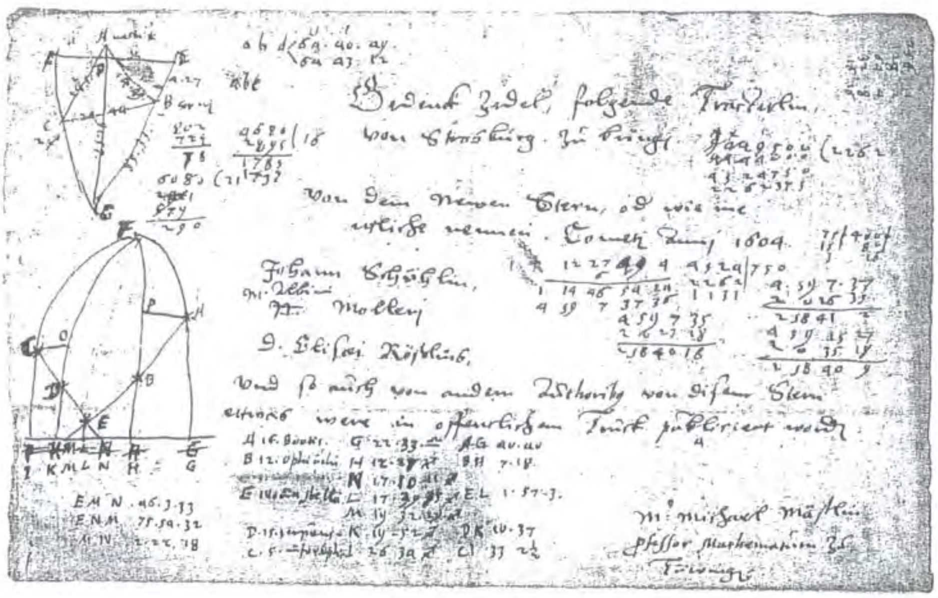

Figure 6.2. Hand-drawn diagram by Michael Maestlin depicting the alignments of stars with V843 Oph. From Maestlin (1605); courtesy of the Württembergische Landesbibliothek Stuttgart.

Figure 6.3. Locations of the various reduced positions for the 1604 supernova (V843 Oph) with respect to today's supernova remnant, 3C 358 (see section 6 of text). The centre of 3C 358 is marked with a cross (×). Seven newly reduced positions from Table 6.4 are plotted. The points labelled B, F, *and* K *represent observations by Brengger, Fabricius, and Kepler (respectively). The subscripts* r *and* u *refer to reductions that did and did not allow for refraction, respectively. The upper-case (non-subscripted) letters* R *(including refraction) and* U *(not including refraction) indicate points that represent averages of all the observers' positions. The points represented as asterisks indicate reduced positions from stellar reference stars only; the points plotted as open circles indicated reduced positions from a combination of stellar and planetary distance measures. .*

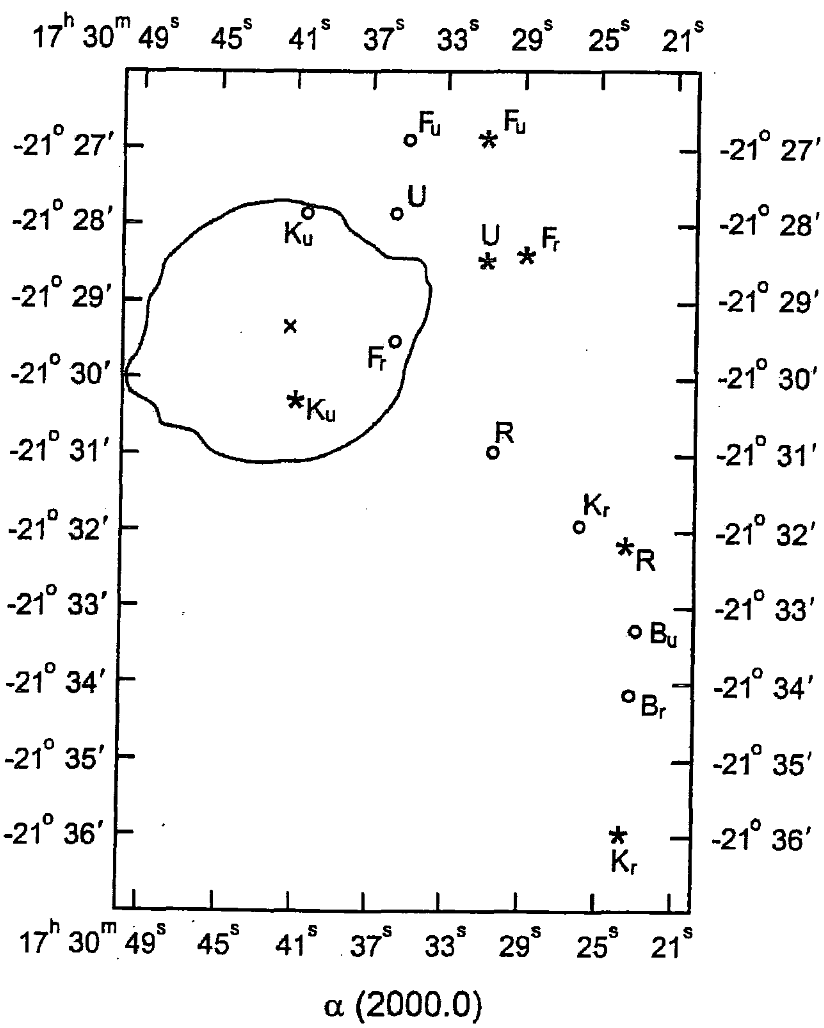

Table 6.4. Reduced positions* for V843 Oph

α	δ	Observers	Reference stars and/or planets used**
$17^h 30^m 41^s$	$-21° 30'.3$	Kepler *et al.*	all six stars, neglecting refraction
17 30 24	−21 35.9	Kepler *et al.*	six stars, including refraction
17 30 41	−21 27.8	Kepler *et al.*	six stars plus three planets, neglecting refraction
17 30 26	−21 31.9	Kepler *et al.*	six stars plus three planets, including refraction
17 30 31	−21 26.8	Fabricius	all eight stars, neglecting refraction
17 30 29	−21 28.4	Fabricius	all eight stars, including refraction
17 30 35	−21 26.9	Fabricius	eight stars plus three planets, neglecting refraction
17 30 36	−21 29.5	Fabricius	eight stars plus three planets, including refraction
17 30 06	−21 35.8	Brengger	all three stars, neglecting refraction
17 30 05	−21 36.7	Brengger	all three stars, including refraction
17 30 23	−21 33.3	Brengger	three stars plus two planets, neglecting refraction
17 30 23	−21 34.1	Brengger	three stars plus two planets, including refraction
17 30 34	−21 27.8	Fabricius; Kepler *et al.*	all star data, neglecting refraction
17 30 27	−21 31.4	Fabricius; Kepler *et al.*	all star data, including refraction
17 30 37	−21 27.2	Fabricius; Kepler *et al.*	all stars and planets, neglecting refraction
17 30 32	−21 30.5	Fabricius; Kepler *et al.*	all stars and planets, including refraction
17 30 31	−21 28.5	all observers	all star data, neglecting refraction
17 30 24	−21 32.2	all observers	all star data, including refraction
17 30 36	−21 27.8	all observers	all stars and planets, neglecting refraction
17 30 31	−21 31.0	all observers	all stars and planets, including refraction
17 30 38	−21 28.3	Fabricius	stars only, including refraction (Schönfeld 1865)
17 30 39	−21 28.9	Fabricius	stars only, nothing stated about refraction (Schlier 1934)
17 30 38	−21 28.9	Fabricius; Kepler *et al.*	stars only, allowance for refraction uncertain (Böhme 1937)
17 30 41.3	$-21\ 29\ 34''$	(see section 6 of text)	adopted position for centre of 3C 358 (epoch 1975)

NOTES:

*equinox J2000.0; epoch 1604.8 for the supernova positions, epoch ca. 1986 for the supernova remnant centre

**as listed by respective observers in Tables 6.2a and 6.2b

6.6. Discussion of the 1604-1605 Data

Table 6.1 contains the working positions for reference stars cited by the contemporary observers of the 1604 supernova. These working positions are from the Hipparcos-satellite catalogue (cf. Perryman *et al.* 1997), for equinox 2000.0, with specified proper motions added to the epoch-1991.25 Hipparcos positions to derive positions for epoch 1604.8. As noted in section 4, above, the distance measures given in Tables 6.3 were reduced by a procedure that is based on my recently published reduction methodology (section 4.1 of this thesis; also Green 2004, Appendix A). Table 6.4 lists my reduced positions for the preparation of this chapter, followed by positions published in the *A.N.* by earlier writers on this subject. The centre of the present-day supernova remnant, 3C 358, is also provided for reference. The adopted centre of 3C 358 is from radio and x-ray observations (cf. van den Bergh and Kamper 1977; Matsui *et al.* 1984; DeLaney *et al.* 2002). Figure 6.2 shows a plot of various reduced positions from the present study, with the outline of the current-day remnant shown for comparison.

The positions of the supernova derived by Schönfeld (1865), Schlier (1934), and Böhme (1937) — which are precessed to equinox 2000.0 for comparison in Table 6.4 — are remarkably similar, suggesting that Böhme (and maybe also Schlier) was (were) relying heavily on the reductions of their preceding *A.N.* authors. Winnecke (1865), Schönfeld, and Böhme all state that they addressed aberration and refraction in their work; it is unclear why aberration would be addressed, as its observable effect would be negligible for the distances and precision involved in the original non-optical measurements. As noted in section 4 (above), allowing for refraction is so problematical (in terms of not knowing precise times of observation, and thus the precise altitudes of the supernova and reference objects, and also not knowing the local atmospheric conditions) that it would be logical for different people looking at refraction to come up with different answers.

The newly reduced positions given in Table 6.4 are clustered first by the three observing locations, and then all of the data are combined to produce a "final" set (the Prague and Osteel data are also combined for comparison as a separate set). Each set contains four positions: the astrometry obtained from star measurements only (both neglecting and allowing for refraction) and that obtained from combining the measurements utilizing distance measures to both stars and planets (again both neglecting and allowing for refraction). The scatter is rather large, the sixteen positions being all west of the centre of 3C 358 at distances ranging from $\approx 0'.5$ to $11'$. Most sets lie outside the boundaries of the present-day remnant; the complete set of data from all three observing sites, neglecting refraction, turns out to be near the edge of 3C 358, a couple of arcmin to the northwest of the remnant's centre. Interestingly, both the 'unrefracted' sets of Prague data (that is, those with stars alone, and those including both stars and planets as references) lie within the boundary of 3C 358 — suggesting that the Prague data were indeed somewhat better than the data of Fabricius and Brengger (the measurements of Brengger are clearly worse than those obtained at Prague and Osteel).

The data of Fabricius corrected for refraction are somewhat closer to the centre of 3C 358 than

are his uncorrected data; curiously, the reverse is true for both the Prague and the Kaufbeuren data. Taking the entire sets of data, the 'unrefracted' data for both stars alone and stars-plus-planets are better than the refraction-corrected data. The best that one can say about refraction is that it was surely a factor, but at the precision level that was attained for distance measures between the supernova and the reference stars/planets, and considering that the time of observations (and thus the altitudes of the objects) are only known to ± 1 hour in the typical case, one can easily see that no more definitive conclusion about the final position of the supernova can be made than from taking the data and neglecting corrections for refraction.

Recent estimates put the distance to 3C 358 at 3000-6000 pc (e.g., Schaefer 1996; Stephenson and Green 2002, who refer to the remnant as G4.5+6.8). Van den Bergh and Kamper (1977) found that the centre of the supernova remnant exhibits a proper motion of $0''.013 \pm 0''.003$ yr^{-1} northward. This would indicate a motion since 1605 of $\approx 4''.8 \pm 1''.1$, a value far too small to account for any discrepancy between the centre of 3C 358 and the derived position for V843 Oph. As noted in my discussion on the 1572 supernova (Green 2004, section 4), given the lack of precision in the measurements made by the contemporary observers, it is considered unrealistic to consider a formal error analysis for the position of V843 Oph. Refraction, which is certainly a factor at altitudes in which the observations of the 1604 supernova were made, is an unknown variable because the observers did not report accurate times for their observations. And yet, refraction effects appear to be lost in the 'noise' of the low-precision measurements themselves; even if proper refraction could be implemented, it is unlikely that such correction would improve our knowledge of the true location of the supernova, which was probably closer to the true centroid of 3C 358 than any of the contemporary measurements would indicate.

My work here shows, then, that the precise position of V843 Oph cannot be ascertained from the contemporary observations: the observations tell us that the supernova erupted in a location that is within a few arcmin of the centre of 3C 358. The benefit of providing the useful positional information from contemporary sources here (and soon to be in print) in their raw form is that it yields potential use by future researchers who do not have ready access to the scattered rare-book collections that contain the original material. The information contained in this chapter (and the parallel paper submitted for publication) then serves as the most definitive study of the position of V843 Oph to date.

Chapter 7: Comet C/1532 R1

In section 1.5, I mentioned the five comets that appeared in the 1530s, noting how Peter Apian led the way in observing these comets and drawing significant attention to them. I also mentioned the Preface to this thesis how my attention was focussed in 2002 upon the comet of 1532 (now designated in our modern system as C/1532 R1[69]). This chapter looks at the astrometry of comet C/1532 R1, with a new orbital assessment of those data. There are records of this comet as having been observed in eastern Asia from 1532 Sept. 2, in China, until Dec. 30, in Korea (Ho 1962, p. 209). The available Asian observations (regarding the comet's location on the sky) are much less precise than are the European positional data, but will be addressed at the end of this chapter in the context of the analysis of the European astrometry. A couple of medieval Russian chronicles recorded that the 1532 comet was visible from October 1 until November 9, noting that "there appeared a star in the morning dawn, two hours before daylight, above the winter sunrise . . . [with] a ray which was shining very brightly, was very wide, and was directed toward noon" (Vyssotsky 1949, p. 39).

There are currently around two dozen comets known to be of short period that are considered lost (cf. Marsden and Williams 2003) — in that they have not been seen at predicted returns and are thus considered "unpredictable" for future returns to perihelion — with about one 'lost' comet being 'accidentally' rediscovered every year or so. Those of us involved with new-comet reports, therefore, are rather keenly focused on the issue of looking for possible linkages of new comets to those that were observed in the past and are considered "lost". New comet-naming guidelines authored chiefly by me (Green 2003b, 2004b), and accepted by the Committee on Small Bodies Nomenclature (CSBN) of the International Astronomical Union (IAU) in 2003, observe that names of "lost" comets are to be preserved wherever possible, and this gives new impetus to make a concerted effort in pulling together all old astrometry of comets into the modern, standardized form (in equatorial coordinates currently for equinox J2000.0).

Whilst I have been researching observational data on old comets for this Ph.D. thesis, a

[69] The letter 'R' in the designation refers to its (assumed) discovery in the first half of September (with the letter 'A' in this system referring to the first half of January, 'B' to the second half of January, etc.), and the '1' after the 'R' indicating the first known comet discovery in that half-month. The 'C/' prefix to the year of discovery is assigned nowadays to any comet with a single known apparition and a recognized/published set of computed orbital elements with orbital period > 30 yr. A 'P/' prefix is assigned to a comet that either is known to have been observed at two or more returns to perihelion or has been seen at only one return but has a definitively known orbital period of < 30 yr; a 'D/' prefix is assigned to 'P/' comets that are considered lost.

Japanese amateur astronomer named Kaoru Ikeya and another from China named Daqing Zhang independently and visually discovered an unknown ninth-magnitude comet in western Cetus (Green 2002a). As is common initially for comets with long orbital periods, a preliminary parabolic orbit was published for this new comet (Marsden 2002a), initially designated C/2002 C1 (Ikeya-Zhang), because the early short arc of observation is not usually sufficient to distinguish much difference from a parabola. Soon, however, it became obvious that the new comet had a path that was significantly elliptical, and it was noticed by Brian G. Marsden and Syuichi Nakano that the angular elements and perihelion distance of comet C/2002 C1 were similar to those of comet C/1661 C1 (cf. Green 2002b). However, no modern reduction of the 1661 observations was available for use in the early linkage attempts, so the computers initially had to "fabricate" observations from the centuries-old orbital elements by Wilhelm Olbers (1787; Schilling 1894, pp. 246ff) or Pierre Méchain (1785) — as actual astrometric observations are needed to try linking one apparition to another with a computer orbit program.

Edmond Halley (1716, p. 440) noted a similarity between the parabolic orbital elements of the 1532 and 1661 comets, cautiously suggesting a possible identification, adding: "But Apian's Observations, which are the only ones we have concerning the first of these Comets, are too rude and inaccurate for any thing of certainty to be drawn from them, in so nice a matter". The suggested link between the 1532 and 1661 comets (having been repeated faithfully in less-uncertain terms down through the centuries following Halley, by author after author!) was now duly noted by us, but of course the period wouldn't allow the 1532 *and* the 1661 comets to be the same as the 2002 comet. Yet the possibility existed that the 2002 comet might be *either* the 1532 *or* the 1661 comet. So it seemed reasonable, in the course of the work for this thesis, to include my research into these two old comets for illustrative purposes — the idea being to compare comet observations made several decades before and after the period of my concentration (which is centred on about 1600).[70]

As it turned out, the arc of current observations extended rapidly enough (considering the current precision of CCD astrometry, yielding orbital residuals generally on the order of 1″ or less) that it quickly became know that the orbital period of C/2002 C1 was much closer to 340 years than to 470 years — so that the 1532 comet was quickly excluded (but not before I had done some research into what data are available on that comet!). And soon thereafter, the 1661 comet was firmly linked to C/2002 C1, eliminating the possibility of a 1532/1661 link. The problem is that observers of the 1532 comet did not make routine distance measures to reference stars, but rather made note of either the ecliptic coordinates of the comet or its altitude and azimuth on various nights. Given a general lack of specified times when altitude/azimuth (or 'altaz') measures were made by the observers, it would be virtually impossible to use altaz measures to obtain

[70] In fact, I was in Durham for thesis discussions in April 2002, when comet C/2002 C1 was a faint naked-eye object, and I managed to catch a view of it from the Durham Observatory hill on the edge of the city (despite the bright, unshielded spotlights unworthy of such a location!).

equatorial coordinates for the comet. But the most careful observer of the 1532 comet, Peter Apian, recorded his observations on several nights from September until November (Apian 1540). He actually recorded the clock times on three of six nights, and in the observations given below (Table 7.1), the dates for the other three nights are simply copied from the previous night for which a time was given. One can compute an approximate time of observation and approximate equatorial coordinates for the comet from the recorded altitudes and azimuths of the comet and various reference stars, when these 'altaz' coordinates are given for the reference stars — the uncertainties being the unknown error in the measurements and the unknown error in the assumed local time. The measurements' uncertainties arise not only from personal errors (including instrumental parallax problems due to sighting along the instrument's guide and problems in reading the instrumental markings at night) but also issues regarding the design/construction of the instrument (including how precise the divisions were in the marking of degrees on the instrument's scale) and some uncertainty in what the true horizon may be (affecting altitude measures). The assumed local time has two uncertainties: First, there is the unknown time between measuring the reference-star's altitude and azimuth and measuring the comet's altitude and azimuth (which, from the recorded experiences of others, such as Tycho Brahe some decades later, is likely to be at least on the order of a few minutes). Second, we must address the unknown (ΔT = ET - UT) correction due to the rotation of the earth in 1532, which is at best unknown to a level of double-digit seconds and at worst to a minute or more (cf. Stephenson 1997, pp. 430 and 502ff). Stephenson (*ibid.*, p. 516) estimates $\Delta T \approx 160$ sec for 1532, but it is around 226 seconds from the following empirical polynomial[71], specified for use during AD 948 to 1600:

$$\Delta T = 50.6 + 67.5T + 22.5T^2, \tag{7.1}$$

where $T = (J{*}2451545)/36525$ (*i.e.*, T is reckoned in centuries from J2000.0, with $T < 0$), and J is the Julian date of the observation. This ΔT correction affects any calculation of the hour angle and thus the equatorial coordinates from the observed altaz coordinates.

The sky rotates through $\approx 15'$ (15 arc minutes) in 1 minute of clock time. For an observer at latitude $\approx 50°$, an object at 30° altitude can generally be expected to move a degree in azimuth every five minutes or so and a degree in altitude every 9 minutes or so; at lower altitudes the altitude will change more rapidly (every 7 minutes or so at 13° altitude). A rough estimate on the total uncertainty in Apian's altitude measures might be taken on the order of 20′-30′ at best (and on the order of several degrees at worst), compared with the precision of observers using similar instruments with likely more experience and standardization a half-century later. The uncertainty in time between the comet measurements and the reference-star measurements must be at least on the order of a degree in translated motion of the sky. So any transformed equatorial coordinates from the type of observations made by Apian for the 1532 comet will not be better

[71] This estimation is currently in wide-spread use in the dynamical-astronomy community, and is adapted from Stephenson's earlier work (Stephenson and Houlden 1986). The form given here, my equation 7.1, is that given by Meeus (1991), p. 73

than 1°-2° at best. Apian did, however, also provide some calculated ecliptic (latitude, longitude) and equatorial (right ascension, declination) coordinates for the comet, and it is these values (in some manner) that Halley used in his orbital computations of this comet (Halley 1752, p. Rrrr2; Halley lamented, "the observations are so very imperfect, being taken with a small instrument for azimuths in a gross manner"). Apian gave α and δ together only for two dates, the second of which was given (apparently erroneously) as Sept. 3 but which should probably be Oct. 3. For two other dates (Oct. 31 and Nov. 1), Apian gives the right ascension but no declination (though he gives latitudes for those two dates).[72]

There was no good star atlas for Apian to work with in 1532, and the only catalogue of star positions was the very poor, error-ridden one by Ptolemy, so the coordinate grid that has been so well defined for us was not a trivial problem for astronomers to deal with then. Nonetheless, the α and δ positions for epoch 1532.8 were computed for Apian's observations (where he did not already do so) from the λ and β values, and then these were precess to equinox 2000.0 (see Table 7.1). The right-ascension (α) and declination (δ) values are given here to an extra figure of precision than Apian gave, as is the time.

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Table 7.1. The positions of the 1532 comet from Apian (1540), precessed to equinox 2000.0, with residuals, solar elongation, and heliocentric and geocentric distances from the orbit in Table 7.2.

Date (UT)	R.A. (2000.0) h m s	Decl. ° '	O-C m	O-C '	Elong. °	r (AU)	Delta (AU)
1532 10 02.1611	10 42 38	-06 49.4	5.3-	8+	40.9	0.71904	1.05742
1532 10 03.1611	10 57 24	-06 20.9	2.6+	10+	40.1	0.70786	1.05937
1532 10 19.1611	12 52 45	-00 24.4	5.2+	21-	31.4	0.60623	1.16392
1532 10 31.1701	14 02 54	+01 35.6	4.2-	34-	28.7	0.65408	1.31599
1532 11 01.1701	14 13 09	+01 39.3	0.1-	34-	28.6	0.66252	1.33043
1532 11 08.1681	14 55 04	+03 45.7	1.8+	82+	28.3	0.73557	1.43618

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Table 7.2. Orbital elements for comet C/1532 R1 from Apian's observations (given in Table 7.1)

C/1532 R1		
Perihelion time	1532 Oct. 19.95	
Arg. of perihelion	15.90	
Long. of asc. node	122.10	(2000.0)
Inclination	41.96	
Perihelion distance	0.6060	
Eccentricity	1.0	

[72] Another problem with these values is that it is well known that errors were made in transformation to α and δ by 16th-century astronomers, so it is better to take the actual measurements (altitude/azimuth) and compute α and δ from those. But this is for a future project.

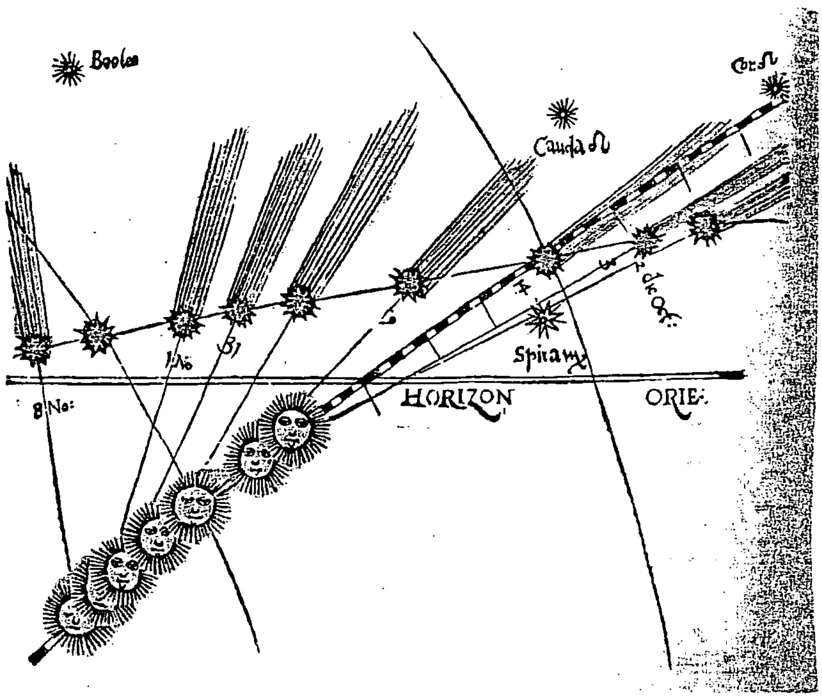

Figure 7.1. Drawing of comet C/1532 R1, from Apian (1540).

Though Apian's magnificient publication on comets appears as pages N(II)b-O(III)a of his 1540 Latin folio book, Apian had actually published a tract on the 1532 comet in German shortly after the comet's appearance (Apian 1532). The title-page woodcut shows a comet/sun combination that moves across the sky (with the comet's tail pointing away from sun); the tract's internal diagrams with comet observations are similar to those in his 1540 *Astronomicum Caesareum.*

Wolfgang Kokott (1984) wrote and published a thesis entirely on the comets of the 1530s, conveniently transcribing text from 16th-century books, showing how the original observers wrote about their observations of the various 1530s comets.[73] Kokott uses celestial longitudes and latitudes derived by Pingré (1783, p. 491) for the comets' observational accuracy, whereas any new analysis should start from scratch to determine new positions from the original data. While the 1530s certainly indicate a beginning in the direction of giving serious observational material on comets, the tracts of that decade tended more toward the astrological (and theological) than observational, following the ages-old pattern of perceiving comets as indicators of events on earth. Thus, though Matthew Brotbeyhel (evidently of Kaufbeuren or Raustbeuren) published two 1532 German tracts with very nice title-page woodcuts depicting the comet amongst the stars, moon, and clouds over a walled city, he shows a skeleton with a giant billows blowing wind at the comet, and the tract's text is very astrological in nature.[74] According to William Henry Black (1845), the Oxford University Library contains a manuscript by John Robyns on the 1532 comet that also appears to be largely astrological, though it is said to contain observations of the comet.[75]

Fracastoro did include numerous observations — both in print and in a manuscript letter (which each contain some unique data and which sometimes have conflicting measurements) — giving longitudes, latitudes, and declinations on Sept. 30, Oct. 1, 2, 3, 12, 16, 23, Nov. 4, and 27; these are given by both Pingré (1783, p. 493) and Kokott (1984, p. 75), but they are generally given to only the nearest degree and they are greatly discordant (e.g., Kokott 1984, p. 76) and will not be considered further seriously. Johann Virdung, a physician at Hassfurt, wrote a 7-page pamphlet that has a title-page diagram with woman at the left, some stylized stars, and a comet

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[73] However, comparison with original texts reveals transcription errors by Kokott, and one should resort to the original literature thesis for any serious analyses of the data. I specifically compared Kokott's transcriptions with original printed observations by Schöner (1531b), Girolamo Fracastoro (1538), and Apian (1540), and each of these yielded at least one or two errors due to Kokott. There are numerous mistakes in the transcriptions of Apian's text, and I provided examples in my *JHA* review (Green 2000).

[74] Brotbeyhel (1532a) is in the British Library under shelfmark 1395.h.40; Brotbeyhel (1532b) is in the Wolfenbuettel library under shelfmark 125.34 Quod (12).

[75] The manuscript is entitled "Ad invictissimum principem Henricum ejusdem nominis octavum serenissimum Anglorum regem et fidei defensorem, Joannis Robyns sui collegii in Oxonia canonici, libellus de accidentibus futuris". Indeed, Clare Brown (in the Department of Special Collections and Western Manuscripts of the Bodleian Library) has e-mailed me that this manuscript is catalogued under shelfmark MS. Ashmole 186, fols. 5-14, 4b-1; I am in the process of ordering a photocopy of this mansucript from their stock microfilm copy.

with a detached tail — perhaps what we now know as a disconnection event?[76]

Achilles P. Gasser of Lindau wrote a tract on the 1532 comet whose title-page diagram has a man on the earth with the comet's head at horizon and its tail pointing upwards.[77] Gasser states that others saw the comet on Sept. 23 and informed him of the new comet. When he first saw it on the following night, Gasser noted that the comet's head was in a straight line with "dem mitlesten rossz dess Heerwagens vnnd ruggsternen des Lewen", which he clarifies as "dem xxvi. Orse maioris/vñ xx. Leonis sternen" (or the 26th star of UMa and the 20th star of Leo, according to Ptolemy's *Almagest*), and he goes on to describe appearance of the comet's tail (Gasser 1532?, page Aii verso). A week later, on 1532 Sept. 30, Gasser noted the comet to rise about 9 minutes later — and to be located a little over 6° from the equator and in the sixth degree of Virgo (longitude $\lambda = 6°$ Vir). A more confusing passage says that, on 1532 Oct. 10, the comet appeared at $\lambda = 15°$ Vir and 3° toward the pole (presumably $\delta = +3°$ — its distance from the celestial equator, or the complement of the distance from the north celestial pole), with a "more upright" tail stretching into the heart of the constellation figure of Leo.

The person perhaps most cited in the early-modern era on the comet of 1532 besides Apian was Johann Vogelin at Vienna, following in the Peurbach/Regiomontanus/Walther school of thought on comet observation (Green 2004c, d, e). Vogelin evidently wrote a manuscript that was not published until Hagecius (1574) did so in a tract on the 1572 supernova (Vogelin 1574; cf. Kokott 1984, p. 98).[78] Vogelin mentions Regiomontanus for his work on comets and gives numerous geometrical diagrams for attempting to place the comet of 1532; including parallax work; included with his treatise is a picture of an astronomical radius (cross staff) showing its use in measuring angles on the sky. On page 164 of Hagecius' tract are given Vogelin's computed ecliptic longitudes and latitudes for the comet for Oct. 6 and 10 (apparently being Oct. 7 and 11, respectively, in UT) — apparently for the 1532 comet. But something appears not correct for the 1532 comet, as Vogelin's figures (Oct. 6, 16^h08^m local time, $\lambda = 15°36'20''$ Leo $= 135°36'20''$, $\beta = 11°20'52''$; Oct. 10, $16^h37^m30^s$ local time, $\lambda = 26°17'05''$ Leo $= 146°17'05''$, $\beta = 14°46'08''$), translate to equatorial coordinates for equinox 2000.0 (Oct. 7.117 UT, $\alpha = 9^h54^m08^s.8$, $\delta = +24°51'39''$; Oct. 11.137 UT, $\alpha = 10^h42^m12^s.9$, $\delta = +24°12'04''$) that are not very close for the comet on those dates ($\alpha \sim 11^h.5$, $\delta \sim -4°$). If it is assumed that the longitudes were in the sign of Virgo instead of Leo *and* the latitudes are taken to be negative, the resulting equatorial coordinates are much closer (Oct. 7.117, $\alpha = 11^h13^m04^s.1$, $\delta = -7°17'36''$; Oct. 11.137 UT, $\alpha = 11^h46^m10^s.7$, $\delta = -14°38'17''$), but the declination on the Oct. 6/7 observation is still inexplicably large (and, of course, these assumptions would anyway be questionable).

[76] This tract (Virdung 1532?) was found in the Jena Universität's manuscript library under shelfmark HZ/4 Bud. Hist. eccl. 209b [tract 26].

[77] A woodcut in another tract by Pruckner (1532), which is in the British Library under shelfmark 531.f.2, depicts a similar-looking man on the earth but shows a different-looking comet that is not on the horizon.

