Molecular hydrogen in galaxies

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MOLECULAR HYDROGEN IN GALAXIES

by

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To the glory

of my friend and Lord

Jesus Christ

'He is the image of the invisible God, the first born of all creation; for in him all things were created, in heaven and on earth, visible and invisible, whether thrones or dominions or principalities or authorities, all things were created through him and for him. He is before all things and in him all things hold together. He is the head of the body, the church; he is the beginning, the first born from the dead, that in everything he might be pre-eminent. For in him all the fulness of God was pleased to dwell, and through him to reconcile to himself all things, whether on earth or in heaven, making peace by the blood of his cross.'

(Colossians 1:15-20)

ABSTRACT

This study aims to understand the key role played by molecular hydrogen in the evolution of galaxies, with a view to constraining its radial distribution in the Galaxy and the $CO \Rightarrow H_2$ conversion factor α_{20}.

The star formation rate is shown to be correlated with the surface density of H_2. A correlation between the molecular hydrogen fraction and the metallicity of a region allows the time evolution of H_2 to be described. This leads to a modified 'Schmidt Law' of the SFR which explains quite naturally the production of galactic metallicity gradients and the constancy of the SFR in the absence of infall.

A consistent closed model of the chemical evolution of the Galaxy is proposed to solve the G-dwarf problem, the stellar age-metallicity relation and the metallicity gradient, leading to the prediction of some initial amount of pre-disc processing of gas into visible and dark matter. It is found that a constant yield of metals is more appropriate than a yield proportional to metallicity. Possible time variations of the returned fraction, the dark matter fraction and the SFR are also studied. For consistency, we suggest that dark matter in the solar neighbourhood could be totally baryonic provided the Miller-Scalo IMF is modified at the lower end, that is, the dark matter resides in low mass stars or brown dwarfs. The production of metallicity gradients in spiral galaxies is shown to be a direct consequence of the radial variation of the total surface density of matter and the age of the disc.

The role of molecular gas in the evolution of the Oort Cloud of comets is examined. It is shown that comet showers with a mean interval of $\cong$ 30My cannot be produced using perturbations of the Oort Cloud by known stars or molecular clouds. If there is indeed an apparent 30My periodicity in the terrestrial mass extinction and geological records, we argue that astronomically induced processes are unlikely to be the primary cause.

Evidence is presented that the lifetime of the molecular gas phase is $\lesssim 2.10^8$ y, and arguments, particularly from CO observations of the Virgo galaxy cluster, favouring longer lifetimes are shown to be not well founded. We suggest that the ICM in Virgo reduces the value of α_{20} as compared to isolated galaxies.

From the above considerations, the radial distribution of H_2 in the Galaxy is derived and shown to agree in the inner Galaxy with that derived from γ-ray analysis. In the solar neighbourhood we find $\alpha_{20} = 2.5 \pm 0.5$, and present evidence that α_{20} varies as a function of Galactocentric radius and from galaxy to galaxy.

PREFACE

The work presented in this thesis was carried out between 1984 and 1987 while the author was a research student under the supervision of Professor A.W. Wolfendale, FRS, in the Department of Physics, University of Durham.

Parts of Chapters 2, 3 and 4 were carried out in collaboration with Dr. N.C. Rana (Tata Institute of Fundamental Research, Bombay), but the calculations reported represent the work of the author. The results and formalism of Chapter 5 were developed as part of a collaboration with Dr. M.E. Bailey (Department of Astronomy, University of Manchester) and Professor A.W. Wolfendale. Parts of Chapter 6 were carried out in collaboration with Professor A.W. Wolfendale but the calculations reported represent the work of the author.

Some of the results contained in this thesis have been discussed more extensively in the following publications:

Rana, N.C. and Wilkinson, D.A., 1986. Mon. Not. R. astr. Soc., 218, 497-532.

Rana, N.C. and Wilkinson, D.A., 1986. Mon. Not. R. astr. Soc., 218, 721-728.

Rana, N.C. and Wilkinson, D.A., 1986. Il Nuovo Cimento, 9C, 714-724.

Rana, N.C. and Wilkinson, D.A., 1987. Mon. Not. R. astr. Soc., 226, 395-422.

Rana, N.C. and Wilkinson, D.A., 1987. In: Astrochemistry, IAU Symp. No. 120, eds. Vardya, M.S. and Tarafdar, S.P., p.323-324, Reidel, Dordrecht, Holland.

Rana, N.C. and Wilkinson, D.A., 1987. Mon. Not. R. astr. Soc., (submitted).

Bailey, M.E., Wilkinson, D.A. and Wolfendale, A.W., 1987. Mon. Not. R. astr. Soc., 227, 863-885.

CONTENTS

CHAPTER ONE

INTRODUCTION

1.1 GALACTIC STRUCTURE AND COMPONENTS

The question of the origin and evolution of galaxies is still one of the important and unsolved problems in contemporary astrophysics. Tinsley (1980) noted that, 'essentially everything of astronomical interest is either part of a galaxy, or from a galaxy, or otherwise relevant to the origin and evolution of galaxies'. This is perhaps the main reason for our still simple understanding, the fact that galaxies are the most complicated configurations of astronomical bodies, and their study requires knowledge of almost every field of physics and the synthesis of universal cosmology with the astrophysics of individual bodies.

Galaxies may be considered to consist of three basic components, a visible round spheroid, a much flatter disc and a dark halo. The proportion of disc to spheroid determines a galaxy's position along the Hubble sequence, ellipticals being pure spheroid while spirals have both significant spheroids and discs. Spheroids are essentially purely stellar systems, while spiral discs contain typically about 10% of gas by mass. In spiral galaxies, the dark halo contains most of the mass in the galaxy in some inert (as yet unknown), collisionless form such as elementary particles, very low mass stars or black holes.

In the conventional cosmological picture, the primordial gas emerging from the Big Bang some 15-20 Gy ago consisted almost entirely of hydrogen and helium (Wagoner 1973). Despite the expansion of the Universe, density perturbations led to some regions becoming locally bound and collapsing. The dark halo is thought to have undergone a non-dissipational collapse, with the dark matter already in its present form. The spheroid and disc formed from the collapse of matter initially in gaseous form. The matter that formed stars during the collapse results in the spheroid as there is no dissipation of energy. The matter that remained gaseous results in a flat disc, as collisions between gas clouds dissipate energy parallel to the net angular momentum vector. Subsequent star formation would then occur in the gaseous disc. The collapse of the disc occurs in a time which is short compared to the age of the galaxy, and therefore the evolution of the disc is relatively independent of the other components of the galaxy.

This thesis is concerned with the properties and evolution of spiral discs after the initial collapse and in particular the role of the gas. Observations of our own Galactic disc provide important information on this (roughly) 10% of its total mass.

The interstellar medium (ISM) has long been recognised as an important component of the Galactic disc. The total amount of gas is composed of $\simeq$ 70% hydrogen, $\simeq$ 28% helium and $\simeq$ 2% elements heavier than helium. The gas provides the sites of star formation and contains the ashes of thermonuclear burning from previous generations of stars.

Following the work of Cowie et al. (1981) and Sanders et al. (1985), the ISM can be divided into four phases which can be labelled as in Table 1 on the basis of different mean temperatures (T). The ionised hydrogen (HII) is produced as the result of star formation or supernova explosions

Table 1 : Components of the ISM

		T(K)	Density (cm^{-3})	Filling factor
Hot	HII	3.10^5	$1.6.10^{-3}$	0.74
Warm	HII	8000	0.25	0.23
Cool	HI	80	40	0.02
Cold	H_2	10	300	0.008

in the ISM, but most of the mass of gas resides in atomic hydrogen (HI) and molecular hydrogen (H_2). The amount of gas and its distribution, both in space and between these components constitute some of the most important parameters in understanding star formation, the chemical evolution of the Galaxy and the evolution of the Galaxy as a whole.

The distribution and amount of HI throughout the Galaxy has been known relatively precisely for some years. It is readily detectable through its 21cm emission line and the observed line intensities can be converted to column densities provided assumptions are made concerning the variations of spin temperature and optical depth. This has led to agreement about its distribution in the inner Galaxy (in the present work the distance to the Galactic Centre is taken to be 10kpc) although in the outer Galaxy there are some problems concerning the appropriate rotation curve to adopt (e.g. Burton and Gordon 1978; Henderson et al. 1982; Li et al. 1983; Blitz et al. 1983; Kulkarni 1987). However, it has only recently been possible to estimate the H_2 distribution. It is generally agreed that a substantial fraction of interstellar gas is in the form of H_2 but the actual distribution has become a subject of much debate. The next section describes that debate and the principal methods used previously to determine the distribution of H_2.

1.2 THE MASS AND RADIAL DISTRIBUTION OF H_2 IN THE GALAXY

The reason for the controversy surrounding the distribution of H_2, is that the molecule itself is not generally directly detectable. The lowest rotational transitions are far greater than the typical kinetic temperatures found in molecular clouds, in addition to which the rotational transition probabilities are very small since the molecule has no permanent dipole moment. It can only be observed directly in some special limited situations, either by absorption in the UV Lyman bands if the extinction is not too high (Bohlin et al. 1978) or by emission from shock heated or UV pumped gas (Beckwith et al. 1978; Shull and Beckwith 1982). The first method is restricted to the local ISM, denser and more distant regions containing H_2 cannot be observed in this way since the extinction becomes overwhelming. Shock heated emission gives a useful probe of denser regions where violent events are occurring but an observation of an unbiased sample of clouds is not possible. As the bulk of the gas is believed to be in dense cold clouds, which are not accessible to these techniques, any global survey of H_2 in the Galaxy must use indirect techniques.

1.2.1 Determination from CO

The most widespread indirect method is to use the 2.6mm $J = 1 \rightarrow 0$ transition of the CO molecule as a tracer of H_2. CO is the most abundant interstellar molecule with a permanent dipole moment and is readily excited by collisions with H_2, for H_2 densities $\gtrsim 100\ cm^{-3}$, even in clouds with low kinetic temperatures (e.g. Scoville and Solomon 1974; Goldreich and Kwan 1974; van Dishoeck and Black 1987). The first mm observations of CO (Wilson et al. 1970) were followed by early studies establishing a qualitative relationship between CO emission and the presence of H_2 in a variety of structures (Liszt 1973; Dickman 1975; Knapp and Jura 1976). The presence of H_2 is required for efficient formation of CO in most chemical schemes (Williams 1985) and CO has become a trace molecule for determining the H_2 distribution.

The first large-scale surveys of CO in the inner Galaxy (Scoville and Solomon 1975; Burton et al. 1975; Gordon and Burton 1976) showed the existence of a 'molecular ring' at approximately 6 kpc from the Galactic Centre, and that most of the emission was confined to discrete clouds, which contrasted to the HI distribution which was rather flat as a function of radius with little tendency to be clumped. More recent surveys of ^{12}CO have broadly confirmed these results (e.g. Sanders et al. 1984; Sanders et al. 1986a; Bronfman et al. 1987), as well as observations of the $J = 1 \rightarrow 0$ line of ^{13}CO (Liszt et al. 1981; Despois and Baudrey 1983; Liszt et al. 1984).

The problem however, is an obvious one: how to transform the observed quantity, the velocity-integrated

^{12}CO line temperature along a given line of sight ($\int T(^{12}CO)dv$), to $N(H_2)$, the column density of H_2 in molecules cm^{-2}? Theoretical arguments are not conclusive (e.g. van Dishoeck and Black 1987) and so it has become fashionable to determine the conversion factor empirically, where

$$\alpha_{20} \ (10^{20} \text{ atoms cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}) = \frac{2N(H_2)}{\int T(^{12}CO)\,dv} \qquad (1.1)$$

(It is to be noted that some other authors define their conversion factor in terms of molecules rather than atoms and therefore will state $\alpha_{20}/2$ - often denoted 'X'). It is hoped that if a large enough area is sampled, α_{20} will be more or less insensitive to cloud properties and structures and consequently a global value can be used for this and other galaxies.

The early surveys (Scoville and Solomon 1975; Solomon, Sanders and Scoville 1979) adopted $\alpha_{20} > 10$, giving rise to the conclusion that H_2 was the dominant component in the inner Galaxy. Much of the controversy concerning the mass of H_2 has arisen because of different estimates of α_{20}, but before these estimates are described, it is important to point out that the major CO surveys themselves have resulted in considerable disagreement about the quantity and distribution of the ^{12}CO. In particular, Figure 1.1 shows the distribution of CO emissivity in the Galactic plane as a function of Galactocentric radius (R_G) from the work of the Massachusetts-Stony Brook group (Sanders et al. 1984, hereafter referred to as SSS) and the Columbia group (Dame 1984). This quantity is obtained from observations of the antenna temperature $T_A^*(l,b,v)$ by an unfolding procedure based on an adopted rotation curve for the Galaxy and a model for the vertical distribution of the ^{12}CO. The difference between the two curves is primarily due to a

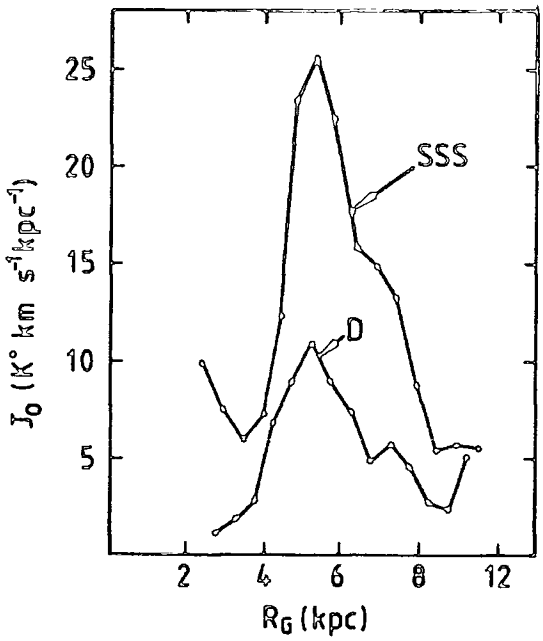


Figure 1.1: The distribution of ^{12}CO emissivity for the Northern Hemisphere as a function of Galactocentric radius from the work of Dame (1984) and Sanders et al. (1984). The emissivity plotted is the peak value, that is allowing for the warp in the CO disk (from Mayer 1986).

different weighting used to obtain the radial emissivity and to a 20% lower CO intensity calibration (Bhat et al. 1986; Solomon and Rivolo 1987; Bronfman et al. 1987). Even if the same α_{20} was used, each curve would lead to different radial distributions of H_2. Therefore in any comparison of α_{20} determinations from different groups, reference needs to be made to the original CO data.

Nevertheless, estimates of α_{20} have been made in a number of different ways both locally and throughout the Galactic disc.

Locally, the integrated CO emission has been measured for a number of regions with high visual extinction, and $N(H_2)$ estimated from measures of visual extinction and the extrapolation of a 'standard' gas-to-extinction ratio. The visual extinction A_V (defined as referring to 0.55μm) is derived from star counts (Dickman 1978) or infra-red extinction (Frerking et al. 1982). This involves major uncertainties, in particular star count estimates are usually very inaccurate and the extrapolation of the gas-to-extinction ratio determined from UV measurements of lightly reddened stars, $N(H)/A_V = 1.59.10^{21}$ cm^{-2} mag^{-1} (Savage et al. 1977) has been questioned (Rouan and Leger 1984). This method can also be compared with a ^{13}CO column density in regions where the ^{12}CO is optically thick (and therefore the observable line intensity is not linearly related to the number of CO molecules) while the ^{13}CO is optically thin. This requires however, a conventional LTE analysis which is uncertain due to theoretical arguments (van Dishoeck and Black 1987; Maloney 1987) and uncertain isotopic ratios (Langer 1977; Bally and Langer 1982). Alternatively, SSS argue that LTE assumptions are unnecessary and propose that the ^{13}CO integrated intensity bears a simple relation to A_V and therefore $N(H_2)$. Problems with applying this method to a Galactic survey have been discussed extensively by Williams (1985) and Bhat et al. (1986). It is sufficient here simply to state that the determinations of α_{20} by different groups using this method range from 2.2 (Lebrun and Huang 1984) to 15 (Blitz 1978), and are listed in Table A.1.1 (Appendix).

An alternative method, used primarily on clouds in the 6 kpc molecular ring, is to estimate the mass of molecular clouds by application of the virial theorem. The simplicity of this method is that the observed line width can be related with the cloud size to the cloud mass, which can be compared to the CO integrated emission and α_{20} derived. There is substantial observational evidence for assuming the clouds satisfy the virial theorem (Larson 1981; Sanders et al. 1985; Myers 1985), and Solomon et al. (1987a) using this method show an impressive empirical relation between the virial mass and the integrated CO emission for $\approx$ 200 clouds in the 6kpc molecular ring, giving α_{20} = 6.0. However there is much controversy concerning the physical interpretation of the line widths (e.g. Kutner and Leung 1985; van Dishoeck and Black 1987) and Bhat et al. (1986) have argued that the virial theorem using the more appropriate optically thinner lines gives $\alpha_{20} \simeq 3.0$ locally, with some evidence of even smaller values in the inner Galaxy.

It is in view of these problems that γ-rays have been used recently to constrain α_{20}, and as this had led to important results it will be discussed in more detail.