[78] This manuscript evidently now resides in the National Library in Vienna (under title "Komet von 1532" and shelfmark Vin 10905. 150-157), though I have not seen it (Zinner 1925, p. 354).

Pingré (1783, p. 495) tabulated four observations by Vogelin on two nights (Oct. 6 and 10), and these are repeated in Kokott (1984, p. 99). After converting these versions of Vogelin's positions to α and δ and precessing to equinox 2000.0 (see Table 7.3), it is noted that the declinations are still off by 3°-4°. Vogelin's observations were thus not included in the orbital solutions. Table 7.3 also includes the $O-C$ residuals from the orbit in Table 7.2 for the precessed observations reduced by Pingré (the UT times there correspond to times that Pingré apparently derived for the local mean time at Vienna based on the measured altitudes of the reference stars; it should be noted that they would thus not be the same as for the comet, and in any case, the low precision of the observations hardly warrants worrying about the time!). Indeed, Pingré stated that he regretted the time that he spent trying to reduce Vogelin's data! One can easily see that, for some of these very old observations, there is a limit as to how much effort one should spend on getting what is, after all, little useful data out of them.

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Table 7.3. Vogelin's observations reduced from Pingré's tabulation

Date (UT)	R.A. (2000.0)	Decl.	O-C	
	h m s	° '	m	'
1532 10 07.113	11 36 04	-01 06.8	13.6+	217+
1532 10 07.143	11 32 02	-01 05.8	9.4+	217+
1532 10 11.133	12 16 46	+00 21.8	25.9+	201+
1532 10 11.172	12 06 24	+00 52.8	15.3+	231+

◇ ◇ ◇

Another well-known writer on astronomy and astrology, Girolamo Cardano, mentioned the 1532 comet in his *De subtilitate*, noting that it was visible from Sept. 22 to Dec. 3, for 71 days, moving from Virgo to Scorpius, and concluding that its slow motion indicated that it had to be further away than the moon because the moon moves faster (Cardano 1582; Hellman 1944, p. 93) — an anti-Aristotelian view.

The 1532 comet was included in Halley's 1705 catalogue as chronologically only the fourth comet for which he was able to find enough observations in the historical record with which to compute an orbit (the previous comets were 1337, 1472, and 1531). Halley (1705b) remarked that he used Apian's observations for his orbit of the 1532 comet.

As noted earlier, Pingré (1783, p. 492) did provide nearly a dozen sets of ecliptic longitude and latitude coordinates for the comet of 1532 from the observations of Apian, Fracastoro, and Vogelin made on nine nights. But he did not re-compute the comet's orbit. As noted earlier, Méchain (1785) followed Halley's suggestion on the possible linkage of the 1532 and 1661 comets, discussing that earlier work and giving Apian's observations. He also presented his reduced values for the 1532 data, giving α and δ for five dates, which I have precessed to equinox 2000.0 and given in Table 7.4, for comparison with the direct reductions done with the Apian data in Tables

7.1 and 7.2.

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Table 7.4. Méchain's reduced values of α and δ precessed to equinox 2000.0, with residuals, solar elongation, and heliocentric and geocentric distances from the orbit in Table 7.5

Date (UT)	R.A. (2000.0)	Decl.	O-C		Elong.	r	Delta
	h m s	° ' "	m	'	°	(AU)	(AU)
1532 10 02.1632	10 46 25.8	-06 51 28	6.1-	14-	39.8	0.77046	1.19865
1532 10 03.1493	11 04 19.4	-05 49 01	5.5+	27+	39.2	0.75918	1.19646
1532 10 31.1701	14 07 57.5	+01 32 24	1.6-	47-	28.5	0.66085	1.33230
1532 11 01.1944	14 18 55.2	+02 06 25	2.7+	21-	28.4	0.66719	1.34387
1532 11 08.1736	14 58 45.0	+03 58 59	0.6-	63+	27.9	0.72578	1.43132

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Méchain also provided new orbital elements from these observations (which, precessed to equinox 2000.0, are T = 1532 Oct. 20.120 TT, $\omega = 16^\circ.67$, $\Omega = 125^\circ.59$, $i = 42^\circ.42$, $q = 0.61255$, $e = 1.0$; cf. Marsden and Williams 1993, p. 54) for the comet. My own elements from Méchain's values for α and δ for the 32-day arc are given in Table 7.5.

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Table 7.5. Orbital elements for comet C/1532 R1 from Méchain's reduced values for α and δ (given in Table 7.4)

Perihelion time	1532 Oct. 22.72 TT	
Arg. of perihelion	21.41	
Long. of asc. node	129.26	(2000.0)
Inclination	46.66	
Perihelion distance	0.63539	
Eccentricity	1.0	

Olbers later was following the same Halley suggestion, equating the 1661 and 1532 comets, that Maskelyne (1786) observed, and he looked closely at the data of Apian, Fracastoro, and Vogelin — following closely what Pingré had done (Olbers 1787; Schilling 1894, pp. 246ff). Olbers did not publish values of α and δ, but rather worked directly with ecliptic longitude and latitude data. He re-computed the orbit of the 1532 comet and found values quite close to those that Halley had published. Olbers's elements, precessed to equinox 2000.0, are T = 1532 Oct. 18.832 TT, $\omega = 24^\circ.53$, $\Omega = 93^\circ.81$, $i = 32^\circ.59$, $q = 0.51922$, $e = 1.0$ (Marsden and Williams 1993, p. 11).[79] One can see that the poor quality of observational precision leaves quite a bit of uncertainty in the orientation of the comet's orbital plane.

7.1. The East-Asian Records

It is curious that the Chinese and Korean records of an autumn 1532 comet indicate a visible duration of 3-4 months (or even longer), whereas the European records indicate a span of only about 5 weeks. The Chinese chronicles stated that the comet first appeared on 1532 Sept. 2 (as reckoned by Ho 1962, p. 209) in the 22nd lunar mansion, *Tung-Ching*, which is the general vicinity of Gemini. As there are 28 lunar mansions — divided up into 'daily' segments along the ecliptic, due to the daily motion of the moon in its month-long orbit — this gives a range of $\approx 13^\circ$ in ecliptic longitude and perhaps a similar uncertainty in ecliptic latitude. The records further state that it moved to the northeast and passed the vicinity of Cygnus (*Thien-Chin*) before increasing in length and sweeping across the various stars of the *Thai-Wei* Enclosure (defined generally as the area bounded by the stars of our modern constellations called Coma Berenices, Virgo, and Leo), the first lunar mansion (or *Chio*, meaning the region around Spica and ζ Vir), and *Thien-Mên* (Virgo). But only one date is attached to a rough position in the Chinese records. A Korean chronicle gives only a single position, placing the comet in the 24th lunar mansion (*Liu*) on Sept. 14, according to Ho, which he says corresponds to our modern constellation Hydra.

In early September, based on the orbital elements (Table 7.2) from the European astrometry, the comet would indeed have been at an ecliptic longitude near that of Castor and Pollux (eastern Gemini), but some 45° to the south. The comet moved steadily northeastwards toward Leo (but nowhere near Cygnus), arriving in the general area of the *Thai-Wei* Enclosure in October. In the latter part of October, C/1532 R1 passed close to ζ Vir. The comet was indeed in Hydra on Sept. 14, as indicated by the Korean records. But none of these east-Asian rough positions enable us to refine the orbital elements of the comet beyond what the European observations give us. They do, nonetheless, give some confidence in the solution given in Table 7.2 from the European data.

Assuming an inverse-third-power total-brightness power-law formula for comet C/1532 R1, one might arrive at an absolute magnitude of $H_{7.5} \simeq 2.5$ in an attempt to represent the observability

[79] Even though not specifically stated, all of the additional sets of orbital elements listed in the "References and Notes" sections in his editions of the *Catalogue of Cometary Orbits* prior to 1995 were indeed precessed to equinox 2000.0 between 1992 and 1995, and to 1950.0 prior to 1992 (Marsden 2004, private communication).

of this object. The ephemeris in Table 7.6, below, indicates the position and projected brightness based upon this assumption and using the orbital elements in Table 7.2. This indicates that the comet indeed faded down to limiting-naked-eye brightness[80] by late December and so could have been observed as long as the Asian records suggest, and it also indicates that it would have been observable from early September onwards. The comet was located well south of the celestial equator in September, making it a more difficult object for the European observers, who were located at least 10°-20° further north than their Chinese counterparts. A third- or fourth-magnitude comet low in the morning sky would easily have been missed by Europeans further to the north. Explaining away the last seven weeks of observability at year's end is a bit more difficult, but given its rather rapid eastward motion, it would be understandable that a fading comet would be lost — especially if periods of cloudy weather (combined, perhaps, with bright moonlight) intervened in November.

[80] noting the previously mentioned observability issues for a moving object that would make a diffuse comet difficult to identify much below fifth or sixth magnitude in the absence of optical aid for confirmation

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Table 7.6. Ephemeris for Comet C/1532 R1

1532 TT	α_{2000}	δ_{2000}	Δ	r	ϵ	m_1
Aug. 8	$5^h54^m.86$	$-17°40'.0$	1.564	1.541	69°.8	4.9
13	6 13.77	−17 36.4	1.484	1.464	68.9	4.6
18	6 34.00	−17 28.1	1.409	1.387	67.7	4.3
23	6 55.68	−17 13.3	1.339	1.310	66.1	4.0
28	7 18.91	−16 49.6	1.274	1.231	64.1	3.7
Sept. 2	7 43.77	−16 14.5	1.216	1.153	61.7	3.4
7	8 10.32	−15 25.3	1.166	1.076	58.9	3.1
12	8 38.57	−14 19.5	1.123	0.999	55.7	2.7
17	9 08.47	−12 55.4	1.090	0.923	52.2	2.4
22	9 39.93	−11 12.7	1.067	0.851	48.5	2.1
27	10 12.77	− 9 13.5	1.056	0.782	44.7	1.8
Oct. 2	10 46.76	− 7 02.2	1.057	0.721	41.0	1.6
7	11 21.62	− 4 46.8	1.072	0.669	37.6	1.3
12	11 56.98	− 2 37.4	1.100	0.631	34.6	1.2
17	12 32.37	− 0 44.8	1.142	0.609	32.2	1.2
22	13 07.15	+ 0 42.5	1.195	0.608	30.5	1.3
27	13 40.61	+ 1 41.0	1.258	0.626	29.3	1.5
Nov. 1	14 12.14	+ 2 13.0	1.328	0.661	28.7	1.8
6	14 41.35	+ 2 23.9	1.403	0.711	28.4	2.1
11	15 08.10	+ 2 20.4	1.481	0.771	28.3	2.5
16	15 32.45	+ 2 08.2	1.560	0.838	28.4	2.9
21	15 54.60	+ 1 51.8	1.641	0.910	28.7	3.3
26	16 14.74	+ 1 34.3	1.721	0.985	29.1	3.6
Dec. 1	16 33.10	+ 1 17.6	1.800	1.061	29.6	4.0
6	16 49.88	+ 1 03.1	1.876	1.139	30.2	4.3
11	17 05.26	+ 0 51.5	1.951	1.217	30.9	4.6
16	17 19.41	+ 0 42.9	2.022	1.295	31.8	4.9
21	17 32.45	+ 0 37.6	2.090	1.373	32.9	5.1
26	17 44.51	+ 0 35.5	2.154	1.450	34.2	5.4
31	17 55.66	+ 0 36.6	2.214	1.527	35.7	5.6

NOTES:

The dates above are given for 0^h TT on the specified date; Δ and r are the comet's geocentric and heliocentric distances, respectively, in AU; ϵ is the comet's elongation from the sun; and m_1 is the total visual magnitude (see text).

Chapter 8:
The Seven Comets Observed by Tycho Brahe's Group

As discussed in Chapter 1, the comet of 1577 was one of the most influential comets in history from the perspective of the understanding of comets — with regard to perceived concepts of the solar system and of astronomy, and especially with regard to thinking about how observations could be made to further knowledge.

Analyzing the positions of comets is a different process from analyzing the positions of supernovae. Comets move with respect to the background stars and are seen in different celestial locations by each observer on each night (at the naked-eye level, such differing apparent celestial coordinates are usually due more to observations being made at different times and dates than due to parallax, buf if the comet is relatively close to the earth, as was the 1577 comet in mid-November of that year, parallax can be a non-ignorable factor). With a supernova, all the observers' astrometric measures are reduced with the goal of obtaining a single reasonably robust position. With comets, a series of positional measurements is analyzed usually via a 2-body orbit-determination and least-squares differential correction of the observations with respect to the orbital elements, as noted at the end of Chapter 4.

This chapter describes the seven comets observed at Hven and includes a detailed re-analysis of astrometric measurements of the 1577 comet by Tycho and his contemporaries. Such re-analysis and intercomparison yields useful information about the abilities and thinking that these observers had, and it provides insight into a field that was developing more rapidly in this period than has perhaps been assumed by most historians until now. The only two previous known orbital calculations for this comet were by Halley and by Woldstedt.[81] Evidently, neither Halley nor Woldstedt had access to Tycho's original logbook observations of the 1577 comet, and so they had to depend on what Tycho presented in his 1588 treatise; they also dismissed the observations by other observers, probably because they didn't trust them, or perhaps because they perceived Tycho's work as more "professional" and more accepted by the astronomical community — and the observations of others as "amateurish" in comparison. Certainly in terms of observation, Tycho's work was perpetuated by the astronomical community as authoritative. Tycho was very definitely in the early stages of his observing career, with only a few of his early (less-precise) instruments available in 1577.[82] His fame for increasing the precision of astrometric observations of Mars by

[81] cf. Halley 1705a, 1705b, 1752; and Woldstedt 1844. Here I am ignoring the pre-Newtonian efforts at orbit determination of this comet by such notables as Tycho, Maestlin, and Kepler.

[82] See the chronological picture of the development of Tycho's instruments that was constructed by Thoren

an order of magnitude over his predecessors is well known, but those planetary observations and his catalogue of some 1000 star positions were still some years in the future at this point. In fact, my results indicate that Tycho's observations of the comet of 1577 (with important implications for his highly-cited position for the supernova of 1572) were not of much higher precision than the astrometric observations of his contemporaries. But the manner in which he presented observations in well-organized mammoth printed tomes, decades later, impressed his colleagues and helped to catalyze a move toward standardization in astronomy.

In the words of Doris Hellman (1970, p. 406), "from Hven, Tycho carried on a vast correspondence that kept alive the personal contacts made in his student days, apprised the scholarly world of his work, and provided him with the observations of others for comparison with his own." As I alluded earlier, Francis Bacon (a contemporary of Tycho) complained in his *The New Organon* that "no search has been made to collect a store of particular observations sufficient in number, or in kind, or in certainty, to inform the understanding, or in any way adequate" ("Aphorisms, Book One", XCVIII; Anderson 1960, p. 94). Some four decades after Tycho died, Descartes harped on this theme in his *Discourse on the Method of rightly conducting one's reason and seeking the truth in the sciences*: "Thus, by building upon the work of our predecessors and combining the lives and labours of many, we might make much greater progress working together than anyone could make on his own. I also noticed, regarding observations, that the further we advance in our knowledge, the more necessary they become" (Cottingham *et al.* 1994, p. 143).

8.1. Tycho's Original Observations of Comets: Availability

Tycho's observational logs of seven comets do not appear to have been widely known, at least in the years soon after Tycho died. Elias Ehinger, who wrote a 43-page historical catalogue of comet apparitions that was evidently published in 1618, does not include Tycho's comet of 1593, though he mentions the comets of 1577, 1580, 1582, 1585, 1590, and 1596 (pp. 36-37). His catalogue is brief, and he does not mention specific observations, so his sources are not obvious. Ehinger included the supernova of 1572 in his comet list (p. 36), evidently because so many people had considered it as an unusual (starlike) comet. Tycho certainly left plenty of messages in his published works that he had carefully observed more than just the comet of 1577. His *Epistolarum astronomicarum* of 1596 provided undetailed observations for the comet of 1585 (Brahe 1596, 14-15, 42-43) and an ephemeris for the comet of 1590 (*ibid.*, 181). Tycho further noted several times in his publications that the remaining comet observations were to appear in the third volume of his grand trilogy — the first two of the trilogy being *De mundi* and *Progymnasmata* (Dreyer 1890, p. 163). Other items were evidently also missed in Tycho's published works, such as his mention in the *Progymnasmata* of his personal copy of Copernicus' unpublished manuscript of *De hypothesibus motuum coelestium commentariolus* — which Dreyer (1890, p. 83) says should have attracted attention; the manuscript was in a library at Vienna, where some of Tycho's manuscripts

1973 and 1990, Ch. 5.

reside, though *De hypothesibus* was not found until 1878.

Hevelius (1668, pp. 865-867), in his grand *Cometographiæ*, mentions Tycho's observations of the comet of 1585 as being in the Dane's *Epistolarum astronomicarum* and in the Astrological and Meteorological Diary published in 1586 at Uraniborg under the name of Elias Olsen (an observing assistant of Tycho's; cf. Dreyer 1890, p. 125). Hevelius (p. 868) also refers to Tycho's *Epistolarum* as the source for observations of the comet of 1590. But Hevelius is largely silent on the other comets observed by Tycho (besides, of course, the comet of 1577). Similarly, Stanislav Lubienietz's 1666 book on comets, *Historia omnium cometarum*, mentions Tycho in connection with observations of the 1577 comet (p. 373), but does not mention Tycho's observations regarding the comet of 1580 (while noting those of Maestlin; pp. 380-382). Lubienietz again mentions Tycho's *Epistolarum* in regard to the 1585 and 1590 comets (pp. 387, 391-393), but is silent on Tycho's other comets. Olbers and Encke (1847, pp. 206-207) refer to Halley's orbits for both the 1580 and 1596 comets as being "nach Moestlin", whereas Pingré's orbits for the same comets are "nach Tycho's bessern Beobachtungen".[83]

In Tycho's 1598 book detailing his instruments, *Astronomiae instauratae mechanica*, he states that during his two decades at Hven, "there was hardly any day or night with clear weather that we did not get a great many, and very accurate, astronomical observations of the fixed stars as well as of all the planets, and also of the comets that appeared during that time, seven of which were carefully observed in the sky from that place" (Ræder *et al.* 1946, p. 109). Tycho then added, "These [observations] I first collected in some big volumes, but later on I divided them up and distributed them among single books, one for each year, and had fair copies made." Very few observations out of the entire set by Tycho were actually published prior to his death, and it would be centuries before all of his data would actually appear in print. They first appeared in their entirety only with J. L. E. Dreyer's *Tychonis Brahe Dani Opera omnia* (1913-1929), though by 1867 the majority of Tycho's observations had been published in many different places.

The movement of manuscripts containing Tycho's observations of comets has been rather complex, and I shall review the history of those manuscripts in light of their pertinence for the analyses of the seven comets' orbits. My chief sources for key elements of this progression of manuscripts are by Dreyer: his 1890 biography of Tycho (especially pages 370-375) and his notes published (in Latin) in his *Opera omnia*. The original English version of those notes (to chapters 2, 3, 4, 6, and 10 of *Opera omnia*) was purchased years ago by Bern Dibner, whence they were given to the Smithsonian Institution, and I used a photocopy made from the original notes now in the possession of Owen Gingerich.

Tycho had been very possessive of all of his observations, fearing plagiarism. Before Tycho died in 1601, his new assistant Kepler even had difficulty accessing the observation logbooks. Kepler laid claim to the logbooks after Tycho's death, as the new Imperial Mathematician. In a feud with Tycho's son-in-law, the logbooks passed back and forth until 1604 (Voelkel 1993),

[83] see also Olbers 1797, where slightly different (but similar) remarks appear.

when Kepler was able to hold the originals until his death, according to Dreyer (1890, p. 371), "as pledges for the considerable arrears of salary due to him". Eventually his son, Ludwig Kepler, benefited by selling the original manuscripts to Danish King Frederick III for deposit in his newly founded Royal Library at Copenhagen. So we now see that Hevelius, Lubienietz, and others in the seventeenth century were kept in the dark via Ludwig Kepler's heavy possession of Tycho's logbooks.

The copies, meanwhile, were incomplete — lacking observations for 1593 and the years prior to 1582. As Dreyer (*op.cit.*) relates, "Albert Curtz, a Jesuit, and Rector of the College of Dillingen, on the Danube, who had corresponded with Kepler both on scientific and religious subjects, conceived the idea of publishing Tycho's observations from these volumes". As Max Caspar *et al.* (1993, p. 365) relate, "Albert Curtius and Christoph Scheiner, two Jesuits who had long been wanting to get [the Tycho manuscripts] for themselves, were mixed up in the agonizing attempt to tear the volumes away by craft [from Ludwig Kepler]." Curtz, who Latinized his name as Curtius, managed to obtain what turned out to be 19 volumes of copied observations, which he apparently thought represented the complete original logbooks. It is not known how Curtz obtained the observations (Dreyer, X, MS; see footnote 21). Curtz proceeded eventually to publish these observations along with those of other observers in a mammoth volume entitled *Historia coelestis* in 1666 (and a second edition in 1672) under the pseudonym Lucius Barretus. But as Dreyer notes (and others soon after the publication of *Historia coelestis* realized), not only are years of Tycho's data missing from Curtz's volume, but there are also observations missing within the years covered by Curtz, and there are also many typographical errors — so much as to make Curtz's effort be considered "well-nigh useless" (Dreyer 1890, p. 373).

Meanwhile, the original observations were accessed by the mathematician Erasmus Bartholin (who was the first to openly criticize the mistakes of Curtz, through a published booklet), and he obtained permission to make a complete copy of the original logbooks in Copenhagen for the purpose of publishing all of Tycho's observations properly. Unfortunately, money for the project stopped in 1670, and Bartholin's publication plans died. In 1671, Jean Picard visited Copenhagen and, upon learning of the status of Bartholin's project, asked to take the copied observations back to Paris for publication there. The copies were approved for the trip to Paris, but under the guidance of Bartholin's Danish assistant, Ole Römer. Unfortunately, the financial support in Paris also soon stopped even though the printing had started. Picard's death in 1683 also hindered the publication project (Dreyer, X, MS).

Years passed, and finally in 1696 the Danish government inquired about the status of "the original manuscripts", which were sent back eventually in 1707 to Copenhagen, according to Dreyer (1890, pp. 374-375), but the Bartholin copy remained in Paris (by an unfortunate error, according to Dreyer, X, MS). Dreyer's remarks suggest a strange policy of letting both the originals and the copied logbooks go to Paris, leaving none of Tycho's observations in Denmark for decades. In fact, Bartholin's copy eventually made it to the Paris Observatory. In 1696, the original manuscripts had been in the possession of Philip de La Hire, Picard's successor. From thence, Joseph-Nicolas

Delisle, or de l'Isle, (1688-1768) acquired apparently the Bartholin copy and made a complete copy of all the observations ("translated into French, but with frequent omissions", according to Dreyer), and this copy of seven volumes (Friis 1867, p. iv) was used extensively by Pingré (1783, pp. 517, 554, 554, 557) for his *Cométographie*.[84] The entry in the manuscripts bibliography of the Paris Observatory (Bigourdan 1895, p. F24) suggests that Pingré may have used Bartholin's copy, as well, though Pingré himself states (p. 517):

> *Feu M. Delisle l'Astronome, m'a communiqué un manuscrit précieux; il fait partie de la bibliothéque qu'il a cédée au Roi, pour être conservée au Dépôt de la Marine. Ce manuscrit contient un grand nombre d'observations de Tycho, entre autres celles des Comètes auxquelles il a eu part, soit directement, soit indirectement.*

Delisle met Halley on a trip to England (Cook 1998, p. 125), and though this presumably occurred after Halley published his catalogue of cometary orbits in 1705, the meeting probably did not occur before Delisle knew of Tycho's observation logbooks residing in Paris. The two must have talked comets, and probably discussed the logbooks; if this meeting occurred in 1706 or 1722,[85] it would help to explain the sudden flurry by Halley, Flamsteed, and Newton to get Tycho's full set of observations.

Other requests were made outside of Denmark to obtain Tycho's observations for publication, including from Amsterdam (apparently around 1600; Dreyer, X, MS); and from London. John Arbuthnott evidently inquired to the Danish government about Tycho's observations on behalf of Isaac Newton; on 1706 July 30, Arbuthnott wrote to Newton:

> *His Royal Highness ordered his Secretary to write about the observations of Tycho Brahe if ther was any thing remaining that was not yet published: I have sent you, by his Royal Highnesses order, a copie of the Answer which you may communicate to those concerned and to Mr Hally. The prince likewise orderd me to tell you that he will use his interest to procure the said observations and will publish what shall be thought fitt for publick use, so I would have you to consult how to proceed in the matter: it is likely by these observations having been sent into France that they contain at least some things not published for Mr Romer who sent them could not but know what the importance of them was. my opinion is that we should draw up a letter to Mr Romer giving*

[84] Though I did not see the copied manuscript at the Bibliotheque during my June 2004 visit to Observatoire de Paris, I am informed by the librarian there that the 147-page manuscript is 33 cm × 21 cm in size and listed under shelfmark B 4-20. The first part concerns general observations spanning 1596-1601, and the second part contains the "Observationes cometarum". It has been microfilmed.

[85] — this because of the letters written by Flamsteed in 1706 and Halley in 1722, discussed below —

> *him an account of the substance of Mr Flamsteds observations that we are now publishing which will be obliging, and at the same time desire the favour of him that he would give us an abstract of what those eight Volumes of observations contain, or perhaps it may be allwayes worth the while to have those eight Volumes wrote by Tychos own hand in our Custody . . .*[86]

This indicates that the English now knew about the French possession of some Tycho observations, probably via correspondence with Ole Römer, and it suggests that Halley was privy to the ongoing discussions (see also Cook 1998, p. 385). The following January, the referees of Flamsteed's star catalogue (including Isaac Newton) wrote to Roemer:

> *. . . & hearing that Tychos Observations were left in the K. of Denmarks Library written in Tycho's own hand, [His Highness] is desirous that those Observations or as many of them as may be of use in Astronomy & come abroad with Mr Flamsteed's. And therefore we desire the favour of you to let us know what books of Observations Tycho has left in MS & what are their contents & how many years they reach & in what method they are written and what your judgment is about printing them or any part of them.*[87]

But according to Dreyer (X, MS), "nothing further came of it".

Meanwhile, John Flamsteed had additionally noticed that there were no comets in Curtz's *Historia coelestis*, despite the fact that Tycho had noted his observations of seven comets in *Mechanica* (Ræder *et al.* 1946, p. 109). Shortly after Halley's *Synopsis of the Astronomy of Comets* was first published, Flamsteed wrote to Isaac Newton on 1706 September 14:

> *"I have consulted Tycho's Mechanica, where he says at that time, when he wrote it, . . . that his volumes contained the accurate observations of 21 years; which shews they commenced in the year 1575. . . . But the Observations of the Historia Coelestis begin no sooner than the year 1582; so that, by this account, there are 7 years' observations wanting in the very beginning.*
>
> *Besides all the observations of the year 1593, which were not to be found in Germany, in the same place he says he had observed seven comets; whereas, in the Historia Coelestis, there are no observations that I can find either of that of the year 1582* [sic] *or 1590, of which he gives an account in his Epistles. The first part of his Progymnasmata gives his tables for calculating the ⊙'s and moon's places, with*

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[86] via Scott 1967, p. 475.

[87] via Scott 1967, p. 481.

his observations of the new star of 1572, and deductions from them. The second part is concerning the comet of 1577; so that we have the observations of but 3 of his 7 comets: and of those, only such as he thought fit to employ. This makes me think that his observations of the comets is made a book by themselves, and that probably it is still to be found in Denmark, with the 7 or 8 years' observations that are missing.[88]

This may have further spurred the referees' attempts to have something done about Tycho's unpublished observations.

Meanwhile, Halley evidently had had access to only those comet observations of Tycho's that appeared in books published during Tycho's lifetime (see section on Newton and Halley's orbit computations, below). For example, Halley (1752, p. O2) mentions only Maestlin as the observer of the comet of 1596. Halley's personal library seems to have included Lubienietz's large and lushly illustrated 1666 work on comets titled *Historia cometarum*; Tycho's *Progymnasmata* and *Epistolarum astronomicarum*; and books on comets by Snell (1619) and Hevelius.[89] But, of course, Lubienietz and Hevelius had no apparent knowledge to Tycho's comets data for 1580, 1582, 1593, or 1596 (as noted above).

Years later, on 1722 November 7, Halley appears to have been again interested in doing something with comet observations, as he wrote to Hans Sloane (noting that he had previously borrowed Maestlin's book from Sloane):

> *I must entreat you to putt into your Coach to morrow Michael Mæstlin's Observations of the Comet of 1580, which I want to compare with Tycho Brahe's Observations of the same, which were putt the other day into my hands by the Society.*[90]

In the biography of Newton by Richard Westfall (1980, p. 830), it reads that "In 1722, [Newton] presented to the society a manuscript by Tycho Brahe with unpublished observations of four comets and, as president, ordered that they be printed"; they apparently never were printed.[91] An inquiry to the Royal Society has produced a manuscript known as MS 57 (R. Baker 1999, private communication). Listed in the Royal Society archive catalogue as *A volume of astronomical observations by Tycho Brahe, J. de Herrera y Sotomayor, and P. B. Suarez*, there appear to be

[88] Baily 1835, p. 261; this letter also appears in Scott 1967, pp. 476-477.

[89] Shortly after Halley died, his library of books were put up for sale, and the catalogue of the sale is still available (Feisenberger 1975). However, Halley's books were mixed with those of another anonymous book collector for that sale, and one can only make a reasonable assumption that many (if not most) of the astronomy books were Halley's (see also Cook 1998, p. 447).

[90] MacPike 1932, p. 131.

[91] Reference is made by Westfall to "Journal Book (Copy) of the Royal Society" **12**, 271. Halley biographer Alan Cook was unaware of any such manuscript associated with Halley.

observations by Tycho for only three comets. Pages 1-9 contain "Tychonis Brahe Observationes Cometae 1585", pages 10-17 include "Tychonis Brahe Observationes Cometae 1590", and pages 18-22 contain "Tychónis Brahe Observationes Cometae 1596" (pages 23-49 contain observations by de Herrera and Suarez). Pages 1, 10, and 18 each bear the inscription "*Presented by Sir Isaac Newton Knt, Pr.R.S. Oct. 25 1722*". Evidently the manuscript made its way back to the Royal Society after Halley looked at it. Westfall may have simply been mistaken in writing "four comets" instead of three. The sudden appearance of this manuscript is puzzling, and not mentioned by Dreyer.

During my visit to the Austrian National Library in Vienna, I viewed a manuscript containing extensive Hven observations of the 1590 comet (Cod. 10689.2), and another manuscript containing observations of the 1585 comet (Cod. 10689.31)[92]

8.2. Content of Tycho's Comet-Observation Logbooks

Now let us look at the original Hven logbooks. Dreyer (X, MS, pp. 28*ff*) specifies that codices *N*, *O*, and *P* are manuscripts of Tycho's comet observations located at Copenhagen. 'Codex N' is a quarto volume containing 197 leaves that begins with a title page written by Tycho himself. This manuscript contains the original observations in Tycho's hand of the comet of 1577; Dreyer notes that "Friis [1867] has evidently not used this volume for this comet, as the placing of the words is sometimes quite different. The pages at the end which he could not read is easy enough [in this particular copy]". 'Codex N' also contains the original observations in Tycho's hand for the comet of 1580 (with a few by Paul Wittich). Those observations of the 1582 comet are stated as being "probably a fair copy", and those of 1585 are "partly original observations, partly a copy" (the copied 1585 data were evidently transcribed from 'Codex C'). The 1590 and 1596 comets' observations in 'Codex N' were copied from 'Codex O', but *N* contains the original observations of the comet of 1593, being "no doubt the identical report given to T. by the observer" (Dreyer, X, MS, p. 30). Those 1593 observations were made by "Christen Hansen, from Ribe in Jutland, who at that time was staying at Zerbst in Anhalt" (Dreyer 1890, p. 162); his Latin name was "Ripensis". 'Codex O' contains the original observations of the comets of 1590 and 1596. 'Codex P' is a copy of all the comet observations.

[92] The library catalogue lists two additional Hven manuscripts of comets that I did not view: items 10689.30 and 10689.18 (Royal Academy of Vienna 1871, p. 227).

Figure 8.1. Dan Green looking over the comet-observation manuscript logbooks of Tycho Brahe in the Royal Library, Copenhagen (August 2002).

In 2002, I visited the Royal Library at Copenhagen for three days to view Tycho's manuscript observing logbooks for the comets that he and his assistants observed (see Figure 8.1). A notebook entitled "Komet-observationer 1577-96"[93] is a collection of comet observations that is 'Codex N' of Dreyer (1923, p. xxii). The first leaf says, in dark-black ink, "OBSERVATIONES COMETARVM Apparenti Annis A CHRISTO 1577 1580 1582 1585 1596" (Figure 8.2), but the comets of 1590 and 1593 are also here. The first observations in this volume are of 1577 comet, in Latin — ending with 1578 Jan. 26 on p. 30(a). The geometrical diagram on folios 32(b)-33(a) and 34(b)-36(a) include the comet in an orbit like that of Venus about the sun (this diagram does not appear in Dreyer's *Opera Omnia*). These sketches are in the same reddish-brown ink that were used for Tycho's corrections over the 1577 comet notes. Folio 38(a) has the title "Obserûationes Cometae Annj 1580 . . . Octobrj", and this section starts with "Anno 1580 die 10 Octobris hora 7 post Meridiem . . ." on p. 39(a), including a diagram at the bottom with a fish (Piscis Australis) and stars numbered 1-9 with a tailed "cometa" just below the fish's head (reproduced on p. 305 of Dreyer 1926).

On folio 80 starts a new section entitled "OBSERVATIONES COMETAE cûi apparûit Mense Maio Anni 1582.". While the 1577 and 1580 data are evidently in Tycho's own hand (along with the introduction to 1582 data), the subsequent pages, starting "Die 12 Maij" on leaf 81(a) are very neat Latin handwriting belonging to somebody else (evidently one of his assistants). On page 87(a) starts a section on the comet of "Anno 1585", and near bottom of the following page appears "Obseruationes huîs Cometae", starting with "Die 18 Octobris Adelboram Distabat a Meridiano Versus Ortum. 56o11' . . ." (this hand is also neat, but is perhaps different than that for the 1582 entries. As for the 1582 entries, the 1585 entries have what appear to be corrections and notations to the data in Tycho's hand. Dreyer's *Opera Omnia* (**13**, 287ff) contains the comet observations under the title "Obseruationes Septem Cometarum", and on page 293, the parenthetical "corrections" that Dreyer puts after the comet-star distance measures are seen in light-brown ink in 'Codex N', in between the "original" black-ink handwriting [folio 10(b) for Nov. 25, f. 11(b) and 12(a) for Nov. 29, leaf 13(a-b) for for Nov. 30, etc.]. For the 1590 comet, curiously Dreyer uses some other text (besides Tycho's handwritten form in 'Codex N') for the bottom of page 373; the Feb. 23 observation is from Vienna 'Codex E', but most/much of rest seems to be from 'Codex N'.

[93] This is the title on the outside spine of a volume with shelfmark Gl. Kgl. Saml. 1826, 4°, stored in a special box. The weak papers have been backed onto heavier paper, and each leaf is numbered in pencil (by a librarian?) in the upper-right corner of the right-side pages.

Figure 8.2. Title page to 'Codex N' (in Tycho's own hand). [Courtesy of Det Kongelige Bibliotek, Copenhagen.]

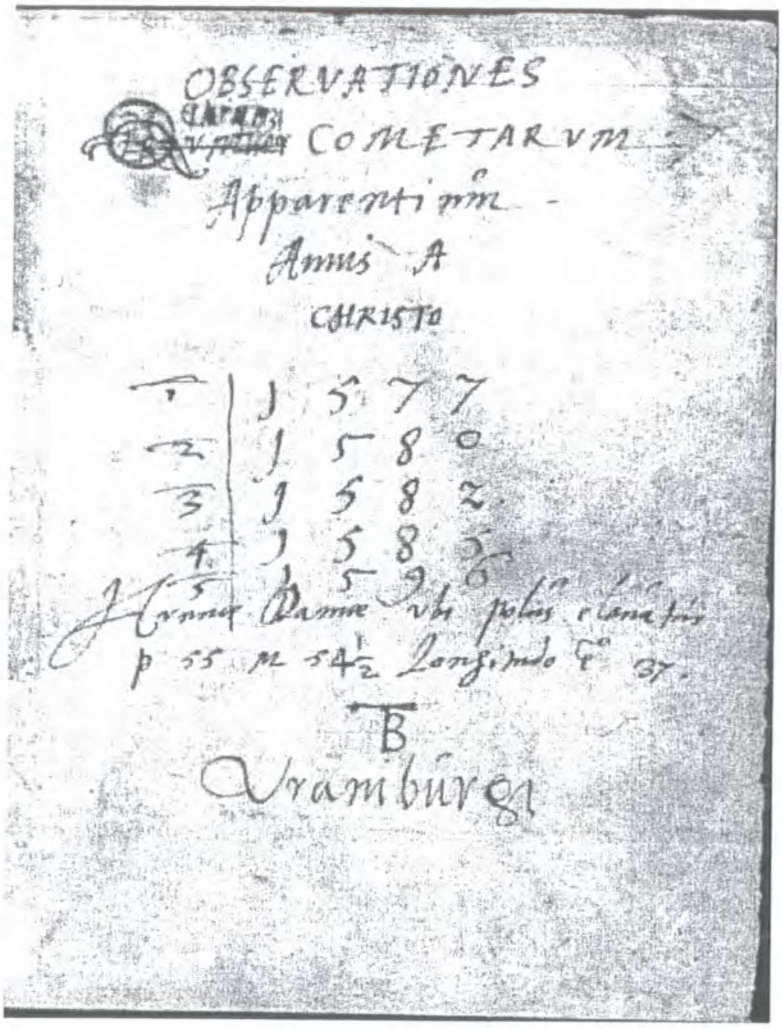


Figure 8.3. Folio 5 of 'Codex N', showing Tycho's handwritten observations of the comet on 1577 Nov. 15. Notice the drawing of the comet at bottom. [Courtesy of Det Kongelige Bibliotek, Copenhagen.]

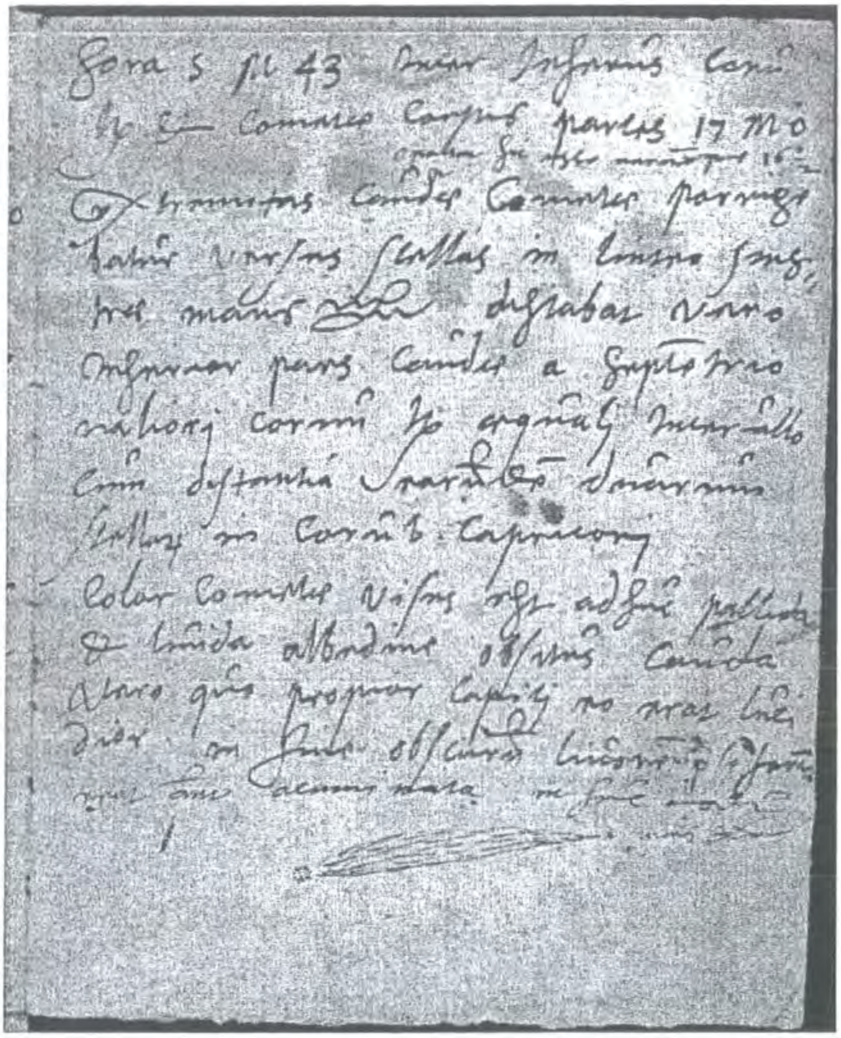
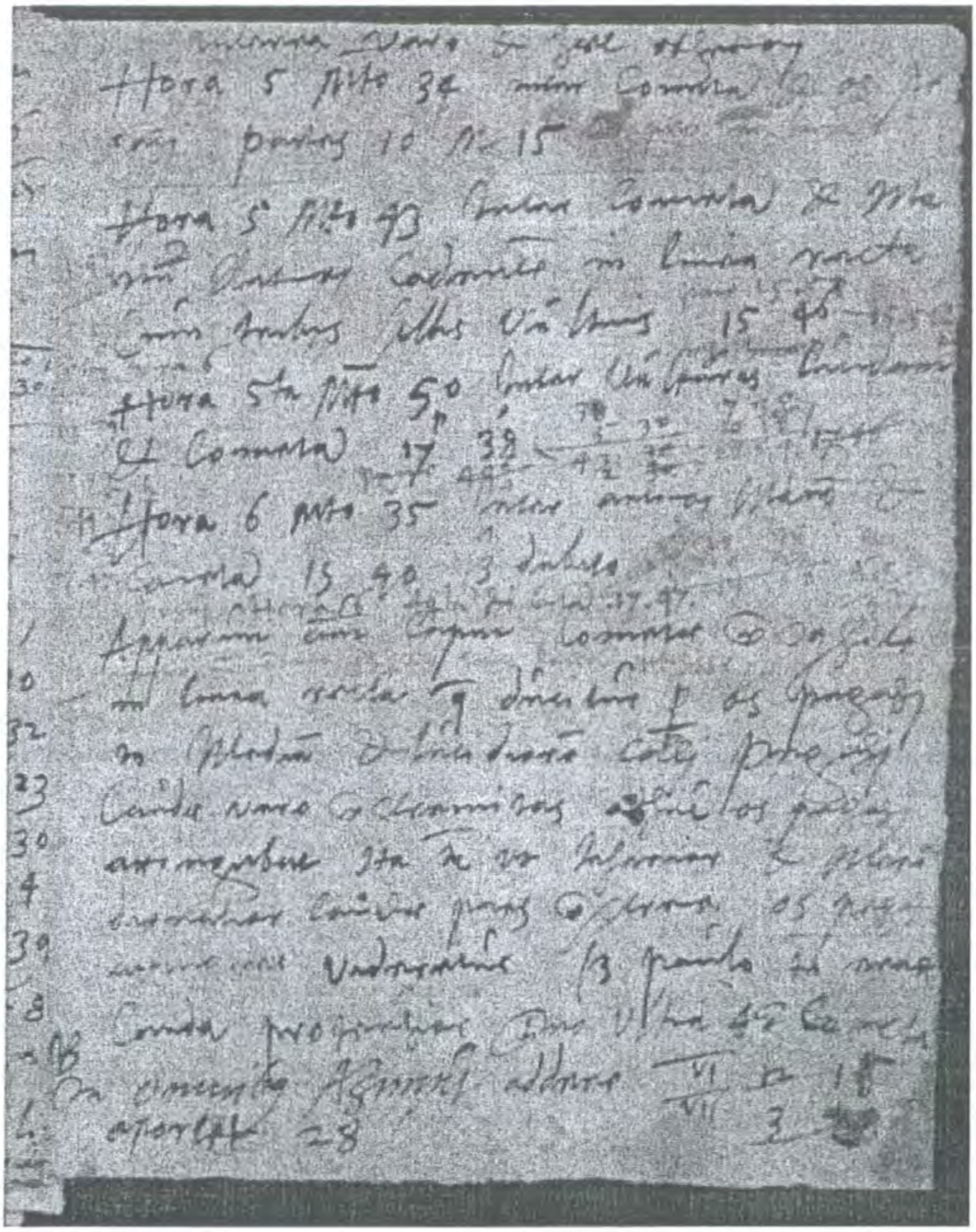


Figure 8.4. Folio 13 of 'Codex N', showing Tycho's handwritten notes for his observation of the 1577 comet on Nov. 30, with his later annotated corrections in lighter ink. [Courtesy of Det Kongelige Bibliotek, Copenhagen.]



Some other entire pages (folios 95-101, 118-119, 138ff, 146b) on the 1585 comet appear also to be in Tycho's hand; folios 120 to 137 are some reductions of the observations in the neater hand. As folio 138(b) has observations by "Christophorus Rothmannus" for Oct. 8 and 9 (longitudes and latitudes) in the same neat hand, perhaps Rothmann is at least one of the copiers here. On folio 149(b) begins a new section titled "Obseruationes Cometae Anni 1590" in a fairly neat hand, starting with a table on p. 150b (not original observations for Feb. 23, 24, 25, 26, 28, Mar. 1, and 2) and with a comet sketch on folio 154a depicting possibly both dust and gas tails (not in the *Opera Omnia*[94]). It is possible that the 1590 observations were penned by Hans Crol, who knew Latin and frequently maintained the observational journals at Hven during 1586-1590 (Christianson 2000, p. 270).

Folio 176a begins a new section with "Observatio Cometae Anni 1593 Mense Julioi Die 22 . . .", with entries to Aug. 24 on f. 177b; crude drawings on page 177 show the comet with a short tail on Aug. 13, but no tail on Aug. 21 and 22 (maybe intended to be slightly elongated on Aug. 21?). Tables on the 1580 comet then follow on folios 178(b)-189(b), starting with neat tables of comet-star distances with the instrument specified ("Rad.", "Sex"), and the last column has the label "correct", with about half of the measures being changed by about 1′-4′ from the "measured" columns. Listings of celestial longitudes and latitudes start on folio 184. Folio 192(a) begins a new section titled "Observationes Cometae Anno 1596 Mense Julio Apparentis", with the following page showing the comet with a tail moving below the Big Dipper on July 14; likewise are diagrams on following pages for July 16 and 21, with observations in between the drawings (copies, not original written observations at the telescope — so the drawings may also be copies?). Folio 21(b) has a positional sketch of the comet with a weak tail against background stars for 1577 Dec. 23.

'Codex O' of Dreyer (1923, p. xxiii) is another volume that begins with "Anno 1590 Die 23 Februarii . . ." on the first page.[95] This is not in Tycho's hand (it is fairly neat handwriting), but certainly these are the comet observations from Tycho's observatory; again there are evidently some notes penned by Tycho in the margins. Some clock corrections are noted, as at the top of page 7 for Feb. 26. A comet-tail sketch (as point A in a triangle ABC) is just like that at fol. 154(a) of 'Codex N' (this is a similar copy of that set of data and tables and notes on the 1590 comet). Tables on pages 8, 10, and 11-27 (Mar. 6) appear to be a mix of Tycho's handwriting and that of others. Page 29 starts a section titled "Observationes Cometae mense julio Ao 1596 apparuites", and page 31 has again the sketch of the comet below UMa (showing that at least some sketches were apparently copied when textual and tabulated observations were copied into new books).

'Codex P' of Dreyer is in a third volume in the Royal Library, with "T. Brahe Observationes

[94] Dreyer included a 'Codex O' sketch version with only one tail in his *Opera Omnia*, perhaps because the 'Codex N' sketch blends into the text above the tail.

[95] Royal Library shelfmark G.K.S. 315, 2° on spine of book box, but Gl. kgl. S. 315 on spine of book. This is a bigger (ledger-sized-paper) book than that for 'Codex N'.

1577-96" on the book's spine.[96] The first page begins with "OBSERUATIONES COMETARUM 7 Apparentiuṁ Annis a CHRISTO 1577 1580 1582 1585 1590 1593 1596", and this black/dark-brown ink is obviously in Tycho's hand. On the second page is a table to correct sighting parallax errors with the use of his sextant. Folio 2(a) starts a section titled "Observatio Cometa quem pri mum conspexi Huenae, Anno 1577 Novembris die 13.", and this appears to be a neat-handwritten copy of 'Codex N' (the latter possibly being an original writing as the comet was being observed). 'Codex P' has Tycho's corrections put neatly into the text after the original figures and data. 'Codex P' has drawings also, but they're inexact copies (though attempts were made at exactness) of what's in 'Codex N' (and in Dreyer 1926); for example, the 1577 Nov. 13 drawing is on the bottom of folio 2(a) of 'Codex P', and page 3(b) has the Nov. 15 drawing. The 1577 Dec. 23 drawing of the comet appears neater in 'Codex P' than in 'Codex N', as does the copy of the "comet-around-sun in epicyles" diagram on fol. 21(b) that appears on fol. 36(a) of 'Codex N'. This same folio in 'Codex P', which is at the end of the section on the 1577 comet observations, contains discussion regarding Regiomontanus that is also in Tycho's handwriting (so the diagram is likely to be in his hand also). On folio 22(a) of 'Codex P' begins a section titled "OBSERUATIONES Cometa Anni 1580 Mense Octobri", with a new copy of the fish drawing for Oct. 10 on fol. 23(a) and a comet drawing for Oct. 11 on fol. 25(a). These sketch copies all indicate the importance that was deemed by Tycho for including the drawings from the originals: he obviously felt that there was something to be added to the textual data through this imagery, and this general thinking about including such images was indeed becoming important to astronomers in this era.

Tycho's logbook[97] shows that he observed the comet on 34 evenings from 1577 November 13 to 1578 January 26, of which it appears that 27 nights have measurements that may be of some use in computing an orbit for the comet. Tycho actually provides 24 sets of celestial longitudes and latitudes in Chapter 3 of his *De mundi*, and Alexandre Pingré (1783, pp. 513*ff*) copied these same 24 positions; in fact, Pingré's publication of these observations appears to be the only other printing of Tycho's observations of the 1577 comet prior to the nineteenth century. The final observation by Tycho on January 26, which was weeks after the last known other observer saw the fading comet, appears to be so badly measured (evidently due to the comet's faintness, which Tycho remarked on) as to be unusable in any orbit determination, having a residual of over 1° — though Woldstedt evidently used it in his 1844 work. (In fact, the errors of Tycho's star positions nearly doubled for faint stars when compared to those of bright stars; cf. Thoren 1990, p. 297.)

Tycho's logbooks do contain typographical errors, including various numbers involving the time of observation and measurement of the comet's position. The majority of his positional measures involve distances of the comet from a specified star, obtained with his astronomical radius and sextant. At the end of his lengthy treatise on the comet of 1577, he provides diagrams of the quadrant and steel sextant used for observing the comet. Tycho did not trust the measures

[96] The shelfmark on the book's spine reads Gl. Kgl. Saml. 1827, 4°. This volume is about 5.5 × 5.5 inches frontal, and about 1.5 inches thick. 'Codex N' is about the same size, except about 2 inches thick.

[97] Friis 1867, 1-18; Dreyer, XIII, 288-304

obtained with his *radius astronomicus*; though he says that his radius "in every respect give[s] better results than [Gemma Frisius'] radius", "no matter how this radius is constructed it cannot . . . give stellar distances precisely in accordance with reality, not even the smaller distances up to 15 degrees" (Ræder *et al.* 1946, p. 97). It seems that Tycho included mainly his steel sextant measures in his formal write-up in *De mundi*. Note that it is not obvious in most cases, regarding the comet of 1577, as to which instrument Tycho was using (sextant *vs.* radius).

The positions in *De mundi* often differ from the actual values written in the logbook, by amounts (on the order of $\leq 5'$) that were generally within the level of Tycho's absolute measuring precision. The applying of corrections by Tycho to his observations has been mentioned by Dreyer (1890, p. 40) and by Thoren (1990, p. 308). Dreyer (X, MS, p. 3) also remarked that "Tycho in his printed book does not quote *all* the observations which he made of this comet, while he sometimes applies corrections to the observed distances, of which we shall here point out only the larger ones." Dreyer adds: "How these corrections were found, Tycho does not explain, and they do not seem to follow any law." Galileo evidently suspected that Tycho had "fudged" some of his observational data, for he remarks in "The Assayer", regarding parallax in the comet of 1577:

> *If the observations were incorrect, then they lack authority and nothing whatever can be determined from them. Tycho himself, among so many disparities, chose those observations which best served his predetermined decision to assign the comet a place between the sun and Venus, as if these were the more reliable.*[98]

But it should be noted that Galileo subscribed to the Aristotelian view of comets, placing comets in the earth's atmosphere.

There are also occasional altitude and azimuth measures with his medium-sized azimuth brass quadrant, which Tycho claimed "was good enough, however, since by its aid it was possible to distinguish sufficiently between the minutes of arc both of altitude and of azimuth" (Ræder *et al.* 1946, p. 19).

8.3. Comet of 1577: Published Observations (Tycho and Others)

Being such a bright comet, many European observers published records of the comet of 1577 in the years immediately following its appearance (Hellman 1944; de La Lande 1970; Grassi 1989). The observations, however, had a wide variation of quality — there being no standards for data acquisition, though many knew of the works by Regiomontanus and Gemma Frisius. Tycho was interested in collecting observations of the comet of 1577 from observers throughout Europe, to look for parallax. Such collecting was a new venture in astronomy for natural philosophers of the early-modern era — being quite different from the more casual efforts inherent in the descriptive comet catalogues mentioned earlier. Of course, Ptolemy had worked to collect observations from

[98] Drake and O'Malley 1960, p. 258.

sites throughout the known world when he worked on his planetary theory as laid out in the *Almagest*, but the concept of archiving data from many locations and then analyzing them seems to have been largely lost in medieval Europe.

Though Tycho wrote a short treatise on the comet of 1577 within a year (Christianson 1979), he waited another ten years to publish the details of his observations, during which time he collected observations and tracts published by others in Europe — allowing him to assess the mass of observations as a whole to draw more concrete conclusions. (Kepler may have partly learned the potential significance of large quantities of observational data from knowing Tycho's and Maestlin's efforts with the comet of 1577.) Several of the better-known astronomers ultimately served as "centers to which information was sent and whence issued criticism, sometimes constructive" (Hellman 1944, p. 118). Numerous observers of the comet of 1577 thus formed an informal group or "society" for discussing matters pertaining to the comet, via published tracts and unpublished letters. Tycho and Maestlin were the foremost of these, but other notable contributors were Hagecius, Cornelius Gemma, the Landgrave of Hesse at Cassel, Helisaeus Roeslin, Scultetus, Nolthius, Johannes Praetorius, and Chytraeus (Hellman 1944; Thorndike 1941b, pp. 79*ff*). Some of these observers, like Maestlin and Tycho, held comets to be supralunar; others adhered to the sublunar concept. Hagecius, through diligent assessment of the data and subsequent discussion with other observers, initially concluded that the comet of 1577 was sublunar, but later was convinced by Tycho and others to embrace the supralunar placement of the comet. So a form of peer review was being formulated as a result of the assessments of the observations of the 1572 supernova and the 1577 comet that would evolve and mature in the coming century, leading to the formation of the first formal national scientific societies.

The four most serious observers of the comet of 1577 could arguably be given as Cornelius Gemma, Tycho Brahe, Michael Maestlin, and Wilhelm, the Landgrave of Hesse at Cassel. The reasons are visible in the published data: the first three published their own tracts on the comet, while we have Wilhelm's data provided by Tycho in *De mundi*. The seriousness that these observers show is reflected in the pains that they took to measure the comet's position on the sky from night to night and in the relatively novel emphases on observational data over astrological interpretation.

There were three basic types of observation that astronomers employed to record the position of the comet of 1577: (1) measures of the comet's distance from various reference stars (using an astronomical radius, cross-staff, or sextant);[99] (2) noting that the comet was in a straight line, or nearly so, with two reference stars (using a straight-edged instrument or a simple string); and (3) measures of the comet's azimuth and/or altitude with respect to the local horizon (using a quadrant). The development of the astronomical telescope by Galileo and others was still more than three decades in the future, so the results are limited to the resolution of the naked eye and to the imperfections of the available instruments, star catalogues, and methods employed

[99] Descriptions of these instruments can be found, for example, in Ræder *et al.* 1946; Haasbroek 1968, p. 23; Pedersen 1976; Thoren 1990; Chapman 1990, p. 24.

by each observer. Method (3), in which the comet's angular distances above and around the horizon are measured, involves the most problems simply because it is the method that is most dependent upon clock time; clocks of that era were generally minutes in error under even the best circumstances, and this corresponds to much error in converting to any sort of celestial-coordinate system. Given the inherent imprecision in the other two methods, their uncertainties are much more dependent upon astrometric measurement errors than upon time errors.

The 1578 January 26 observation of the comet by Tycho is also interesting because all other observers had lost sight of the comet by the first or second week in January (except Gemma, who saw it on Jan. 18), including Maestlin, who evidently had quite good eyesight himself (he made a drawing that shows eleven stars in the Pleiades down to sixth magnitude in 1579; cf. Jarrell 1971, p. 91). Maestlin observed the 1577 comet from Backnang (near Stuttgart), where he held a brief position as assistant pastor of the Lutheran church there. He made positional measurements, as we have noted, by using a thread held to the sky for aligning two sets of stars with the comet, and Maestlin claimed that his method of astrometry was superior to the quadrant/sextant measurements of other observers. Thus deriving the comet's position through trigonometric reduction from Copernicus' catalogue of approximate star positions (Copernicus 1543, pp. 46-63), he produced longitudes and latitudes for the comet from night to night. But Tycho knew (and stated) that the Copernican/Ptolemaic star positions were extremely poor, and that poor results were likely come out of any attempted use of them; Tycho did attempt to remedy this problem himself with the better observations, by providing his new measures of comparison stars for the observations by Hagecius and Maestlin (Dreyer, IV, 217, 264). Maestlin also knew of many problems in Copernicus' star catalogue, but it was the only such catalogue available for practical use in 1578.

Thaddaeus Hagecius of Prague was an eager observer of the 1577 comet, and he published not only a 1578 treatise on it but also a 36-page book in 1580 that discusses his debating correspondence with other observers. Hagecius made fourteen comet/star-distance measures from November 16 to January 3 that I reduced for the orbital calculations presented in section IX of this chapter. Though some of his measures seem as good as those by Gemma and Tycho, Hagecius seems to not have been quite as careful in making his measurements, and his reference star descriptions sometimes make unambiguous identifications very difficult (if not impossible).

Gemma's 75-page treatise on the comet, published at Antwerp in 1578, is perhaps second in length only to Tycho's 1588 *De mundi*. Gemma's Chapter 2, containing his numerous observations covering more nights than any other observer except Tycho, constitutes a full quarter of his book. The observations themselves appear in Gemma's second chapter (pages 22-32), and span November 14-January 18 (Gemma noting the comet being quite faint and difficult to see towards the end). Tycho provides Gemma's observations in several pages of his *De mundi* (Dreyer, IV, 238-248), but he does not include all of Gemma's data (which is typical of Tycho's noncomprehensive presentation of his contemporaries' data). Gemma obtained measurements of the comet with respect to stars on 23 nights, and he obtained the last known quantitative comet-star distance

measures on January 14 (two nights later than Tycho's final such measures). These observations attest to Gemma's good eyes and his persistence in obtaining what he hoped were useful data, and the influence of his father's work (*e.g.*, Gemma Frisius 1545) is obvious in his own celestial astrometry work. As displayed in section IX of this chapter, many of Gemma's data are comparable to those of Tycho in their precision.

Tycho made extensive notes about observing conditions, as clouds and moonlight were frequently a factor. Also included in his logbook are notes about setting the clock and the faintness of the comet, and descriptions of the position of the tail are also frequently provided. A rough sketch of the comet from his logbook is shown in Figure 6 (taken from Christianson 1979). Tycho was aware that many things contribute to obtaining qualitative observational data, and this distinguished his work from those of his predecessors. Gemma also noted when clouds interfered, and he listed the nights that the weather made observing impossible.

In Maestlin's 1578 treatise on the comet of 1577, he details his positional observations in chapter 6 (pages 28-34). He derived celestial longitudes and latitudes for the comet on eight nights (Nov. 12-Jan. 8), but his methods for determining the position are anything but standard and are even bizarre at times. Maestlin's intention was clearly to find two sets of star pairs whose connected lines intersected at the comet. In practice, as I have shown above, this is very difficult to do, and he was only able to do so on three or four nights. His other measurements are not always clear in terms of what he was trying to do, unfortunately. Maestlin's attention to astrometric detail is also apparent in his cluttered star map showing the comet's path on the title page of his 1578 treatise (see Figure 5). Maestlin used a weight-driven clock for his observations in 1577; Jarrell (1971) states that while "the accuracy of his clock is impossible to assess, . . . [Maestlin] seems to have been pleased enough with it as it was employed for a great number of observations after 1577, particularly for eclipses". Maestlin's observations get extensive exposure in Tycho's *De mundi* (Dreyer, IV, 207-238), where Tycho also examines Maestlin's orbit for the comet (which happens to be similar to what Tycho derived). The very lengthy tenth chapter of *De mundi* details all of the observations of the 1577 comet that were collected (and assessed) by Tycho.

Cornelius Gemma included positional data on the comet in his treatise of 1578, which also contains nice diagrams showing the appearance of the comet's tail and the progression of the comet over time against the background of the constellations. The observations themselves appear in Gemma's second chapter (pages 22-32), and span November 14-January 18 (Gemma noting the comet being quite faint and difficult to see towards the end). Tycho provides Gemma's observations in several pages of his *De mundi* (Dreyer, IV, 238-248). Gemma obtained measurements of the comet with respect to stars on well over a dozen nights; on numerous evenings, he measured the distances of the comet from two separate stars, though for some observations he provides only a longitude and/or latitude with no raw data.

Simon Grynaeus (1580) wrote a Latin tract that included some fifteen of his observations of the comet of 1577 made from Heidelberg, commencing with a sighting on November 14. Grynaeus

does not give distances from the comet to specific stars, but he does state numerous examples of the comet being on a straight line with two other specified stars, and he gives frequent altitude and longitude measures (pp. 76-81). He may actually have provided more useful data (for a new orbital analysis today) than did Maestlin on this comet, but Tycho relegated mention of Grynaeus to little more than a page in his *De mundi* (Dreyer, IV, 359), providing virtually no observational data — likely because of Grynaeus' sublunar and astrological views of comets.

Also in the tenth chapter of *De mundi*, we find Wilhelm's extended positional data on the comet of 1577, which are problematical because they consist entirely of altitudes and azimuths. One would like the accuracy of his clocks to be no worse than 10-20 seconds to derive celestial coordinates from altitude/azimuth ('altaz') measures for the comet — corresponding to something like the accuracy of Tycho's measurements — and this cannot have been possible. However, Wilhelm's altaz positions yield surprisingly good residuals for the comet's celestial position via the contemporary derived ecliptic coordinates, as shown below in section 8.4.

As noted previously, many tracts were published on the 1577 comet, a good number of them already mentioned in section 3.5 of this thesis. Hellman (1944, 1971) lists well over a hundred titles in her doctoral bibliography on this comet, many of which she never saw herself but extracted from bibliographies. I have actually seen more than 80 different European comet tracts published within a couple of years of the comet's appearance in late 1577. This number includes at least eight tracts that were missed by Hellman: printed books or pamphlets by Anonymous (1578), Roch le Baillyf (1577), David de Mauden (1578),[100] Giovanni Ferrerio (1577), Hector Mithobius (1578), Pachymerius (1577), Johann Padvani (1578), and Gaspare Torella Valentino (1578) — most of which emphasize astrological discussion, with little observational material on the 1577 comet. The 8-page French pamphlet by de Mauden and the 19-page German tract by Mithobius both say that the comet was first seen at 6 p.m. on 1577 Nov. 11. Mithobius added some comments about the comet's visibility over time with respect to the phase of the moon. Leonhard Thurneysser (1577?) gave some very extensive observational descriptions of the 1577 comet from Oct. 19 to Dec. 16 in a sort of running diary, in which he described weather conditions even on days when he couldn't see the comet due to clouds — but he gave no real positional measurements beyond noting the comet's location between various stars on a given night.