1.2.2 <u>The γ-ray method</u>

Diffuse γ-radiation, with energy ~100MeV - 5GeV, in the Galactic plane is produced by cosmic ray interactions with the ambient hydrogen nuclei. The γ-ray flux can thus be used to measure the total gas concentration (HI + H_2) provided the cosmic ray flux and its variations are known (e.g. Black and Fazio 1973; Li et al. 1982, 1983; Mayer-Hasselwander 1983; Lebrun et al. 1983; Riley et al. 1984; Bhat et al. 1984, 1985; Blitz et al. 1985). Outside the solar circle, CO is weak, and therefore HI is presumed to be rather more abundant than H_2. The 21cm line intensity can therefore be used to fix the zero point in the γ-ray emissivity. The method of course is indirect since γ-rays are formed by the cosmic ray interactions, thus the pre-requisite of determining the mass of gas is to know how the cosmic ray intensity varies on a small scale (i.e. whether they penetrate molecular clouds) and on a galactic scale (i.e. is there a Galactocentric gradient in cosmic ray intensity?).

There seems to be no evidence either theoretical (Cesarsky and Völk 1978) or observational (Houston and Wolfendale 1985) that cosmic rays of energy sufficient to generate γ-rays above 35MeV do not penetrate clouds and therefore 'see' all the gas. Studies of Orion and other local clouds by the Durham group (Issa and Wolfendale 1981; Li et al. 1983; Houston and Wolfendale 1985; Bhat et al. 1985) have yielded values for α_{20} of 2.3-3.7, lower than the value of the COS B collaboration (Bloemen et al. 1984) of $\alpha_{20} = 5.2$ for the same region. This is due to the use of a lower local γ-ray emissivity value in the latter work. However, all these values are lower than the $\alpha_{20} = 6$ quoted recently by Solomon et al. (1987a,b) and Scoville and Sanders (1987) and much lower than the early estimates of α_{20}.

The evidence for large scale gradients in the proton component of the cosmic rays has been somewhat ambiguous (Bloemen et al. 1984; Bloemen 1985; Bhat et al. 1985) but recent work seems to confirm its existence (Strong et al. 1987; Bloemen 1987; Mayer et al. 1987). The γ-ray emissivity is the product of gas density and cosmic ray intensity; thus neglecting an increase of cosmic ray intensity with decreasing R_G will lead to an overestimate of α_{20}.

Arguing in favour of a cosmic ray gradient, Bhat et al. (1985) derived $\alpha_{20} \approx 1.5$ for the SSS CO-distribution at R_G = 6kpc, that is a decrease by a factor of two from the local value. This decrease was attributed, following Blitz and Shu (1980) to the increase in metallicity observed in the inner Galaxy (Pagel and Edmunds 1981). Specifically $\alpha_{20} \propto [O/H]^{-1}$ gave good agreement with the 'γ-ray' H_2 distribution. However, there are arguments, both theoretical (Kutner and Leung 1985) and observational (Young et al. 1985b) that metallicity cannot be a major influence on α_{20}. The true situation will be very complex since the gas phase abundances are likely to be controlled by a balance between accretion and shock disruption of dust grain surfaces (Williams and Hartquist 1984). More recent work on external galaxies (Bhat et al. 1986 and references therein) points strongly toward large-scale variations in α_{20} but factors other than metallicity could be causing these changes. In particular, the detailed theoretical models of Kutner and Leung (1985) suggest that temperature is the dominant factor in determining α_{20}, such that

$$\alpha_{20} \propto T_K^{-1.3} \qquad (1.2)$$

(see also Maloney and Black 1987). If the clouds in the inner Galaxy are hotter than the clouds in the outer Galaxy, as claimed by Kutner and Mead (1981), then α_{20} should fall with R_G.

It should be noted, that the COS B collaboration (e.g. Lebrun et al. 1983; Bloemen et al. 1986) find $\alpha_{20} \simeq 5.6$, constant with Galactocentric radius. However, this uses the Columbia CO survey (curve D in Figure 1.1), so that when the mass of H_2 is calculated for the inner Galaxy (shown explicitly in Table A.1.2 (Appendix)) the results from the Durham group and the COS B/Columbia group are very similar.

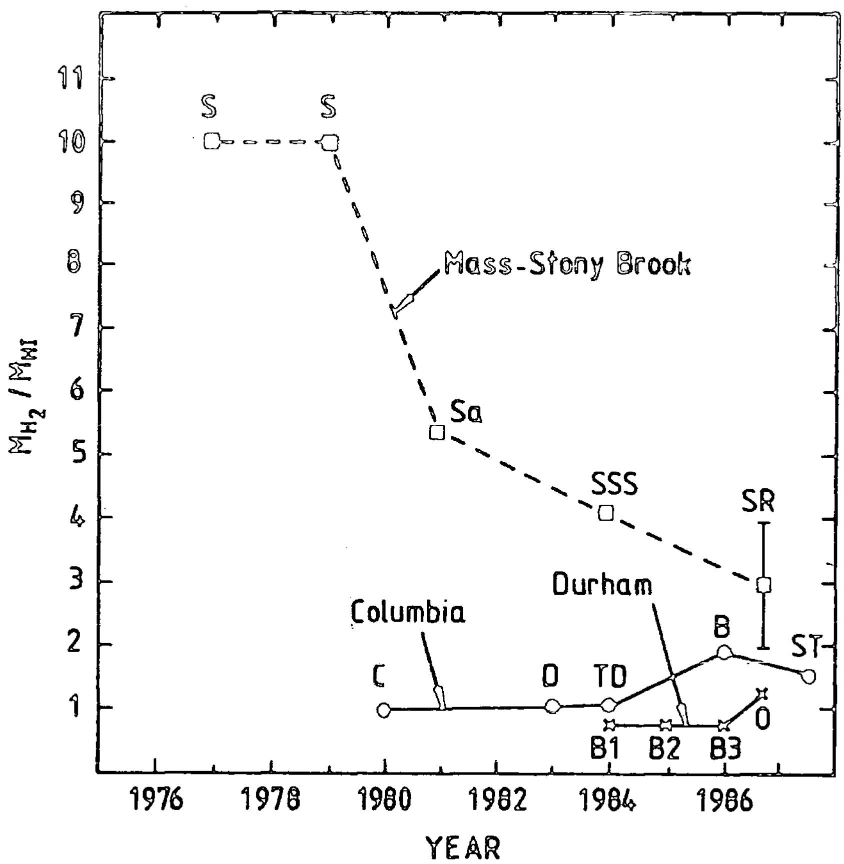


Figure 1.2: The time history of estimates of the mass of gas in the Galaxy, shown by the ratio of the estimated mass of H_2 to that of HI in the Galactocentric distance range R_G = 4-8kpc (from Bronfman et al. 1987; Osborne et al. 1987).

Mass-Stony Brook	S: Solomon, Sanders & Scoville (1979); Solomon, Scoville & Sanders (1979); Solomon & Sanders (1980).
	Sa: Sanders (1981)
	SSS: SSS (1984)
	SR: Solomon & Rivolo (1987)
Columbia	C: Cohen et al. (1980)
	D: Dame (1983)
	TD: Thaddeus & Dame (1984)
	B: Bronfman et al. (1987)
	ST: Strong et al. (1987)
Durham	B1,B2,B3: Bhat et al. (1984,1985,1986)
	O: Osborne et al. (1987)

Figure 1.2, illustrates the situation, showing the mass ratio of H_2 to HI between R_G = 4-8 kpc as a function of time! It can be seen that the Columbia group, recently

using an α_{20} from COS B, are similar to the Durham group, consistently below the estimates of Solomon and his collaborators. The massive amounts of H_2 claimed by the early surveys have been considerably reduced, although there is still significant disagreement.

1.2.3 Other methods

Apart from the main methods, described above, to determine α_{20} and M_{H_2} for the Galaxy, there are a number of other possible avenues.

Arguments from theoretical chemical models of the ISM (Duley and Williams 1984) together with observations of different molecules in molecular clouds are unable at present to be used for surveying the ISM on a large scale. However, current models of interstellar chemistry provide no support for the use of a canonical $CO:H_2$ ratio in dark clouds and the ratio may vary from point-to-point in a cloud, and between clouds reflecting a number of different factors (Williams 1985).

Optical extinction methods to determine α_{20} locally are not available in the inner Galaxy. Bhat et al. (1986) have summarised other techniques to calibrate α_{20} in the inner Galaxy. Most of the Galactic X-ray sources exhibit a low energy cut-off in their spectra because of absorption of soft X-rays through photoelectric interactions with chiefly atoms of oxygen, carbon, nitrogen and hydrogen (Adams 1980). Therefore by comparing the observed X-ray spectrum with the production spectrum an estimate of the total gas can be made. There are major uncertainties in the production spectrum, but Bhat et al. (1986) derive $\alpha_{20} = 3.8$ locally, decreasing towards the inner Galaxy.

Unlike the optical region, the extinction by interstellar dust at near infra-red wavelengths is sufficiently small to enable the inner Galaxy to be seen. By examining the degree of reddening suffered at these wavelengths, an estimate can be made of the gas column density along various directions under the assumption of a large scale uniformity in the Galactic dust-to-gas ratio. Again there exists considerable uncertainty in this method,

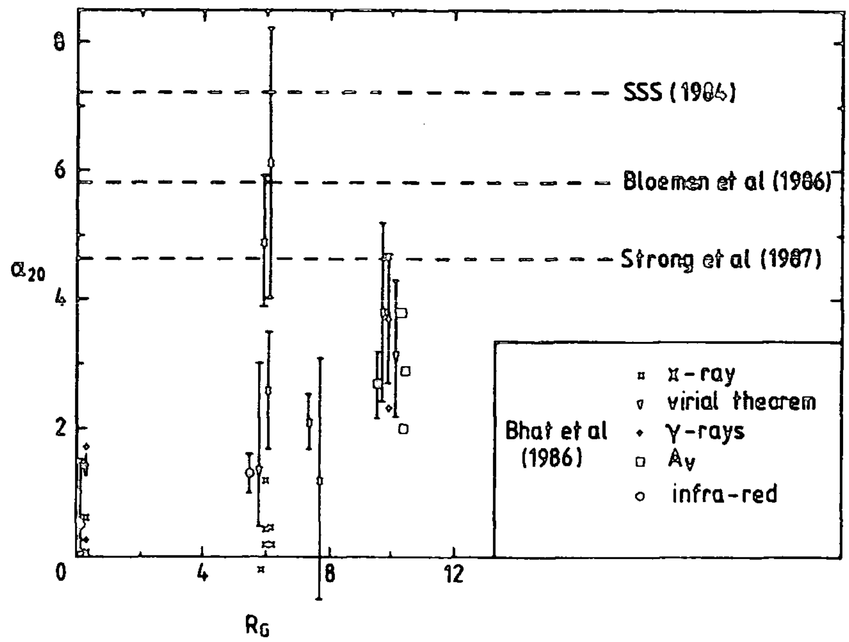


Figure 1.3: Summary of estimates of α_{20} as a function of Galactocentric radius. The points shown are taken from the various methods of Bhat et al. (1986), suggesting a gradient in α_{20}. Also shown for comparison are the constant values of α_{20} claimed by SSS (1984), the COS B/Columbia collaboration (Bloemen et al. 1986) and the recent paper of Strong et al. (1987).

but Bhat et al. (1986) have argued from this method for a low value of α_{20} at $R_G \simeq$ 6kpc.

The situation can be summarised by Figure 1.3, taken from Bhat et al. (1986), showing estimates of α_{20} as a function of R_G. In the inner Galaxy, the scatter is large, but taken with results for the Galactic centre (Bhat et al. 1984, 1985; Blitz et al. 1985), the data are compatible with the argument that α_{20} varies from place to place in the Galaxy.

These results for a 'low' α_{20} and low H_2 have been further strengthened by a study of IR emission in the inner Galaxy and Galactic centre (Parkinson et al. 1987; Osborne et al. 1987). This method uses fluxes at 150μm, 250μm, 300μm and IRAS wavelengths to determine the mass of dust and then uses an assumed dust-to-gas ratio to determine the total gas.

It must be stressed that all of the above methods contain assumptions and uncertainties, and although Bhat et al. (1986) claim consistent results on the value of α_{20}, these results are still the subject of much debate (e.g. Solomon and Rivolo 1987; Scoville and Sanders 1987).

1.3 THE ROLE OF MOLECULAR HYDROGEN IN THE GALAXY

From the discussion above, it is clear that the controversy concerning the mass and radial distribution of H_2, and the $CO \rightarrow H_2$ conversion factor α_{20} is not yet concluded. In an extensive review, van Dishoeck and Black (1987) conclude that 'theoretical justifications of the empirical relations are still scarce and the range of validity of the conversion factors is still poorly understood'. Further work is in progress on the empirical determination of α_{20} (e.g. Solomon et al. 1987a; Strong et al. 1987; Richardson and Wolfendale 1987) as well as observations and study of molecular cloud chemistry (e.g. van Dishoeck and Black 1986; Maloney 1987). However, there is an alternative way of constraining the mass of H_2 in galaxies. This involves attempting to understand the global physics of H_2 and its role in the many processes in galaxies. This study should not only be helpful in understanding the global evolution of galaxies, but could shed light on H_2 and therefore α_{20}.

Figure 1.4 shows the surface density of hydrogen as a function of Galactocentric radius. Following the discussion

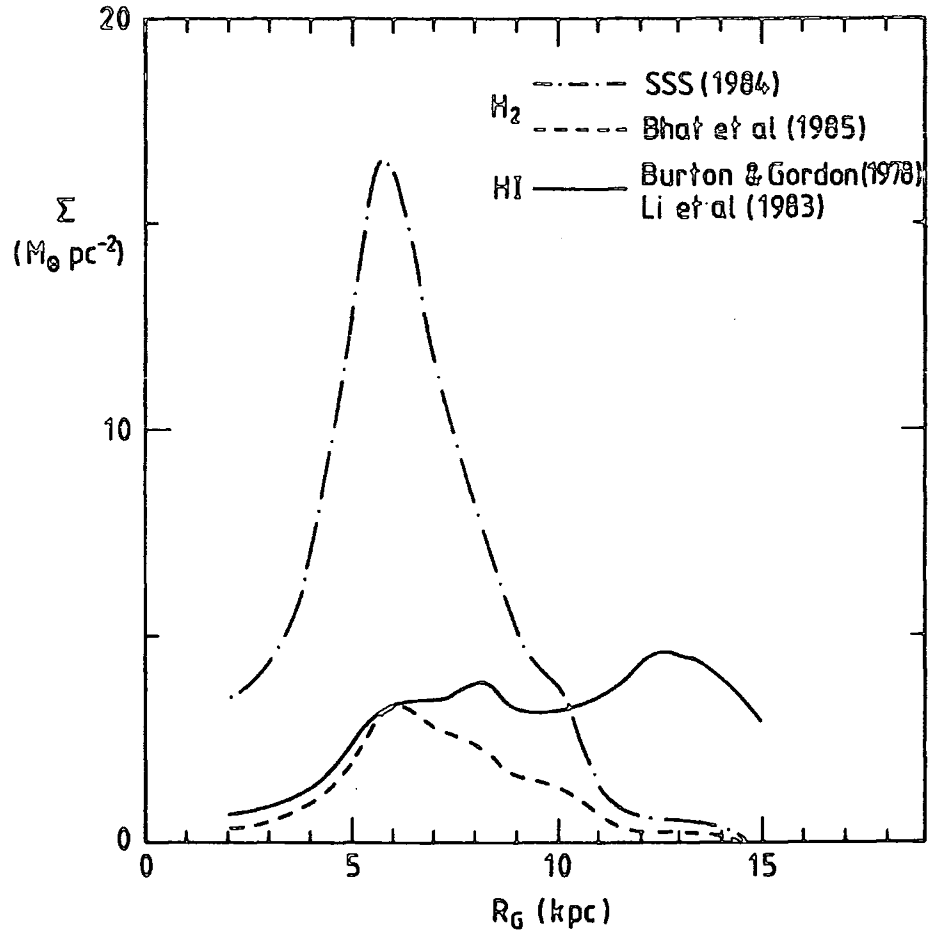


Figure 1.4: Surface density of H_2 and HI as a function of radius from the centre of the Galaxy. HI is the average of the determinations of Burton & Gordon (1978) and Li et al. (1983), while two contrasting H_2 distributions are shown.

of Section 1.2 the H_2 distributions of SSS (1984) and Bhat et al. (1985) are shown in comparison with HI. Bhat et al. (1984, 1985, 1986) pointed out that such a dramatic decrease in the estimate of H_2 would have implications for star formation, Galactic chemical evolution and even perturbations of the Sun's Oort Cloud of comets. It is the intention of this work to study in detail those initial remarks, to understand the processes involved and to constrain the H_2 distribution.

In the Galaxy, virtually all known regions of star formation activity are associated with molecular clouds (e.g. Shu 1985; Scoville and Sanders 1987). In Chapter 2, the relationship of the star formation rate to the mass of H_2 is investigated and an empirical law of star formation is suggested. Evidence from external spiral galaxies from IR and CO fluxes is used to further examine this relationship. The dust-to-gas ratio in spiral galaxies is then used to constrain α_{20}.

The chemical evolution of galaxies studies the processing of hydrogen through stars into heavier elements and their distribution in galaxies. It is a subject of great contemporary interest particularly with respect to metallicity gradients observed in spiral galaxies (Pagel and Edmunds 1981). Bhat et al. (1984, 1985) suggested that lower masses of H_2 would provide better fits to metallicity gradients in the Galaxy and other spirals. Tosi and Diaz (1985) did show that in their models, 'metallicity corrected' H_2 distributions did give better agreement with observations of spiral galaxies, while Güsten and Mezger (1982) in fact, chose a distribution similar to that proposed by Bhat et al. (1985) in their model of the chemical evolution of the Galaxy. However, these authors did not take into account the very important role of H_2 in star formation.

Chapters 3 and 4 present a self-consistent model of the chemical evolution of the Galaxy, using the star formation rate as derived in Chapter 2. Chapter 3 presents the model and compares its predictions with the observational problems of Galactic chemical evolution. The production of a metallicity gradient is shown to depend quite sensitively on the distribution of H_2. Chapter 4 examines the consistency of the model with respect to the yield of metals from stars, and the nature of the dark matter in the solar neighbourhood. In addition, model predictions for metallicity gradients in external spirals are presented. Finally the distribution of H_2 is derived from the observed metallicity gradient and its time evolution is explained.

One of the results of the early studies of CO, was the realisation that the majority of H_2 was contained in Giant Molecular Clouds (GMCs) with mass $\cong 10^5 - 3.10^6 M_\odot$ (Sanders et al. 1985), which are therefore the most massive objects in the Galaxy. Dynamical arguments also suggested massive GMCs (Stark and Blitz 1978), and the observed mass spectrum means that most of the mass in the ISM is contained in the largest clouds (e.g. Sanders 1981; Tereby et al. 1986). GMCs therefore become important in dynamical processes in the disc, for example the disruption of open clusters (Spitzer 1958; van den Bergh and McClure 1980; Lyngå 1982; Wielen 1985; Terlevich 1987) and globular clusters (Grindlay and Hertz 1984), the disruption of wide binaries in the solar neighbourhood (Weinberg et al. 1987) and the evolution of the velocity distribution of stars in the Galactic disc (Lacey 1984; Villumsen 1985; Carlberg 1987). Of current interest is the claim (Clube and Napier 1984a,b; Rampino and Stothers 1984a) that perturbations of the Oort Cloud of comets by GMCs are the cause of the claimed 30My periodicity in the record of terrestrial mass extinctions. Chapter 5 reviews the claims of periodicity and shows that perturbations by GMC (or any other known astronomical bodies) cannot be the cause of a 30My periodicity. Bhat et al. (1986) suggested further, that reduced GMC masses would not totally disrupt the Oort Cloud in the way that had been understood previously (e.g. Clube and Napier 1982a; Napier and Staniucha 1982). This suggestion is re-examined with particular reference to the masses of GMC.

The final part of this work examines the question of GMC lifetimes and H_2 in other spiral galaxies. Scoville and Hersh (1979) claimed GMC lifetimes > 10^9y and linked this to large H_2 masses in the inner Galaxy. Chapter 6 examines these claims and the link to H_2 masses.

At present there exist single dish CO measurements in over 100 spiral galaxies and well sampled radial distributions exist for 23 Sc and 19 Sb/Sbc galaxies (Young 1986; Scoville and Sanders 1987). The conventional approach has been to assume that the value of α_{20} determined locally, applies universally (Young and Scoville 1982a; Dickman et al. 1986). Thus all radial variations of CO within a galaxy and overall differences between galaxies have been attributed solely to variations in the amount of H_2. Apart from the controversy concerning the value of α_{20} locally, Maloney and Black (1987) have recently used sophisticated modelling techniques to show that this assumption could lead to an order of magnitude error in the estimated H_2 mass due to differences in temperature, mean cloud density and metal abundance.

Alternatively, Thronson et al. (1987b) have suggested the use of IR data to calculate the mass of dust in a galaxy. Then, assuming a constant dust-to-gas ratio (taken as the solar neighbourhood value), the mass of H_2 can be determined if the HI mass is known. The weakness of this method is the assumption of a constant dust-to-gas ratio and whether all the dust in a galaxy is sampled. Nevertheless, if this IR method could be used to calibrate α_{20} in external galaxies there would be great advantages.

Using the assumption of a constant α_{20}, there have been claims about H_2 content and lifetime in galaxies in the Virgo cluster (Kenney and Young 1986; Stark et al. 1986; Knapp et al. 1987). Chapter 6 reviews these claims, and then examines the effect on α_{20} of the cluster environment using data from other wavelengths. In addition, the constancy of the dust-to-gas ratio between galaxies is investigated. (A similar investigation is also carried out in the context of the star formation rate in Chapter 2).

Chapter 7 summarises the main conclusions and gives an outline for future work.

CHAPTER TWO

THE STAR FORMATION RATE

2.1 INTRODUCTION

Our poor understanding of star formation is one of the main obstacles preventing us quantifying how galaxies evolve. There are two functions related to the process of star formation which are of fundamental importance and application to many fields of current research, the frequency distribution of stellar masses at birth and the spatially averaged star formation rate (SFR) in a galaxy. Despite extensive observational and theoretical investigations, the question of the physical mechanisms involved in star formation and their relationship to these two functions remain conspicuously obscure. It has been recognised for a long time that the diffuse component of the interstellar gas had to be initially compressed in some way before gravitational forces could take over, star formation occurring by the fragmentation of these self gravitating clouds (Goldreich and Lynden-Bell 1965). Although there have been many attempts to relate cloud-scale processes to the galaxy scale (e.g. Seiden and Gerola 1982; Comins 1984; Freedman and Madore 1984; Struck-Marcell and Scalo 1987), the problem still remains of a general theory or parameterisation of the SFR in disc galaxies. This is vital in understanding or predicting the gross physical, chemical and photometric properties of galaxies (Tinsley 1980).

In this Chapter, previous global formulations of the

SFR are reviewed, followed by an attempt to relate empirically the SFR to gas density and metallicity in the Galaxy. The properties of this new formulation are qualitatively discussed and evidence for its application is sought from other spiral galaxies. Finally the effect of the gas-to-dust ratio is discussed in relation to the SFR and the amount of H_2 in galaxies.

2.2 PREVIOUS FORMULATIONS

The star formation rate has generally been thought to be related to the surface or volume density of the total interstellar gas. However, there is no prima facie reason why it should be related to the density of gas rather than the magnitude of the initial density contrast and the scale size of the spatial inhomogeneity. It is also not clear whether the SFR should be physically more related to the volume density of gas (ρ_g) than the surface density of gas (Σ_g) for a thin but non-uniform disc such as the Galaxy. The conventional wisdom has, however, been to look for an empirical power-law relationship between the SFR (ψ_s or ψ_v) and the corresponding density of gas, that is

$$\psi_s \propto \Sigma_{H_2}^{k} \tag{2.1}$$

$$\psi_v \propto \rho_{H_2}^{a} \tag{2.2}$$

where ψ_s is the SFR in $M_\odot pc^{-2}\,Gy^{-1}$, Σ_g is the surface density of the total gas (atomic and molecular) in $M_\odot pc^{-2}$, ψ_v is the SFR in $M_\odot pc^{-3}\,Gy^{-1}$, ρ_g is the volume density of the total gas in $M_\odot pc^{-3}$, and k and a are the corresponding exponents.

Schmidt (1959, 1963) made an analysis of the variation of star formation with height above the Galactic midplane and proposed the relationship (2.2) with $\underline{a} \simeq 2$ (see also Mathis 1959; Salpeter 1959). This 'law' was supported on the basis of a theoretical treatment of fragmentation by Field and Saslaw (1965). Sanduleak (1969) proposed that in the case of a thin disc, Σ could be used to represent ρ, and there then followed many observational tests of the law in local galaxies (van Hoerner 1960; van Genderen 1969; Hartwick 1971; Einsato 1972; Emerson 1974; Madore et al. 1974; Hamajima and Tosa 1975; Azzopardi and Vigneau 1977; Smith et al. 1978; Bruck 1980). The correlations obtained were not good, and the value of k had a wide range, 0.5 - 3.5 for different determinations and galaxies.

There are a number of objections to the above 'Schmidt law' of the SFR. Firstly, Madore (1977) pointed out that in many observational tests the observed quantity is the number of stars formed, not the SFR, and showed that this led to an overestimate of k. Secondly, the fact that k appears to vary within and among galaxies indicates that the total gas density is not the only relevant quantity (Larson 1977; Tinsley 1980). More recently, Donas and Deharveng (1984) and Donas et al. (1987), although finding some evidence for a correlation between total SFR and total HI mass, find only a very weak correlation in terms of surface densities. In particular the Small Magellanic Cloud (SMC) is exceedingly gas rich and yet produces only about 20% of the mass of stars per unit mass of gas that the Large Magellanic Cloud does (Lequeux 1984). It must be pointed out that all of the above determinations have simply used HI as the total gas, neglecting H_2, a point that will be discussed shortly.

The final reason for rejecting the Schmidt law concerns the apparent constancy of the SFR with time in this and other spiral galaxies. Miller and Scalo (1979), from a detailed study of the mass spectra of stars in the solar neighbourhood, in order to fulfill the constraint that the initial mass function (IMF) be continuous, required ψ_s to be roughly constant over the age of the Galaxy. Although subsequent studies of the IMF have weakened this continuity constraint (Scalo 1986; Larson 1986; Rana 1987a and Chapter 4), the constancy of ψ_s with time in the solar neighbourhood has been supported by the luminosity function of white dwarfs (Liebert et al. 1979; Rana 1987b), the distribution of initial masses of planetary nebulae (Tinsley 1978), the metallicity distribution and velocity distribution of nearby F and G stars (Twarog 1980; Vader and de Jong 1981; Meusinger 1985; Fuchs and Wielen 1987) and data on stellar lithium abundances and calcium emission line strengths (Scalo 1986). It also seems that star formation has proceeded at a relatively constant rate over the lifetime of most late-type disk galaxies (Searle et al. 1973; Mayor and Martinet 1977; Rocca-Volmerange et al. 1981; Kennicutt 1983b; Gallagher et al. 1984; Sandage 1986; Hunter and Gallagher 1986), while Tinsley and Danly (1980) argued for a constant ψ_s from the point of view of star formation in the Universe. Now comparing the total mass of the Galactic disc to the present mass of the gas, it is seen that the mass of gas (assuming that at the time of the formation of the disc, the majority of the mass was in the form of gas) has been depleted by a factor of ~ 10. Relationship (2.1) with $k \gtrsim 1$ therefore predicts a very sharp decrease of the SFR with time which contradicts the above results.

In the light of these objections, a number of different alternatives have been explored. Some workers have ignored the first two objections and have continued using relations (2.1) and (2.2) (e.g. Smith et al. 1978; Güsten and Mezger 1982; Caimmi and Dallaporta 1982; Chiosi and Matteucci 1982, 1984; Güsten 1986; Matteucci and Greggio 1986; Arimoto and Yoshii 1986, 1987). With this form for ψ_s, infall of gas from the halo to the disc has been invoked to keep Σ_g and therefore ψ_s roughly constant with time (e.g. Lacey and Fall 1983, 1985; Clayton 1984, 1985a,b, 1986, 1987).

Other workers have suggested that the star formation rate depends not only on gas density, but the gas density multiplied by some other quantity such as the frequency with which a parcel of gas encounters a density wave (Talbot and Arnett 1975), the volume of gas (Caimmi 1978), the dust-to-gas ratio (Viallefond et al. 1982), the velocity dispersion of the gas (Brosche and Leutes 1985), the temperature of the gas (Caimmi and Secco 1986) and the total mass (i.e. gas and stars) of a region (Dopita 1985). The model of Dopita (1985) has received particular attention (e.g. Maddox 1985), but once again neglects H_2, both in theory and in correlation plots.

There have also been many who have rejected the empirical forms (2.1) and (2.2), and inserted a SFR independent of gas density into models of chemical or photometric evolution (e.g. Tinsley 1980; Tosi 1982). Either a constant ψ_s has been taken (e.g. Twarog 1980; Twarog and Wheeler 1982, 1987) or the time evolution left as a free parameter, varied to fit observational results (e.g. Larson and Tinsley 1978; Tosi and Diaz 1985). Recently, Larson (1986) has used bimodal star formation in order to attempt to solve the dark matter problem in the solar neighbourhood, the basic idea being that massive and low mass stars are formed in distinct locations in space and/or time. Using the constraint on the high mass mode that the model should predict enough mass in remnants to account for the unseen matter near the Sun, he finds a SFR which decays with time as exp(-t/3.4 Gy). Wyse and Silk (1987) have extended this argument, having stars > 2 $M_{\odot}$ forming at an exponentially declining rate, while lower mass stars form at a constant rate. Güsten and Mezger (1982) had also proposed a bimodal IMF, massive stars forming primarily in spiral arms, while all masses of stars forming in the inter-arm regions. Indeed there is growing observational evidence for bimodal star formation, such as the discontinuous slope of the IMF (Larson 1986; Rana 1987a), the observation of nearby dark clouds with a high abundance of low mass pre-main sequence stars but virtually no high mass stars (Scoville and Sanders 1987) and that the largest HII regions and most massive GMCs are confined to spiral arms (Dame et al. 1986).

However, none of the above formulations explicitly take account of molecular hydrogen. It is well known that the giant molecular complexes are the primary seats of star formation, and a simple law linking the star formation rate to the density of H_2 would be intuitively satisfying. Talbot (1980) investigated the relationship of the SFR to the density of gas assuming the emission per unit area from ionised hydrogen to be proportional to the number of massive stars and therefore to the rate of formation of massive stars Ψ_h. He then plotted Ψ_h against the surface densities of total gas, atomic hydrogen (Σ_{HI}) and molecular hydrogen (Σ_{H_2}) and concluded that the rate of formation of massive stars is more significantly correlated with Σ_{H_2} than with Σ_{HI} or even Σ_g, for both the Galaxy and M83. Subsequently DeGoia-Eastwood et al. (1984) confirmed this conclusion from a study of NGC 6946. In the light of the contemporary debate concerning the distribution of H_2, the following sections re-examine this conclusion and show how a SFR proportional to the surface density of H_2 solves quite naturally the initial objections to the Schmidt law.

2.3 STAR FORMATION RATE AND GAS DENSITY IN THE GALAXY

2.3.1 SFR in relation to the surface density of gas

The analysis of Talbot (1980) for the Galaxy has been repeated using different available distributions of Σ_{HI}, Σ_{H_2} and Σ_g, and an independent SFR taken from Smith, Biermann and Mezger (1978, hereafter referred to as SBM). The total gas Σ_g is defined as

$$\Sigma_g = X^{-1} [\Sigma_{H_2} + \Sigma_{HI}], \qquad (2.3)$$

X being the chemical mass fraction of hydrogen in the ISM ($X^{-1} = 1.36$). SBM derive a SFR from the rate of emission of Lyman continuum photons from giant HII regions. Other estimates of the SFR have been made by Mezger (1978) and Güsten and Mezger (1982) using different assumptions concerning the lifetime of HII regions and spiral structure but a recent compilation of SFRs based on supernova remnants and pulsars (Lacey and Fall 1985) seems to favour SBM rather than the other two. Talbot (1980) has systematically underestimated the SFR and the radial dependence is also somewhat different, compared with that of SBM.

Table 2.1 shows the results of plotting the SFR (ψ_s) against different distributions of Σ_{HI}, Σ_{H_2} and Σ_g and using

Table 2.1: Correlation of SFR and surface densities of gas.

(SFR from SBM 1978)

Σ_g in relation (2.1) replaced by	Source of data		k	R_C
Σ_{HI}	Li et al. (1982)		-7.3 ± 2.4	-0.74
	Burton & Gordon (1978)		3.5 ± 1.6	0.61
Σ_{H_2}	Bhat et al. (1985)		1.6 ± 0.3	0.90
	SSS (1984)		1.1 ± 0.2	0.91
Σ_g	H_2	HI		
	Bhat et al. (1985)	Li et al. (1982)	-0.9 ± 2.5	-0.13
	SSS (1984)	Burton & Gordon (1978)	2.7 ± 0.7	0.81
	Bhat et al. (1985)	Burton & Gordon (1978)	3.8 ± 0.8	0.85

a least squares fit to calculate k, the standard errors and the corresponding correlation coefficients R_c. The two surface density distributions for H_2, SSS (1984) and Bhat et al. (1985) are used to illustrate the sensitivity of the results. The surface density distributions, scale heights and SFR are given in Table A.2.1 (Appendix). The corresponding plots for ψ_s against these surface density distributions, after eliminating their explicit dependence on Galactocentric radius (R_G) between 4.5 and 14.5kpc are shown in Figure 2.1. Of course the statistics of the data are not very good as at most only 10 points were available for each plot, which means that the derived value of R_c should not be taken too seriously. Nevertheless a number of factors may be noted in view of the above analysis.