8.4. Analyzing the Astrometric Observations of the 1577 Comet

It appears that, prior to my work presented in this thesis, no attempt has been made in the past 150 years to recompute the orbit of comet C/1577 V1 from the available observations. At first glance, it is surprising that nobody else had bothered to re-analyze the observations of this comet following the first full printing of the logbook observations by Friis in 1867 (and later again by Dreyer in 1926). But having re-analyzed them myself, I would now venture to say that the immense amount of labor involved in reducing the observations, along with the obvious respect

[100] translated from Flemish into French by Estienne de Walcour

for what Woldstedt had done,[101] kept others from undertaking this difficult project.[102] Having access to the observations of observers other than Tycho means making the effort to seek the rare treatises that exist in only a few libraries in Europe and the United States, and even Tycho's observations of his comets are in publications that are not easily available to most astronomers. Once a researcher gains access to the relevant literature, there is the daunting task of wading through the contemporary Latin texts, trying to determine what stars were being referred to (which in many cases involved highly ambiguous descriptions that defy interpretation, as we have seen), and then trying to assess how to reduce the data properly into a form that can be used with today's astronomical reference system and standard procedures of astrometric analysis for solar-system objects. In dealing with the astrometry of the comet of 1577, I evaluated such issues as refraction, proper motion of the reference stars, and various problems involving time (including local time *vs.* Universal Time, including the correction in four centuries for the earth's slowing rotation rate, and the equation-of-time correction).

There have been only two serious studies of the orbit of the comet of 1577 following the release of Newton's *Principia* — that by Halley (1752) and that by Frederik W. Woldstedt in the form of a 1844 doctoral dissertation at Helsinki under the title *De gradu praecisionis positionum cometae anni 1577 a celeberrimo Tychone Brahe per distantias a stellis fixis mensuratas determinatarum. . .*[103] The 1577 orbit represented only the sixth comet (chronologically) for which Halley could find sufficient observations to work with. Pingré computed orbits for numerous comets in the late eighteenth century for his two-volume history of comets, but interestingly he did not deem it urgent to usurp the calculations by Halley that were done some 80 years earlier; and further published work on the orbit thus did not occur for yet another 60 years. Both Halley and Woldstedt used only the observations by Tycho Brahe for their orbital calculations. Woldstedt actually re-reduced 80 comet-star distance measures by Tycho, and produced residuals that range from $0'.3$ to $20'.8$ (with a mean residual of $\sim 4'.3$).

I originally proceeded to extract Tycho's positional observations from the tabulation by Pingré, which are consistent with the ecliptic and equatorial coordinates in Chapters 3 and 4 of Tycho's 1588 work on the comet (Tycho's data are given in textual form, so Pingré's format is much easier to use). Of course, any celestial coordinates originally published by the contemporary observers

[101] In actuality, few people seem to have had access to Woldstedt's thesis over the years, although his chief results were published prominently by Friedrich Argelander (1846) in *Astronomisches Nachrichten* and widely cited in catalogues thereafter.

[102] The definitive comet-orbit collections of the past two centuries consistently list only the orbital elements by Halley and by Woldstedt for the comet of 1577 (cf. Pingré 1783; Olbers 1797; Olbers and Encke 1847; Carl 1864; Galle 1894; Marsden 1994).

[103] see Poggendorff 1863; Dreyer 1890, p. 357; Galle 1894, p. 8; Hellman 1944, p. 429. Woldstedt's results were apparently largely made known via Argelander's (1846) mention of his work, with a recitation of the actual orbital elements given in the *Astronomische Nachrichten.* The 15-page thesis contains many more details than were provided in the half-page summary by Argelander, but unfortunately, the complete thesis is rather rare.

utilized poor star-catalogue positions. Dreyer (1917) also notes that Tycho made frequent arithmetic slips in converting between coordinate systems. So a re-reduction must be done of all the observations, and ultimately this must include selection of modern-day star positions with 400 years' worth of proper motion applied, and generally an iterative computer solution to get the comet positions from the star/comet distances recorded by the observers.

All that one can do with equatorial coordinates alone is to precess them to equinox 2000.0, and with ecliptic coordinates to first convert them to equatorial coordinates; in the absence of distance data from reference stars, they cannot be re-reduced, and so in addition to any uncertainty from real distance measures, one must consider an additional unknown amount of error (which surely varied greatly from observer to observer) in deducing their celestial coordinates. Few observers gave equatorial coordinates; most who gave coordinates for the comet gave ecliptic celestial coordinates, and/or "altaz" topocentric coordinates. And it was most common to simply give ecliptic coordinates to the nearest degree; even careful observers such as Gemma and Hagecius, who gave comet-star distance measures to the arc minute, gave their reduced ecliptic coordinates only to the nearest degree. With the precision of the positions derived from comet-star distance measures being as good as one or two tenths of a degree, it makes no sense to concern ourselves with low-precision ecliptic coordinates. The rare example can be found with observers such as Tycho Brahe (1588) and Michael Maestlin (1578), who derived ecliptic coordinates (and, in the case of Brahe, also equatorial coordinates) for the comet of 1577. Tycho made occasional altitude and azimuth measures with his medium-sized azimuth brass quadrant, which he claimed "was good enough, however, since by its aid it was possible to distinguish sufficiently between the minutes of arc both of altitude and of azimuth" (Ræder *et al.* 1946, p. 19). Also, Wilhelm (the Landgrave of Hesse at Cassel, Germany), made a great many measures of the comet's altitudes and azimuths over twelve nights from Nov. 11 to Dec. 30, aided by clocks made by perhaps the greatest clockmaker of the era, Jost Bürgi, giving times to the minute and sometimes to the second. We can briefly look at their published coordinates by way of illustration.

A computer program was thus written to determine as accurately as possible the altitude and azimuth of the comet as a function of time, as seen from the island of Hven (formerly part of Denmark, now part of Sweden), from whence Tycho made his observations, and the program was then applied also to the data obtained by observers elsewhere. This program was modified for use in determining conversions to Universal Time (UT), for use in our standard orbital-calculation programs, and in determining the altitudes of observed objects (comets, reference stars) for observers in other locations in Europe. Problems that were addressed in writing this altitude/azimuth program include: (1) the proper longitude, latitude, and elevation above sea level for each observing site, for conversion to and from topocentric angular measures; (2) correction for the changing rotation rate of the earth; and (3) correction for apparent place (chiefly as a result of precession). For 1578.0, the correction to Universal Time due to the progressive slowing of the earth's rotation rate is $\Delta T \simeq 2^{m}46^{s} \pm 30^{s}$ (cf. Stephenson and Houlden 1986; Stephenson 1997); this was incorporated where appropriate into all of the calculations performed for this project.

The equation of time is defined such that the correction amount, t_E, is equal to the apparent solar time minus the mean solar time; that is, $t_E = t_a - t_m$ (*e.g.*, Meeus 1991, 171). The 'Equation of Ephemeris Time' that I used for the reduction of data by Tycho is equation (9) of Hughes *et al.* (1989).[104] To find the local mean time (theoretically necessary for obtaining the Universal Time values utilized in computer programs for assessing the comet's motion), one thus corrects by subtracting the equation-of-time correction from the observer's reported local apparent time, $t_m = t_a - t_E$. There has been evidently very little written on the use of the equation of time by 16th-century astronomers such as Tycho Brahe. Even though Tycho was well aware of the equation of time, as were all astronomers since the time of Ptolemy via his *Almagest* and its supplementary *Handy Tables* (Thoren 1990, 491; Neugebauer 1975), we will assume here that Tycho and other observers did not correct their local mean solar time for the equation of time. Actually, few other observers of comets in the late 16th century took much pain to record the time for each observation; Tycho and the Landgrave of Hesse were the notable ones to do so, as they had the means to afford some of the better clocks of the period, and they record times generally to the minute and sometimes fraction of a minute. By making a correction for the equation of time, t_E, a maximum correction of $\approx +13$ minutes occurs near the time of discovery for the comet of 1577 (second week in November), diminishing to $\simeq +6.4$ min by Nov. 30, enroute to a minimum (0 min) about a month later. By Jan. 5, $t_E \simeq -10.74$ min, increasing to ≈ -14 min in mid-January. This correction does not make much difference in the comet's motion, but it would be a factor in determining refraction in some cases (where a difference of 13 min in time can translate into a difference of nearly 2° in the comet's altitude above the local horizon). On 1577 Nov. 29, Tycho's final observation of the night occurred at 9:33 p.m. local time with the comet at only $\approx 5°$ above the horizon, meaning that (due to refraction) it appeared $\approx 10'$ (or about a third the apparent size of the moon) above its true location on the sky.

Tycho produced altitude and azimuth measures for the comet of 1577 on nine nights (1577 Nov. 30-1578 Jan. 5), or on less than one-third of the nights for which he measured comet-star distances. I computed predicted altitudes for the comet on each night, both with and without correction for the equation of time, to see if part of the discrepancies could be reasonably explained by correcting for t_E. Any correcting for t_E appears inconclusive with regard to the astrometric positions in Table 8.3, due to the large measuring errors in both time and position, and thus will not affect the orbital elements in a way that can be conclusively quantified. When I looked at the average value of the observed altitude minus calculated altitude, *(O–C)*, from 40 measures by Tycho, I found *(O–C)* $\simeq -1^{\circ}\!.0$, corresponding to an average difference in clock time of ≈ 7.5 minutes. After applying the equation-of-time correction, the average *(O–C)* $\simeq -0^{\circ}\!.32$, which corresponds to an average

[104] The same equation appears in Smart (1936), p. 149, and in Meeus (1991), p. 173. The plot by Hughes *et al.* of the Equation of Ephemeris Time as a function of time over several millennia (their Figure 2) is in error by the sign: negative values should be positive and *vice versa*. This plotting mistake has been confirmed to me by co-author Catherine Hohenkerk (1999, private communication).

time difference of ≈ 2.4 min. None of these Tycho-measured altitudes occurred at altitudes < 10° (though he did occasionally make comet-star distance measures at lower altitudes), so any corrections due to refraction would presumably be < 0°.1 for any given measurement. The general observed altitudes by Tycho have a nightly range around half a degree, in terms of *(O–C)*, even after correcting for t_E and refraction. If one assumes that his clock wasn't losing time significantly in the couple of hours in a typical observing session (a quite-possibly incorrect assumption), this may translate to an uncertainty of a few tenths of a degree in his altitude measures around this time. But sometimes Tycho had tremendous problems with his clocks, as seems to have been the situation on 1577 December 30, for which the logbook notes his frustration.

Wilhelm never published his data himself, but thanks to Tycho, his data appear in *De mundi* (Dreyer, III, 183*ff*). Tycho tabulates 66 sets of altitude and azimuth measures by the Landgrave, covering 14 separate evenings from 1577 Nov. 11 to Dec. 30. I converted the local Cassel times to Universal Time, factoring in the correction due to the equation of time. After applying standard refraction corrections, I analyzed Wilhelm's altitude measures and note that there was a general variation on each night of ≈ 0°.5-1°.0, which can probably be assumed as not due to clock error (as most measures were made over the course of about an hour or two, and the clocks that Wilhelm worked so hard to maintain via Jost Bürgi would conceivably be unlikely to have gained or lost more than a minute or so in such an observing interval. Indeed, Wilhelm recorded clock times to a quarter of a minute, whereas Tycho infrequently recorded times to more precision than a whole minute.

The variation seen in Wilhelm's altitude measures correspond to several minutes of real clock time (depending upon both the comet's azimuth and its declination, as the comet will descend more rapidly as it nears the western horizon because its motion across the sky is more vertical and less horizontal than when closer to the meridian, and comets further south in declination will set more rapidly than those that are closer to the North Celestial Pole, as seen from northern Europe). The altitude values for Wilhelm's data range from $O - C \approx +1°.8$ to $-1°.8$, the majority being within ± 0°.8 of the calculated values.[105] The significant point here is that Wilhelm's precision in obtaining altitude measures of the comet of 1577 were only good to ± 0°.5 at best, on average.

Table 8.1 gives several sets of coordinates for the 1577 comet from these three observers (TB = Brahe; WL = Wilhelm; MM = Maestlin), which are converted from their published ecliptic longitudes and latitudes for the comet, with the corresponding residuals to show their closeness to what would be expected from the main orbital elements. As might be expected, there is quite a bit of scatter, though some of the observations are rather close to the calculated orbital location. Given the care with which Wilhelm made his observations and the use of the Bürgi clocks, it

[105] These calculations were done with Woldstedt's orbital elements. As noted in section IX, below, there is considerable difference between my new solution (based on actual observations) and Woldstedt's (based on data that were artificially smoothed by Tycho) in terms of the comet's position on the sky (as much as 10′ in mid-December), and additional work will address the implications for the altitude measures of both Tycho and Wilhelm.

might be worthwhile as a future project to formally convert his altitudes and azimuths directly to modern equatorial coordinates.

◇ ◇ ◇

Table 8.1. Coordinates of the 1577 comet derived from the observers' published ecliptic coordinates

Date (UT)	R.A. (2000.0)	Decl.	Obs.	O-C		Elong.
	h m s	° ' "		m	'	°
1577 11 15.680	19 18 01.74	-09 54 04.7	TB	1.7+	0	41.5
1577 12 14.6975	21 46 16.40	+15 46 51.7	TB	0.1-	15+	60.1
1577 12 30.7	22 19 24.04	+20 31 47.2	TB	0.8+	14+	55.4
1577 11 11.7191	18 21 33.12	-16 51 49.4	WL	2.5-	50+	31.0
1577 11 11.7201	18 20 25.67	-16 45 24.8	WL	3.7-	57+	31.0
1577 11 16.6708	19 27 30.82	-08 10 40.1	WL	0.3+	5-	43.8
1577 11 16.6740	19 27 12.65	-08 13 23.2	WL	0.0	8-	43.8
1577 11 16.7665	19 27 51.93	-07 53 39.9	WL	0.4-	2+	44.0
1577 11 16.7681	19 27 56.57	-07 48 25.6	WL	0.3-	7+	44.0
1577 11 17.6819	19 37 57.55	-06 24 34.7	WL	0.4+	4-	45.9
1577 11 12.7153	18 39 41.75	-16 04 46.5	MM	1.1+	23-	33.8
1577 11 17.8000	19 43 17.52	-05 41 25.9	MM	4.6+	28+	46.1
1577 12 02.7208	21 09 58.08	+09 37 44.8	MM	0.2-	6-	60.1
1577 12 07.7226	21 26 02.15	+12 22 42.5	MM	1.3-	10-	60.7
1577 12 07.8580	21 28 06.94	+12 36 10.3	MM	0.4+	1-	60.7
1577 12 15.7253	21 48 59.74	+15 56 20.0	MM	0.2+	2+	59.9
1577 12 31.7306	22 20 36.28	+20 28 27.2	MM	0.2+	5-	55.0
1578 01 08.7326	22 30 44.93	+21 42 13.6	MM	2.3-	42-	51.9

Combined with the inaccuracies of Tycho's altitude measures, indications are that visual altitude measures were much more difficult to pin down accurately than were distance measures between stars. Whether this was due to problems with physically mounting or erecting the altitude instruments, or to problems in determining the true horizon, or to problems in making the sightings and reading the proper figures off the instruments, is not known — but it is likely that all three factored to produce the final uncertainties.

Regarding refraction, we are chiefly concerned with objects within $\approx 10°$ of the horizon at sea level, as this corresponds to $> 5'$ in displacement, which is greater than Tycho's precision even in 1577-1578. Refraction of $2'$ or more is evident already at altitudes of 26°. For the comet of 1577, both the comet and reference stars were often observed at altitudes $< 30°$ (though the reference stars were generally higher than the comet in the sky). Actually, times of observation are known usually only for Tycho's, Wilhelm's, Grynaeus', and Maestlin's astrometry, though among the other serious observers whose data were analyzed in this thesis, Hagecius and Gemma sometimes gave either times or altitude measures, and it can be generally seen that most observers obtained their astrometric data while the comet was around 20°-30° above the southwest horizon in their evening skies. The corresponding refraction corrections are on the order of $1'$-$3'$ for most observations, which is below the precision capability of the visual observers at this time. As noted in section 2.4, the proper recording of time was an issue that Tycho understood, and he constantly fussed with his clocks and corrected them frequently by solar time. Again, in 4 minutes of time, the earth rotates $\approx 1°$ (one degree); in 4 seconds of time, the earth rotates $\approx 1'$ (one minute of arc). Tycho knew that his clocks were off by minutes, sometimes as much as a quarter of an hour or more; as this translates into several degrees of altitude for a celestial object, it can be significant. Among the 77 observations used for my orbit calculation described in this chapter, the average refraction correction for the comet is $\approx 2'$, with only 16 measurements having been obtained when the comet was at altitudes where the refraction was $> 2'$.

I used the standard refraction formula derived by G. G. Bennett (and repeated by, *e.g.*, Meeus 1991, p. 102). Strictly speaking, the reference-star positions should be corrected for refraction, as well, but this more laborious step was not undertaken due to the poor results obtained in exploring refraction for the 1604 supernova (discussed in Chapter 6 of this thesis). The only reasonable way to apply differential refraction corrections for data such as these is to compute the comet's (or star's) altitude at the time of observation by converting the comet's *predicted* celestial coordinates (from the orbital elements) to the local altazimuthal coordinates (using the standard rotation spherical trigonometric formulae provided in astronomical books everywhere), then adding the refraction correction to the altitude (because refraction due to the earth's atmosphere makes the observed celestial object appear slightly higher in the sky than it really is) and re-converting back to equatorial celestial coordinates (α, δ).[107] Again, the uncertainty in the times of observation, together with any unknown local circumstances that might cause real-life deviation from a stan-

[107] The best way to approach this problem would seem to be to take the orbital elements computed from as many observations as possible when the comet and reference stars are fairly high in the sky, and then treating all

dardized refraction-correction procedure, are enough to make correction for differential refraction a dubious venture. In dealing with refraction at Hven, at altitudes less than 15°, it should be noted that the comet of 1577 would get $\approx$ 1° lower for every 7.72 minutes of elapsed time during its first week of observation. The uncertainty in the time becomes greater at lower altitudes; for example, at altitudes $< 10°$, a difference (uncertainty) of 1° in the comet's true altitude would correspond to $\geq 0'.5$ in refraction, and at altitudes $< 7°$, the refraction error exceeds $\sim 1'$ for errors of 1° in the altitude. This uncertainty is not a big problem here, because most observations occurred with the comet above 10° altitude, but there are 25 examples on eight nights where the comet's position was determined when it was at altitudes $\leq 10°$ (for which the total refraction exceeds 5′, and thus exceeds Tycho's likely positional errors even in his early observing career in 1577). An analysis of Tycho's measured altitudes showed notable night-to-night discrepancies that well exceed (sometimes by several times) the general 0°.5 ranges reported on a single night. Part of this is due to the clock errors, which Tycho fretted about considerably.

It is interesting to look at Tycho's own display of his contemporaries' data on the comet of 1577, which appear in Chapter 10 of *De mundi*. Tycho was not at all unbiased in his presentation of others' observations and thoughts on the comet. Possibly to reflect his feelings of the quality of the work involved, Tycho ordered (organized) the observations of other observers separately, beginning with Wilhelm, then giving prominently the results of Maestlin, Gemma, Helisaeus Roeslin, Thaddaeus Hagecius ab Hayck, and Bartholemaeus Scultetus (the first four of these considered the comet to be supra-lunar). Tycho does not approve of Maestlin's use of a string to determine alignments of the comet with pairs of stars, noting numerous problems with such a procedure. But Tycho gives Maestlin's work a most prominent place in his *De mundi* (Dreyer, IV, 207-238) because Maestlin obviously gave a very serious and impressive presentation, with very little astrological discussion, aimed at producing a careful analysis of his observations. Andreas Nolthius also had made positional measurements aimed at obtaining parallax for the supernova of 1572, and he made some positional measurements of the comet of 1577, particularly noting it to be in a straight line with other pairs of stars (and including altitude/azimuth measures). Hagecius has many detailed observations, giving measurements of the comet with respect to various stars from night to night, and also noting straight-line arrangements involving the comet and pairs of stars; his observations begin on November 16 and continue to January 3 (Dreyer, IV, 262-273). Scultetus apparently observed the comet on 14 nights from November 9 to January 12, but one is left largely with computed longitudes and latitudes, though there appear to be some comet/star distances without specific times provided, and his observations are of little use now. Other observers such as Grynaeus are relegated to a few paragraphs each, indicating Tycho's lack of respect for their results (most of whom assumed that the comet was high in the earth's atmosphere, not beyond the moon).

observations below, say, 15° altitude with refraction corrections based on the initial orbital elements and adding those lower-altitude observations for a new orbit solution.

Other observers who recorded numerous star-comet alignments or who made star-comet distance measures were given less visibility by Tycho, evidently because they adhered to a sublunar existence for the comet — a location that Tycho denied was possible due to the lack of a parallax larger than that of the moon. Perhaps Tycho felt that observers such as Grynaeus who wrote gave more emphasis to astrological interpretation than to observational analysis, and who arrived at "erroneous" sublunar placement of the comet, were not treating their analyses seriously enough — and to give prominence to their observations might have weakened Tycho's case. In any case, though absolutely no observations by Gryneaus are presented by Tycho in *De mundi*, neither does Tycho list all of the observations made by Hagecius and Gemma (though he does give most of the star-comet distance measures and even notes some of the recorded star-comet alignments). Perhaps Tycho assumed that any serious analyst would go to the original sources (that is, each observer's published tracts on the comet) for the data. Even though Tycho polished his own raw comet-star distance measures for publication in *De mundi*, it appears that his presentation of observations made by other observers were unaltered by Tycho.

There were two notable exceptions to Tycho's presentation of data by other observers in his Chapter 10 of *De mundi*: For both Maestlin and Hagecius, Tycho published tables of his own measured positions for the reference stars that these two observers used. The stars used by Maestlin in his recorded alignments are all given in a table on page 260 (Dreyer, IV, 217-218); Maestlin's star positions, of course, were merely taken from Copernicus' error-filled 1543 star catalogue (though Maestlin annotated many positional corrections into his copy of *De revolutionibus*; an example is given in Figure 2.1a). Tycho's astrometry for Hagecius' reference stars appears on page 324 of *De Mundi* (Dreyer, IV, 264). No other observer's data received this special tabular attention by Tycho.

Observers who gave positional data for the 1577 comet that are of low precision (generally not given to better than 1° for latitudes, longitudes, and altitudes/azimuths) are too numerous to detail; examples include Micon (1578), Steinmetz (1577; he first saw the comet at 5 a.m. on Nov. 11), Roeslin (1578), Grynaeus (1579?, 1580), de Mauden (1578), and Busch (1577). The observations by Tycho, Gemma, and Hagecius of the 1577 comet are at such an advanced level over the observations of earlier comets that those observers who provided only ecliptic longitudes and latitudes or equatorial right ascensions and declinations (which would have either been derived from the poor star catalogues then available, or would have been even worse if derived simply from one of the poor-resolution celestial maps or globes in use then) need not be considered).

The parallax for the comet of 1577 would have been detectable only with a telescope. On 1577 November 14, for example, about the time that most of the serious observers were starting to observe the comet, it was 0.66 AU from the earth,[106] and the difference in the true observed position of the comet (with respect to the background stars) for observers at Hven and Prague

[106] This is $\approx$ 99 million km; 1 astronomical unit is approximately the mean sun-earth distance of $\approx$ 150 million km.

viewing simultaneously would have been only $\approx 1''.2$ (and less difference for Gemma at Louvain *vs.* Tycho at Hven). Meanwhile, when the comet was closest to the earth in November, its visibility in northern Europe was also limited due to its southerly declination and its small elongation from the sun, so that little parallax ($< 1''$) would be discernible from a single site by merely letting the earth turn; by the time the comet was further into a dark evening sky, its distance made the parallax that much smaller.

8.5. Reducing the 1577-1578 Observations: Reference stars and star maps

Recall that Tycho was not very consistent in how he referred to stars, and in fact he was quite sloppy and careless in many places (Dreyer, III, MS). This is a problem even when sifting through his observations of comets, as he tends to abbreviate many of his star references/designations and even use different words for the same star. A typical example of ambiguity in star identifications can be seen in Tycho's measures of the comet's distance from the star α Peg during the second two-thirds of December 1577 and into the second week of January 1578. Tycho refers to this star by "primam colli Pegasi" (brightest or first star in the neck of Pegasus, the horse) in his *De mundi* (Dreyer, IV, 16) for observations on December 10, 12, and 17, and even by "primam colli Pegasi maiorem" in his logbook (Dreyer, XIII, 296). But in his *Uranometria* atlas, based on Tycho's star catalogue, Bayer (1603, page T) places ζ and ξ Peg squarely in the horse's neck ("ceruice"), while α Peg is on the shoulder or "arm of the wing" ("in scapulis & armo alæ"); Bayer's illustration of the stars of Pegasus is shown in Figure 8. In Tycho's own star catalogue, Dreyer (III, 367) identifies the star "prima alæ, Marchab" as α Peg, whereas ζ Peg and ξ Peg are listed as "lucida colli" and "sequens in collo", respectively. In fact, in Tycho's primary list of reference-star astrometry for the comet of 1577 in *De mundi* (Dreyer, IV, 36), he has separate entries for α Peg ("prima alæ Pegasi") and ζ Peg ("lucida colli Pegasi"). But at least Tycho was consistent in referring to α Peg as "primam colli Pegasi" in 1577 and 1578 with regard to the comet; his star catalogue was many years away from compilation, and he may have forgotten by then about which star he called "primam colli".

Upon realizing that ζ Peg was several degrees off from Tycho's measures between the comet and "primam colli Pegasi", I looked at several other candidate stars before settling on α Peg as the correct star on each of these nights. In fact, this procedure of checking distance measures with stars on a star atlas (*e.g.*, Ridpath 1989), for the scenario in mid-December 1577 was repeated often for problem distance measures by Tycho and the other observers with numerous reference stars. So it is curious that Tycho consistently makes the error of naming ζ Peg for α Peg as the reference star on several nights in December. On December 31 and the first few days of January, Tycho was still using this star for his astrometry, and on this night the comet was nearly the same distance from α Peg and from ζ Peg (and similar solutions are obtained for both α and ζ), but I assume that α Peg was what Tycho meant. Woldstedt did not seem to have caught this error, and he elected to ignore all of Tycho's mid-December measures between the comet and α Peg; this is

unfortunate, because some of these measures are quite good. On December 31, Hagecius (1578, p. 10) also evidently referred to α Peg as his reference star, with the remark "humero dextro [Pegasi]" ("right shoulder"), which might be construed as β Peg, as Toomer (Ptolemy and Toomer 1998, p. 358) identifies β Peg as "the star on the right shoulder and the place where the legs joins [it]" in his translation of Ptolemy's star catalogue, and Copernicus (1543, 51A; also Copernicus and Wallis 1995, p. 98) followed Ptolemy. Hagecius probably used either Ptolemy or Copernicus (or both) for his reference stars, and it appears that he also misidentified α Peg, with a different star than that by Tycho! Clearly, Bayer's atlas containing Greek and Roman letters for identifying the stars of each constellation was long overdue.

In one case on January 14, Gemma (1578, p. 32) reported that the comet was 6°16′ from "scapula [Pegasi]", but nearly equally poor/reasonable solutions can be derived from either β Peg or η Peg; the residuals are not good for either star, but these are the only two possible candidates around this distance from the comet. Star 18 of Copernicus (1543, 51A) is said to be "in dextro humero & cruris eductioe" ("at the juncture of the wing"; Copernicus and Wallis 1995, 98), while star 17 of the same catalogue is given as "in scapulis & armo alæ" ("at the beginning of the leg"; *ibid.*); Tycho/Dreyer (III, 367) and Bayer (1603, T) both agree on these two stars as being β and α Peg, respectively. Thus, β Peg appears to be the correct star used by Gemma on January 14.

One can speculate that the general unavailability of good star atlases and star catalogues with easily identifiable stars would lead to many such errors; in fact, even though Bayer supposedly based his atlas on Tycho's star catalogue, there are many discrepancies in the placement of the stars within a constellation figure — one of the most common differences being to make mirror images of the star map. This curious 'reversed-image' mapping was a practice used in celestial-globe manufacture to show the celestial sphere as if one were looking down on the globe, rather than up at the constellations from the perspective of a ground-based observer. For a good example of different astronomers using different words for the same star (in this case, usually unambiguously), we return to the case of ϵ Peg (mentioned in section 2.3, above), which is given variously as "in the open mouth" ("in rictu"; Copernicus 1543, 51A; Copernicus and Wallis 1995, 97; Bayer 1603; Gemma 1578, 27; Hagecius 1578, 7), "mouth" ("os Pegasi" and "ore Pegasi"; Tycho and Dreyer, III, 366; IV, 36; XIII, 297), "nose" ("narem Pegasi" or "nare Pegasi"; Tycho and Dreyer, XIII, 293; Gemma 1578, 27). So we see that both Tycho and Gemma used different words for the same star on different nights!

Drawings of the comets of the preceding decades, showing their motions with respect to the stars and their tails with respect to the sun, were reflective of the more serious attitudes of observers towards these celestial events, and the publication of these images undoubtedly had an impact in addition to the influence provided by the measures and analysis in the text. Illustrations in the various treatises on the comet of 1577 ranged from drawings showing the comet and its tail with respect to the stars roughly to the proper scale (see Figures 3.9 and 3.11), to those concentrating on its nightly position (Figure 3.10), to those depicting its location in the celestial sphere relative to the earth (Figure 3.12), to more stylized images of the comet intended to indicate

the awe (and fear) that it cast on its earthly viewers. Maestlin and Tycho were more concerned with presenting geometrical illustrations showing their procedures for reducing observations into celestial coordinates, and from there to heliocentric placement of the comet. Tycho, Maestlin, and Roeslin all wrote about their belief that the 1577 comet was in a Venus-like orbit about the sun.

8.6. Reducing the 1577-1578 Comet Observations: Celestial-sphere measures

The idea of determining a comet's position on the celestial sphere by measuring the distances between the comet and two different reference stars dates back to the fifteenth century, when Regiomontanus recommended this in his description of the "ninth problem" in his treatise on the *Sixteen Problems* (Jervis 1985, p. 105). This concept was followed occasionally by a few observers in the following century, but the procedure really began to reach maturity with the supernova of 1572. By 1577, numerous observers of the great comet undertook such comet-star distance measures.

Hagecius and Gemma would usually give comet-star distance measures on a single night for only two, three, or (rarely) four stars. In most cases, they did not provide the time, and I assumed a time corresponding to an altitude as per Tycho's altitude measurements, such that the comet was reasonably high and also in a reasonably dark sky (some observations were made by Tycho in twilight, for example); the assumed times generally corresponding to comet altitudes of 20° or 25° for both Gemma and Hagecius. When more than two comet-star distance measures were provided by these observers on a single evening, I calculated all possible distances from the various sets.

With Tycho, the situation is more complex, because he usually (though not always) gave times with each individual comet-star distance measure. I therefore tried to keep my calculations to utilizing mainly those measures of star pairs that were made reasonably close in time (within 15-30 min if possible), and in most cases this would not be a problem because the comet's motion was too slow in the time between individual comet-star measures to be a real factor here. Let Δt represent the time lapsed between Tycho's measurement of the comet's distance to star A and his measurement of the comet's distance to star B. Comet C/1577 V1 was much closer to the sun and the earth in November than in January, and thus it was moving much more rapidly then. Most of my computations of the comet's position from two sets of comet-star distance measures were done with $\Delta t \leq 10$ minutes, and the adopted time then being the average of the two values. Given that Tycho's clock times were uncertain up to a quarter of an hour or more in 1577, there is hardly cause to look at the times more closely. Nevertheless, for purposes of illustration, if one takes the orbital elements in Table 8.2a, one can see that in a passage of 10 minutes of time, the comet moved $\simeq 0'.75$ eastward in α and $\simeq 0'.5$ northward in δ. These values are well below the precision level of Tycho's instruments. By the time we get to 1578 Jan. 1, even with $\Delta t = 2^h20^m$, the comet moved $2'.2$ eastward and $1'.5$ northward in that time — still well within the possible precision.

One computer program written for this project determines the right ascension and declination

(α, δ) for equinox J2000.0 from pairs of PPM star positions (Röser and Bastian 1991), corrected for proper motions back to the sixteenth century, when distances are provided between the object of study and two catalogued stars. The largest proper motions from 1578.0 to 2000.0 amongst the stars utilized by the observers of the 1577 comet were those for α Aql (4'.7 motion in 422 years), ξ Peg (3'.9), and β Aql (3'.4); this indicates the need to account for proper motions, even for these visual measurements. The intersection of the two great circles passing through each star and the comet cannot be determined because a unique equation for each great circle cannot be determined. One can, however, generally derive two solutions to the spherical triangle involving the positions of the two stars and the unknown object, by way of involving three spherical triangles that include the three objects and the north celestial pole (NCP). Section 4.1 describes this procedure more fully. Note that with the two spherical-trigonometric solutions, sometimes these solutions can be quite close together in the sky. At such times, the situation had to be analyzed closely, because one must be aware of either incorrect star identifications (by either the observer or the analyst) or very poor star-comet distance measures. This program tends to fail when the comet and both reference stars are very nearly in a straight line, because the angles become very small and the rough visual measures sometimes do not correspond with reality (which can be illustrated easily by considering an exact straight-line scenario). Consequently, I reduced all sets of measures (where one set comprises two stars and the comet) with both the spherical-trig program and the iterative program. This also provided good checks for a majority of the reduced positions, because in most cases, I obtained good solutions from both programs; in a few cases, however, neither program produced a usable solution. Sometimes other reference stars were searched for, with mixed results.

8.7. New Orbital Calculations for the Comet of 1577

Woldstedt's thesis appears to have been the only other orbit computation for the comet of 1577 undertaken since the work by Edmond Halley, who produced the first catalogue of cometary orbits in 1705, until my present work (though others before Halley had tried to make sense of the comet's motion). This encouraged me to take a new look at the available data, and I soon realized that Halley and Woldstedt had not had access to the actual observations of the comet, but rather some "polished" data provided by Tycho a decade later.

In my initial work on this comet, I extracted Tycho's positional observations from the tabulation by Pingré, which are consistent with the ecliptic and equatorial coordinates in Chapters 3 and 4 of *De mundi* (Tycho's data appear to have been faithfully copied by Pingré). Of course, modern orbit calculations for the comets observed by Tycho cannot employ the celestial coordinates originally published by the observers because they utilized poor star-catalogue positions, and that is why a completely new re-reduction had to be undertaken.

I omitted Tycho's final observation on 1578 January 26 from my solution, as its declination is off by more than 1° from the orbital elements — an error possibly due to the faintness of the comet on that last date, and the fact that he only gave a rough description of its location that night. Other regular observers who followed the comet into January (including Michael Maestlin,

Johannes Praetorius, and Gemma) were unable to see the comet after the second week of January due to its faintness (*e.g.*, Hellman 1944, pp. 147, 158), as the comet became increasingly difficult to distinguish from the stellar background. The other 23 observations (*i.e.*, not including that of Jan. 26, which was fabricated) of Tycho have average residuals of $\simeq 5'$ in both right ascension (α) and declination (δ); of these 46 values of α and δ, six have residuals $> 10'$, while nine have residuals around $1'$ or less. But these were from "polished" data, as Tycho noted the uncertainty in the individual observations and evidently saw it appropriate to "smooth" the data for formal presentation in *De mundi*, so as to bolster his evidence in promoting his heliocentric comet orbit and his new cosmological model.

From the star-comet distance measures, I have now reduced 157 total astrometric observations, each of which includes a date and time (UT), α and δ for equinox 2000.0, and a note giving the observing site. In order to obtain a single reduced astrometric observation of this form, it was necessary to have two separate star-comet distance measures, and most were chosen such that one star-comet distance measure was made within about an hour of the second such measure, so as to minimize any errors due to the comet's actual motion on the sky. When Tycho made his first observations of the comet on 1577 November 13, it was moving across the sky at the fast rate of $9'.5$/hr, or 1 minute of arc in every 6.3 minutes of time. If one takes $5'$ as a resonable resolution limit for Tycho's star-comet distance measures at this early stage in his observing career, one should try to only deal with triangles in which the two separate star-comet measures were obtained within about half an hour in time. By November 18, the comet's motion was under $8'$/hr, and by November 24 it was under $5'$/hr — reflecting the comet's movement away from the earth in space. By December 6, the motion of the comet had decreased to $2'.5$/hr, meaning that one could use separate comet-star distance measures that were obtained perhaps as much as two hours apart. And by January 1578, the comet's motion was down to $1'$/hr, so that its motion can be completely ignored for observations made on a single night in its last few weeks of visibility. Nonetheless, most of the comet-star distance measures by Tycho that I used for a single spherical-triangle reduction to α, δ coordinates were obtained within about half an hour of each other; with the other observers, the times were given much less frequently and it is not possible to know very precisely the times between measures.

Of these 157 total reduced observations, 91 (60%) were by Tycho, 42 (27%) were by Gemma, and 24 (15%) were by Hagecius. Of the 77 observations chosen for the final solution having single-coordinate residuals $< 15'$ (a quarter of a degree), 54 were Tycho's, 12 belong to Gemma, and 11 belong to Hagecius. This indicates that a slightly higher percentage of Tycho's data were of better precision than those of Gemma and Hagecius, but the difference in total *vs.* "usable" observations from one observer to the next is not great.

Table 8.2a contains my parabolic orbital elements[108] for C/1577 V1, from 77 observations spanning 77 days (1577 Nov. 13-1578 Jan. 14) whose individual coordinates (α, δ) each have

[108] Listed here are the usual orbital elements for comets: the time (T) and distance (q) of perihelion passage, given in Terrestrial Dynamical Time and astronomical units, respectively; and the three angles describing the

residuals < 15′. For comparison, Table 8.2b shows the parabolic orbital elements for comet C/1577 V1 as computed by Woldstedt in his 1844 dissertation (given here as precessed by Marsden and Williams 1992).

◇ ◇ ◇

Table 8.2a. My New Parabolic Orbital Elements for C/1577 V1

$$T = 1577 \text{ Oct. } 27.4024 \text{ TT} \qquad \left.\begin{array}{l} \omega = 256^\circ\!.5260 \\ \Omega = 32.1299 \\ i = 106.7329 \end{array}\right\} 2000.0$$

$$q = 0.181146 \text{ AU}$$

◇ ◇ ◇

Table 8.2b. Parabolic Orbital Elements for C/1577 V1 from Woldstedt

$$T = 1577 \text{ Oct. } 27.448 \text{ TT} \qquad \left.\begin{array}{l} \omega = 255^\circ\!.673 \\ \Omega = 31.237 \\ i = 104.883 \end{array}\right\} 2000.0$$

$$q = 0.1775 \text{ AU}$$

◇ ◇ ◇

Table 8.3 shows the residuals for the observations used to calculate this orbit; it contains the Date (Universal Time), the reduced right ascension and declination, the comet's altitude above the horizon at the time of observation, the observer (TB = Tycho Brahe; TH = Thaddaeus Hagecius; CG = Cornelius Gemma), two columns for single-letter-coded notes (O = observation reduced from data in Tycho's observing logbook; t and T both indicate that the time was assumed, not given by the observer; r and s indicate observations where Tycho indicated use of his astronomical radius or sextant, respectively; c and C indicate that Tycho indicated some sort of clock/time problem in connection with the observation), the residuals for each coordinate in minutes of arc,[109] and the elongation of the comet from the sun at the time of observation.

Table 8.4 shows the residuals of the same observations (represented by UT date only, in the same order as given in Table 8.3) with reference to the Woldstedt elements (Table 8.2b), for comparison. From a comparison of Tables 8.3 and 8.4, one can see that my new orbit presents significantly better residuals, particularly for the December and January observations.

[109] for $O-C$ in α, the value tabulated is $15(O-C)[\cos\delta]$; note that the corresponding column in Table 8.4 is not converted to minutes of arc.

Table 8.3. My Reduced Observations of comet C/1577 V1

(residuals from my orbital solution in Table 8.2a)

Date (UT)	R.A. (2000.0) h m s	Decl. ° '	Alt. °	Obs.	N	Residuals R.A. '	Residuals Decl. '	Elong. °
1577 11 13.6875	18 51 39	-13 41.1	10.6	TB	O	1.7-	2.8+	36.5
1577 11 15.680	19 16 30	-09 50.7	14.4	TB	Ob	2.8+	2.2+	41.5
1577 11 16.701	19 26 50	-08 02.5	18.9	TH		10.8-	0.9-	43.9
1577 11 21.7315	20 11 44	-00 32.5	19.8	TB	O	6.0-	12.9-	52.5
1577 11 21.7425	20 11 52	-00 32.4	18.3	TB	O	5.1-	13.6-	52.5
1577 11 21.744	20 11 42	-00 20.0	25	CG	t	7.7-	1.3-	52.5
1577 11 23.666	20 25 37	+02 04.4	31.5	TB	O	3.1+	3.4+	54.8
1577 11 23.6685	20 25 26	+02 00.9	31.0	TB	O	0.1+	0.3-	54.8
1577 11 23.6705	20 26 05	+01 47.9	31.5	TB	Ob	9.6+	13.3-	54.8
1577 11 23.6895	20 25 27	+02 02.7	28.8	TB	O	1.7-	0.2+	54.8
1577 11 23.6895	20 25 37	+02 12.4	28.8	TB	O	0.7+	9.9+	54.8
1577 11 23.6895	20 25 44	+02 08.2	28.8	TB	O	2.5+	5.6+	54.8
1577 11 23.6895	20 25 20	+02 07.0	28.8	TB	O	3.5-	4.4+	54.8
1577 11 23.6925	20 25 18	+02 08.0	28.0	TB	O	4.2-	5.2+	54.8
1577 11 23.695	20 25 36	+02 05.7	28.0	TB	O	0.1+	2.8+	54.8
1577 11 23.695	20 25 21	+02 07.3	28.0	TB	O	3.8-	4.3+	54.8
1577 11 23.740	20 26 03	+01 57.0	20.1	TB	O	2.5+	9.0-	54.8
1577 11 23.757	20 26 35	+02 13.9	20.1	TB	O	8.9+	6.7+	54.9
1577 11 23.7605	20 26 27	+02 19.0	17.6	TB	O	6.4+	11.6+	54.9
1577 11 25.699	20 38 10	+04 03.4	29.7	TB	O	7.8+	6.5-	56.6
1577 11 25.702	20 37 47	+04 03.2	28.9	TB	O	1.7+	7.0-	56.6
1577 11 25.702	20 37 38	+04 08.7	28.9	TB	O	0.3-	1.4-	56.6
1577 11 25.702	20 38 05	+04 14.6	25.9	TB	O	6.4+	4.5+	56.6
1577 11 25.702	20 37 54	+04 18.2	25.9	TB	O	3.5+	8.1+	56.6
1577 11 25.702	20 37 59	+04 10.7	28.9	TB	O	4.8+	0.5+	56.6
1577 11 25.702	20 37 51	+04 16.3	28.9	TB	O	2.8+	6.2+	56.6
1577 11 29.7095	20 57 08	+07 45.7	31.7	TB	O	8.9-	7.0+	59.1
1577 11 29.7415	20 57 29	+07 44.2	25.9	TB	O	5.8-	4.0+	59.1
1577 11 29.7415	20 57 37	+07 41.7	25.9	TB	O	4.0-	1.5+	59.1
1577 11 29.7555	20 57 30	+07 47.2	23.9	TB	O	6.5-	6.4+	59.1
1577 11 29.7555	20 57 49	+07 41.0	23.9	TB	O	2.0-	0.2+	59.1
1577 11 29.7555	20 57 38	+07 44.7	23.9	TB	O	4.7-	3.9+	59.1
1577 11 29.7585	20 58 20	+07 30.0	23.9	TB	O	5.6+	11.0-	59.1
1577 11 29.7665	20 58 45	+07 41.3	21.0	TB	O	11.2+	0.1-	59.1
1577 11 29.79	20 57 58	+07 28.2	25	CG	T	1.8-	14.2-	59.1
1577 11 29.79	20 57 49	+07 39.1	25	CG	T	4.2-	3.3-	59.1
1577 11 29.79	20 58 36	+07 45.5	25	CG	T	7.5+	3.1+	59.1
1577 11 30.79	21 02 27	+08 16.8	25	CG	T	0.5+	9.7-	59.5
1577 11 30.79	21 02 46	+08 21.6	25	CG	T	5.0+	4.9-	59.5
1577 11 30.8175	21 03 15	+08 26.3	12.2	TB	O	10.6+	1.4-	59.5
1577 11 30.836	21 03 19	+08 27.1	8.1	TB	O	10.4+	1.4-	59.5

TABLE 8.3. (continued)

Date (UT)	R.A. (2000.0)	Decl.	Alt.	Obs.	N	Residuals R.A.	Residuals Decl.	Elong.
	h m s	° '	°			'	'	°
1577 12 01.846	21 07 03	+09 18.3	8.2	TB	O	4.5+	7.9+	59.9
1577 12 03.75	21 13 26	+10 37.2	30	TH	T	8.8-	14.2+	60.3
1577 12 05.75	21 21 52	+11 30.1	35	TH	t	12.7+	1.5-	60.6
1577 12 09.6755	21 32 56	+13 19.9	41.3	TB	Or	2.6-	8.4-	60.7
1577 12 11.76	21 37 55	+14 17.1	30	TH	T	13.9-	5.4-	60.5
1577 12 11.76	21 38 27	+14 25.3	30	TH	T	6.3-	2.8+	60.5
1577 12 11.76	21 37 55	+14 17.7	30	TH	T	14.0-	4.8-	60.5
1577 12 11.76	21 37 53	+14 21.4	30	TH	T	14.3-	1.0-	60.5
1577 12 11.76	21 37 51	+14 16.7	30	TH	T	14.9-	5.7-	60.5
1577 12 12.714	21 41 19	+14 39.5	37.1	TB	Or	0.8-	6.2-	60.4
1577 12 12.730	21 41 06	+14 39.0	31.7	TB	Or	4.5-	7.1-	60.4
1577 12 12.730	21 41 05	+14 43.8	31.7	TB	Or	4.9-	2.3-	60.4
1577 12 13.76	21 44 25	+15 12.5	30	TH	T	5.6+	2.2+	60.3
1577 12 13.7715	21 44 26	+15 09.5	26.6	TB	O	5.4+	1.1-	60.3
1577 12 13.7755	21 44 26	+15 08.5	26.0	TB	Or	5.3+	2.2-	60.3
1577 12 14.6975	21 46 43	+15 35.5	39.5	TB	Or	5.3+	4.0+	60.1
1577 12 14.76	21 46 47	+15 33.4	30	TH	T	4.3+	0.4+	60.1
1577 12 17.8025	21 53 52	+16 28.9	20.7	TB	O	4.4+	8.3-	59.5
1577 12 17.8065	21 52 59	+16 44.9	19.0	TB	O	8.4-	7.7+	59.5
1577 12 17.809	21 53 54	+16 40.5	19.0	TB	O	4.6+	3.2+	59.5
1577 12 18.701	21 54 50	+16 54.8	39.3	TB	Os	10.1-	0.2-	59.2
1577 12 19.818	21 57 16	+17 26.6	16.8	TB	O	9.7-	10.2+	59.0
1577 12 31.705	22 20 18	+20 35.0	38.5	TB	O	1.0+	2.4+	55.0
1577 12 31.7505	22 20 01	+20 36.8	26.3	TB	Oc	4.2-	3.7+	55.0
1577 12 31.7745	22 20 11	+20 33.8	25.6	TB	OC	2.3-	0.3+	55.0
1577 12 31.78	22 20 42	+20 30.4	30	CG	T	4.9+	3.2-	55.0
1578 01 01.718	22 22 56	+20 53.0	35.6	TB	O	14.3+	5.8+	54.6
1578 01 03.75	22 25 24	+21 17.6	30	TH	T	2.2+	1.6+	53.8
1578 01 03.78	22 25 38	+21 18.6	30.0	CG		5.0+	2.1+	53.8
1578 01 08.80	22 32 45	+22 29.8	25	CG	T	4.7-	5.2+	51.8
1578 01 08.80	22 32 36	+22 27.6	25	CG	T	6.8-	3.0+	51.8
1578 01 08.80	22 32 43	+22 30.7	25	CG	T	5.2-	6.1+	51.8
1578 01 09.7685	22 35 14	+22 30.0	25.2	TB	Or	9.7+	7.3-	51.4
1578 01 09.7755	22 35 31	+22 29.2	23.8	TB	O	13.3+	8.2-	51.4
1578 01 09.789	22 35 07	+22 43.5	19.7	TB	O	7.5+	5.9+	51.4
1578 01 14.79	22 41 25	+23 34.0	25	CG	t	5.4-	7.5-	49.3

Table 8.4. Residuals of Observations in Table 8.3 from Woldstedt Orbit

Date	UT	Residuals m	Residuals ′	Date	UT	Residuals m	Residuals ′
1577 11	13.6875	0.8−	5+	1577 11	30.8175	0.4+	4−
1577 11	15.680	0.2−	6+	1577 11	30.836	0.4+	4−
1577 11	16.701	1.1−	3+	1577 12	01.846	0.0	4+
1577 11	21.7315	0.6−	11−	1577 12	03.75	1.0−	9+
1577 11	21.7425	0.5−	11−	1577 12	05.75	0.4+	7−
1577 11	21.744	0.7−	1+	1577 12	09.6755	0.8−	16−
1577 11	23.666	0.0	5+	1577 12	11.76	1.6−	14−
1577 11	23.6685	0.2−	1+	1577 12	11.76	1.1−	6−
1577 11	23.6705	0.5+	12−	1577 12	11.76	1.6−	13−
1577 11	23.6895	0.3−	1+	1577 12	11.76	1.6−	10−
1577 11	23.6895	0.1−	11+	1577 12	11.76	1.7−	14−
1577 11	23.6895	0.0	7+	1577 12	12.714	0.7−	15−
1577 11	23.6895	0.4−	6+	1577 12	12.730	1.0−	16−
1577 11	23.6925	0.4−	6+	1577 12	12.730	1.0−	11−
1577 11	23.695	0.2−	4+	1577 12	13.76	0.3−	7−
1577 11	23.695	0.4−	6+	1577 12	13.7715	0.3−	10−
1577 11	23.740	0.0	8−	1577 12	13.7755	0.3−	11−
1577 11	23.757	0.4+	8+	1577 12	14.6975	0.4−	6−
1577 11	23.7605	0.3+	13+	1577 12	14.76	0.4−	9−
1577 11	25.699	0.3+	6−	1577 12	17.8025	0.5−	19−
1577 11	25.702	0.1−	7−	1577 12	17.8065	1.4−	3−
1577 11	25.702	0.2−	1−	1577 12	17.809	0.5−	8−
1577 11	25.702	0.2+	5+	1577 12	18.701	1.6−	11−
1577 11	25.702	0.0	8+	1577 12	19.818	1.6−	1−
1577 11	25.702	0.1+	1+	1577 12	31.705	1.1−	12−
1577 11	25.702	0.0	6+	1577 12	31.7505	1.5−	11−
1577 11	29.7095	0.9−	5+	1577 12	31.7745	1.3−	14−
1577 11	29.7415	0.7−	2+	1577 12	31.78	0.8−	17−
1577 11	29.7415	0.6−	1−	1578 01	01.718	0.2−	9−
1577 11	29.7555	0.7−	4+	1578 01	03.75	1.1−	13−
1577 11	29.7555	0.4−	2−	1578 01	03.78	0.9−	13−
1577 11	29.7555	0.6−	1+	1578 01	08.80	1.7−	10−
1577 11	29.7585	0.1+	13−	1578 01	08.80	1.8−	13−
1577 11	29.7665	0.5+	2−	1578 01	08.80	1.7−	10−
1577 11	29.79	0.4−	17−	1578 01	09.7685	0.7−	23−
1577 11	29.79	0.6−	6−	1578 01	09.7755	0.4−	24−
1577 11	29.79	0.2+	1+	1578 01	09.789	0.8−	10−
1577 11	30.79	0.3−	13−	1578 01	14.79	1.9−	24−
1577 11	30.79	0.0	8−				

◇ ◇ ◇

In the 77 observations used for this solution, the average deviation of each of Tycho's observations is 7.′4 from the orbit (5.′2 in α and 5.′2 in δ). The average total residual for Gemma's observations is 7.′2 (4.′9 in α and 5.′3 in δ), while the average residual for Hagecius is larger at 10.′5 (9.′8 in α and a curiously low average residual of 3.′7 in δ). Of course, only about half of the total observations that were reduced in this study were used for the above orbit solution, the remaining observations having residuals $> 15'$. Thirteen of Hagecius' 24 observations fall into this "unusable" category, and 71 percent of Gemma's observations are in this sense "bad", while only ≈ 40 percent of the positions derived from Tycho's data were discarded. So while the average residuals

of the observations by Gemma and Hagecius are in the same vicinity as those from Tycho's data, it is clear that even at this point early in Tycho's career, he was taking more pains to produce higher-quality celestial measurements than had been undertaken by others.

These elements are similar to those orbital elements computed by both Woldstedt and Halley, but these are evidently the first orbital elements to be actually computed from the observations themselves (Woldstedt and Halley used the 'polished' observations published by Tycho in *De mundi*). This orbit also gives positions on the sky that differ by $> 10'$ in mid-December 1577 from the orbital elements of Woldstedt. Two results from this work tend to refute what has been commonly said about Tycho's work on the comet of 1577: (1) Tycho's observational precision was not an order of magnitude better than that of his fellow observers of the same comet, and in fact Tycho's observational precision is almost twice as bad as has been stated for a century and a half, based on Woldstedt's thesis.[110] (2) Only two orbits appear to have been computed for the comet of 1577 following Newton's development of his mechanics for use in parabolic (and elliptical) cometary orbits, and both of those published solutions (by Halley in 1705 and by Woldstedt in 1844) appear clearly to have utilized only those observations provided by Tycho in his *De mundi*; this is the first apparent formal orbital calculation for this comet using the original observations, the observations of observers other than Tycho, and much better reference-star positions. Combined with the luxury of modern computing capability, it is now possible to assess more fully the limitations and successes of astronomical observation at this point in the sixteenth century.

8.8. The Six Comets From 1580 to the Turn of the Century

As stated in my Preface, I had originally intended to tackle all seven of the comets observed at by Tycho Brahe and his colleagues at Hven for this thesis. Because my attention was drawn instead to the 1572 and 1604 supernovae and the 1532, 1661, and 1783 comets (each addressed in different chapters herein), it was deemed prudent to stick to analysis of the all-important 1577 comet for this particular project and to put off finishing my work on the other "Hven" comets until later. But I consider it useful and instructive to include a summary of what was published on those other six comets, with some brief remarks about what work has been done on them in the last few centuries. None of the other six comets approached the 1577 comet in terms of brightness and grandeur. The observations of Tycho and his Hven colleagues are as they appear in his still-extant observing logbooks, described above and first published in the nineteenth century. One must very much consider the observational program of Tycho Brahe and the programs of his contemporary observers as products of their predecessors and the current state of astronomy with regard to comets, of their exchange of observations and theories with each other, and of the instruments (and star catalogues) available to them. All these factors helped to determine what

[110] Woldstedt actually re-reduced 80 comet-star distance measures by Tycho, and produced residuals that range from $0\overset{'}{.}3$ to $20\overset{'}{.}8$ (with a mean residual of $\sim 4\overset{'}{.}3$).

data were obtained and how they were measured.

8.8.1. Comet of 1580

The comet of 1580 (now designated as C/1580 T1) may have been the brightest of the six comets observed during 1580-1596, being one of the brighter objects in the night sky for a short time. C/1580 T1 was observed at Hven by Tycho, Paul Wittich, and Peter Jacobsen Flemløse. Together, they recorded distance measures from the comet to reference stars on nineteen nights from 1580 Oct. 10 to Dec. 13 — with some nights containing as many as 11-13 separate distance measures that can be converted into usable modern equatorial coordinates (Dreyer, XIII, pp. 287ff). Many altaz coordinates were also recorded, both for the comet and for reference stars — as were numerous star alignments with the comet over the 2-month period. An interesting thing happened when Tycho went off to Helsingsborg for a few days in the last week of October: Tycho took his smaller astronomical radius with him and continued observing the comet from the mainland, while Wittich and Flemløse continued using the better instruments at Hven. So, on Oct. 26, Tycho obtained 13 star-comet distance measures while his colleagues at Hven obtained an additional eight such measures. But what Wittich and Flemløse did on six nights (Oct. 21-31) that Tycho never did at any other time (though he was apparently present again at the island on Oct. 29 and 30 before returning to Helsingsborg on Oct. 31) was to give the times for each measurement according to two different clocks. From this, we see that one clock ran slow by a total of over 5 minutes in only 1.3 hours' time on Oct. 21 (Dreyer, p. 315). Likewise, on Oct. 30, one clock was off from the other by 13 minutes and 10 seconds after a passage of only 2 hours. The observers clearly were unsure of the accuracy of both clocks.

Maestlin (1581) published what was perhaps the most serious tract devoted to the 1580 comet (see Figure 8.5). He had evidently absorbed Tycho's criticism for having performed no comet-star distance measures on the 1577 comet, for he published such measures obtained at Backnang with an astronomical radius for 21 nights spanning Oct. 2-Dec. 12 — getting data on two more nights than did the Hven group. Because this extends the arc of observation by over a week, compared to the Hven observations, one clearly should rework this orbit and take in the additional observations made at locations outside of Denmark. Maestlin also included equatorial (α, δ) and ecliptic (λ, β) coordinates for the comet on each night, and he recorded numerous observed alignments of the comet with star pairs. As I noted earlier, Hagecius (1581) also wrote a 46-page tract on the 1580 comet.

Conſideratio & obſeruatio
COMETAE
AETHEREI ASTRONO-
MICA, QVI ANNO M D LXXX
MENSIBVS OCTOBRI, NOVEMBRI ET DECEM-
bri, in alto Aethere apparuit. Item, Deſcriptio terribilium aliquot & por-
tentoſorum Chaſmatum, quae his annis M D LXXX.
& M D LXXXI. conſpecta ſunt.
AVTHORE
M. MICHAELE MAESTLINO GOEPPINGENSI,
Matheſeos in Academia Heidelbergenſi Profeſſore ordinario.

HEIDELBERGAE.

Figure 8.5. Title page of Maestlin's 1581 tract on the 1580 comet. Note the changing tail lengths for both the 1580 comet (whose motion is horizontal in this picture) and the 1577 comet (which moves from lower left to the center).

George Henisch, a mathematics professor at Augsburg, published an 8-page pamphlet in which he notes that the comet was first seen on 1580 Oct. 8; he says that the comet brightened as it passed Delphinus on Oct. 18; the last date he recorded seeing the comet was Oct. 24 (Henisch 1580?). Henisch also wrote tracts on the 1577 and 1596 comets. Albinus Moller published a short 3-page piece on the 1580 comet that was appended to a slightly longer astrological almanac (Agricola and Moller 1580?). Moller reports that he observed the comet, located under the stars of Pegasus and Aquarius, at 9 p.m. on 1580 Oct. 11, but he doesn't give much else in the way of useful observations. There is also a 10-page manuscript (five double-sided sheets) on the 1580 comet by Michael Apffel of Vienna, located now in the Library of the Royal Astronomical Society in London.

Zacharias Rivander (1581) reported seeing the comet between 7 and 8 p.m. on 1580 Oct. 10, and says that he followed the comet for 8 weeks until Nov. 29. But there is not much else observational in Rivander's tract, which tries to connect the comet to eclipses and planetary conjunctions, and later goes into astrology and theology; indeed, his title-page woodcut depicts a comet in the sky over a skeleton, fighting peoples, and crumbling city buildings. Numerous other tracts and pamphlets were published regarding the 1580 comet that contain astrological/theological speculations and/or poems without any real observations (*e.g.*, Albino 1581; Anonymous 1580;[111] Crausius 1580; Fulminati 1581; Praetorius 1580; Thurneyssers 1581?; Wainstler 1581). The 4-page pamphlet by astrologer Ascanio Fulminati says that the comet was observed at the end of September 1580.

After Halley and Pingré had performed the first orbital calculations for C/1580 T1, detailed analysis of Tycho's observations and orbital computations for the comet of 1580 were published by Schjellerup (1855). No further work on this comet appears to have been done since Schjellerup. Perihelion passage occurred on 1580 Nov. 29.0 TT at $q = 0.60$ AU. The comet passed only about a quarter of an AU from the earth in the second week of October, and the comet may have been near total visual mag 0 then. Brahe wrote that the comet was a little fainter than α Aql ($V = 0.77$), and perhaps near $m_1 \simeq 1.0$, on Oct. 30 and 31 (Dreyer, XIII, pp. 321-322); apparently an assistant of Tycho's wrote an entry for Nov. 25 that mentioned the comet being similar in brightness to a star of the second magnitude (*ibid.*, p. 324). Of course, the magnitude scale was not at all precise then, so this could easily mean $V = 2.0 \pm 1.0$. From this, assuming a power-law exponent of $n = 3$, we could adopt an absolute magnitude of $H(n = 3) \simeq 3.5$-4.0. With this assumption for a power-law magnitude relationship, the comet would have brightened rapidly in late September as it approached the earth and as it moved northward near opposition from well south of the celestial equator. This would explain Fulminati's sighting of the comet in late September. By December, the comet had moved to rather small elongation from the sun and would have been fading rapidly in the twilight as it again moved southward. A similar scenario is seen if we adopt $n = 4$, and $H(n = 4) \simeq 4.0$, where the comet peaks in October near $m_1 = 1.5$ and fades only gradually by half

[111] The authors initials are given as P.S.T.A.F.

a magnitude through November. A remark in Tycho's logbook (apparently not by Tycho himself; Dreyer, XIII, p. 325) states that Roeslin was evidently able to follow the comet until 1581 Jan. 1 — certainly a possibility though it would not been a difficult object perhaps near total visual mag 3–4 low in the sky in twilight.

8.8.2. Comet of 1582

Comet C/1582 J1 was a fainter comet and was only observed by the Hven observers on three nights (1582 May 12, 17-18, and 18), with some 21 comet-star distance measures useful for modern reduction of positions (Dreyer, XIII, p. 334). Possible observers of this comet with Tycho include Flemløse, Gellius Sascerides (Christianson 2000, p. 351), and Anders Viborg (*ibid.*, p. 373). The Hven observation logbook notes that the comet was between second and third magnitude when first observed on May 12, fading to about fourth magnitude by May 19 — remembering that these estimations were being made to stars in the Ptolemaic magnitude system, which (as noted above) must be assumed to be highly approximate. Nonetheless, using the parabolic orbit catalogued by Marsden and Williams (2003),[112] one can see that the comet would indeed have faded that rapidly according to a standard power-law equation with $H(n = 3) = 7.0$ (which fits the observations well). The closest approach to the earth occurred around May 9 at $\Delta \simeq 0.84$ AU. What is remarkable about these observations of comet C/1582 J1 is that it was only 14° from the sun on May 12, moving out to elongation 24° by May 18; it would have been better placed for northern-hemisphere observers, being nearly due north of the sun. It would have faded below naked-eye brightness shortly after the last reported observations. But this suggests that the observers at Hven were closely monitoring the sky, as it still was a twilight object.

Due its poor placement in the sky, the 1582 comet was only observed by serious observers. Two other elite observers of that era did report observations of it: Maestlin and Roeslin. Maestlin never published his observations, though he evidently planned to publish all of his observations of comets over the years in a single volume on comets later in his life (Jarrell 1971, p. 127). A series of manuscripts written by Maestlin now resides in the library at Wolfenbüttel[113] that includes some handwritten observations by Maestlin of the 1582 comet, with ecliptic coordinates given in paragraph form. Also in this manuscript collection is a letter dated 1582 May 18 from "Samuel Siderocrates D." to Maestlin saying that the comet was seen on May 17 and at 9-10 p.m. on May 10; a letter from Maestlin back to him on May 21 mentions that the comet seen by himself at Heidelberg on the 17th, in which he gives the comet's ecliptic longitude and latitude. Roeslin (1597, p. 15) reported observations of the comet on May 17 and 18.

[112] They precessed the orbit by Marth (1878) forward to equinox J2000.0, with T = 1582 May 6.9 TT, q = 0.17 AU, and i = 118°. H. d'Arrest (1854) also published orbital elements for the comet of 1582.

[113] under shelfmark 15.3 Aug 2°; material regarding comets appears beginning on leaf 103(a) = 171; "COMETA Anni 1582." starts a section on leaf 106a. A letter from Rothmann to Maestlin dated 1587 Mar. 6 discusses the 1572 "comet", the 1577-1578 comet, and the 1585 Oct./Nov. comet with respect to parallax.