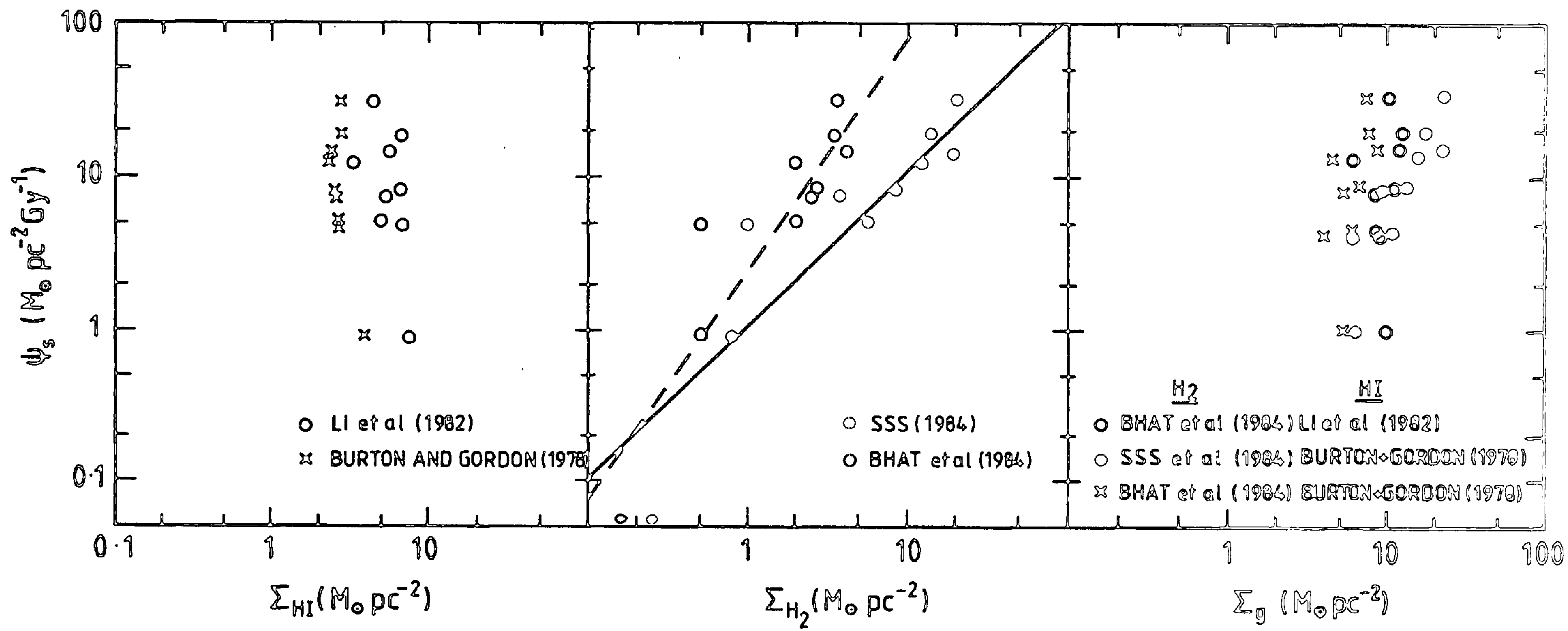


Figure 2.1: Star formation rate as given by SBM is plotted against the various surface density distributions of gas (given in Table A.2.1) after eliminating R_G. Σ_{HI} and Σ_g show virtually no correlation, but both the H_2 distributions show some degree of correlation with $k = 1.1 \pm 0.3$ for SSS (1984), and $k = 1.6 \pm 0.3$ for the Bhat et al. (1985) H_2 distribution.

(i) Even with the uncertainties involved, ψ_s seems to be better correlated with Σ_{H_2} than Σ_g or Σ_{HI}, as found earlier by Talbot using independent data. The lack of any correlation with HI is also found for external galaxies (Kennicutt and Kent 1983; Hunter et al. 1982) and is consistent with the observation that the HI distribution is often extended relative to the places where stars are currently forming (Bosma 1981b). The correlation with H_2 is further strengthened by the observation that stars form in dense H_2 clouds (e.g. Pudritz 1986; Myers et al. 1986; Waller et al. 1987) and the z-dependence of H_2 is similar to that of young stars (Fich and Blitz 1982; SSS 1984). In fact, within 3 kpc of the Sun only one GMC has been found without traces of star formation (Blitz 1987), indicating that once a GMC forms, star formation is almost inevitable and takes place very quickly.

(ii) Although the estimated distributions in total gas are widely different, no relationship of the form $\psi_s \propto \Sigma_g^k$ seems to exist, which is consistent with the poor correlations and widely different estimates of k made earlier for external galaxies (Section 2.2). Fall (1987) has cautioned, however, that present uncertainties in the estimation of ψ_s and Σ_g do not exclude $\psi_s \propto \Sigma_g^k$.

(iii) A relationship of the form $\psi_s \propto \Sigma^k$, if existing at all, will perhaps be relevant only to Σ_{H_2}. But uncertainties mean that at the present stage nothing conclusive can be said about the more acceptable of the surface density distributions of H_2 as they finally lead only to different values of k, with roughly the same correlation coefficient. The difference in the value of k will however, become apparent in the chemical evolution model of Chapter 3.

(iv) Bhat et al. (1984) had observed that their Σ_{H_2} as a function of R_G is very similar to that of HII regions (Lockman 1976), pulsars (Taylor 1979) and supernova remnants (Huang and Thaddeus 1986), all having a peak around R_G = 6 kpc. In addition to which OH/IR stars (Baud et al. 1979) and cool giant stars (Ito et al. 1977) also have a peak at $R_G \cong$ 6 kpc. All of these Population I tracers reflect enhanced star formation in the recent past (Lester et al. 1985) and the further link between the SFR and distributions reinforces that all these processes are physically related.

It must be stressed that the above surface densities of gas and their ensuing conclusions are preliminary as the gas distributions used for H_2 are averaged over the incomplete rings around the centre of the Galaxy. In particular the measurements of Σ_{H_2} outside the solar circle given by SSS (and therefore derived by Bhat et al.) are incomplete, being only for the northern declinations. Recent results (Robinson et al. 1984) may suggest more H_2 in the outer Galaxy than that given by SSS (1984). Therefore an average of the SFRs given by Lacey and Fall (1985) and SBM (1978) was taken and a correlation looked for in the inner Galaxy where the data are complete. Figure 2.2 shows the result, the points in the left half of the Figure corresponding to the outer Galaxy, the dotted lines being extrapolations from the inner Galaxy. It can be easily seen that the points in the outer Galaxy do not fit the extrapolation, possibly due

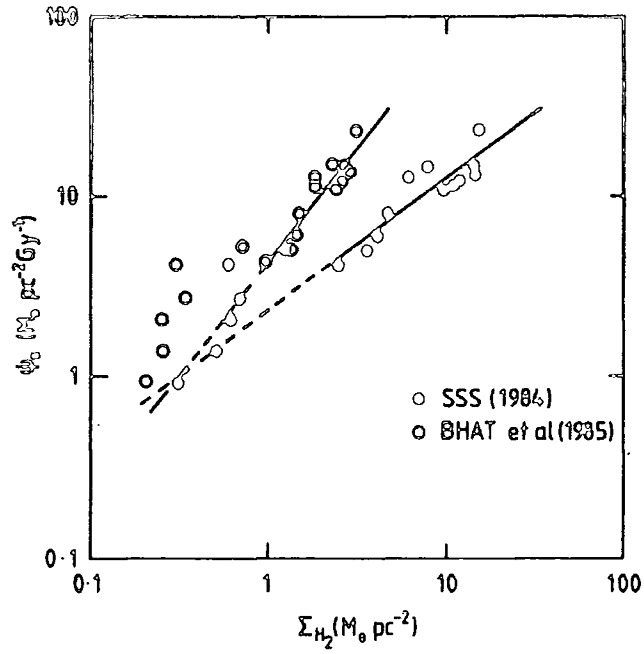


Figure 2.2: SFRs averaged from SBM (1978) and Lacey and Fall (1985) plotted against the surface density of molecular hydrogen. A good correlation (R_c = 0.91) is found for the inner Galaxy (shown by the solid line) with k = 0.7 $\pm$ 0.2 for the SSS distribution and 1.2 $\pm$ 0.2 for the Bhat et al. distribution. If the line is extrapolated to the outer Galaxy (dashed line) where the H_2 data are incomplete, the values of Σ_{H_2} seem to be underestimates.

to an underestimate of Σ_{H_2}. This is an important point which will be investigated further in Chapter 4.

This more detailed study shows roughly the same correlation, but a reduction in the value of k to 0.7 $\pm$ 0.2 for the SSS distribution and 1.2 $\pm$ 0.2 for the Bhat et al. distribution of Σ_{H_2}.

2.3.2 SFR in relation to the volume density of gas

Guibert et al. (1978) studied such a relationship as given by equation (2.2) and concluded that the exponent a is 1.2 - 2.5. At present such an analysis can be extended only for the incomplete gas distributions, using scale heights for H_2 from SSS (1984) and for HI from Kulkarni et al. (1982). From ψ_S as given by SBM, one can possibly derive ψ_V, assuming that the scale heights for ψ_S are the same as those for the H_2 distributions, because it is known that star formation takes place primarily, if not necessarily, inside the molecular complexes. The results of fitting a relationship (2.2) to the different distributions of ρ_{H_2}, ρ_{HI} and ρ_g are shown in Table 2.2. The values of the

Table 2.2: Correlation of SFR and volume densities of gas.

(SFR from SBM 1978)

ρ_g in relation (2.2) replaced by	Source of data		a	R_c
ρ_{HI}	Li et al. (1982)		4.6±1.8	0.66
	Burton & Gordon (1978)		3.0±0.6	0.86
ρ_{H_2}	Bhat et al. (1985)		1.5±0.3	0.89
	SSS (1984)		1.0±0.2	0.90
ρ_g	H_2	HI		
	Bhat et al. (1985)	Li et al. (1982)	3.1±0.6	0.86
	SSS (1984)	Burton & Gordon (1978)	1.7±0.4	0.83
	Bhat et al. (1985)	Burton & Gordon (1978)	2.2±0.3	0.93

exponent a and the correlation coefficient R_c, derived from least-squares fitting are calculated as before.

It can be seen that, as for the surface densities, ψ_v is once again correlated with ρ_{H_2} rather than ρ_{HI}. The values of a and k are similar as the scale heights of H_2 stay roughly constant over the range of R_G considered. Therefore, most of the conclusions that are noted previously from Table 2.1 are still valid in the present context. Fits are found to be equally good for both the SSS and Bhat et al. volume density distributions of H_2, but leading to two different values of a, namely, 1.0 ± 0.2 and 1.5 ± 0.3 respectively. However, the volume density of the total gas is also well correlated with ψ_v. This is largely due to the small contribution of HI (as its scale height is appreciably larger) compared to that of H_2, which means that the distribution of H_2 'controls' the ρ_g distribution and hence ψ_v is primarily controlled by H_2 densities. The large value of a for the ρ_g correlation is highly inconsistent with the fact that the SFR has stayed fairly constant as has been argued previously.

Scoville et al. (1986) claim that locally the number density of giant HII regions is proportional to the square of the density of H_2, and suggest that this implies that OB stars form as a result of cloud-cloud collisions (Brosche 1970; Larson 1977). They also suggest that lower mass stars show a linear correlation implying that they are formed from individual clouds. The results of Table 2.1 and 2.2 possibly suggest a gross average over both high mass and low mass star formation with respect to H_2.

The conclusion of the above analysis is that if a phenomenological relationship of star formation rate as a power of gas density exists, then it is only relevant to H_2. Between the surface densities and volume densities the existing data do not make a sharp distinction. Mathematically, equations (2.1) and (2.2) will be compatible only if k = a = 1 or if the scale-height is constant with R_G. Some may feel that physically the SFR should be related to the volume density rather than surface density. But the surface density gives the mass of gas in a particular region and therefore the total number of clouds. As Clayton (1986, 1987) has pointed out, if star formation proceeds at a fixed rate in molecular clouds then it is the number of clouds that will determine the SFR. The surface density is to be preferred to the volume density also for practical reasons. Any measurement of ρ_g depends strongly on the spatial resolution of the observations (Tinsley 1980). In external galaxies, the observations measure Σ directly, while a knowledge of the scale-height is needed for ρ. As the scale-height is not well known, Σ is a much better quantity to work with in the study of external spiral galaxies. The equations of chemical evolution (Chapter 3) can also be solved more naturally for surface densities. The rest of this work will therefore adopt a SFR expressed in terms of the surface density of H_2, that is

$$\psi_s \propto \Sigma_{H_2}^{k} \qquad (2.4)$$

where a larger value of k is favoured by the Bhat et al. (1985) distribution than the SSS (1984) distribution of H_2.

Finally, the delineation of spiral arms by active regions of star formation has led many workers to believe that spiral arms are an important trigger of star formation in galaxies (e.g. Baade and Mayall 1951; Roberts 1969; Toomre 1981; Gerola and Seiden 1978). However, Elmegreen (1987c) has questioned this view, arguing that star formation simply follows the gas with no preferential trigger related to the density wave. Comparisons between galaxies with and without density waves reveal no significant differences in the SFR or metal abundances (Elmegreen and Elmegreen 1986; McCall 1986). From a study of supernovae in external galaxies (McCall and Schmidt 1986) it appears that density waves do not enhance the efficiency of massive star formation, while some irregular galaxies have high ψ_s but no spiral arms (Hunter and Gallagher 1986).

Elmegreen (1987c) suggests that spiral arms simply re-organise the matter within the discs without actually enhancing the SFR. As McCall (1986) points out, "if the underlying details of density waves are indeed inconsequential to star formation the task of identifying the physical properties controlling the chemical evolution of spiral galaxies is greatly simplified". No doubt the real situation is quite complex, but over large scales and long time-scales a relationship such as (2.4) may be applicable.

2.4 THE TIME EVOLUTION OF THE SFR IN THE GALAXY

It has been shown above that there is an empirical correlation in the disc of the Galaxy between the SFR and the surface density of molecular hydrogen, to be understood at a simple physical level that it is from H_2 that stars form. The next question is: can equation (2.4), derived empirically from the radial distributions, be used to predict the time evolution of the SFR? Any such law of star formation is in any case possibly a smoothed average over stochastically occurring bursts, but can it predict the gross variation of the SFR over the age of the Galaxy? Although it has been known for some years that stars form out of H_2, and Talbot (1980) proposed the relationship (2.4), the problem faced by evolutionary models is how to deal with the evolution of H_2 quantitatively. In chemical evolution models for example, the absolute values of the SFR are important for studying the age-metallicity relation for stars in the solar neighbourhood (Twarog 1980) while its radial distribution with time will manifest itself in shaping the abundance gradient of the processed elements in the Galaxy.

Molecular clouds in the Galaxy differ from the diffuse atomic clouds in that they are optically thick to UV radiation and visible continuum and that they are self gravitating. Their formation has been ascribed to shock compression in the ambient gas, agglomeration of smaller clouds and spontaneous instabilities in the gaseous disc (e.g. Elmegreen 1987a,b). These formation mechanisms seem to explain some of the observed cloud complexes in the Galaxy, although there is still no general agreement on which is the dominant mechanism. In addition, the current formation mechanisms do not at present distinguish between H_2 and HI. The lifetime of GMCs is another controversial issue, which will be examined in detail in Chapter 6. At this time, it seems very difficult to link these processes to the global time and radial variation of H_2 in the Galaxy.

Wyse (1986) has attempted to understand the difference in H_2 and HI profiles in galaxies in terms of enhanced GMC formation in local gravitational potential perturbations such as spiral arms, proposing

$$\Sigma_{H_2} \propto \Sigma_{HI}^{2} \cdot (\Omega(R_G) - \text{constant}) \qquad (2.5)$$

where $\Omega(R_G)$ is the local angular frequency. If CO is a good tracer of H_2, using a constant α_{20}, this form provides good fits for the Galaxy, NGC 2841, M51 and M31 but not too good for M101. It also explains the steep fall off of the molecular gas in the outer regions reflecting that of the angular frequency. However, Stark et al. (1987) have shown no obvious correlation between the surface brightness of CO and arm class for over 100 spiral galaxies, which suggests that spiral arms are not required to form H_2 in a galaxy. From their data it appears that molecular clouds form continuously, whether or not a spiral density wave is present in a galaxy. In addition, apart from the assumption of a constant α_{20} in this law, the main problem against it is its time evolution. In order to solve analytically the equations of chemical evolution, Σ_{H_2} needs to be expressed as a function of the total mass of gas rather than Σ_{HI}. In order to do this the following argument will attempt to connect the amount of H_2 to Σ_g through the abundance of metals in the ISM.

If the SFR has not changed appreciably since the formation of the disc (Section 2.2), one must argue that, in spite of the constant depletion of H_2 because of continued star formation, the amount of H_2 has somehow been continually replenished. It is known that HI continually evolves into H_2 in the presence of grains (Savage and Mathis 1979; Duley and Williams 1984) and this may be the reason. The formation of H_2 is critically dependent on the availability of interstellar grains, unless the density of gas is as high as 10^9 H atoms cm^{-3} (Williams 1985). Theoretical studies by Hollenbach and Salpeter (1971) showed that approximately one-third of H atoms striking grains formed H_2 and observational support has been put forward by O'Donnel and Watson (1974) and Jura (1975). It is also known that for catalysis of H_2 formation, the grains must have a temperature of approximately 20K (Schmidt 1967). Recent infra-red studies at 60 and 100μm (Burton et al. 1986) reveal that interstellar grains do have a temperature

20–25K in the plane, but also the surprising result that the scale-height of the dust is nearer that of HI than H_2 (Burton and Deul 1987). This latter result does not fit the general picture of H_2 formation and is not easy to

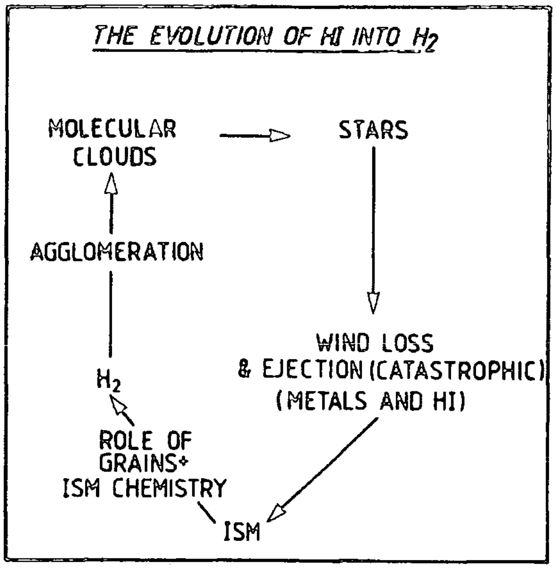


Figure 2.3: A qualitative scheme of re-cycling HI through H_2 in the ISM. Molecular clouds evolve into stars which eject metals and HI into the ISM. Metals segregate into grains which catalyse formation of H_2. This H_2 finally agglomerates into molecular clouds, thus completing the cycle. Every generation of star formation leaves some stars behind, dead or alive.

understand unless there is some temperature effect perpendicular to the plane. Measurements at larger wavelengths, where more of the dust is sampled, are needed before firm conclusions can be drawn. It is these uncertainties in temperature as well as the actual number and size distributions of the grains at various distances from the Galactic Centre that make it a formidable task to rigorously handle the process of HI$\rightarrow H_2$ conversion in the ISM. A further uncertainty involves the estimation of the so-called returned fraction which essentially determines how much matter in the form of HI is returned in the end to the ISM, assuming that all H_2 went initially into star formation. Therefore only a qualitative scheme of recycling HI through H_2 is presented in Figure 2.3.