8.8.3. Comet of 1585

Comet C/1585 T1 was the third of the seven comets observed by Tycho's Hven group to have been extensively monitored (Dreyer, XIII, p. 336). Those observing the 1585 comet at Hven included Hans Crol, Rudolphus Groningensis, and Elias Olsen Morsing (Christianson 2000, pp. 99, 323), with Gellius Sascerides and Flemløse also possibly assisting. There are close to 50 comet-star distance measures that should be usable today for astrometric purposes — made on seven nights spanning 1585 Oct. 18 to Nov. 9 (two additional nights have only a single star-comet distance measure).[114] The records from the nights of Nov. 4 and 5-6 are amazing in the number of measures made: the Nov. 4 pages contain ≈ 68 measures of all kinds made over ≈ 5 hours, while the Nov. 5-6 pages contain ≈ 165 measures over ≈ 8 hours! These include altaz measures for the comet and for reference stars, but it clearly shows that Tycho must have had a small army of assistants helping him at Hven to handle the volume of measurements and recording. From this we can see that measurements were being made sometimes at the rate of one per minute, but with additional people available to monitor instruments and to record data by candlelight, this would have been much more feasible than with only a single observer or with only one assistant. Frequent comments appear in the logbook of the nebulosity of this comet, as if it were distinctly different in appearance from the three comets seen at Hven in the previous decade.

Brahe appended an early 6-page report on the 1585 comet to Morsing's 1586 meteorological diary, printed at Hven. Morsing's tract contains observations for nine nights during the period Oct. 18-Nov. 12 in the form of ecliptic (λ, β) and equatorial (α, δ) coordinates, but there were no comet-star distance measures given here. On Oct. 15, between 9 and 10 p.m., the Morsing report says that the comet appeared similar to Praesepe (M44) — perhaps in size? — and the comet's magnitude was apparently somewhat exceeded by that of a first-magnitude star (this comment appears also in the extant logbooks in a hand other than Tycho's; cf. Dreyer, XIII, p. 336). I have viewed four different copies of Morsing's book, but the copy in the Danmarks Natur- og Laegevidenskabelige Bibliothek in Copenhagen[115] is highly interesting, being very heavily annotated in two different shades of brown ink with underlinings and with words crossed out in the comet section — as if a knowledgeable editor (perhaps Tycho himself) were preparing for a revised version. As I mentioned earlier, Brahe later included non-detailed observations of this comet in his printed book of correspondence (Brahe 1596, pp. 14-15, 42-43).

Christopher Rothmann logged and tabulated careful measurements of the comet of 1585 from two stars at a time, for 14 total sets of such distance measures made on ten nights spanning October 8 to November 8; these were published posthumously by Snell (1619, pp. 69-156; tabulated observations on pp. 78-79), who devoted some 90 pages of a book that contained Snell's own comet

[114] The Gregorian calendar was adopted in Catholic countries in 1582, but not in the northern Protestant countries. The dates that I give for the comets of the 1580s and 1590s in my summaries here are the dates provided by the original authors; obviously, conversion from Julian to Gregorian calendar must be made when doing any serious calculations.

[115] under shelfmark 4° Astr. 58350

observations made in 1618. The practice by Tycho and Maestlin of producing a (calculated) daily table of positions (celestial longitude, latitude) for the comet from the date of first observation to that of final observation was continued by Rothmann (Snell 1619, pp. 88-89) for the comet of 1585. (Rothmann had an extensive correspondence with Tycho and visited Hven in 1590; cf. Christianson 2000, p. 349.) Isaac Newton evidently knew at an early stage in his career about the Rothmann observations in this particular volume (see Ruffner 1966, p. 208).

In their analysis of the orbit of the comet of 1585, Paul Laugier and Victor Mauvais (1844) note that they found the observations of Tycho in his "*Epist.*, p. 14 et 15 . . . et dans la *Cométographie* de Pingré (t. I, p. 551 et suiv.)". They also used observations by Rothmann, and the residuals of both the Tycho and Rothmann observations (with respect to their orbital elements) are given in a table (Lagier and Mauvais 1844, p. 702), and I suspect that the French astronomers obtained Rothmann's positions from the manuscript published in Snell (1619). Peters (1849) performed a monumental set of calculations in publishing his orbit for the many observations of the comet of 1585, surpassing the earlier work by Laugier and Mauvais (1844) and by Hind (1846a). A later version of the Hven observations for the comet of 1585 appeared in detail by Schumacher (1845a).

Using the parabolic orbital elements of Peters,[116] I find that one might get very rough power-law magnitude parameters of $H \simeq 5.5 \pm 0.5$ for both $n = 3$ and 4. These parameters would have the comet fading from $m_1 \simeq 1.5$-2 to 5-5.5 over the observed arc. The comet passed closest to the earth in the third week of October (Gregorian calendar), at $\Delta \approx 0.14$ AU. Its apparent large size and small degree of coma condensation (*i.e.*, not-very-prominent nuclear condensation) would make this comet harder to see even despite a reasonably high total visual magnitude, because it may have had fairly low surface brightness.

Curiously, I found no other tracts on the 1585 comet, as it appears not to have drawn attention from any but the most serious observers.

8.8.4. Comet of 1590

Tycho's assistants for observing the 1590 comet likely included Morsing (who died around the time of the comet's disappearance) and/or Christian Longomontanus (cf. Christianson 2000, p. 314). The observations of the Hven group for comet C/1590 E1 encompass ten nights from 1590 Feb. 23 to Mar. 6 — with only three nights having multiple star-comet distance measures that can be readily reduced to modern astrometric data (Dreyer, XIII, p. 372). The last seven dates have many distance measures from the comet to a single reference star on each night, along with numerous altaz measures, and the data are converted in the logbook to equatorial (α, δ) and to ecliptic (λ, β coordinates.

On 1590 Feb. 23 (Julian calendar presumed),[117] the logbook starts by saying (in a hand other than Tycho's) that the comet was first seen around 7:20 p.m. about as bright as a second-

[116] as precessed by Marsden and Williams (2003): T = 1585 Oct. 8.5 TT, q = 1.09 AU, i = 6°

[117] Dreyer (1890, p. 280) states that Tycho adopted use of the Gregorian calendar in his writings from 1599 July 22 onwards.

magnitude star, but toward the end of that day's entry, Tycho entered a couple of sentences for 9:10 p.m. that put the brightness like that of a first-magnitude star (a comment repeated in different wording by Tycho in his entry-ending comments for Feb. 24). Tycho's entry for Feb. 25 at 8:54 p.m. says that the head of the comet had a diameter of $2\overset{'}{.}5$-$3'$ with a magnitude like that of Capella ($V = 0.08$). By March 2, the comet's tail was no longer apparent, and a sketch of the comet by Tycho with respect to two background stars for the evening of March 6 shows a round coma with no tail. All of this suggests an intrinsically faint comet that underwent a large rapid increase in brightness (possibly near the time of discovery, when the comet was moving away from the sun, low in the sky near elongation 31°) and probably also a rapid decline after Feb. 25.

Taking the parabolic orbital elements of Hind (1846e),[118] an ephemeris calculation would suggest that $H(n = 4) \simeq 5.0 \pm 1.0$ (which would have the comet fading from $m_1 \simeq 1$ to $\simeq 4$ over the observed time span) might represent the data, but if the comet was indeed in outburst, this would be rather meaningless information in terms of comparison to other comets.

Again, I have not found other tracts on the 1590 comet — either in my library searches or in the several astronomical bibliographies of European books published in this period. Hind (1846b, d) also published reduced observations of the Hven observations of this comet, as well as an earlier orbit (Hind 1846c).

8.8.5. Comet of 1593

The observations of comet C/1593 O1 in Tycho's logbook are strange in that they are only given to the nearest $10'$ (or 1/6 of a degree) — quite a change from earlier comet observations, which were given to $1'$ or even to a fraction of an arc minute. There are four nights spanning 1593 July 22-Aug. 22 (Julian calendar presumed) with two comet-star distance measures each, plus another night (Aug. 21) where the comet was stated to be on top of the ninth star of Cepheus (Dreyer, XIII, p. 388). Many of Tycho's earlier assistants were gone in 1593, and Tycho adds at the end of the entries for this comet that it was not observed at Hven and that the given observations were by "Servuestae Christiernus Johannis Ripensis". In his biography of Tycho, Dreyer (1890, p. 162) had attributed them to "a former pupil of Tycho's, Christen Hansen, from Ribe in Jutland, who at that time was staying at Zerbst in Anhalt"; Dreyer later (*ibid.*, p. 383) gives a list of Tycho's pupils (from a manuscript likely written by Hans Crol), equating this Christen Hansen with the "Christiernus Joannis Ripensis" on the names list. Thoren (1990, p. 198) notes that this "Christian Johansson" worked with Tycho for four years ending in 1590, but that he sent astronomical observations to Tycho during the following decade. Longomontanus and possibly Sascerides were present at Hven at the time of this comet's appearance, but possibly the weather was bad or other reasons prevented them from observing it.

Anyway, though the astrometry is rather crude for the 1593 comet, it has perhaps the most extensive list of brightness estimations. At around 11 p.m. on 1593 July 25, the comet was said to be as bright as a third-magnitude star, and still between third and fourth magnitude

[118] as precessed by Marsden and Williams (2003): T = 1590 Feb. 8.5 TT, q = 0.57 AU, i = 150°.

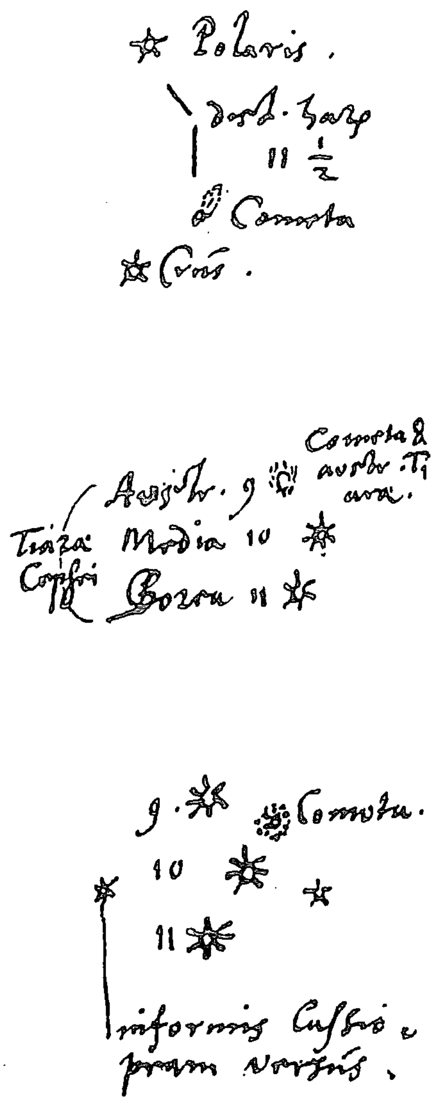
on Aug. 6. On Aug. 13, the comet was similar in brightness to "crure sinistro Cephei" (which Ptolemy, Copernicus, and Tycho all referred to as "pede" instead of "crure"), which translates to the "modern" Bayer designation γ Cep (Ptolemy and Toomer 1998, p. 345; Peters and Knobel 1915, p. 28; Dreyer, III, 357). The Yale *Catalogue of Bright Stars* (Hoffleit 1964) lists this as a red star (type K1 IV, $B-V = +1.03$) of $V = 3.22$; using an empirical formula developed by Howarth and Bailey (1980; see also Green 1997a, p. 65), relating visual magnitude, m_v, to the Johnson V bandpass based on the $B-V$ color,

$$m_v = V + 0.16(B - V), \tag{8.0}$$

we can take a value of $m_v \simeq 3.4$. Granted, we do not know how the magnitude estimation was made — probably the observer did an assessment of the larger comet's brightness based on the "conspicuousness" of the comet *vs.* the reference star, along the lines of Johann Holetschek in the 1890s (see my review of the development of brightness estimation of comets; Green 1996c) — so the precision to tenths of a magnitude is probably unwarranted here, but it is rare in this era to find any comparisons of comet brightness to specific stars fainter than first or second magnitude.

Ripensis went on to note that on August 22, the comet was as bright as the tenth star of Cepheus, and he provided a diagram showing the roundish comet near the 9, 10, and 11 stars of Cepheus (a short tail is evident on his drawing from Aug. 13, depicting the comet then 11°.5 from Polaris; see Figure 8.6) — the star numbers referring to their order in both Ptolemy's and Copernicus' catalogues. The tenth star is ζ Cep, a very red star ($V = 3.36$, $B-V = +1.60$, $m_v \simeq 3.6$). Strangely, Ripensis says that the comet was about sixth magnitude on Aug. 23 (no specific star listed for reference), but as the magnitude system in the catalogues was inconsistent and imprecise, it is difficult to ascertain whether the comet was beginning a drastic fade (as we sometimes see with comets falling apart) or not.

Figure 8.6. Sketches of the 1593 comet from the Hven observation logbook for Aug. 13 (top), 21 (center), and 22 (bottom), by the Julian calendar. Note the short tail on the first date, a possible elongation on the second, and a fairly round coma with no tail on the last date.



An orbit catalogue by Thomas Barker (1757) includes what was evidently the first orbit for the comet of 1593, by Lacaille (1752), which had the comet passing within 0.1 AU of the sun at perihelion just ten days before it was found. Recall that the observations for 1593 were not published until Friis did so in 1867, so Lacaille was evidently using either the Bartholin or the Delisle manuscript copy in Paris (see section 8.2, above). Using the parabolic orbital elements for C/1593 O1 by Lacaille,[119] an ephemeris computation indicates that $H(n = 3) \simeq 5.0$ represents the observations fairly well, indicating that the brightness on the first night was possibly closer to second magnitude, and on the final night closer to fourth magnitude. This would also indicate how far off the Ptolemaic magnitudes could throw the observer (*i.e.*, by a magnitude or more in either direction). Of course, even today, without a catalogue of magnitudes or a good atlas at hand, an astronomer taking a random look at the night sky might estimate the visual magnitude of many stars in a way that could well be the better part of a magnitude in error. Taking the observations seriously (perhaps unwarranted at anything other than an approximation to reality), if the nuclear condensation was fading, this could affect the "impression" or "conspicuousness", in the Holetschek sense. But one of the things that I noted about early brightness estimates of comets (Green 1996c) is that early observers tended to focus on the brightness of the nuclear condensation when reporting comet magnitudes, rather than the total integrated brightness of the coma (something much harder to accomplish).

8.8.6. Comet of 1596

Comet C/1596 N1 has multiple star-comet distance measures from the Hven group on only two nights: 1596 July 21 and 24 (Dreyer, XIII, p. 390); there is also a single comet-star distance measure from July 18 — all given to the usual Hven precision (sometimes to a quarter or a sixth of an arcmin). The last sentence in the logbook entry (*ibid.*, p. 393) says that Bishop Anders Foss of Bergen and "Christoph. Ceruinus" (Longomontanus) were involved with the observations. Indeed, Foss was visiting Hven then, and Christianson (2000, p. 292) adds that Christopher Hjort also observed this comet with Tycho both in Copenhagen and at Hven. When first seen by Tycho at Copenhagen on July 14, comet C/1596 N1 was recorded as being as bright as a second-magnitude star — specifically like a star in the back of UMa ("inferior duarum antecedentium dorso", which may be α UMa ($V \simeq 1.8$), but may well refer to something else. On July 19, the comet was apparently as bright as a third-magnitude star, and on July 24 it was a small and difficult object — evidently fading rapidly — with the brightness like the star "in pede posteriori Vrsae maioris". This last star reference is highly ambiguous, as Tycho's own catalogue lists new fewer than eight stars in this particular anatomical section (feet, or legs) of the great bear. Seven of these eight candidates all have visual magnitudes in the range 3.3-3.9 (the eighth has $V = 4.8$).

An anonymous 8-page German pamphlet says that the comet was as bright as a first-magnitude star on July 27 (presumably Julian calendar), sporting a 1° tail (Anonymous 1596a). I located several other German tracts containing some observations of the 1596 comet, including a 23-

[119] as precessed by Marsden and Williams (2003): T = 1593 July 19.0 TT, q = 0.09 AU, i = 88°

page tract by Andreas Grothenius (1596) of Göttingen, a 15-page tract by Johann Krabbe, a 23-page tract by Guilhelmo Rechperger (1596), and the previously mentioned 70-page tract by Roeslin (1597). Grothenius has some rough observations of the comet beginning on July 11, giving ecliptic coordinates for the comet to the nearest whole degree. Krabbe's little booklet gives ecliptic coordinates for the comet on July 15, 16, 18, and 21 — to slightly higher precision (half a degree) using a "mathematical instrument"; on July 21, he noted that the tail was 2° long. Based on his title-page diagram (Figure 8.7), could this be similar to the appearance of comet C/1996 B2 (see Figures 1.1, 8.8, and 8.9), with the narrowish tail of small width compared to the coma size? That 1996 comet was widely noted as being one of the most spectacular comets of the 20th century — more so than the brighter comet C/1995 O1 (Hale-Bopp) that was easily visible for weeks the following year, because C/1996 B2 was nearly overhead at its brightest and had a much longer tail. More than one astronomer commented to me that seeing C/1996 B2 at that close approach to the earth must have been the sort of cometary apparition that instilled genuine fear in the hearts of ancient peoples who did not understand them (whereas C/1995 O1 was much farther from the earth when at its brightest, and much lower in the sky — so not observable as long each night — so that it wasn't as striking as the slightly fainter comet overhead was in 1996).

Krabbe was a mathematician from Braunschweig and nearby Wolfenbüttel, and Rechperger was also a mathematics professor at Vienna. Rechperger also gives some rough positional information for the comet during his observing from July 9 to August 2, and he also notes the comet's "corpus" (or head/coma) to have been similar in brightness to a second-magnitude star. Roeslin first saw the comet on Sunday evening, 1596 July 11, at 9 p.m., and he recorded additional observations for July 12, 13, 15, 18, 22, and 25 — giving rough ecliptic coordinates only to the nearest whole degree.


COMETA.

Gründliche obserua-
tion des newen Cometen lauff/ hö-
he/ vnd grösse/ welcher in diesem 1596 Jahre/ im Mo-
nat Julio am Himmel ist erschienen/ vnd gesehen wor-
den/ sampt desselben bedeutunge.

Durch

Johannem Krabben von Münden / der Mathemati-
schen Kunst besondern Liebhaber/ vnd Fürstlichen Braunsch-
weigischen bestalten *Geometrum* zu Wolffenbüt-
tel/ obseruirt vnd beschrieben.

CVM GRATIA ET PRIVILEGIO, &c.

Zu Magdeburgk bey Johann Francken/ 1596.

Figure 8.7. Title page of Krabbe (1596), showing a the 1596 comet with a tail of width that is more narrow than the diameter of the comet.

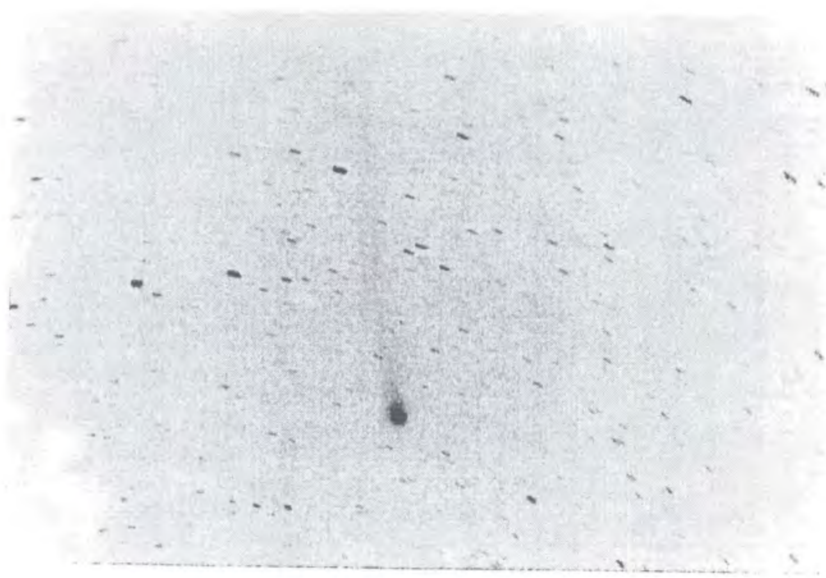


Figure 8.8. Photograph of comet C/1996 B2 taken by Dan Green on 1996 Mar. 25 with a 50-mm f/1.4 camera lens (Ektachrome 400 35-mm slide film), on a tripod with no clock drive (thus the short trails due to the earth's rotation). The faint tail is evident upward, which to the naked eye was some 40° long — but from light-polluted urban sites the tail was invisible.

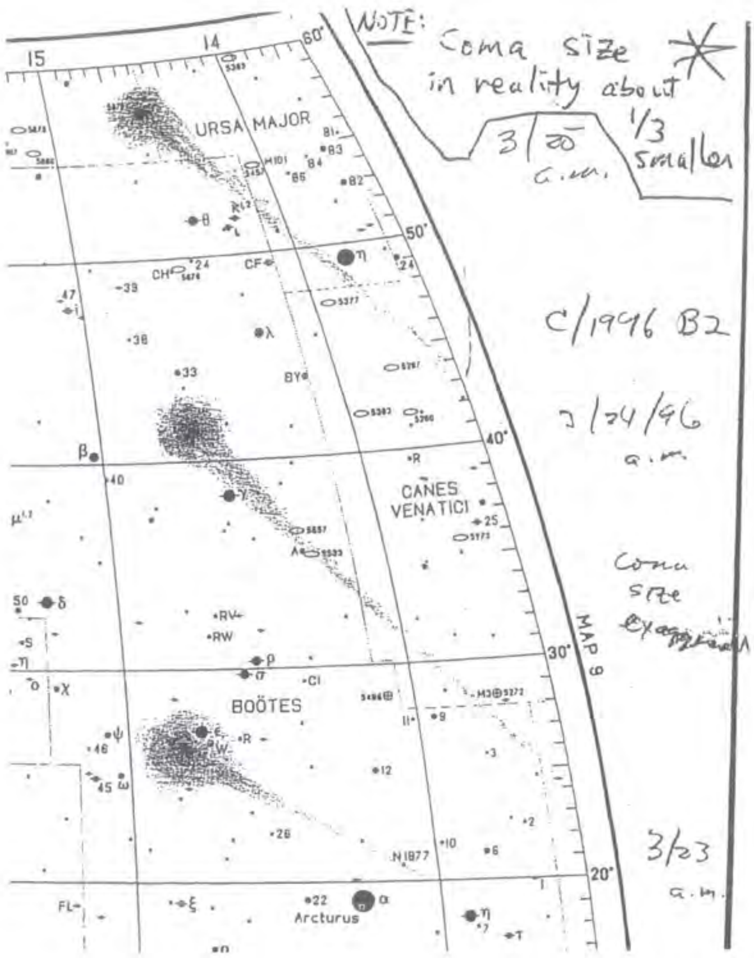


Figure 8.9. Figures of comet C/1996 B2 drawn by Dan Green (onto photocopies of an old Norton's Star Atlas), showing its naked-eye appearance and motion northward (Mar. 23, 24, and 25 shown here). Compare with Figure 1.1.

Simon Maier (1596) of Gunzenhausen (southwest of Nuremberg) also wrote a more serious 24-page tract with a title-page woodcut depicting the comet's motion past the stars of Ursa Major during eight nights in the period July 12-25 (presumably Julian calendar, corresponding to July 22-Aug. 4 on the Gregorian calendar). Maier says that the comet was evidently first seen on July 1; on July 7, he says that the comet made a triangle with two faint stars in the paw of the left foot of the great bear (not entirely useful, as we do not know the shape or size of the triangle). Maier seems to say that the comet resembled Mercury in color and brightness (without saying which date this referred to for the comet), apparently referring to his observations of that twilight planet in March of the same year; Mercury is usually around $m_v = 0.0 \pm 1.0$ when visible.[120] Mercury was indeed observable from Germany in twilight in the second half of March 1596, at apparent magnitude ranging from ≈ -1.3 on Mar. 16 to $\approx +0.5$ when at maximum elongation on Apr. 1 (Gregorian calendar).[121] But he then vaguely also says that the comet was as bright as a second-magnitude star (again no accompanying date). Maier's brightness comparison to Mercury is clearly suspect, with the planetary observations being months apart from those of the comet. He last observed the comet on July 25. Brüning (2000, p. 112) identifies this author as Simon Mair; whether this is correct or not, I found it interesting that a well-annotated copy of the 1602 edition of Tycho Brahe's *Astronomiae instauratae progymnasmata* in the Forschungsbibliothek at the Gotha Schloss contains the signature "Simon Mair" at the top left of the title page.[122]

Halley said that Maestlin observed this comet, almost implying that this was where he got the observations for computing its orbit (Halley 1752, p. Oooo2), but I have found nothing to support this claim in bibliographies or in the dozens of rare-book libraries that I have visited. Reduced, detailed observations for the comet of 1596 were published by Hind (1845), Schumacher (1845b), and Valz (1846). Hind (1845) and Valz (1846) published elements for this comet. Ephemeris calculations using Hind's parabolic orbital elements,[123] yield $H(n = 3) \approx 5.0$ or $H(n = 4) \approx 6.0$. It makes sense that the comet was becoming rapidly smaller and harder to see, as it was moving away from the earth and near $\Delta = 1.0$ AU when last observed.

Again, numerous tracts and pamphlets were published in Europe concerning the 1596 comet that contain little or not useful observations — speculating mostly on the astrological and/or theological implications of the comet's appearance. Two editions of one such 23-page tract published in Strassbourg had simply the initials "E. W. W. I. G. F. V. D." given to "identify" the author (Anonymous 1596c, d). The title-page diagram appears identical to that in the tract by Greiff (1596), which was published in Erfurt, and includes a tailed comet with what appears

[120] that is, when it is at solar elongations > 20°; ephemeris data perused in various editions of the annual *Astronomical Almanac*

[121] These ephemeris calculations were via the JPL *Horizons* program (Giorgini *et al.* 1996).

[122] This copy of *Progymnasmata* is the first of two tracts under shelfmark FBG-Math 4° a5/6 (2) [Tycho's *De mundi* is the second tract in this volume]. The same library also has a second, unannotated copy of the same edition.

[123] as precessed by Marsden and Williams (2003): T = 1596 July 25.7 TT, q = 0.57 AU, i = 128°

to be a diffuse, broad anti-tail. Another anonymous pamphlet on the 1596 comet without substantive observations includes a title-page woodcut with astronomers using instruments to look at the comet (Anonymous 1596e). Yet another 8-page theological/astrological pamphlet seems to be confusing the comet with something else seen in Oct. 1595 and through the entire summer of 1596 (Anonymous 1596b). Other mainly astrological and/or theological tracts on the 1596 comet that I found in my library searches include a 22-page French tract by Jean de Seville (1596?), a 24-page German tract by a pastor at Mühlberg (located in the modern Bundesland of Brandenburg) named Johann Faust (1596), and a 16-page German pamphlet by Sebastian Greiff (1596) of Erfurt. The most interesting aspect of an 8-page pamphlet written by George Henisch (1596) is the title-page diagram depicting what appears to be two different types of tail on the comet.

8.8.7. Closing Remarks on the Comets of 1580-1596

We see from this that some observations of the six comets observed during 1580-1596 and logged in Tycho's books were made by some other observers, some of which may have benefitted from the ongoing correspondence on the 1572 supernova and 1577 comet. The nineteenth century saw a flurry of activity regarding Tycho's comet observations that ultimately ended with the publication of the entire manuscript of seven comets by Friis in 1867. Additional useful bibliography on these comets can be found in Carl (1864) and Galle (1894, pp. 160-161). As none of these six comets has had modern orbital analyses (the most recent such calculations having been made in the 1870s), re-reducing all of the available observations (meaning also those made by observers *not* included by the 18th- and 19th-century orbit computers) via modern star catalogues is a worthy future goal.

Chapter 9: A Seventeenth-Century Comet Example: C/1661 C1 and C/2002 C1 = 153P

The impact of Tycho Brahe on comets was immense prior to Newton. Other chief players in this arena included Kepler (supernova of 1604, comets of 1607 and 1618), Hevelius, Lubienietz, and Hooke. There were numerous important minor players, as well. But the standardization of observing was catching on, and with new star and better catalogues being published (particularly with the aid of the telescope in the late 17th and early 18th centuries), this would rapidly change the precision of cometary astrometry. It is no coincidence that comets form an important cornerstone of Newton's *Principia*, helping him to formulate the concept of gravitation.

We are fortunate that the pre-eminent comet observer of the seventeenth century, Johannes Hevelius, carefully observed the 1661 comet. Hevelius was a very serious observer who built a large observatory and wrote about his astronomical observations in numerous books.[124] Hevelius' masterpiece on comets is his *Cometographia*, published in 1668, and this includes a lengthy section on the 1661 comet (pages 718ff).

Hevelius made a long series of distance measures between the comet and various reference stars, beginning 1661 Feb. 3 and ending on Mar. 10 (82 total such measures on nine different nights). This extensive program for observing a comet had not been seen since Tycho Brahe's own efforts in the late sixteenth century. Hevelius also recorded measurements of the altitudes of the comet and various reference stars, and he recorded the time of his observations to the nearest minute (and sometimes to the second!) for every observation. Hevelius described the comet's appearance, and provided drawings of it from night to night (see Figures 9.1 and 9.2). The comet's conspicuous tail on Feb. 3 was about 6 degrees long, shortening to about 4 degrees two nights later. On the first five nights, Hevelius' drawings show the tail expanding outward in width away from the coma (narrower than the coma diameter at the head) before tapering again at the extreme tip. From Feb. 13 onwards, the tail tapers from the coma outward. The appearance is suggestive of both ion and dust tails being present prior to Feb. 13, while indicating mainly an ion tail thereafter (no tail was depicted toward the end of the observing period (Feb. 20, Mar. 10, and 28). Hevelius also noted that the comet was around fifth magnitude at the end of February and early March.

[124] For background on Hevelius, see MacPike (1937). Another good source is *Johannes Hevelius and His Catalog of Stars* (Provo, UT: Brigham Young University Press), published in 1971.

Table 9.1 contains reference stars used by Hevelius for the 1661 comet, reduced to epoch 1661.2 using proper motions from the recent Hipparcos/Tycho satellite catalogue.

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Table 9.1. Reference Stars Used by Hevelius for 1661 Comet (Epoch 1661.2, Equinox 2000.0)

Modern Star Designation	R.A. (2000.0) h m s	Decl. ° ' "	Mag. V	Hevelius' Description
alpha Aql	19 50 34.72	+08 49 55.3	0.8	Lucida Aquilae
beta Aql	19 55 17.74	+06 27 07.5	3.7	Collum Aquilae
gamma Aql	19 46 15.22	+10 36 48.8	2.7	Humerus Aquilae
mu Aql	19 34 00.51	+07 23 36.8	4.4	boreali Stell. alae Austr.
sigma Aql	19 39 11.59	+05 23 53.2	5.2	ab Australiori (to mu Aql)
beta Aqr	21 31 33.02	-05 34 14.0	2.9	Humerus sinister
alpha Cyg	20 41 25.86	+45 16 48.7	1.8	Caudae Cygni
delta Cyg	19 44 57.09	+45 07 34.5	2.9	ancone alae Bor./sup. Cygni
epsilon Cyg	20 46 02.98	+33 56 21.0	2.5	ancone alae Austr./infer. Cygni
zeta Cyg	21 12 56.01	+30 14 00.0	3.2	extrema alae Austr. Cygni
omicron1 Cyg	20 13 37.77	+46 44 28.2	3.8	Praeced. in ped. boreali Cyg
alpha Lyr	18 36 50.51	+38 45 23.9	0.0	Lucida Lyrae
alpha Oph	17 34 53.52	+12 34 51.6	2.1	Caput Serpentarii
nu Oph	17 59 01.83	-09 45 45.8	3.3	Infer. in dextr. manu Serpent.
eta Peg	22 42 59.80	+30 13 25.3	2.9	Dextro genu Pegasi
eta Ser	18 21 30.99	-02 49 58.3	3.2	Penult. Caud. Serpentis

Figure 9.1. Hevelius' drawing of the 1661 comet moving through Delphinus and Aquila. Note that the tail virtually disappears by the last time he saw the comet.

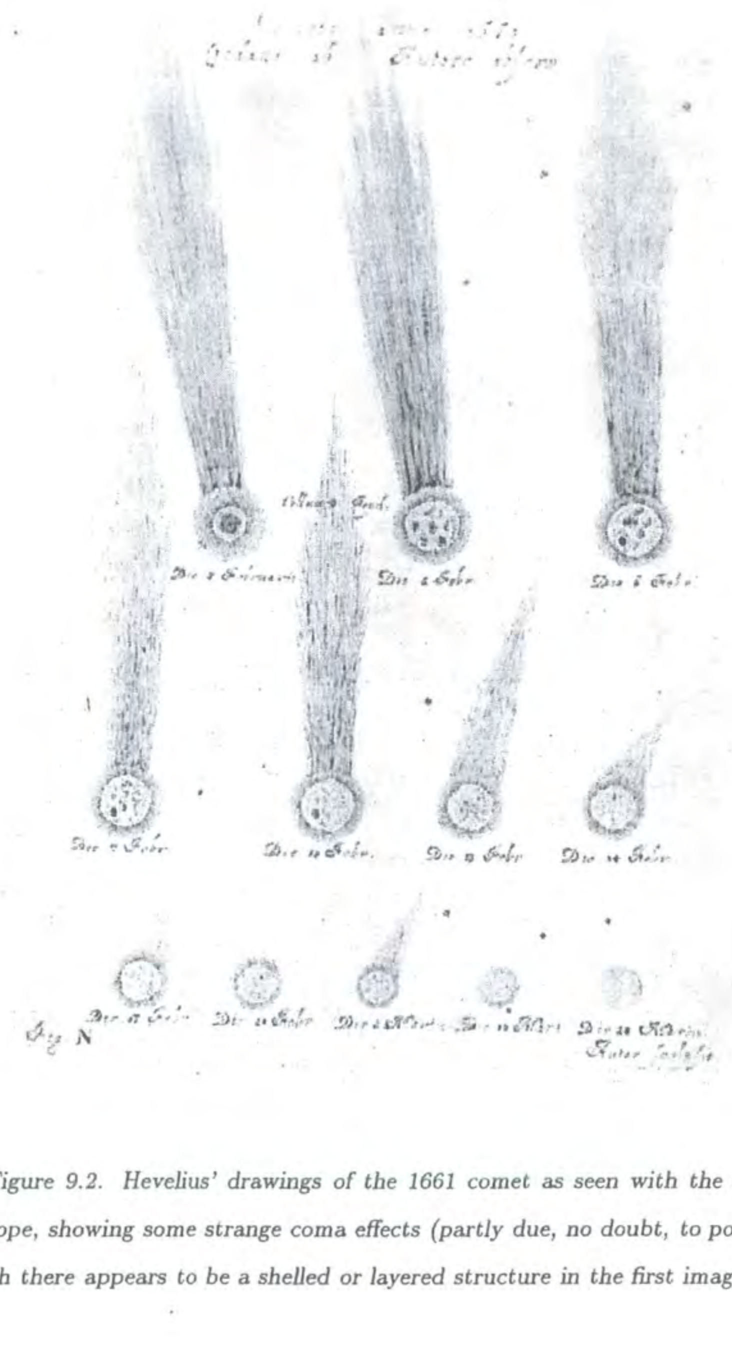

Figure 9.2. Hevelius' drawings of the 1661 comet as seen with the aid of his telescope, showing some strange coma effects (partly due, no doubt, to poor optics, though there appears to be a shelled or layered structure in the first image).

I reduced all of Hevelius' comet-star distance measures, acquiring 47 sets of times, right ascensions, and declinations. He identified stars by their Latin designations in the ancient (not-very-standard) system, so some considerable time was spent identifying the stars. As with the other reductions that I have done for distance measures to supernovae and comets from reference stars, I extracted the modern catalogue positions (usually from Tycho/Hipparcos), applied specified proper motions back to the observation epoch, and reduced the observations for equinox of date before precessing back to J2000.0. The 47 reduced observations by Hevelius are given below in Table 9.2; all were published in the July 2002 *Minor Planet Circulars* (Green 2002c), except those with asterisks. The residuals are shown with respect to the orbital elements in Table 9.3, and the elongation from the sun (in degrees) is shown to indicate how close to the sun the comet was when the observations were made. Refraction has not yet been employed with these observations, but this may be a good candidate for such an attempt, given the careful timings of the observations by Hevelius (along with various altitude measures). The rather systematic residuals in Table 9.2 (negative-to-positive-to-negative signs on the $O-C$ residuals for α, and nearly-all positive $O-C$ residuals for δ) are suggestive of the presence at some level of nongravitational forces.

Table 9.3 contains the orbit for epoch 1661 Feb. 2.0 TT, computed by B. G. Marsden (and published to lower precision in Marsden and Williams 2003, p. 110), from 1513 observations spanning the years 1661-2002; this orbit was the first to represent my newly reduced data (from Table 9.2), used for computing the linked orbits and permitting the comet to be formally numbered as comet 153P/Ikeya-Zhang (comets prior to the 1780s have not traditionally been named, thus the lack of Hevelius' or anybody else's name from 1661) via the criterion of two well-observed apparitions (Marsden 2002b). Marsden, Syuichi Nakano of Japan, and I all consulted together in the orbital computations of the linked comet. Nakano, working subsequently with Ichiro Hasegawa, found (but was unable to definitively prove) possible linkages of comet 153P to comets observed in Asia in 877 and 1273 AD (Hasegawa and Nakano 2003).[125]

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[125] Nakano's orbital elements for 1661 and 2002 epochs are also given in this *MNRAS* paper.

Table 9.2. Reduced Hevelius observations of the 1661 comet

(with residuals based on the orbit in Table 9.3)

Date	(UT)	R.A. (2000.0)	Decl.	O-C		Elong.
		h m s	° '	m	'	°
1661 02 03.184		20 43 35	+04 46.7	1.8-	8+	22.3
*1661 02 03.190		20 44 14	+05 28.0	1.1-	49+	22.3
*1661 02 03.198		20 44 49	+04 45.8	0.4-	6+	22.3
1661 02 05.163		20 32 05	+05 45.0	0.4-	10+	25.4
1661 02 05.173		20 32 05	+05 46.5	0.4-	11+	25.4
1661 02 05.181		20 31 52	+05 48.1	0.5-	12+	25.4
1661 02 05.188		20 32 01	+05 37.8	0.3-	2+	25.5
1661 02 05.194		20 32 03	+05 39.2	0.3-	3+	25.5
1661 02 05.206		20 30 37	+05 40.3	1.6-	4+	25.5
1661 02 06.178		20 25 56	+06 08.7	0.5-	11+	27.1
1661 02 06.182		20 25 51	+06 02.7	0.5-	5+	27.1
1661 02 06.197		20 25 17	+06 04.1	1.0-	6+	27.1
1661 02 06.210		20 25 54	+06 00.1	0.3-	2+	27.1
1661 02 06.216		20 25 52	+05 58.3	0.3-	0	27.1
1661 02 07.153		20 20 22	+06 24.0	0.5-	9+	28.7
1661 02 07.163		20 19 59	+06 25.7	0.9-	10+	28.7
1661 02 07.174		20 20 12	+06 27.1	0.6-	11+	28.7
1661 02 07.183		20 20 28	+06 22.7	0.3-	7+	28.7
*1661 02 07.194		20 19 08	+06 09.1	1.5-	7-	28.7
1661 02 07.200		20 19 20	+06 23.5	1.3-	8+	28.8
*1661 02 10.155		20 05 07	+06 59.4	1.0-	9+	33.5
1661 02 10.162		20 05 37	+06 58.1	0.5-	8+	33.5
1661 02 10.166		20 05 52	+06 55.8	0.2-	6+	33.5
1661 02 10.173		20 06 01	+06 54.1	0.1-	4+	33.5
1661 02 10.183		20 05 59	+06 54.8	0.0	5+	33.5
1661 02 10.189		20 05 37	+06 56.2	0.4-	6+	33.5
1661 02 10.195		20 05 35	+06 54.1	0.4-	4+	33.5
*1661 02 10.203		20 04 54	+07 13.5	1.0-	23+	33.6
*1661 02 10.208		20 04 42	+06 58.9	1.2-	8+	33.6
1661 02 13.143		19 54 50	+07 07.0	0.3+	5+	37.9
1661 02 13.155		19 55 56	+07 02.5	1.4+	0	37.9
1661 02 13.171		19 55 13	+07 06.0	0.7+	4+	38.0
1661 02 13.185		19 55 22	+07 05.1	0.9+	3+	38.0
1661 02 20.081		19 37 19	+06 49.5	0.4+	5+	46.8
*1661 02 20.114		19 39 16	+06 53.9	2.4+	9+	46.9
*1661 02 20.151		19 39 36	+06 58.1	2.8+	14+	46.9
1661 02 20.157		19 38 38	+06 57.6	1.9+	13+	46.9
*1661 02 20.158		19 37 12	+07 04.2	0.4+	20+	46.9
1661 03 02.116		19 24 26	+05 45.8	0.2+	1+	57.7
1661 03 02.123		19 24 42	+05 44.4	0.4+	0	57.8
1661 03 02.135		19 24 01	+05 45.4	0.2-	1+	57.8
1661 03 02.143		19 24 14	+05 46.4	0.0	2+	57.8
*1661 03 02.151		19 25 15	+05 40.9	1.0+	4-	57.8
1661 03 10.072		19 16 14	+05 02.5	2.1-	5+	65.9
*1661 03 10.079		19 15 16	+05 08.3	3.0-	11+	65.9
1661 03 10.088		19 15 27	+05 05.6	2.8-	8+	65.9
*1661 03 10.095		19 15 01	+05 04.1	3.3-	7+	65.9

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Table 9.3. Orbital elements from the linked orbit of comets 153P/2002 C1 and 153P/1661 C1

Epoch	1661 Feb. 2.0 TT	
Perihelion time	1661 Jan. 28.983833 TT	
Arg. of perihelion	35.065211	
Long. of asc. node	93.408170	(2000.0)
Inclination	28.068933	
Perihelion distance	0.51293728 AU	
Eccentricity	0.99026703	
Orbital period	382.59 yr	

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9.1. Other Observers of Comet C/1661 C1

Eberhard Welper of Strassburg produced several publications of the comet of 1661, which included illustrations and observations made evidently with a quadrant (Welper 1661a, b, c). As early as 1618, Welper had made measurements of the distances between a comet and reference stars with the aid of an astronomical radius and a quadrant on at least six nights — giving fully five comet-star distance measures (only to the nearest half-degree, however), and one distance measure between Mars and the comet, on 1618 Nov. 27, recording a 30° tail and stating the comet's derived ecliptic coordinates (Welper 1619). He also published in Nuremberg an undated tract on the use of the quadrant,[126] and he authored a tract on the 1652 comet (Welper 1653). But for some reason, Welper's distance measures between the 1661 comet and two reference stars on each of four nights were only given to the nearest degree, and they produce positions for the comet that are substantially in error (on the order of several degrees for the worst ones).

On Jan. 29 at 5 a.m., Welper (1661a) records the first observation by saying that the comet was 10° from "Collo Aquilae" (the neck of Aquila the eagle, most likely what we now know as β Aql) and 12° from "cauda Delphini" (the tail of Delphinus, probably ϵ Del); the comet was noted as being 8° above the east horizon. Doing the calculations, one sees that the date was given on the old-style calendar, as the comet was not above the horizon on Jan. 29 but indeed it was at 9°.3 altitude at 5 a.m. local apparent solar time on Feb. 8. (We also can note that the comet would have been at 8° altitude at 4:52 a.m. in Strassburg, but it would not be prudent to speculate that the clock was off by 8 minutes with the lack of confidence in the altitude reading — whether from error in the actual measurement or from error in the observer's knowing his true horizon.) On Jan. 30 at the same time, the comet was 10° above the horizon while located 8° from "media sive collo Aquilae" and 11° from "cauda Delphini"; on Jan. 31 at the same time, the comet was 12° above the horizon while located 7° from "lucida Aquilae" (α Aql) and 9° from "cauda Delphini". Welper's last observation (page 8) was at 5 a.m. on Feb. 1/11 (*i.e.*, Feb. 11 new-style calendar)

[126] in the Wolfenbuettel library under shelmark 55.1 Astronomica (3)

with the comet at altitude 15° while also 4° from "spendida Aquila" (presumably also α Aql) and 8° from "cauda Delphini". On page 18, it is stated that the comet was less bright than a star of second magnitude.

Another curious aspect to these observations is Welper's use of the ancient system of star designations, while in his 1653 book he clearly refers to Bayer's 1603 star atlas for identifying stars. Arguably, the ancient Ptolemaic designation system leaves open much more possibility of misidentifying stars than the use of standard designations from widely used charts. But this illustrates, as also via Hevelius' own usages, that it took many years for Bayer's Greek-letter designation scheme to be widely used.

Abdiam Trew, Professor of Mathematics and Physics at the Universitaet Altdorff Mathematum, published a tract (Trew 1661) on the comet seen at end of Jan. and start of Feb. 1661, which has nice fold-out diagrams showing the comet's motion with respect to various stars (Feb. 7, 8, 9, 10, 11 new-style) and spherical-trigonometric diagrams; the text contains values of longitude, latitude, right ascension, and declination, and among other measures. Included in at least two copies of this tract by Trew[127] is a fold-out page entitled "Die Erste OBSERVATION dess Cometens/Gehalten in Strassburg den 29. Jenner. . . .", with a square diagram having the constellation "Adler" on the left, "Delphin" on the right, the comet below and between them, little people at bottom right, and a little village at bottom left — with "Durch M. E. W. Math." at the bottom; immediately after *this* is a 4-page piece entitled "Warhafftige Beobachtung . . ." This appears to be the same as two publications attributed to Welper (1661b, c). Another completely unauthored, undated tract with no publisher information, with the same woodcut as given with Trew (1661) and containting a section on the observations of the 1661 comet by other observers — for example, noting that a "Patribus S.J." (Jesuit father) at Augsburg observed the comet on Feb. 1 (new-style), and stating that an observer at Olmuetz on Feb. 8 found the comet to be 5°20′ from "dem hellen Stern auf der Schulten des Alders".[128] The "M. E. W." obviously is Eberhard Welper, but the text is unclear on what roles Trew or Welper or a possible third person had to do with its publication and content.

Other anonymous tracts were also published on the 1661 comet, some of which contain observational material. One 4-page unnumbered gothic-lettered pamphlet in German included an inserted a fold-out broadside entitled "Kurtze Auffinerckung ueber den COMET-Stern/welcher sich dess Morgens in diesen Landen gegen Suedt-Osten sehen lassen/im Jahr 1661" has a figure showing a comet observed at 3 a.m. on 1661 Jan. 27 in Aquila.[129] This broadside depicts the comet

[127] Wolfenbuettel library copy with shelfmark L294.4° Helmst. (15); Danmarks Natur- og Laegevidenskabelige Bibliotek (Universitetsbiblioteket) copy with shelfmark 4°/18780 Kometen 1661 [tract 2].

[128] *Die Erste Observation dess Cometens/Gehalten zu Strassburg den 29 Jenner dess lauffen den 1661 Jahrs/Morgens umb 5 Uhr* (Crawf library copy with shelfmark CR.C1.145).

[129] The tract is titled *Beschreibung Des newen Liechts/so Anno 1661 ueber halben Jenner ange=fangen sich sehen zulassen/und den 11 Febr. darauff das letzte mahl gesehen worden/umb und zu Augspurg; wie auch zu Nuernberg und Strassburg/von dannen/den 17 und 18 Febr. zu Augspurg Zeitung eingelanget* (Augspurg: bey

at centre top with a bright head and a not-so-bright and not-so-long tail (like a gas tail), with a walled city at the left and people at bottom (and bottom left) looking at/pointing to the comet (see Figure 9.3). Images of this same comet in 2002, taken by world-renowned comet photographer Michael Jäger, are shown as Figures 9.4, 9.5, and 9.6 — where the varying nature of the comet's tail over time is very evident.

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Figure 9.3. Woodcut of comet 1661 from a broadside (courtesy Crawford Library). Note the narrow tail suggestive of a gaseous ion tail.

Johann Schultes) [Crawford Library copy with shelfmark CR.C1.142; DNLB copy with shelfmark 4°/18780 Kometen 1661 (tract 4)]. The broadside alone is in the British Library, under shelfmark 8563.aaa.34 (tract 12 of 18). The same British Library volume contains another broadside between tracts 13 and 14, "Abbild-und Beschreibung des Cometens . . .", discussed in the following text.

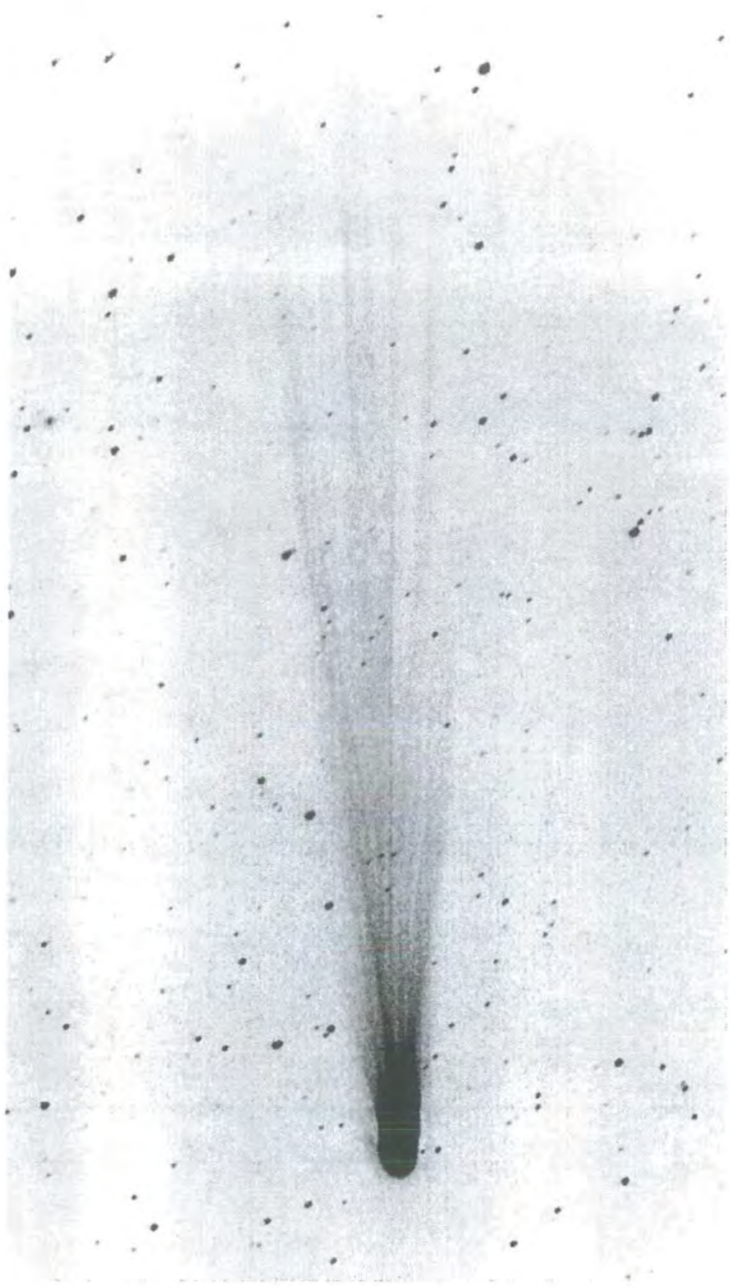

Figure 9.4. Photograph of comet C/2002 C1 (= 153P/Ikeya-Zhang) taken on 2002 March 10 near Vienna, Austria, with a small telescope. Note the fine streamers in the tail. Courtesy Michael Jäger.

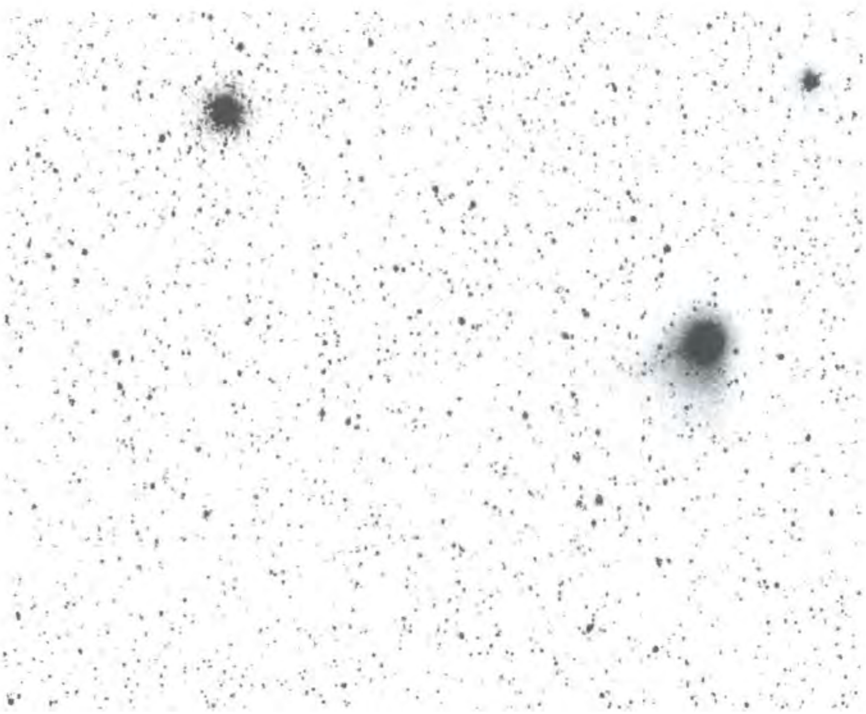

Figure 9.5. Photograph of comet C/2002 C1 (= 153P/Ikeya-Zhang) taken on 2002 May 18 near Vienna, Austria, with a small telescope. Note the fine streamers in the tail. Note the long, narrow ion tail extending from the comet's head (at the right) toward the lower left, and the short, stubby, wider dust tail extending downward from the coma. (At upper left is the globular star cluster M13.) Courtesy Michael Jäger.

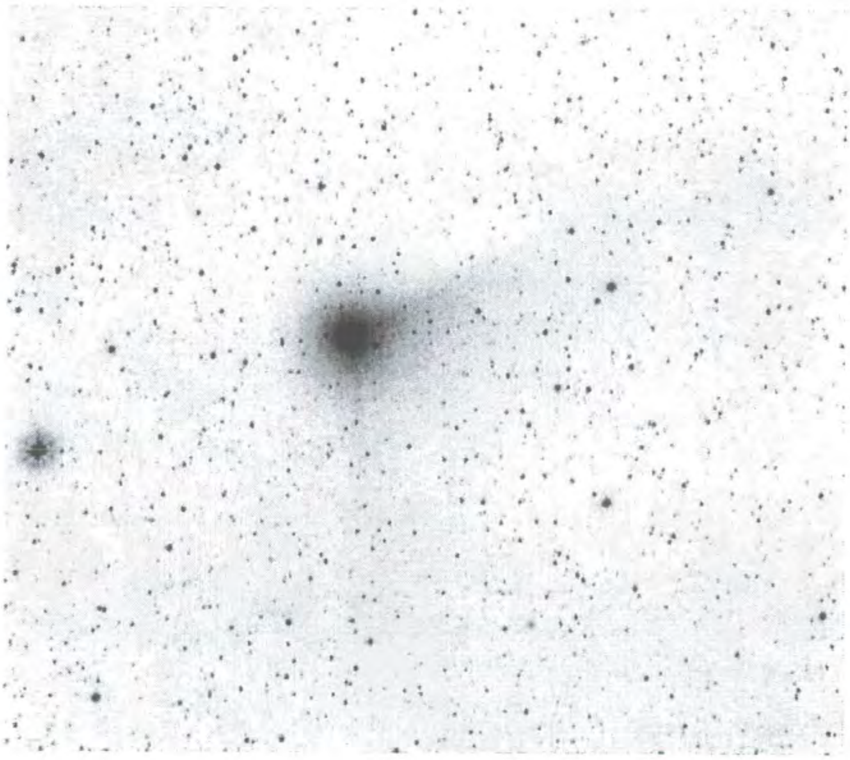

Figure 9.6. Photograph of comet C/2002 C1 (= 153P/Ikeya-Zhang) taken on 2002 May 30 near Vienna, Austria, with a small telescope. By now, the gas/ion tail has nearly disappeared (pointing downward in this view), but the dust tail now appears longer (toward the upper left). Courtesy Michael Jäger.

Another broadside sheet entitled "Abbild-und Beschreibung des Cometens weltcher, durch ober-und nider-Teuetschland, etc: im Ienner 1661 gesehen worden", says that the comet was visible on the morning of Jan. 25 (evidently old-style calendar) at 4 a.m. in Zuerich, seen also through a "Fehrnglas"; it shows the comet between Delphinus and the head of Aquila head, and at the right of this image, it indicates that the body of the comet was between second and third magnitude in brightness. Curiously, this anonymous broadside (with no publisher given) appears immediately after Welper's (1661a) tract in the same bound volume in the British Library, but the two printings are not obviously related.

A 24-page tract by Michael Cruegener (1661?) of Dresden, found in the British Library,[130] remarks that others saw the 1661 comet first on Jan. 28 (old-style N12 calendar) at 4 a.m.; Cruegener himself saw it first on Jan. 29, and he describes its position with respect to constellation stars without giving any distances, as well as the size and brightness of the tail. George Fehlauen (or Feylauen), a preacher at the Marien-Kirchen in Danzig, published a tract in March 1661 in which he says that the comet was first seen on 1661 Feb. 3 with a tail that was 1° long (Feylauen 1661).

Caspar Marchen, Professor of Medicine and Mathematics apparently at Rostock, wrote a tract in February (published in at least two different typesettings, evidently) with not much useful observational material, but immediately after the Wolfenbuettel library copy[131] is an untitled page with a picture of constellations (Aql, Sge, etc.) and the comet by Aquila's neck that does not obviously belong to the Marchen piece; Dantzig is mentioned for Jan. 24 (o.s.) = Feb. 3 (n.s.) in the text, so perhaps it has something to do with Hevelius(?).

Peter Megerlin, a man with degrees in law and philosophy, published a couple of rambling tracts — a 15-page one in Latin (Megerlin 1661?) and a 20-page one in German (Megerlin 1661a?), both in the British Library.[132] Both tracts have the same title-page woodcut showing the comet for three dates with its tail depicted on a longitude/latitude grid as it passed between Del, Aql, and Antinous. Megerlin remarked that he observed the comet on Jan. 30 with an "optic tube" (telescope), which he says showed a forked tail. He called the comet's light feeble to the naked eye, only like the brightness of a second-magnitude star. He then produces what appears to be a letter written from Stephan Spleissen (Rector of the Gymnasium at Schaffhausen) to him on Feb. 5,

[130] shelfmark P.P.2370 (tract 15 of a great many in a huge volume of tracts)

[131] shelfmark L294.4° Helmst. (14)

[132] The Latin tract is the ninth tract in a volume of 18 tracts with shelfmark 8563.aaa.34, while the German tract is the tenth tract. Between these two tracts in the bound volume is a 1-page diagram, with a landscape of hills, castles, fields, and a big complex like a monastary labelled with "Colleg. Ienense", and a man at lower-right corner looking at the tailed comet off the head of Aquila in upper left corner, with a table upon which lie a book, globe, armillary sphere, quadrants, etc., at the bottom; an angel at upper right has a shield that reads "Erhard Weigels Math. P.P. Zur betrachtueng des Himmels an Puehrender Comet. Anno 1661.", while at the bottom is written "In verlegueng Thomi Maetthi (Goetzens?) and Johann Duerr sculpsit." A possible connection between Megerlin and Weigels is unknown; Weigels' tract is discussed in the text below.

stating that the comet was observed on Jan. 30 at 5 a.m. with a tail and with the body being seen via naked eye as between second and third magnitude in brightness.[133] Johannes Placentinus, a professor of mathematics at the Universitaet zu Frankfurt an der Oder, wrote a small tract on the 1661 comet, in which he mentions an observation by Johan Hewelcken of Danzig who diligently observed the comet on Feb. 3 (new-style) at 6 a.m. in the eastern sky, using a "handsome and expensive instrument" and noting a long tail — but not giving much else useful observational data (Placentinus 1661).

One other, more-lengthy tract on the 1661 comet worth mentioning is that by Erhard Weigel, Mathematics Professor at Jena and at Weimar. This publication includes a poorly printed white-on-black diagram showing the comet's position and appearance on four nights while it moved northward through or near the noted constellations Sge, Aql, Del, and Antinous, with an apparent attempt to be fairly to-scale, and he notes that he used Bayer's *Uranometria*. The first-page diagram in the Wolfenbuettel library copy has an angel depicted with a shield that reads "Erhard. Weigels Math . . . Comet Anno 1661".[134] Weigel later says that the comet was first observed on Feb. 1, providing some ecliptic latitude and longitude values for the comet, but not much that can be used today to reassess the data. As noted with the Megerlin tracts above, figures are sometimes misbound in these old books, and one must be careful about authorship and context. Stanislaus Lubienietz (1667, p. 436) included some of Weigel's observations that curiously do not appear in Weigel's own tract, indicating that there may have been some correspondence between the two men. On Feb. 8 (possibly at 3:40 a.m.), Lubienietz indicates that Weigel found the comet to be $5^{\circ}20'$ from the "stella ista lucidiori secundae magnitudinis (quae in medio Aquilae exactè humero ascripta est, & aliàs plerumque Aquilá aicitur)" — apparently long-hand for Altair (α Aql).

The first orbit computed for the 1661 comet was that by Edmond Halley (1705a, b), but unfortunately he did not give clear accounts of where he got his observations nor what actual observations he used. Though Halley computed only a parabolic orbit, he speculated (as he did with the comet named after him, correctly) that the 1661 comet had elements similar enough to those of the 1532 comet that they might be the same comet. Halley does state that he used the 1661 observations of Hevelius (1705b). Halley was not entirely satisfied with the quality of

[133] Spleissen was also involved with a Rev. Menzinger in publishing a tract on the 1664 comet, in which was included a diagram showing that comet with a long tail, noting as being apparently 23° long at 4 a.m. on Dec. 17. Spleissen writes that he used a quadrant to determine that the comet was $30^{\circ}40'$ from "Cor Hydrae α" (of Bayer's *Uranometria*, which he cites) and $14^{\circ}20'$ from γ Crt on Dec. 20. He noted the comet as bright as the star Arcturus. This undated 16-page tract (with no publisher or location given) is titled *Beilaeufftiger Bericht von dem jezigen Cometsternen wie solcher In disem zu end lauffenden 1664. Jahr/bei anfang dess Christmonats/in Schaffhausen und benachbarten Orten beobachtet worden/ . . .* is the last tract in a bound volume of 18 tracts in the British Library under shelfmark 8563.aaa.34.

[134] The Wolfenbuettel shelfmark is 42.1 Astron (7). This differed from the copy that I saw in the Crawford Library, shelfmark CR.C1.149, in the placement of the figures in the book, and this first-page figure in the Wolfenbuettel copy seems missing from the Crawford copy.

Hevelius' observations of the 1664 comet, writing to Newton on 1695 Sept. 7 that "for want of Telescope sights, Hevelius could not sufficiently distinguish the Nucleus thereof" (via Scott 1967, p. 165) — Robert Hooke maintaining that "it were not possible with these Sights (be the Instruments never so large or accurate) to make Observations nearer then to Two or Three whole Minutes" (*op.cit.*, p. 166). This proposed linkage was taken seriously by astronomers for quite some time. Nicolaas Struyck (1740, pp. 11 and 263), after noting Halley's suggestion, suggests that, with a 129-year period, the 1661 comet may be identical not only with the 1532 comet but also those seen in 1402, 1274, 1145 or 1146, 1018, 891, 762, 632, 504, 375 AD, 12 BC, and 525 BC! Even as improbable as this suggestion sounds to us today, it shows how astronomers were excited at the new understanding of comets having predictable orbits about the sun. Today we know of only two comets [135] that have appeared at numerous returns dating back to more than a millennium ago: comets 1P/Halley (30 accepted apparitions back to 240 BC, at intervals of $\approx$ 77-78 years) and 109P/Swift-Tuttle (five accepted apparitions back to 69 BC, at intervals of $\approx$ 130 years). The third- and fourth-place comets, in terms of multiple-apparition comets with the earliest accepted observed appearances, are 55P/Tempel-Tuttle (first seen with high certainty in 1366, and seen only four times since then, despite its orbital period of $\approx$ 33 years) and one of the comets focused upon in this thesis, 153P/Ikeya-Zhang (first seen with high certainty in 1661). Most comets with short enough orbital periods for multiple apparitions in recorded history are simply not bright enough intrinsically to be detected easily by naked-eye observers, and so could not have been seen with the frequency that Halley and Struyck (and others) assumed might be possible in that early era of the modern science of comets.