Knowing that grains do play a vital role in forming H_2 from HI, let us investigate whether the fractional abundance (p_2) of H_2 in the total amount of available hydrogen, in a given region, is related to the average metallicity (Z) of that region. Actually a link should be sought with the abundance of grains rather than metallicity in the gas phase, but the abundance of grains is assumed to roughly follow the metallicity (Viallefond et al. 1982; Franco and Cox 1986). In fact metals in the gas phase may themselves be important in forming H_2 clouds as they act as coolants (van den Bergh 1981) and increase opacity (Franco and Cox 1986). Following the discussion of Section (2.3.2), p_2 is defined in terms of the surface densities

$$p_2 = \frac{\Sigma_{H_2}}{(\Sigma_{H_2} + \Sigma_{HI})} \qquad (2.6)$$

The available distributions of Σ_{HI} (as given in Table A.2.1) have been averaged to derive $\overline{\Sigma_{HI}}$ and a probable range of error in its estimates. Then substituting this value in (2.6), $\overline{p_2}$ has been computed for both the SSS and Bhat et al. distribution of H_2. The variation of p_2 with Galactocentric radius is shown in Figure 2.4, the errors reflecting the uncertainties in HI. Both of the distributions behave similarly, although the absolute values are quite different. The fraction of molecular gas flattens out below R_G = 6-7 kpc and falls off towards the outer edge. The sharp change in the trend just above R_G = 10 kpc could be due to the underestimate of H_2 in the outer Galaxy (Section 2.3.1).

Elmegreen and Elmegreen (1987b) have noticed a similar radial dependence of this molecular fraction in individual

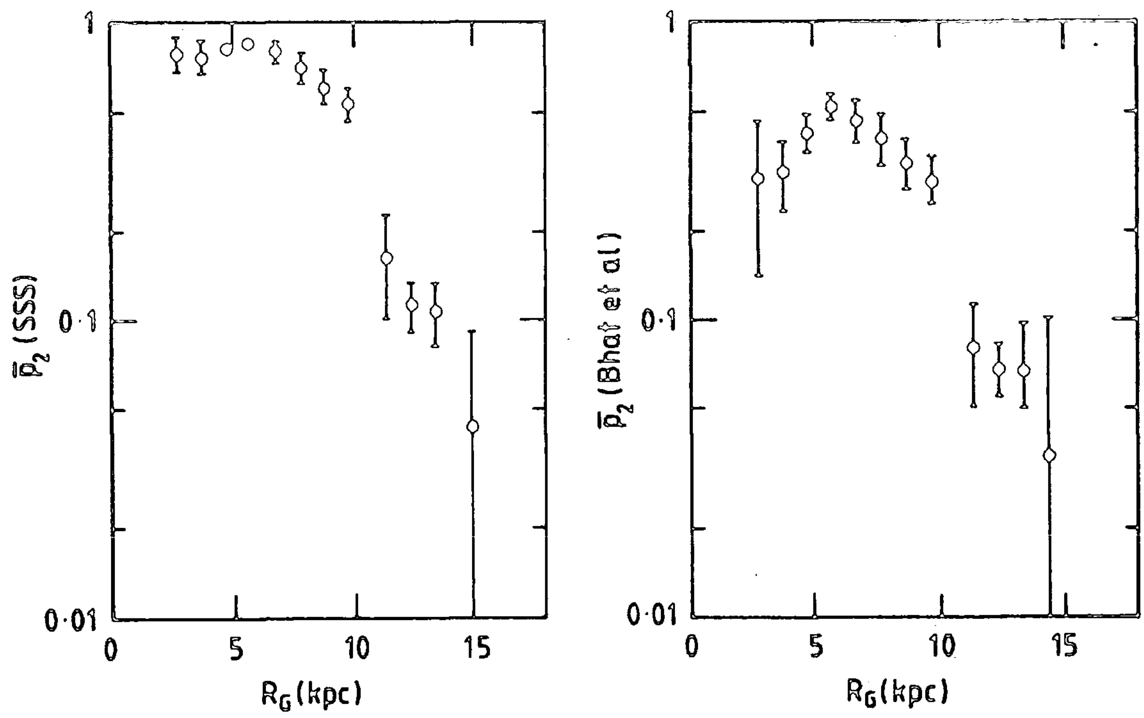


Figure 2.4: The variation of the molecular fraction of gas ($\bar{p}_2$) with Galactocentric radius R_G. Two estimates are made of $\bar{p}_2$ for the different distributions of H_2, as given by SSS (1984) and Bhat et al. (1985). The forms are found to be similar although the absolute values are quite different.

'super cloud' complexes, consisting of HI and H_2, with masses $\gtrsim 10^6 M_\odot$. The total mass of the complexes appears to be constant as a function of R_G, which suggests that the molecular cores to these clouds become less massive with increasing R_G, while their atomic envelopes become more massive. This is ascribed to an increase in the average pressure of the clouds in the inner Galaxy, leading to larger densities and molecular line shielding of the background UV radiation becoming more important. However, one may expect increased metallicity (and/or grains) to have the same effect (Section 6.2).

Figure 2.5 shows the variation of metallicity or more precisely log(O/H)+12, with R_G, essentially compiling all the available data from a number of sources. There are few

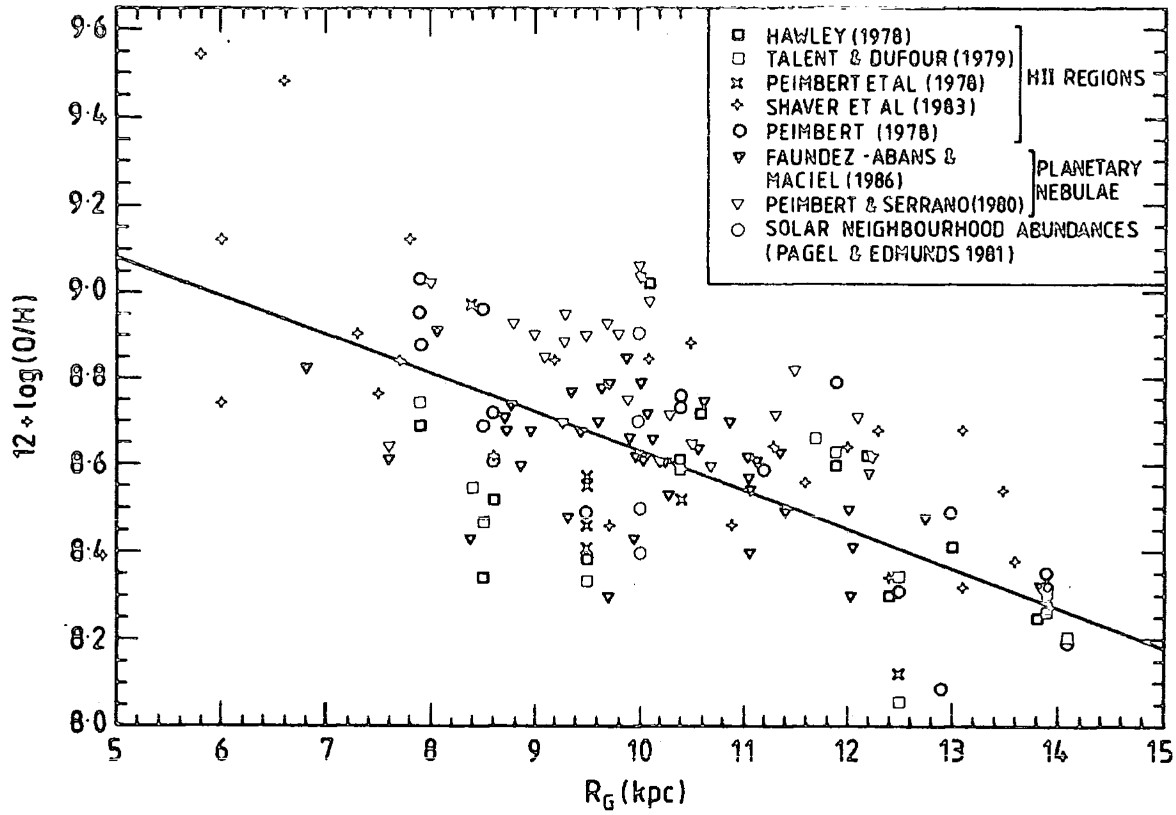


Figure 2.5: A compilation of the observational data on the variation of oxygen abundance measurements with Galactocentric radius. The objects comprise HII regions, planetary nebulae and some main sequence stars in the solar neighbourhood. The gradient from a least squares fit for $R_G > 6$kpc is shown and is $\simeq -0.09 \pm 0.01$ dex kpc^{-1}.

observations for $R_G < 6$kpc. Although the individual estimates have a considerable spread in the ordinate there seems to exist a general trend of metallicity with R_G, with a gradient

$$\frac{d\log(O/H)}{dR_G} = -0.09 \pm 0.01 \text{ dex kpc}^{-1} \qquad (2.7)$$

extending between $R_G = 6$ and 14 kpc. Abundance gradient determinations by different authors using different objects are compiled in Table A.2.2 (Appendix). There are large uncertainties in abundance determinations from HII regions and this is probably the main cause for the spread in metallicity at any particular R_G. However, there may be also some genuine evolutionary effects. Stars themselves (as shown by the solar neighbourhood) show an increase in metallicity with time of formation, while the metallicity spread in HII regions could be due to the locking of metals into grains (e.g. Mathis 1986). For planetary nebulae, Peimbert (1978) argues that for most the O enrichment due to their evolution has not been considerable and that differences are related to gradients present in the ISM at the time of formation of the progenitor stars (Peimbert and Serrano 1980). This will be discussed in more detail in Chapter 3.

Assuming that $Z \propto O/H$, O being the major contributor to the metallicity (Peimbert and Torres-Peimbert 1974; Peimbert et al. 1986), p_2 is investigated as a function of Z, aiming to fit a relationship of the form

$$p_2 \propto Z^b \qquad (2.8)$$

In Figure 2.6, $\bar{p}_2$ is plotted against metallicity after eliminating R_G, for $6 < R_G < 14$ kpc only. Errors shown are only formal errors and could be larger due to systematic effects.

Considering the errors involved, fairly good correlations are obtained for least-squares fits between the data and equation (2.8), yielding the exponent b as

$b = 1.3 \pm 0.3$ for the Bhat et al. distribution of H_2,

$= 1.4 \pm 0.3$ for the SSS distribution of H_2.

They now agree well with each other within the large error bounds. If there is more H_2 in the outer Galaxy than presently estimated, as suggested earlier, this will have the effect of reducing b although due to errors in HI this will be a small effect. Preliminary though this correlation

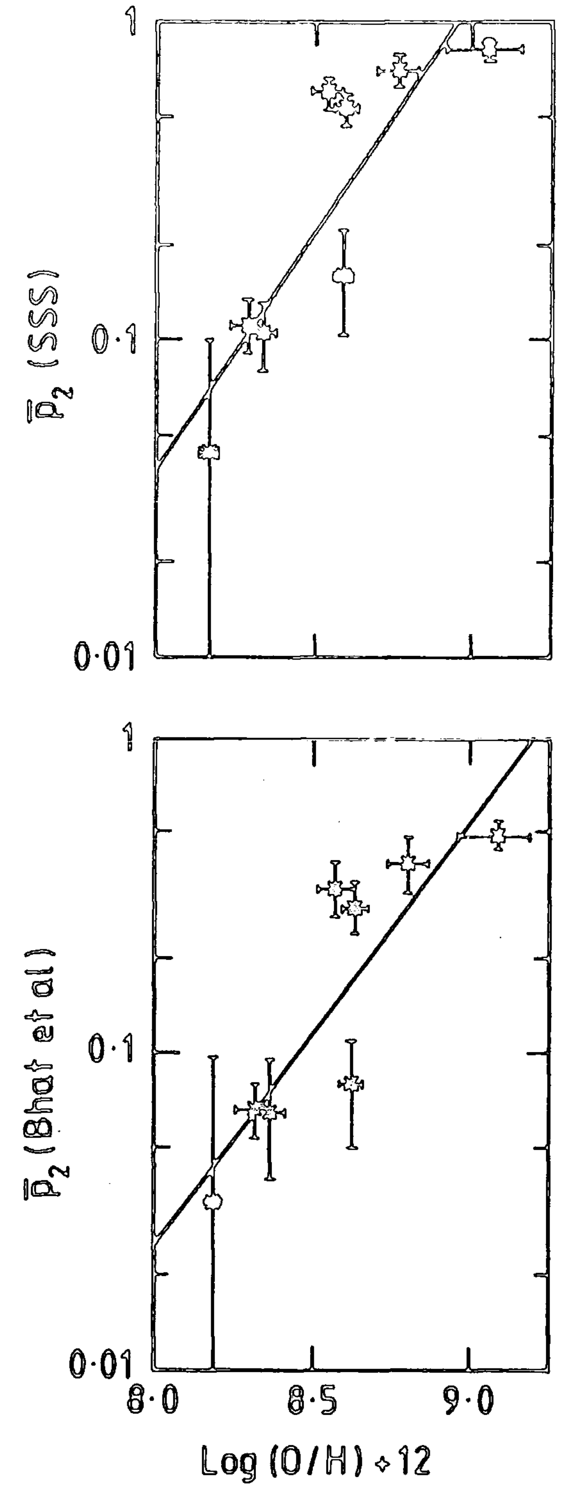


Figure 2.6: The molecular gas fraction $\bar{p}_2$ is plotted against the metallicity (assuming $Z \propto O/H$), for $6 < R_G < 14$kpc in the Galactic disc. Both H_2 distributions are shown and a correlation is found for $\bar{p}_2 \propto Z^b$, with b = 1.3-1.4.

between the molecular hydrogen fraction and metallicity is, it would nevertheless mean that metallicity may not monotonically increase right up to the centre of the Galaxy and it may eventually flatten off for $R_{G} < 6$ kpc as the Galactocentric variation of $\bar{p}_2$ indicates. The metallicity in the very central regions is highly uncertain, in the range 12 + log(O/H) = 9.0 - 9.6 (Mezger et al. 1979; Shaver et al. 1979; Wink et al. 1983) but a value of $Z \cong 3Z_{\odot}$, i.e. a flattening out of the gradient, is not unreasonable (Güsten and Ungerechts 1985).

Now, using (2.8), a more explicit functional form of the SFR may be obtained as follows. Let μ be defined as the gas fraction of the total mass available in the form of gas and stars per unit area of the disc

$$\mu = \frac{\Sigma_g}{\Sigma_T} \tag{2.9}$$

where $\Sigma_T = \Sigma_g + \Sigma_s'$, (2.10)

Σ_s' being the total surface density of matter locked in stars, dead or alive. The measured rotation curve of the Galaxy yields Σ_T (the estimated values are given in Table A.2.1 (Appendix)). Combining equations (2.4), (2.6), (2.8) and (2.9) one obtains

$$\psi_s \propto (\Sigma_T X \mu Z^b)^k . \tag{2.11}$$

The SFR given by (2.11) has the following significance. (i) This form of the SFR has primarily been derived from phenomenological considerations of the spatial variations of various quantities with Galactocentric radius. But the form (2.11) is now such that it can be used to study the time variation of ψ_s for any given annulus, provided that the evolution of μ, Σ_T , X and Z with time is known. When the disc first stabilised, its rotation curve and therefore the distribution of Σ_T presumably also stabilised (except for local variations due to the propagation of density waves). The chemical fraction of hydrogen, X, is a very slowly decreasing function of time. So for a given region, such as that near the Sun, assuming no infall, $\Sigma_T X$ may be regarded as a constant. Consequently, the evolution of ψ_S in that region may be studied by the evolution of the quantity $(\mu Z^b)^k$. At the time of formation of the disc, the gas fraction $\mu_0 \leqslant 1$ and non-zero. In order therefore for a non-zero ψ_S, the initial metallicity of the disc, Z_0, cannot be indefinitely small, a suggestion that was first made in the context of the chemical evolution of the solar neighbourhood (Truran and Cameron 1971). In fact, if ψ_S remains constant with time and the gas is depleted at most by a factor of 10, log (Z_p/Z_0) cannot exceed $\cong 0.7$ (Z_p being the present metallicity in the solar neighbourhood.)

(ii) With the ageing of the disc, μ decreases whereas Z increases due to star birth and death (van den Bergh 1958), thereby effectively balancing one another and leading to a constant SFR. Equation (2.11) is then a modified Schmidt law. In fact Talbot and Arnett (1973) in attempting to model the chemical evolution of the solar neighbourhood had suggested that star formation was enhanced by the presence of metals and had multiplied the mass of gas by a term dependent on the metallicity in the standard Schmidt law. The metallicity term in equation (2.11) is due to the consideration of molecular hydrogen in the role of star formation.

(iii) Since the value for the exponent b in (2.8) has been derived for $6 < R_G < 14$ kpc one must be careful in extending the application of (2.11) outside the above domain. However, presumably when the disc was formed, $\mu_{\circledcirc}$, $X_{\circledcirc}$ and $Z_{\circledcirc}$ were constant as a function of R_{G}. It was therefore the variation of Σ_T with respect to R_G that determined the initial value of the SFR, $(\psi_s)_{\circledcirc}$. Since Σ_T increases sharply towards the centre of the Galaxy, $(\psi_s)_{\circledcirc}$ should have been very high in the inner part of the Galaxy - thus leading to faster evolution there and thereby initiating the future metallicity gradient as well as a sharp gradient in μ. Clayton (1987) has re-emphasised the point that a large abundance gradient cannot be modelled if ψ_s/Σ_g is a constant and so uses infall of gas to the disc to produce the gradient. The SFR given by (2.11) predicts a non-constant ψ_s/Σ_g with radius and time and therefore will lead to an abundance gradient.