The most complete account of the orbital calculations done on the 1661 comet, prior to the discovery of comet P/2002 C1 (Ikeya-Zhang), was that given by Méchain (1785), who provided detailed reduction of all of Hevelius' observations. Méchain then discussed Halley's work and gave new elements for the 1532 comet. (Mechain uses time counted from noon on previous day.)

Halley evidently had such respect for his work that, a few decades later, the Astronomer Royal Nevil Maskelyne (1786) wrote that "there is no reason to doubt that all the other comets [suggested by Halley as periodic] will return after their proper periods, according to the remark of the same author". Maskelyne was writing to suggest that, since "Halley's comet" had return as Halley had predicted in 1759, this "linked" 1532/1661 comet would return in 1788. He noted that the Royal Academy of Sciences in Paris had offered a prize of "6000 livres" for satisfactory answers concerning calculations of the planetary gravitational "disturbances of the comet of 1532 and 1661, and thence to predict its return", so it was taken quite seriously indeed! Maskelyne remarks that Halley's orbit, which he uses to produce a search ephemeris for 1788, was determined from the observations of Hevelius in 1661 (Maskelyne simply precessing the elements and assuming the time

[135] As of mid-2004, there were 1168 comets observed by groundbased observers in all of recorded history having published orbital elements (based on Marsden and Williams 2003, plus comets discovered since this 15th edition of the *Catalogue of Cometary Orbits* was published).

of perihelion as 1789 Jan. 1). Maskelyne ends his paper with a curious attempt to estimate how bright the comet might appear in 1788 (and thus how large a telescope might be needed). Sir Henry Englefield (1788) published a short tract giving tables of predicted positions for various times of perihelion from 1788 Aug. 25 to 1789 Aug. 12; he basically took the orbit given to him by Maskelyne for the "1532/1661" comet, rather than working with the original observations himself to compute an orbit. Englefield's text and tables are followed by a huge, fold-out diagram (with several folds) of the comet's neatly drawn orbit with respect to the earth's orbit. When Johann Gottfried Galle (1894, pp. 10 and 162) collected the two known orbits for the 1661 comet (those by Halley and Méchain), he remarked that Welper's observations from Jan. 29 to Feb. 1 appear in the *Astronomische Jahrbuch 1788* (p. 195), and noted that the prediction of a linked 1532/1661 comet in 1759 was not observed. While Olbers did much work on the 1532 comet, in regard to linking it with the 1661 comet for a possible 1789 return, he did not do anything further with the 1661 observations (Olbers 1787; Olbers and Schilling 1894).

Chapter 10: The Comet of 1783 and Comet P/2003 A1

Early in 2003, a "new" comet was discovered by the LINEAR survey, a search project that scans the sky with CCD-camera detectors each clear night to search for minor planets that pass near the earth. The detectors are mounted on U.S. Air Force telescopes in New Mexico that are operated by the Lincoln Laboratory of the Massachusetts Institute of Technology (Stokes *et al.* 2002). That comet found in January 2003 was initially reported as "asteroidal" (i.e., not diffuse and/or not showing a tail that would be typical of cometary appearance) by the LINEAR team, but its motion was deemed unusual and it was posted on the Minor Planet Center's website (cf. Marsden and Williams 1998). Follow-up observations then showed it to be slightly diffuse, and it was designated comet C/2003 A1 and announced to the world in the course of my daily work with the International Astronomical Union's Central Bureau for Astronomical Telegrams (IAU CBAT) at the Harvard-Smithsonian Center for Astrophysics (Green 2003a). The initial short 4-day arc used for the first orbit of comet C/2003 A1 was assumed as a parabola, though it was soon recognized that it was likely of short period and that the orbital elements of the new LINEAR comet were similar to those of comet D/1783 W1 (Pigott), the 'D/' prefix indicating that the comet was long-lost (i.e., its location totally unpredictable, and possibly even defunct — many comets have been seen to break apart and essentially to cease existing as minor-planet-like bodies).

It is customary today that we compare preliminary orbital elements of newly discovered comets with those elements of lost short-period comets, for purposes of naming (it is preferred that lost comets with names continue to be known by only those names if at all possible; cf. Green 2003b). When a new orbit was published by Marsden (2003) a week later, there were enough astrometric observations to definitely show that the comet was of short period (with an orbital period of 7.1 years, which held up through later orbital calculations including the three full months of observations available at that return to perihelion), and it was assigned a 'P/'-prefixed designation (i.e., P/2003 A1), as is usual for such objects (Marsden 1995a). While P/2003 A1 would normally have been named 'LINEAR', the CBAT took the unusual step of recommending to the IAU Committee on Small Bodies Nomenclature that comet P/2003 A1 remain unnamed until it could be shown definitively that it is or is not the same as comet D/1783 W1.

Given the work that I was doing on my Ph.D. thesis regarding the modern reduction of older comet observations, it seemed natural to make the effort to find the old observations of Pigott's comet and to reduce them to see if they would help resolve the problem of P/2003 A1. This work

is thus presented here as a separate chapter of this thesis.

10.1. The Comet of 1783: Observations

Edward Pigott (1784a) of York, England, discovered a comet (now designated D/1783 W1) on the night of 1783 Nov. 19-20. His observations on six nights, together with those on two nights by John Goodricke (also of York, according to Pingré 1784), were conveyed in a letter to the Rev. Nevil Maskelyne, then Astronomer Royal (Pigott 1784b). Pigott commented on "the faintness of the comet's light", and noted that the astrometry of Nov. 20, 24, and 26 were made with a transit instrument, while those on Nov. 26 and Dec. 3 were made with a Dollond 2.5-foot "night glass" with a magnification of 20×. The coma had a diameter of about 2′ on Nov. 21. He later determined the positions of his reference stars from observations made with "the meridian instruments"; he was "much chagrined in not being able to see the comet in our equatorial when the [cross-hair] wires were illuminated." Pigott added that "the comet had exactly the appearance of a nebula: its light was so faint that it could not be seen in a good opera glass"., observing further that "in the night-telescope, the nucleus was scarcely visible, and the diameter of the surrounding coma was about three minutes of a degree" (date for this not specified). He found a slight decrease in brightness between Nov. 19 and 26, and on Dec. 1 and 3 found the comet "very difficult to be seen, occasioned perhaps by its little elevation above the horizon". Moonlight made the comet invisible on Dec. 3 and 10. Though stars of eighth or ninth magnitude were visible on Dec. 10, he could not find the comet.

P. F. A. Méchain discovered the comet independently on 1783 Nov. 26 at 9 p.m. at Paris, and an hour and a half later he determined his first position. After another four hours, he found that the comet had moved a dozen or more arc minutes to the northwest. Charles Messier, also in Paris, evidently began observing the comet the following night after having been alerted to it by Méchain. Both Méchain (1786) and Messier (1786) recorded positional measurements of the comet until Dec. 21.

Table 10.1 lists the original observations by Méchain (1786).

Table 10.1. Observations of D/1783 W1 by Méchain

1783	*Temps moyen*	*Star description*	*Comet's distance from star in α*	*in δ*
Nov. 26	$14^h02^m30^s$	f du Taureau	15°03′43″ W	+ 3′57″
27	11 57 20	104e. étoile des Poissons	12 00 20.5 E	+ 9 43
28	9 59 29	19e. du Bélier	+ 2 52 32	+11 18
29	8 47 49	1 θ du Taureau	31 35 40.6 W	+ 3 31
	12 22 52	4e. du Bélier	8 14 05.8 E	− 9 13.9
Dec. 1	12 07 37	γ du Bélier	+ 5 27 28.6	−16 59
2	7 37 57	1 θ du Bélier	1 13 42 W	+ 3 54.5
11	5 58 49	α du grand triangle	12 24.2 W	−74 34.6
	6 40 49	α du petit	6 37 45 W	−20 38
12	5 54 17	α du grand triangle	− 40 21.6	−25 47.7
13	6 20 46	α du grand triangle	1 07 03.5 W	+22 16.5
14	6 28 15	δ d'Andromède	+16 42 14	− 1 56
18	6 51 13	π d'Andromède	+15 50 20.7	− 3 44.6
19	10 19 48	δ du triangle	9 08 03.6 W	0
21	6 00 42	β d'Andromède	6 54 53 E	+ 6 57.5

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The mean time (MT) reported by Méchain was converted to Universal Time (UT) via UT = MT − λ, where λ is the observer's longitude east of Greenwich (in this case, $\lambda = 2^\circ\!.337$ for Paris, or $2^\circ\!.337/[15^\circ/\mathrm{hr}] = 0.1558$ hr). During the reduction, I confirmed that at least three typographical errors appeared in Méchain's table: (1) the offset in δ for the first observation on Dec. 11 was originally given as +74′34″.6; (2) the offset in δ for the final observation was originally given as +6°57″.5; and (3) the comet's declination for the final observation was given as +31°21′31″, but it should read +34°21′31″ (Méchain's comet positions are deleted here because they were reduced using better, modern star positions). The problems with the final observation were not settled with the proper apparent corrections of the typographical errors; this observation still had to be excluded from the final calculations. The Bayer and Flamsteed star designations specified by Méchain were basically confirmed, so that the stars in the above table are what we now refer to as (from top to bottom in the table): f = 5 Tau, 104 Psc, 19 Ari, θ^1 Tau, 4 Ari, γ Ari, θ Ari, α Tri, 10 Tri, δ And, π And, δ Tri, and β And.

The original observations by Messier (1786) are given in Table 10.2.

Table 10.2. Observations of D/1783 W1 by Messier

Date 1783	Temps Moyen	Difference in position between the comet and the reference stars R.A.	Decl.	Reference star position R.A.	Decl.	Ref. star mag.
	h m s	° ′ ″	′ ″	° ′ ″	° ′ ″	
Nov. 27	7 44 23	-1 44 15	-27 13	35 48 45	+13 35 20	9
	8 22 35	-1 45 28	-25 34			
28	7 28 14	-6 35 30	+ 8 39	39 53 47	+14 10 58	6
	7 59 33	-6 35 15	+10 01			
	8 31 10	-6 38 52	+11 27			
29	7 27 01	+1 28 45	+40 41	31 02 10	+14 48 26	8
	8 10 12	+1 26 45	+42 22			
Dec. 1	7 50 51	+5 35 45	-28 04	25 25 25	+18 13 59	4
	8 16 06	+5 34 45	-27 11			
2	6 51 11	+4 54 45	+33 45			
	7 15 13	+4 53 45	+35 02			
	7 38 39	+4 53 22	+36 12			
3	6 57 03	-0 32 30	-19 30	30 10 54	+20 11 10	6
	7 26 39	-0 33 07	-19 20			
	7 35 53	-0 33 45	-19 14			
12	6 23 16	-0 42 00	-24 56	25 12 08	+28 31 19	4
13	6 15 17	-1 08 35	+22 30			
14	6 02 31	+1 16 52	+41 39	22 22 16	+28 57 00	7
18	8 28 02	-8 57 36	-19 09	31 07 52	+32 50 24	4
19	7 36 56	-9 15 00	+17 13			
20	7 37 45	+7 09 25	-40 39	14 25 16	+34 28 14	2
21	7 35 37	+6 54 13	- 4 46			

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The time of the second observation on Dec. 2 was given erroneously in the printed text as $6^h15^m13^s$. The stars were readily identified (after precession to equinox 2000.0) with stars in the Hipparcos-satellite catalogue, the Hipparcos positions being within an arc minute or two of Messier's star positions in most cases.

The identities of Méchain's original reference stars had to be confirmed by producing star positions from his published offset observations. The Hipparcos-catalogue proper motions were then used to derive star positions for equinox 2000.0 and epoch 1783.9 for all of the Méchain and Messier observations — and, from these, I derived new comet positions, as given in Table 10.3, for equinox 2000.0. The Pigott and Goodricke observations were merely precessed to equinox 2000.0, as they gave no information about the reference stars or offsets from them.

Table 10.3. Reduced Astrometry for D/1783 W1

better observations:

DATE (UT)	R.A. (2000.0) Decl.	Observer
1783 11 20.9481	02 51 20.55 +05 26 52.7	Pigott
1783 11 24.9274	02 37 33.07 +10 33 10.6	Pigott
1783 11 26.9174	02 30 58.99 +13 01 26.1	Pigott
1783 11 27.07858	02 30 25.60 +13 13 15.4	Mechain
1783 11 27.81600	02 28 04.15 +14 06 50.6	Messier
1783 11 27.99166	02 27 28.73 +14 19 32.6	Mechain
1783 11 28.80478	02 25 00.50 +15 18 46.5	Messier
1783 11 28.84848	02 24 47.12 +15 21 36.9	Messier
1783 11 28.90982	02 24 35.76 +15 26 25.0	Mechain
1783 11 29.80394	02 21 54.58 +16 28 59.8	Messier
1783 11 29.83392	02 21 46.63 +16 30 42.1	Messier
1783 11 30.00939	02 21 16.56 +16 43 05.2	Mechain
1783 12 01.82049	02 16 00.49 +18 46 26.1	Messier
1783 12 01.83802	02 15 56.50 +18 47 19.8	Messier
1783 12 01.99880	02 15 27.76 +18 57 36.7	Mechain
1783 12 02.77905	02 13 18.59 +19 48 42.5	Messier
1783 12 02.79574	02 13 14.63 +19 50 00.1	Messier
1783 12 02.81202	02 13 13.16 +19 51 10.4	Messier
1783 12 03.78313	02 10 33.38 +20 53 29.3	Messier
1783 12 11.77185	01 52 09.47 +28 22 06.8	Mechain
1783 12 14.74526	01 46 51.79 +30 43 48.6	Messier
1783 12 14.76313	01 46 53.64 +30 43 56.9	Mechain
1783 12 18.84631	01 41 00.21 +33 37 13.3	Messier
1783 12 19.92392	01 39 43.84 +34 19 46.9	Mechain
1783 12 20.81139	01 38 40.45 +34 53 58.2	Messier
1783 12 21.80991	01 37 40.59 +35 29 58.7	Messier

worse observations:

DATE (UT)	R.A. (2000.0) Decl.	Observer
1783 11 19.9542	02 55 22.02 +04 04 46.5	Pigott
1783 11 22.7798	02 44 51.97 +07 45 28.1	Pigott
1783 11 24.8385	02 37 46.73 +10 27 37.9	Goodricke
1783 11 27.84252	02 27 59.35 +14 08 30.5	Messier
1783 11 28.7508	02 25 07.15 +15 15 45.9	Goodricke
1783 11 28.82653	02 25 01.58 +15 20 08.3	Messier
1783 11 29.86005	02 21 42.59 +16 31 22.0	Mechain
1783 12 02.81153	02 13 11.41 +19 58 49.2	Mechain
1783 12 03.81009	02 10 30.89 +20 53 39.7	Messier
1783 12 03.83068	02 10 28.35 +20 53 46.1	Messier
1783 12 04.1589	02 09 27.76 +21 17 12.4	Pigott
1783 12 11.74269	01 52 10.97 +28 19 30.8	Mechain
1783 12 12.73954	01 50 20.36 +29 08 33.2	Mechain
1783 12 12.75967	01 50 13.77 +29 09 25.8	Messier
1783 12 13.75412	01 48 28.61 +29 57 06.3	Messier
1783 12 13.75793	01 48 34.76 +29 56 52.0	Mechain
1783 12 18.77908	01 41 03.99 +33 34 00.5	Mechain
1783 12 19.81082	01 39 51.49 +34 13 44.0	Messier
1783 12 21.74399	01 37 43.86 +35 41 41.8	Mechain

10.2. The Orbit of Comet D/1783 W1

Earlier orbital computations were undertaken of comet D/1783 W1, collections of which were made by Carl (1864, pp. 129-130) and Galle (1894, pp. 26, 178). Méchain (Pingré 1784, p. 511; Méchain 1786) himself made the first apparent orbital calculation, computing a parabolic orbit. Burckhardt (1818) and Peters (1860) were convinced that Pigott's comet was of short period, finding orbital periods of 5.6 and 5.9 years, respectively. Burckhardt even compared the residuals for orbits of 5 and 10 years, finding the residuals to be smaller for the smaller orbit.

I obtained the following orbital elements (listed in Table 10.4) for comet D/1783 W1 from 26 observations spanning 1783 Nov. 20–Dec. 21 (those listed as the "better observations" in the top portion of Table 10.3). The residuals from the observations in Table 10.3 are given in Table 10.5. What was surprising to me is how poor the Paris observations are. But then, the large distances of the comet from most of the reference stars, particularly in α, raise warning signs immediately. The uncertainty in the orbital elements is still rather high, due to the poor accuracy of the observations. After performing numerous calculations with a large number of different sets of observations, I estimate the following uncertainties: T, ± 5 days; ω, ± 4°; Ω, ± 2°; i, ± 7°; q, ± 0.1 AU; P, a few years.

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Table 10.4. My New Orbital Elements for D/1783 W1

T = 1783 Nov. 20.5034 TT	ω = 354°.7002	2000.0
e = 0.544805	Ω = 58.7147	2000.0
q = 1.456925 AU	i = 44.9514	2000.0
a = 3.200664 AU	n° = 0.1721250	P = 5.73 years

Table 10.5. Residuals of Observations of D/1783 W1

Date	UT	R.A. (2000.0) Decl. h m s ° ' "	Obs.	Residuals (arcsec) R.A.	Decl.
1783 11	19.9542	2 55 22.02 +04 04 46.5	EP	444.38+	242.66-
1783 11	20.9481	2 51 20.55 +05 26 52.7	EP	12.95+	27.47+
1783 11	22.7798	2 44 51.97 +07 45 28.1	EP	27.74-	198.09-
1783 11	24.8385	2 37 46.73 +10 27 37.9	JG	52.69-	67.17+
1783 11	24.9274	2 37 33.07 +10 33 10.6	EP	16.26+	4.55-
1783 11	26.9174	2 30 58.99 +13 01 26.1	EP	24.17+	27.13-
1783 11	27.07858	2 28 58.07 +13 13 18.5	PM	1274.73-	25.50-
1783 11	27.81600	2 27 49.67 +14 06 50.2	CM	219.18-	40.32-
1783 11	27.84252	2 27 44.72 +14 08 30.1	CM	215.97-	55.85-
1783 11	27.99166	2 28 44.67 +14 18 59.7	PM	1077.70+	73.10-
1783 11	28.7508	2 25 07.15 +15 15 45.9	JG	22.12-	70.62+
1783 11	28.80478	2 24 07.16 +15 18 42.0	CM	742.57-	14.37+
1783 11	28.82653	2 24 08.19 +15 20 03.8	CM	667.71-	3.24+
1783 11	28.84848	2 23 53.17 +15 21 32.5	CM	824.40-	1.75-
1783 11	28.90982	2 24 54.76 +15 25 50.6	PM	235.46+	5.00-
1783 11	29.80394	2 22 04.41 +16 28 42.2	CM	137.95+	2.38-
1783 11	29.83392	2 21 56.19 +16 30 24.6	CM	99.75+	25.41-
1783 11	29.86005	2 22 58.93 +16 31 01.1	PM	1071.69+	98.08-
1783 11	30.00939	2 22 31.04 +16 42 33.4	PM	1067.54+	27.04-
1783 12	01.82049	2 17 06.46 +18 45 56.4	CM	958.57+	1.32+
1783 12	01.83802	2 17 02.33 +18 46 50.2	CM	943.55+	14.84-
1783 12	01.99880	2 16 32.81 +18 57 07.2	PM	923.43+	36.29-
1783 12	02.77905	2 14 19.82 +19 48 13.7	CM	881.48+	34.40-
1783 12	02.79574	2 14 15.72 +19 49 31.5	CM	863.59+	21.69-
1783 12	02.81153	2 12 52.94 +19 58 51.4	PM	266.50-	476.68+
1783 12	02.81202	2 14 14.22 +19 50 41.7	CM	881.45+	14.93-
1783 12	03.78313	2 10 21.97 +20 53 15.1	CM	156.66-	13.69+
1783 12	03.81009	2 10 16.62 +20 53 32.0	CM	169.33-	71.76-
1783 12	03.83068	2 10 19.32 +20 53 25.5	CM	83.88-	156.31-
1783 12	04.1589	2 09 27.76 +21 17 12.4	EP	60.20-	39.77+
1783 12	11.74269	1 52 00.18 +28 20 50.3	PM	170.21-	22.83-
1783 12	11.77185	1 48 41.84 +28 22 18.1	PM	2741.98-	22.36-
1783 12	12.73954	1 49 53.95 +29 09 54.9	PM	355.83-	4.90-
1783 12	12.75967	1 49 47.16 +29 10 47.5	CM	414.88-	10.74-
1783 12	13.75412	1 47 46.21 +29 58 30.1	CM	608.22-	24.85+
1783 12	13.75793	1 47 53.22 +29 58 15.7	PM	511.79-	0.26-
1783 12	14.74526	1 47 34.21 +30 43 25.7	CM	528.36+	9.73-
1783 12	14.76313	1 57 01.12 +30 42 11.6	PM	7860.56+	132.50-
1783 12	18.77908	1 52 54.84 +33 32 06.2	PM	8876.84+	163.10-
1783 12	18.84631	1 34 07.59 +33 37 47.8	CM	5140.93-	17.91+
1783 12	19.81082	1 32 36.35 +34 14 20.5	CM	5373.99-	56.85-
1783 12	19.92392	1 36 12.02 +34 22 39.0	PM	2595.60-	181.16+
1783 12	20.81139	1 44 39.45 +34 52 52.9	CM	4385.31+	27.76-
1783 12	21.74399	1 43 40.44 +35 40 37.3	PM	4331.07+	769.19+
1783 12	21.80991	1 43 34.12 +35 28 54.6	CM	4302.31+	77.85-

Table 10.6 contains my own orbital elements for comet P/2003 A1, from 34 observations spanning 2003 Jan. 5-Apr. 6 (mean residual $0''.53$). When these elements are run backward in time, allowing for perturbations by the major planets and minor planets (1) Ceres and (4) Vesta — *excluding* the 1783 observations — times of perihelion passages are found to fall around 1787 Mar. 6 and 1780 Aug. 29. This falls years away from the known perihelion time for comet D/1783 W1. So what are we to make of this?

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Table 10.6. My New Orbital Elements for Comet P/2003 A1

Epoch = 2003 Feb. 10.0 TT

T = 2003 Feb. 1.23708 TT	ω = 357°.07624	2000.0
e = 0.4810219	Ω = 55.19241	2000.0
q = 1.9158130 AU	i = 46.26212	2000.0
a = 3.6915101 AU	n° = 0.13896262	P = 7.093 years

◇ ◇ ◇

What this indicates is that, if P/2003 A1 is identical with D/1783 W1, we cannot now be certain if there were 33 or 34 revolutions about the sun in the intervening years. There are two major reasons for our uncertainty: (1) Passages close to planets such as Jupiter make successive backwards integration more uncertain, and there are known approaches to within 0.2 AU of Jupiter (*e.g.*, to 0.15 AU on 1971 Feb. 19). (2) Unknown nongravitational forces can cause great problems. A combination of these two sources of uncertainty may well be at play here. Independent calculations attempting to tie the 2003 observations to the 1783 observations have been carried out by two long-time experts on orbit computing affiliated with the Minor Planet Center, at my request: Gareth Williams and Syuichi Nakano. We are agreed that one cannot represent the 1783 and 2003 observations with a single calculation, whether gravitational or nongravitational. Any nongravitational solutions appear to be unreasonably large. Creative attempts to force a fit still yield residuals in 1783 of more than 1° at best, with systematic residuals that are just teasing enough to suggest that they might be the same comet — but not conclusive. One possibility is that there was a splitting of the comet's nucleus, and that we are looking at one of the surviving components.

Based on the 2003 observations, one can derive power-law magnitude absolute magnitude H_{10} $\approx$ 12.0, though a higher value of n (*i.e.*, $n \geq 5$) is more likely for such a short-period comet, for reasons discussed in Chapter 3 of this thesis. The 2003 light curve is strange, in that the comet should have faded by $\approx$ 1 mag from January to April, but in fact it remained steady or brightened by $\approx$ 0.5 mag over this 3-month span (so a lower value of n is needed to better approximate the data). In 1783, one can derive $H_{15} \approx 7.0$ or $H_{10} \approx 8.0$, though this could be on the bright side

by up to a magnitude (I would lean towards the brighter value simply because earlier observers tended to underestimate the brightness of comets due to problems in dealing with the integration of the light from the entire coma; cf. Green 1996c). I have calculated orbital elements from the orbit in Table 10.6 for the 40-day Julian-date epoch nearest each perihelion passage back to 1787, and from these I computed ephemerides using power-law magnitude parameters $H_{15} = 11.0$, in order to see what the observability of the comet might have been. Why was it missed all these centuries? There is quite a difference in the absolute magnitude between 1783 and 2003, indicating that if they are the same comet, there was a substantial outburst in 1783 (which would be expected if there were a splitting of the nucleus then). Here we assume the 2003 brightness in looking at ephemerides over the last couple of centuries.

In late 1967 and early 1968, P/2003 A1 might have been near visual $m_1 \approx 13$ in the evening sky — moving northward from southern-hemisphere skies into northern-hemisphere skies. In 1961 Aug.-Oct., the comet would have been about the same brightness (perhaps) and well placed for northern-hemisphere observers in the morning sky. Very favorable apparitions would have occurred for northern-hemisphere observers in the last third of 1948 and the autumns of 1935 and 1922, the comet possibly reaching 12th magnitude on each occasion. In the fall of 1909, the comet may have reached 11th magnitude near a perihelic opposition for northern-hemisphere observers. There are numerous such examples going back through the 19th century, as well. Of course, the sky was not as well monitored as it is now — with the large-scale automated CCD surveys in progress since 1997. But it would still be somewhat odd that it was missed at all these returns if it weren't, in fact, somewhat fainter than these magnitude parameters would make the comet.

Following discussions of these results with Brian Marsden (who serves with Williams and me on the IAU Committee on Small Bodies Nomenclature), we are agreed that if P/2003 A1 is to be named now, it must be named 'LINEAR' for its 2003 discoverer; it is premature to apply the name 'Pigott' to this comet, and it could well be years before we are certain one way or the other. Certainly more observations at its next return to perihelion will be needed to help resolve the case, and even then it may not be possible to decide. The CSBN has been deliberating on what to do about the naming of P/2003 A1, and these calculations will now enable it to decide whether to name it 'LINEAR' now (the likely solution) or to wait until the next return to perihelion before seeing if 'Pigott' should be the sole name (or if it might become 'Pigott-LINEAR').

Even through most of the nineteenth century, when visual micrometric measurements of comet positions were being performed telescopically (prior to the implementation of photography for astrometric purposes), measuring errors were typically on the order of $5''$-$10''$. In my study of comet 122P/de Vico, which was first discovered in 1846 and then lost until its re-discovery in 1995, the visually measured offsets of the comet's observed nucleus from comparison stars were re-reduced using modern star-catalogue positions. Yet still about half of the 1846 observations were discarded in the final orbit solution connecting the 1846 apparition to those observations of the comet that were made in 1995 (Green 1995a). The problem was probably a combination of difficulty in making accurate visual measurements and of time problems. Again, astronomers in

the nineteenth century either were not aware that recording seconds of time precisely could make a difference in the value of their astrometric measurements or were not able to access clocks of sufficient accuracy (noting that mean local solar time was in use in 1846).

Epilogue: Future Potential

This thesis has given extensive astrometric treatment to several objects, including the 1572 and 1604 supernovae and the comets of 1577, 1661, and 1783 — through the development of techniques and computer programs discussed herein. In terms of comets and supernovae, I have shown in this thesis that there are several things that can be gleaned from historical observations made prior to the photographic and spectroscopic eras that began in the 19th century:

(1) Positions can be refined in many cases using modern star catalogues. In the case of comets, this can lead to better determination (and, in some cases, initial determination) of orbital elements. For supernovae, one can look at identifications of existing supernova remnants with supernova explosions seen centuries ago.

(2) The brightness can be ascertained in many cases. For comets, this can sometimes help put constraints on somewhat-indeterminate orbital elements and can give insight into production rates of gas and dust from the cometary nucleus (thus giving some indication of a comet's size). In the case of supernovae, attempts have been made to determine absolute magnitudes and even supernova types from light curves of old supernovae (based on precise modern data from recent supernovae). Negative observations (by observers following a comet or supernova over weeks or months) can also help to constrain brightness parameters.

(3) The physical appearance can help in discussing the physical nature of a comet or supernova. For old supernovae observed visually, the only physical data available besides position and brightness (and, somewhat equivalently, the duration of visibility) is the colour. Again, attempts have been made with the supernovae of 1572 and 1604 to estimate supernova type from the changing colour, based on modern data regarding colours evolving over time. For comets, it has generally been overlooked that many old manuscripts and tracts containing observations of pre-17th-century comets contained detailed information on the tails and coma that can help to determine a tentative classification of a comet in terms of the dust-to-gas ratio in its coma and tail (and possibly even to place some constraints on the size of the comet).

(4) Available details supplied by observers of comets and supernovae can also contribute to assessments of statistics, in terms of how many objects might be observable over time. Careful reading of the pre-17th-century observers' methods in acquiring the data can also help to put constructive constraints on many of the measurements that have inherent errors of imprecision due to the observers' lacking the quality of instruments and star catalogues available today.

This thesis looks at each of these potential contributions to modern-day astronomy via analysis of older observational data. But, as I discovered in the course of this thesis research, there is much more available material than can be covered in a thesis such as this. Indeed, this work is now seen as the beginning of a lifetime of research into old data that will hopefully produce many new insights and results regarding comets and supernovae (perhaps contributing also to research of

objects such as meteor showers, fireballs, aurorae, and even sunspots). And it is anticipated that other researchers will build on this work, as well.

Historical medieval and early-modern European records continue to find use in scientific analyses, as with studies of eclipses (e.g., Stephenson 1997; etc.), floods in Europe (Mudelsee et al. 2003), and other topics. This thesis shows that much scientific data can still be gleaned from old astronomical tracts and manuscripts that have been largely ignored in the modern era. I have established several important points in this research that surprised me — including the fact that many useful old observations have evidently never been tapped by modern researchers for use in computing orbits of comets and in analyzing the physical nature of these objects.

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I gratefully acknowledge the help and expertise of the librarians at the following libraries that I have visited in the last several years to seek information from original sources for re-analyzing the astronomical observations discussed in this thesis: Austrian National Library (Augustinerlese Library of Manuscripts, and Augustinerlesesaal), Vienna; Bibliotheque Nationale de France, Paris; Boston Public Library (MA); British Library, London; Cambridge University Library; Columbia University (Butler Library), New York City; Cornell University (Olin Library), Ithaca, NY; Danmarks Natur- og Laegevidenskabelige Bibliotek, Universitetsbiblioteket, Copenhagen; Forschungsbibliothek (Schloss), Gotha; University of Durham Library (Archives and Special Collections); University of Göttingen Library; Universitäts- und Landesbibliothek, Halle; Harvard University (Houghton Library; Wolbach Library; Widener Library; Andover Harvard Theological Library; Hilles Library), Cambridge, MA; Herzog August Bibliothek, Wolfenbüttel; Herzogin Anna Amalia Bibliothek, Weimar; Universitäts Bibliothek, Jena (main library and manuscripts library); Det Kongelige Bibliotek, Copenhagen; University of London Library; Manchester University (John Rylands Library); Marciano Library, Venice; New York Public Library, New York City (General Research Division Library; Rare Books and Manuscripts Library; Science, Industry, and Business Library); Observatoire de Paris Bibliotheque; Oxford University (Bodleian Library; Christ Church College Library; Magdalen College Library; Hertford College Library; New College Library; All Souls College Library; St. John's College Library; History of Science Museum Library); Royal Astronomical Society Library, London; Royal Observatory, Edinburgh (Crawford Library); Royal Society Library, London; Tübingen Stift Library, Germany; Yale University Library (Lewis Walpole Library, Farmington, CT). I also am pleased to acknowledge the use of books from the personal libraries of Prof. Owen Gingerich, Dr. Brian G. Marsden, and Prof. F. Richard Stephenson.

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