(iv) The main problem of the original Schmidt law, that of a constant SFR, can be overcome quite naturally by the time dependence of $(\mu Z^b)^k$. Previous workers (Larson 1972; Clayton 1984, 1985, 1986; Lacey and Fall 1985) with a SFR proportional to gas density, needed infall to show why the SFR has practically stayed constant over the age of the Galaxy. However, a SFR proportional to a power of the surface density of H_2 resolves this problem without infall.

The above qualitative points will be examined quantitatively in the context of chemical evolution in Chapters 3 and 4. But before calculating it in detail for the Galaxy, evidence from other spiral galaxies needs to be examined in order to determine how universal the application of equation (2.11) can be.

2.5 STAR FORMATION IN EXTERNAL SPIRAL GALAXIES

2.5.1 Star formation rate and molecular hydrogen

The detection of CO in external spiral galaxies (Rickard et al. 1975; Solomon and de Zafra 1975) has allowed investigation of the star forming component of the ISM in these galaxies. However, just as in the case of the Galaxy, the problem is the conversion factor to H_2, and just how much H_2 is really there. In a sense, knowledge of α_{20} for external galaxies is even more problematic than for the Galaxy, as the γ-ray method (Section 1.2.2) cannot (yet) be used to calibrate α_{20}. Many past attempts (e.g. Young and Scoville 1982a) have assumed that the local value of α_{20} applies universally, thereby determining H_2. Although Young and Sanders (1986) have argued that this method is correct to a factor of 2, many have questioned this (Rickard and Blitz 1985; Bhat et al. 1986; Lo et al. 1987a; Stark et al. 1987) even to the extent of suggesting that radial distributions of H_2 in galaxies cannot be determined from the CO data with any confidence at all (Blitz 1985).

In the light of this uncertainty concerning α_{20} and the effects of temperature and metallicity, any rigorous testing of $\psi_s \propto \Sigma_{H_2}^k$ and in particular the value of the exponent k is fraught with difficulty. However, we do see a qualitative correspondence, certainly between CO (and probably H_2) and the tracers of recent star formation.

The Population I tracers which are extremely similar radially to CO in the Galaxy (Mihalas and Binney 1981) have the same trend in M51 (Scoville 1983) and M33 (Freedman

1986). Young and Scoville (1982a,b) have shown that the CO luminosity (L_{CO}) follows that of the blue luminosity (L_B) with radius in NGC 6946 and IC 342, and the existence of a linear correlation between L_B and L_{CO} for the central 5 kpc of Sc galaxies, both isolated and in the Virgo cluster (Young et al. 1985b; Young 1985a). If the CO traces the H_2 and L_B is taken to be mostly from Population I stars, thereby indicating the amount of star formation over the last 2.10^9 y (Scoville and Young 1983) this implies $k \cong 1$ in the $\psi_S \propto \Sigma_{H_2}^k$ relation. This correlation has been discussed extensively by Bhat et al. (1986) who argue that the correlation is improved by introducing a metallicity correction to α_{20}. From their Figures 13 and 14, the effect of a metallicity correction implies $k > 1$, in agreement with the Galactic analysis (Section 2.3.1).

A possibly more direct measure of the young stellar content of a galaxy is the infra-red luminosity (e.g. Telesco et al. 1986). It has been argued that the far infra-red luminosity gives a direct measure of the energy output from recently formed stars (Cox et al. 1986; Bushouse 1986) based on the fact that Galactic regions of star formation are always associated with dusty and relatively dense molecular clouds, with nearly all the luminosity emerging in the FIR (e.g. Knapp et al. 1977). Therefore, as expected, CO is found to correlate with the FIR luminosity, within galaxies (Scoville and Young 1983) and between galaxies (e.g. Young et al. 1985a). If the FIR luminosity is a measure of ψ_S, then Rickard et al. (1985) found $k = 1.48$ in the centres of nearby spirals. The availability of IR fluxes from the IRAS satellite for external galaxies has seen a study of CO and IR emission in dwarf irregular galaxies (Tacconi and Young 1987), isolated and interacting galaxies (Rickard and Harvey 1984; Rengarajan and Verma 1986; Young et al. 1986b), IRAS bright galaxies (Young et al. 1986a; Sanders et al. 1986b), radio bright spirals (Sanders and Mirabel 1985) and ultra-luminous IR galaxies (Sanders et al. 1987). These studies have confirmed the correlation between IR and CO over six orders of magnitude, but there is a wide dispersion, which appears to be due in part to temperature effects (Young et al. 1986a; Solomon et al. 1987b) or variations in the dust-to-gas ratio (Rydbeck 1985). Interacting galaxies seem to have a higher efficiency of star formation (higher IR luminosity for the same CO) than isolated galaxies, but both seem to follow the same trend with $k \simeq 0.75$ (Young et al. 1986b).

Figure 2.7 summarises the situation for the IRAS bright galaxy sample of Young et al. (1986a) and the isolated and interacting galaxy sample of Young et al. (1986b). The mass of H_2 has been calculated from maps of the CO emission using $\alpha_{20} = 8$. The SFR, ψ_S, is calculated following Scoville and Young (1983) using

$$\psi_S(M_\odot y^{-1}) = 7.7.10^{-11} \frac{(L_{IR} + L_B)}{L_\odot} \qquad (2.12)$$

where the blue luminosity (L_B) has been derived from RC2 (de Vaucouleurs, de Vaucouleurs and Corwin 1976) and the total FIR luminosity (L_{IR}) is given by

$$L_{IR}(L_\odot) = 4.10^5 CD^2 (2.58S_{60} + S_{100}). \qquad (2.13)$$

In the above equation, S_{60} and S_{100} are the $60\mu m$ and $100\mu m$ fluxes (in Jy), D is the distance to the galaxy (in Mpc), and the correction factor C is taken from the IRAS

Extragalactic Catalogue (Lonsdale et al. 1985). As Young et al. (1986a) point out, these estimated SFRs do not account for either the formation of low mass stars (as it assumed the observed luminosities are produced primarily by O,B and A stars) or for the re-cycling of gas in the ISM, although to some extent these two effects may balance each other. For galaxies with Hα flux measurements (Kennicutt and Kent 1983), the above ψ_s has been compared to the ψ_s derived from Hα (Kennicutt 1983b) and found to agree within 50%.

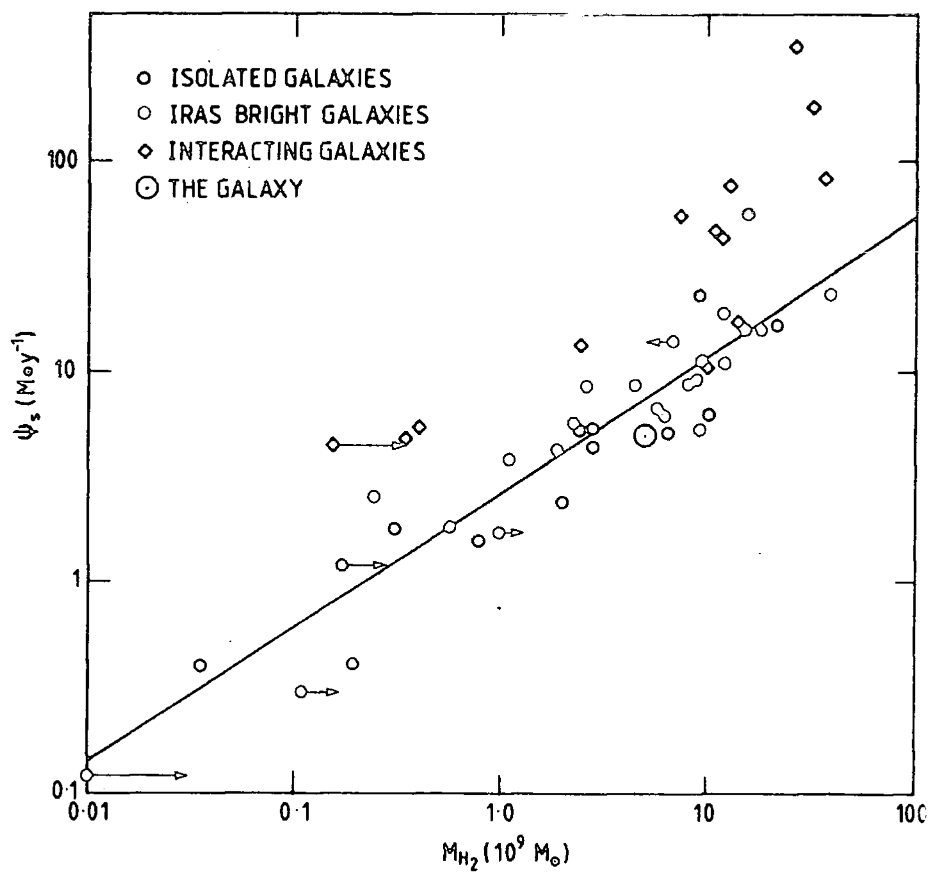


Figure 2.7: SFR determined from the blue and infra-red luminosities plotted against the total mass of H_2 (using $\alpha_{2\odot}$ = 8, $H_\odot$ = 50kms^{-1} Mpc^{-1}) for IRAS bright galaxies (Young et al. 1986a) and isolated and interacting galaxies (Young et al. 1986b). Excluding the interacting galaxies a good correlation is found (R_c = 0.92) with slope = 0.60 ± 0.05. Arrows show the effect of a metallicity correction to $\alpha_{2\odot}$ having the effect of increasing the slope.

Excluding the interacting galaxy sample, a good correlation is found (correlation coefficient = 0.92) with k = 0.6 in $\psi_S \propto M_{H_2}^k$. The interacting galaxies seem to show the same trend but have systematically higher SFRs indicating a different efficiency (cf. Kennicutt et al. 1987). The arrows on certain points illustrate the effect of introducing a metallicity correction to α_{20} (Bhat et al. 1984; 1985) where metallicities have been taken from a variety of sources (Matteucci and Chiosi 1983; Hunter et al. 1982; McCall et al. 1985; Hunter and Gallagher 1986). With only a few metallicities available for these galaxies, it can only be said that a metallicity correction seems to increase k. The Galactic analysis gave k = 0.7 - 1.4, which is consistent with the above value.

Finally, as mentioned in Section 2.3.1, the Hα emission which is an indicator of the star formation rate correlates with CO for the Galaxy and for M51 (Young 1985a). Talbot (1980) using a metallicity corrected H_2 distribution found $k \simeq 1.2$ for M83, while DeGoia-Eastwood et al. (1984) found $k \simeq 0.8$ for NGC 6946 in the $\psi_S \propto \Sigma_{H_2}^k$ relation.

Therefore, apart from large uncertainties concerning the estimation of ψ_S and Σ_{H_2} in external galaxies, $\psi_S \propto \Sigma_{H_2}^k$ is certainly consistent with present data with k in the range 0.6 - 1.5 (this range being possibly entirely due to uncertainties in the estimation of ψ_S and Σ_{H_2}).

2.5.2 Molecular hydrogen and metallicity

In Section 2.4, a relationship of the form $p_2 \propto Z^b$ was found for the Galaxy, with b = 1.3 ± 0.3. This Section compiles the available data on the radial distributions of HI, H_2 and (O/H) for nine other spiral galaxies in order to see whether this relationship is applicable in external galaxies.

The references from which the data have been taken are shown in Table A.2.3 (Appendix). The HI distributions are taken from the sources listed in the second column of Table A.2.3, as used by Diaz and Tosi (1984) and Tosi and Diaz (1985) with their adopted distances. The H_2 distributions are inferred from the observed CO distributions along the respective galactic discs, except M33 where the CO distribution was assumed to follow the blue luminosity profile (Diaz and Tosi 1984) and normalised according to the CO nuclear detection of Young and Scoville (1982b). Two possible radial H_2 distributions are derived because of the controversy surrounding α_{20}. The first Σ_{H_2} (S) follows SSS (1984) assuming a constant $\alpha_{20} = 7.2$. The second Σ_{H_2}(B) follows Bhat et al. (1984, 1985, 1986), reducing α_{20} in the solar neighbourhood, and introducing a metallicity correction, M_Z, so that

$$\Sigma_{H_2}(B) = \Sigma_{H_2}(S) \quad \frac{2.7}{7.2} \cdot \frac{1}{M_Z} \qquad (2.14)$$

where $\log M_Z = 12 + \log (O/H) - 8.9$ (2.15)

The data on the galactocentric gradients of (O/H) used in deriving M_Z are primarily those calibrated and used by Diaz and Tosi (1984) and Tosi and Diaz (1985). Dopita and Evans (1986) have recently examined the semi-empirical abundance diagnostic ratios used to determine metal abundances (Pagel et al. 1978; Edmunds and Pagel 1984a; McCall et al. 1985) and suggested lower abundances particularly for the most metal rich HII regions (see also Pagel 1986c and Evans 1986). In Figure A.2.4 (Appendix), the calibration curves for the oxygen abundance against the ratio ([OII] + [OIII])/Hβ are shown. But until there is agreement, this work will follow Tosi and Diaz (1985) using the curve of Edmunds and Pagel (1984a).

Having obtained two alternative distributions of Σ_{H_2}, the corresponding p_2 values were calculated using the same distribution of Σ_{HI}. Each metallicity measurement at a particular galactocentric radius of any particular spiral galaxy, with its quoted error where possible has been plotted against p_2 for that radius and galaxy, so eliminating the explicit radial dependence of the same quantities for individual galaxies. This is shown in Figure 2.8 where the calculation of the two sets of p_2 has been based on $\Sigma_{H_2}(S)$ and $\Sigma_{H_2}(B)$ respectively. From this Figure the following points may be noted:

(i) The points shown seem to have a large spread, nevertheless a general trend is apparent. For a higher observed metallicity, the higher is the molecular fraction of the gas in the respective region of the galaxy. This means that metal poor spirals will have in general little H_2 in comparison with HI. This may be the reason why gas rich irregulars (Elmegreen et al. 1980; Tacconi and Young 1985), irregular dwarf galaxies (Israel and Burton 1986) and the LMC and SMC (Israel 1984) show extremely weak CO signals. These galaxies have low gas metallicities (Rocca-Volmerange 1984; Hunter and Gallagher 1986) and this could be the reason for the apparent low H_2/HI ratio. In fact, Tacconi and Young (1987) find that dwarf irregular galaxies have low H_2/HI ratios and qualitatively ascribe this as possibly due to low metallicity. However, the situation is complicated by the fact that α_{20} may be dependent on metallicity and other factors so that low CO emission does not necessarily

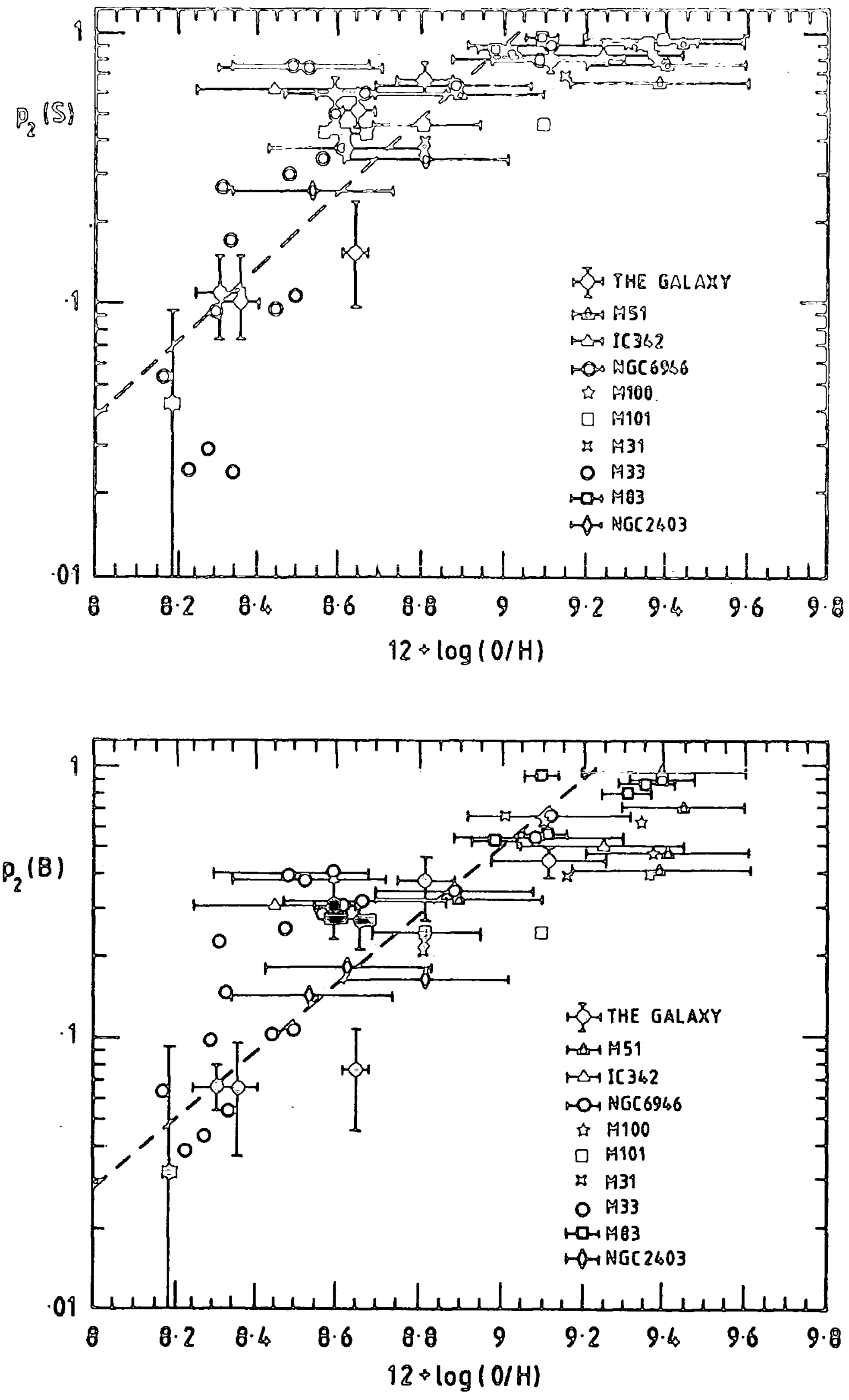


Figure 2.8: The fraction of molecular hydrogen, $p_2 = \Sigma_{H_2}/(\Sigma_{H_2} + \Sigma_{HI})$ plotted against the metallicity for different regions of various spiral galaxies. The upper plot uses a constant $\alpha_{2\odot}$ in determining Σ_{H_2}, while the lower plot uses a metallicity dependent $\alpha_{2\odot}$. Shown on both plots are the corresponding $p_2 \propto Z^b$ relation deduced for the Galaxy (Figure 2.6).

imply low H_2 content (Young et al. 1984; Bhat et al. 1984; Hunter and Gallagher 1986; Israel et al. 1986; Maloney and Black 1987; Thronson et al. 1987a).

(ii) Shown on both plots is the corresponding $p_2 \propto Z^b$ relation deduced for the Galaxy (Section 2.4). Data from the other spirals seem to confirm this trend. In fact if the data are taken together the value of $b = 1.35 \pm 0.10$ for p_2(S) and $b = 1.30 \pm 0.10$ for p_2(B) are obtained, in agreement with our previous determination of b in the Galaxy. There is a suggestion that the trend may flatten off at 12 + log(O/H) > 9.1, but the errors are large and if in fact the new calibration of Dopita and Evans (1986) is used (Figure A.2.4) the high metallicity measurements are reduced.

(iii) It should be noted that the errors in the above compilation of data are rather large. They reflect the controversial aspects of the $CO \Rightarrow H_2$ conversion ratio and the large uncertainties in the derivation of the O/H ratios for the HII regions. It could even be argued that the above correlation is due to a possible correlation between the intensity of CO emission and the abundance of oxygen. However, that the correlation between p_2 and Z still holds, and in fact improves for the metallicity corrected H_2, suggests against this possibility.

Therefore, this preliminary study of external spiral galaxies seems to support the empirical law of star formation of equation (2.11). At present the empirical correlations do not distinguish between the competing distributions of H_2, although the Bhat et al. (1985) type of distribution has a marginally better correlation. However, the application of this empirical law in models of the chemical evolution of the Galaxy, presented in Chapters 3 and 4, will show the importance of the powers k and b, from which the distributions can be distinguished. To conclude this Chapter, the dust-to-gas ratio in spiral galaxies is briefly examined, in order to confirm the above law of star formation rate, but also to possibly constrain α_{2D}.

2.5.3 The dust-to-gas ratio

Young et al. (1986a) have used the 60μm and 100μm fluxes from IRAS observations of external galaxies to estimate the mass of dust (M_D) in those galaxies. They found M_D to be correlated with the mass of H_2 in a relation $M_{H_2} \propto M_D^{1.2}$, but also concluded that variations in the relative amounts of HI and H_2 in a galaxy are not obviously correlated with any other galaxy properties.

This work has previously emphasised the importance of the role of dust in the evolution of HI$\rightarrow H_2$. In the Galaxy it was more practical to use the metallicity (assuming it to be proportional to the dust) in correlating against the fraction of molecular gas in the total gas. However, for external galaxies the situation is almost reversed. Very few, apart from nearby spirals have published metallicities, whereas many have had 60μm and 100μm fluxes measured by the IRAS satellite. The calculation of the mass of the dust however, has large uncertainties.

Following Young et al. (1986a) one first assumes a λ^{-1} emissivity law and calculates the dust temperature, T_D, using the 60 /100μm flux ratio. The physical interpretation of this temperature when referring to a whole galaxy is not clear (Thronson et al. 1987b), but in the Young et al.

(1986a) sample T_D is in the range 30–46K. The following includes the colour correction to the temperature (King 1986) and uses the fluxes as given by Young et al. (1986a). The 100μm flux can now be used to calculate the mass of warm dust. Longer wavelengths are required to sample the colder dust. The mass of dust from a flux density S_ν at frequency ν is given by

$$M_D = Q_\nu' \left[\frac{S_\nu D^2}{B(\nu, T_D)} \right] \qquad (2.16)$$

where Q_ν' is taken from Hildebrand (1983) and $B(\nu,T_D)$ is the blackbody intensity.

The suggestion of Section 2.3 is that the fraction of molecular hydrogen should be correlated in some way with the amount of dust. Defining p_2 this time in terms of masses rather than surface densities, and taking HI and H_2 masses (with $\alpha_{20} = 8$) from Young et al. (1986a), p_2 has been calculated for the IRAS bright galaxy sample. Total galactic masses (M_T) and HI masses for the isolated galaxy sample of Young et al. (1986b) have been taken from the literature (Rogstad and Shostak 1972; Bosma et al. 1977; Shostak 1978; Crutcher et al. 1978; Reakes 1980; Fisher and Tully 1981; Bottinelli et al. 1982; Huchtmeier 1982; Hunter et al. 1982; Matteucci and Chiosi 1983; Rubin et al. 1982; Hunter and Gallagher 1986).

No correlation is found for p_2 against M_D/M_T, but a rough correlation is found for p_2 against M_D. However a much better correlation is found for p_2 against the dust-to-gas ratio (M_D/M_g), where of course

$$M_g = 1.36 \, (M_{H_2} + M_{HI}), \qquad (2.17)$$

the factor 1.36 accounting for He. This is shown in Figure 2.9. Although once again the scatter is large, the general

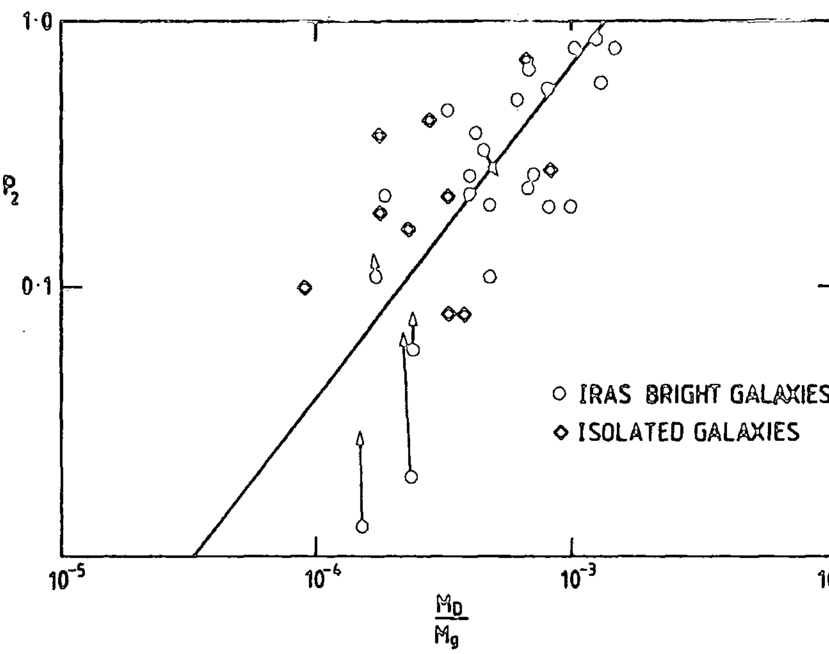


Figure 2.9: The fraction of molecular hydrogen, $p_2 = M_{H_2}/(M_{H_2} + M_{HI})$, as a function of the dust-to-total gas ratio for the IRAS bright galaxies of Young et al. (1986a) and the isolated galaxies of Young et al. (1986b). The mass of dust is calculated from the 100μm flux and therefore only represents the warm dust component. Arrows represent the effect of metallicity correction to M_{H_2}.

trend is that the greater the dust-to-gas ratio of a galaxy, the more gas is in the form of molecular hydrogen. Of course this is the $M_{H_2} \propto M_D^{1.2}$ trend found by Young et al. (1986a), but if confirmed would suggest that the relative amounts of HI and H_2 in a galaxy are determined by the dust-to-gas ratio. Even more interesting, ignoring the possibly important distinction between surface densities and total integrated mass, this is the general trend of relationship predicted by $p_2 \propto Z^b$ if Z is proportional to M_D/M_g. A gradient of 1.3 has been fitted by eye to the points in Figure 2.9 to illustrate this. In fact the effect of metallicity corrections to M_{H_2} (shown by arrows in the Figure) in general improves the correlation.

However, the biggest drawback to this analysis is that the 100μm flux does not sample all of the dust in a galaxy

(Young et al. 1986a). This can be readily seen from Figure (2.9) as all galaxies are at least an order of magnitude below the canonical dust-to-gas ratio of 10^{-2} determined in the solar neighbourhood (Spitzer 1978).

Chini et al. (1986) have recently published 1300μm measurements of 26 spiral galaxies. The 1300μm fluxes are more sensitive to colder dust and therefore should sample more of the dust than 100μm. Chini et al. (1986) argue that their observations cannot be explained by dust emitting at a uniform temperature, and adopt a warm and cold component model with corresponding temperatures T_W and T_C. Following Chini et al., the dust mass for these galaxies is calculated using T_C and the 1300μm flux. Measurements of CO emission, either total or for the central area, were available for nineteen of these galaxies (Young et al. 1983; Rickard et al. 1985; Sanders and Mirabel 1985; Verter 1985; Kenney and Young 1986; Young et al. 1986a,b; Sanders et al. 1986b, 1987; Knapp et al. 1987) and HI masses were taken from the previously described literature. There are now two problems, one is to convert the CO emission for certain galaxies which do not have maps but only one central measurement to total CO emission, and secondly to then reduce the gas distributions to the area sampled by the 90" beam of the 1300μm measurements. In the absence of detailed HI and H_2 maps, a crude attempt has been made to do this. It is well known that in general HI distributions are all very similar and have relatively flat profiles over the disc (Rogstad and Shostak 1972), apart from a few galaxies with pronounced low R_G 'holes', and therefore HI masses are scaled by the ratio of the area of the beam width to the optical size of the galaxy. However, in many spiral galaxies CO is peaked and follows the exponential luminosity profile (Young 1985a). The CO emission is therefore assumed to fall off exponentially with a scale-length of 5 kpc (Young and Scoville 1982a). This has been used by Young et al. (1985a) and discussed extensively by Verter (1983) who concludes that this type of extrapolation is correct to within a factor of 2-3. Thus, taking account of the inclination of the galaxy, integrating over the beam width of the CO observation and over the entire galaxy, the fraction of CO emission in the 90" beam is calculated. The mass of H_2 for that area is then determined using $\alpha_{20} = 8$ (following Young et al. 1986a).

The dust-to-gas ratio as determined from the 1300μm flux in the central 90" of a galaxy is shown as a function

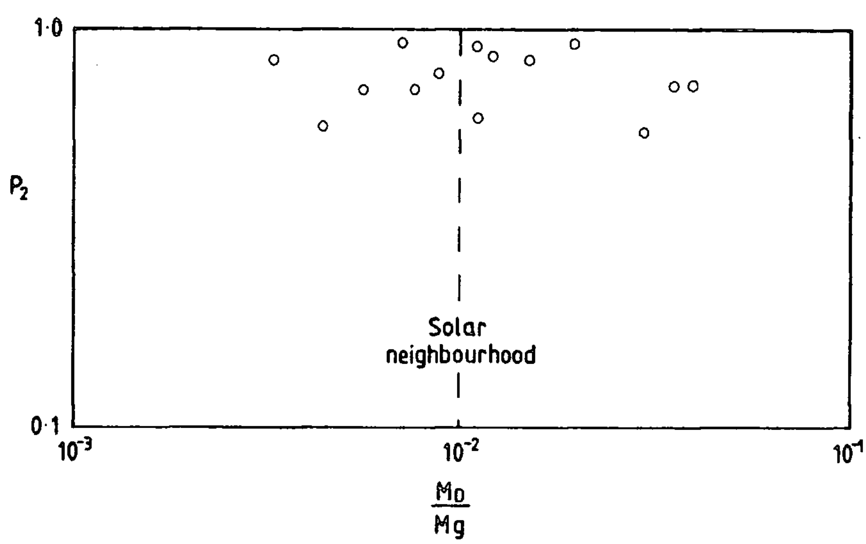


Figure 2.10: The dust-to-gas ratio as determined from 1300μm flux measurements for the galaxies of Chini et al. (1986), as a function of the fraction of molecular gas to the total gas. The dust-to-gas ratio for the solar neighbourhood is also shown.

of p_2 in Figure (2.10). The following points may be noted from this Figure:

(i) There is no evidence of the correlation with p_2 seen for the warm dust. This could possibly be due to only the warm dust taking an active role in H_2 formation.

(ii) With $\alpha_{20} = 8$, the central 90" of these galaxies is dominated by H_2, assuming an exponential profile.

(iii) The distribution of dust-to-gas ratios has a mean value close to the solar neighbourhood value suggesting that the 1300μm samples most of the dust, but even so, spans an order of magnitude. Therefore the use of a constant dust-to-gas ratio must be questioned.

(iv) However, in the central regions of spiral galaxies we may expect a dust-to-gas ratio, 2-3 times higher than the solar value. If the dust-to-gas ratio follows the metallicity (see Appendix A.2.5), the dust-to-gas ratio in the centre of the Galaxy should be $\approx$ 3 times the solar value. In this case only 3 or 4 galaxies in Figure 2.10 seem to have 'normal' dust-to-gas ratios. If $\alpha_{20} < 8$ and not constant then the other galaxies could be increased in their dust-to-gas ratio. For instance in order for NGC 660 to have $M_D/M_g > 2.10^{-2}$ in its central regions $\alpha_{20} < 1$. It seems therefore for M_D/M_g to be constant in different galaxies, α_{20} must vary from galaxy to galaxy. Alternatively a constant α_{20} implies a large variation in M_D/M_g.

(v) The uncertainties in the above analysis are very large. A factor of at least 2 or 3 is involved in the assumption of an exponential profile of the H_2 distribution. Detailed radial maps for both HI and H_2 for the Chini et al. (1986) sample of galaxies are required in order to improve this aspect. The use of T_w rather than T_c in the calculation of the mass of dust, decreases the dust mass by at least 50%.

Once again more 1300μm measurements are required both of these galaxies and more to enlarge the sample.

In conclusion, a study of the dust-to-gas ratio in external spiral galaxies gives at present ambiguous evidence for the claim that the amount of dust controls the relative amounts of HI and H_2 in a galaxy. However, there seems to be more evidence, either for a variable α_{20} or a variable dust-to-gas ratio from galaxy to galaxy (or both). More observations, especially at 1300μm are needed to confirm this. This subject will be further examined in the context of the Virgo cluster of galaxies in Chapter 6.

CHAPTER THREE

GALACTIC CHEMICAL EVOLUTION I - THE MODEL

3.1 INTRODUCTION

The chemical evolution of galaxies studies the chemical processing of hydrogen and helium through stars to produce metals (defined as all elements heavier than helium). At an early epoch galaxies condensed out of a primordial gas which consisted by mass of $\sim$ 78% H, $\sim$ 22% He and traces of D, ^{3}He and Li. This chemical composition is quantitatively explained by nuclear reactions taking place in the early universe (Yang et al. 1979, 1984). At the present time galaxies consist of $\sim$ 70% H, $\sim$ 28% He and $\sim$ 2% heavier elements including C, N and O. It is this process of enrichment of metals and their distribution with which chemical evolution studies are concerned. Burbidge et al. (1957) showed that this chemical evolution could be explained as a byproduct of nuclear reactions in stars which form out of the ISM and in their final evolutionary stages return heavier elements to the ISM. Therefore it depends critically on the properties of the constituent stars, their mass spectrum, formation rates and mass and composition of the processed material returned to the ISM. As these questions cover such wide areas, a wealth of literature and models have grown up since the pioneering work of Schmidt (1959, 1963). The subject has been comprehensively reviewed many times (e.g. Lynden-Bell 1975; Tinsley 1980; Pagel 1981, 1986a, 1987; Chiosi and Jones 1983; Güsten and Mezger 1983; Mould 1984; Peimbert 1985; Güsten 1986) and such a review is outside the scope of the present work. This Chapter discusses a self consistent model of the chemical evolution of the Galactic disc component based on the adopted SFR of $\psi_S \propto \Sigma_{H_2}^k$ and shows how such a model can explain the G-dwarf problem, the age-metallicity relation of disc stars, the constancy of the SFR and the metallicity gradient. The consistency of the model and its consequences particularly for the nature of the dark matter and distribution of H_2 will be discussed in Chapter 4.

3.2 FORMULATION

3.2.1 The Simple Model

Any model of Galactic chemical evolution is to some extent reliant on a number of important assumptions, these assumptions being partially justified by comparison with observation (Pagel and Patchett 1975). The so called simple model (Searle and Sargent 1972) assumes:

- (i) The gas is chemically homogeneous at all times.
- (ii) A region can be modelled as a closed system.
- (iii) The system has started with 100 per cent metal-free gas.
- (iv) The initial mass function of stars is invariant.

Every one of these assumptions has since been questioned but the simple model still provides a good framework for study.

Two further assumptions will be used below. Firstly, it is assumed to first order that spiral discs are axisymmetric, allowing the disc to be divided up into a set of concentric annuli with uniform properties around each annulus. Stars are born on roughly circular orbits and therefore their migration has a negligible effect on chemical evolution and the processed gas follows the trajectory of the progenitor. Consideration of a disc annulus is an accepted assumption (Clayton 1986) based on the idea that mixing within the annulus by differential rotation and turbulence may homogenise the ISM within it whereas angular momentum barriers inhibit radial mixing.

The second assumption is commonly referred to as the instantaneous recycling approximation which assumes that stars dominating chemical evolution evolve so rapidly in comparison with Galactic timescales that ejecta are immediately returned to the ISM (Talbot and Arnett 1971; Searle and Sargent 1972). This greatly simplifies the calculation and removes the need of explicitly specifying the initial mass function. Clayton and Pantelaki (1986) have shown that this simplification is surprisingly satisfactory unless one is interested in the very early evolution when the differential evolution times of the first stars matter or in late evolution when the mass of gas is so small that it is dominated by return from small old dwarfs (Pagel and Patchett 1975). The instantaneous recycling approximation is no longer useful in the study of time dependent abundance ratios or when the SFR is a strongly decreasing function of time (Tinsley 1980) or for predicting integrated colours of galaxies (Arimoto and Yoshii 1986). However, for the discussion below instantaneous recycling is adequate and allows analytic solutions, following the spirit of Clayton

(1986) that 'nothing illustrates the ideas of chemical evolution of galaxies as well as a system of differential equations plus their solutions'.

Following Tinsley (1980, 1981) the basic analytical equations for simple models of galactic chemical evolution, using the instantaneous recycling approximation, take the following form,

$$\Sigma_T = \Sigma_g + \Sigma_s + \Sigma_D, \tag{3.1}$$

$$\left.\begin{aligned} \mu &= \Sigma_g / \Sigma_T \\ \sigma &= \Sigma_s / \Sigma_T \\ \delta &= \Sigma_D / \Sigma_T , \end{aligned}\right) \tag{3.2}$$

$$\frac{d\Sigma_g}{dt} = -(1-R)\psi_s , \tag{3.3}$$

$$\frac{d\Sigma_s}{dt} = (1-R-D)\psi_s , \tag{3.4}$$

$$\frac{d\Sigma_D}{dt} = D\psi_s , \tag{3.5}$$

and $$\frac{d(Z\Sigma_g)}{dt} = -Z(1-R)\psi_s + (1-R-D)\,y_z\,\psi_s , \tag{3.6}$$

where Σ_T is the total mass density of the system, Σ_s is the total mass density locked up in visible stars, Σ_g is the total mass density of gas and ψ_s is the star formation rate (in $M_{\odot} pc^{-2} Gy^{-1}$).

The so-called returned fraction R is the fraction of matter that is returned in the form of gas to the interstellar medium by a generation of stars compared with the total initial mass in that generation that went into stars. Following Tinsley (1981) and Rana and Wilkinson (1986a, hereafter referred to as Paper I) the above equations also include an explicit expression for dark matter. Previous formulations (e.g. Tinsley 1980) do not make any distinction between the visible stars and invisible or so-called dark remnants. Observations for the G-dwarf metallicity distribution or the age-metallicity relation of the disc stars are relevant only to visible stars. If the proportion between the dark remnants and the visible stars varies from place to place or from time to time, it is better to express the dark matter explicitly. Also there may be an amount of pre-disc dark matter incorporated into the disc. Therefore, D represents the dark matter fraction. Since R has already been defined to be the returned fraction, the fraction (1-R) represents the mass locked into stars visible or invisible. The latter fraction is now divided into two parts (1-R-D) as the visible stellar fraction and D the dark matter fraction (for example, cold dwarfs, neutron stars and black holes). The mass density of dark matter is now $\Sigma_{\mathfrak{D}}$ and μ, σ and δ the fractions of gas, visible stars and dark matter compared to the total mass of the region.

The metallicity by mass fraction of the interstellar gas (Z) is linked to the mass of gas and SFR through the yield (y_{Z}) defined as the ratio of total mass of new metals ejected by a generation of stars and the total mass of visible stars. It should be noted that the above yield, defined for analytic convenience, differs from the standard definition of the yield by the relationship

$$y_{Z} = \frac{(1-R)}{(1-R-D)} y' \qquad (3.7)$$

where y' is the value used by all previous workers (e.g. Tinsley 1980).

For completeness it is necessary to define some of the above parameters which depend on the initial mass function (IMF), $\phi(m)$. This frequency distribution of stellar masses at birth is usually normalised according to

$$\int_{m_{\ell}(t)}^{m_{u}(t)} m\phi(m)\,dm = 1 \tag{3.8}$$

where m_{ℓ} and m_{u} represent the lower and upper mass limits of the range of possible stellar masses, m being the mass of a star in solar units. The returned fraction is therefore defined by

$$R(t) = \int_{m_{1}(t)}^{m_{u}(t)} (m - w_{m})\phi(m)\,dm \tag{3.9}$$

where m_1 is the turn-off stellar mass corresponding to the main sequence lifetime of the star bounded by the age of the disc t, and w_m is the consequent remnant mass for a white dwarf, neutron star or black hole depending on the value of intial mass of the star.

The dark matter fraction is given by

$$D(t) = \int_{m_{z}(t)}^{m_{u}(t)} w_{m}\phi(m)\,dm + \int_{m_{\ell}(t)}^{m_{\odot}} m\phi(m)\,dm \tag{3.10}$$

m_z being the mass above which the star collapses only to a neutron star or black hole, but not a white dwarf and $m_{\odot}$ being the mass limit below which the star ends up as a brown or cold dwarf. The yield is therefore given by

$$y_z = \frac{1}{(1-R-D)} \int_{m_{1}(t)}^{m_{u}(t)} m p_{zm}\phi(m)\,dm \tag{3.11}$$

where p_{zm} is the mass fraction of a star of mass m that is converted to metals and rejected.

Usually, R, D, y_z and ψ_s are externally specified, either ad hoc or by assuming specific forms for $\phi(m)$, remnant masses, lifetimes, production of metals and SFRs. Basically one attempts to solve equations (3.3) and (3.6) for $\Sigma_g(t)$ and Z(t) respectively using the rest as auxiliaries.

3.2.2 Additions to the simple model

In view of difficulties the simple model had in reproducing the observations of the G-dwarf problem and abundance gradients, each of the inherent assumptions of the model have been questioned:

(i) In their model of metal enhanced star formation Talbot and Arnett (1973) used inhomogeneities in the gas on the scale of individual star forming regions in an attempt to solve the G-dwarf problem. But in order to work this requires large inhomogeneities in the gas when the metallicity is very low which is difficult to obtain.

(ii) It has been argued that disc annuli are not closed systems and that gas flows are important in the chemical evolution (Larson 1972). Dynamical collapse models of spiral galaxy formation suggested the gradual and delayed build up of the disc by settling halo gas, this gas acting as infall of metal poor gas onto the disc (Tinsley and Larson 1978). It has also been claimed that gas could be accreted from the general inter-galactic or inter-group medium (Hunt 1971; Gunn and Gott 1972). Lynden-Bell (1975) and Tinsley (1975) showed that infall could solve the G-dwarf problem in the solar neighbourhood and the effect has been incorporated into a large number of investigations of chemical evolution (e.g. Fowler 1972; Searle 1972; Sciama 1972; Quirk and Tinsley 1973; Biermann and Tinsley 1974; Audouze and Tinsley 1976; Chiosi 1980; Chiosi and Matteucci 1982; Peimbert and Serrano 1982; Tosi 1982; Yokoi et al. 1982; Yoshii 1984).

However, one of the problems with infall is that it is not fixed observationally. Oort's (1970) interpretation of high velocity clouds (HVC) as evidence for infall implying an infall rate of $1-2M_{\odot}y^{-1}$ was strongly contested (Davies 1974; Verschur 1975). Bregman (1980) instead interpreted HVC within a Galactic fountain model where hot gas rises up several kpc from the disc and then condenses into clouds which fall back to the disc. Of course, if clouds return to their original position the standard equations need no modification. If the clouds re-enter at larger R_G then this would amount to a radial gas flow. Güsten (1986) argues that their chemical composition, which within uncertainty is consistent with local disc abundances, and their velocity field imply that HVC are probably not related to the early halo gas at all. Mirabel and Morras (1984) have argued that at least some of the clouds do represent infall of a total rate $\approx 0.2M_{\odot}y^{-1}$ to the disc but the situation is far from clear (cf. van Woerden et al. 1985; Kaelbe et al. 1985).

Diffuse gas would almost certainly be highly ionised and emit X-rays in a cooling flow as it approached the disc. From a set of detailed hydrodynamical calculations and observations of the soft X-ray background, Cox and Smith (1976) derived the present infall rate in the solar neighbourhood to be $\lesssim 1M_{\odot}pc^{-2}Gy^{-1}$. It therefore seems that even if infall was important in the past it has in fact faded away, which calls into question temporally constant infall models (e.g. Tosi 1982; Diaz and Tosi 1984; Tosi and Diaz 1985; Twarog and Wheeler 1982, 1987). In fact, in order to avoid this problem, decaying infall rates have been invoked (Vader and de Jong 1981; Güsten and Mezger 1982; Lacey and Fall 1983, 1985; Clayton 1984, 1985a,b, 1987) with even the suggestion of terminated infall or periodic infall

(Clayton 1986). Further evidence against infall being a global event in the evolution of disk galaxies stems from the failure to detect directly the source or reservoir of infalling gas in external spirals (Bothun 1985).

The evidence for infall has primarily been indirect, that is it was claimed it was needed to solve chemical evolution problems. Chapter 2 has already pointed out that with $\psi_S \propto \Sigma_{H_2}^k$, infall is not required to explain the constancy of the SFR over the age of the Galaxy. There were suggestions (Larson 1972; Twarog 1980; Larson et al. 1980; Tinsley 1980) that the present constant SFR in spiral galaxies implied that the ISM would be used up on too short a timescale if there was not gas replenishment by infall. This problem however can be easily dealt with also by $\psi_S \propto \Sigma_{H_2}^k$. Both of these points will be shown explicitly in Section 3.6. (It should be noted that the bimodal model of star formation of Larson (1986) also avoids these problems removing the need for infall). Although problems in the solar neighbourhood can be solved by infall alone (Twarog 1980), abundance gradients across the disc are much more difficult. Tosi and Diaz (1985) have claimed good fits to the abundance gradients using infall, but other workers using more realistic SFRs and infall rates have needed supplementary assumptions such as variable yield (Peimbert and Serrano 1982; Güsten and Mezger 1982) or radial gas flows (Lacey and Fall 1985) for the same fits.

In fact the situation may be quite complex with radial gas flows (Mayor and Vigroux 1981; Lacey and Fall 1985) and gas outflows from the disc (Hartwick 1976; Vigroux et al. 1981; Wyse and Silk 1985) being important. Arimoto and

Yoshii (1986, 1987) have extensively studied the sudden ejection of gas heated by supernovae explosions from elliptical galaxies and shown good agreement with photometric and chemical evolution.

In view of the above discussion, the interesting question is, can the Galactic disc be successfully modelled as a closed system, neglecting the effect of infall, outflow and radial gas flows? Of course the neglect of gas flows simply means the assumption that the rate of flow is small compared to the SFR (Tinsley 1977). After all, the disc has to initially form by accreting matter from the surroundings. A case without infall may be interpreted as to imply a small time constant for the formation of a stable disc. In fact from dynamical considerations a galactic disc can form as quickly as $\sim 2.10^8$ y (Vader and de Jong 1981; Burkert and Hensler 1987). Therefore, in the following, the Galactic disc will be assumed to form quickly and then evolve as a closed system with gas flow rates small compared to the SFR.

(iii) The third assumption of the simple model may not be correct if the gas which forms the disc was pre-enriched in metals by a previous generation of stars outside the disc (Truran and Cameron 1971). Chapter 2 pointed out that for the new formulation of the SFR to be non zero at t = 0, an initial metallicity $Z_{\odot}$ was required. This point will be discussed more extensively in the context of the G-dwarf problem (Section 3.3). However, assuming a $Z_{\odot}$ and gas fraction $\mu_{\odot}$ ($\lesssim 1$) when the disc formed, the derived SFR of Chapter 2 can be written as

$$\psi_S(R_G,t) = C\left[\Sigma_T(R_G)X(R_G)\frac{\mu(R_G,t)}{\mu_{\odot}}\left(\frac{Z(R_G,t)}{Z_{\odot}}\right)^b\right]^k \qquad (3.12)$$

showing the explicit dependence on time and Galactocentric radius, C being a constant. It will be the properties of this SFR that will be studied in the following chemical evolution model.

(iv) It has been argued that in order to successfully model the chemical evolution of the disc, the initial mass function of stars varies (Schmidt 1963). Many dependences have been proposed such as relatively more massive stars produced at smaller R_{G} (Quirk and Tinsley 1973; Güsten and Mezger 1982) or at low Z (Terlevich and Melnick 1984; Melnick and Terlevich 1986) or at high Z (Peimbert and Serrano 1982). (Of course a high $Z_{\odot}$ may be interpreted as a variable IMF between disc and halo stars). Such a variation in the IMF leads inevitably to a variable yield, an addition to the simple model which has been used recently by a number of workers. Peimbert and Serrano (1982) proposed that the yield is linearly related to the metallicity, Güsten and Mezger (1982) used a yield dependent on Galactocentric radius and Edmunds and Pagel (1984a) suggested that the yield was a function of the total mass surface density. Paper I proposed an ad hoc assumption of the yield proportional to the metallicity. In this work, this assumption will be generalised to

$$y_{Z} = KZ^{n} \qquad (3.13)$$

where K is a constant and n is a power, with n = 0 corresponding to the simple model (with finite initial metallicity) and n = 1 corresponding to the assumption of Paper I. (In fact, Caimmi (1978) had previously suggested $y' \propto Z^{0.5-1.0}$ for the halo population). The equations of chemical evolution will be derived for all values of n but will be solved only for the cases n = 0 and n = 1 for comparison. The strict validity of this assumption and in particular the value of n from the point of view of the IMF and stellar nucleosynthesis will be discussed in detail in Chapter 4. It needs to be emphasised that although a variable IMF implies a variable yield, a variable yield does not necessarily imply a variable IMF. The variation in the yield could be due to details of stellar nucleosynthesis.

It is now easy to see that equations (3.1) - (3.13) will allow the following solutions

$$\frac{\mu}{\mu_0} = 1 - \frac{(1-R)}{(1-R-D)} \frac{(\sigma - \sigma_0)}{\mu_0} \qquad (3.14)$$

$$\delta - \delta_0 = \frac{D}{(1-R-D)} (\sigma - \sigma_0) = \frac{D}{(1-R)} (\mu_0 - \mu) \qquad (3.15)$$

For convenience G is defined as

$$G = \frac{(1-R)}{K(1-R-D)} \qquad (3.16)$$

and then the fraction of gas is related to the metallicity by

$$\mu = \mu_0 \exp\left[\frac{G}{(1-n)} (Z_0^{1-n} - Z^{1-n}) \right] \qquad n \neq 1 \qquad (3.17a)$$

$$\mu = \mu_0 \left(\frac{Z}{Z_0} \right)^{-G} \qquad n = 1 \qquad (3.17b)$$

All the quantities with subscript '0' represent the initial values. Finally, the age-metallicity equation is given by

$$\frac{dZ}{dt} = \frac{C(1-R)\Sigma_T^{k-1}}{G\mu_0} \frac{Z^{kb+n}}{Z_0^{kb}} \exp\left[\frac{(k-1)G(Z_0^{1-n} - Z^{1-n})}{(1-n)} \right] \qquad n \neq 1 \qquad (3.18a)$$

$$\frac{dZ}{dt} = \frac{C(1-R)\Sigma_T^{k-1}}{G\mu_0} \left(\frac{Z}{Z_0} \right)^{-G(k-1)+kb} \qquad n = 1 \qquad (3.18b)$$

In the following sections these equations will be applied to problems in the solar neighbourhood and across the Galactic disc.

3.3 THE G-DWARF PROBLEM AND FINITE INITIAL METALLICITY

van den Bergh (1962) and Schmidt (1963) originally discovered a problem concerning the metallicity distribution of long-lived disc dwarfs in the solar neighbourhood. The problem is that there are far fewer metal poor stars than are predicted by the simple model of Galactic chemical evolution. This is termed 'the G-dwarf problem' and has proved to be one of the most powerful constraints on models for the solar neighbourhood. The simple model (for example, following Pagel and Patchett 1975) predicts the fraction of stars (visible and invisible, however) with metallicities not exceeding Z, to be given by

$$S(Z) = \frac{M_S}{M_{S_1}} = \frac{(1-\mu_1^{Z/Z_1})}{(1-\mu_1)} \qquad (3.19)$$

where the subscript '1' (and henceforth everywhere) refers to the value of the parameter at present, M_S being the visible stellar mass. This expression is obtained on the assumption that $Z_0 = 0$ and y_Z = constant. The observational data and the above prediction are shown in Figure 3.1. The metallicity curve deviates quite significantly at the lower end of the range. It is relatively insensitive to the value taken for the gas fraction μ_1 (Tinsley 1980) so that the controversy over H_2 estimates in the solar neighbourhood (Chapter 1) does not provide a solution. A similar metallicity distribution has since been confirmed for M dwarfs (Mould 1978).

There have been two main solutions to this problem. Lynden-Bell (1975) proposed a solution by using infall of gas from the halo to the disc. Alternatively Truran and Cameron (1971) postulated a pre-galactic burst of massive

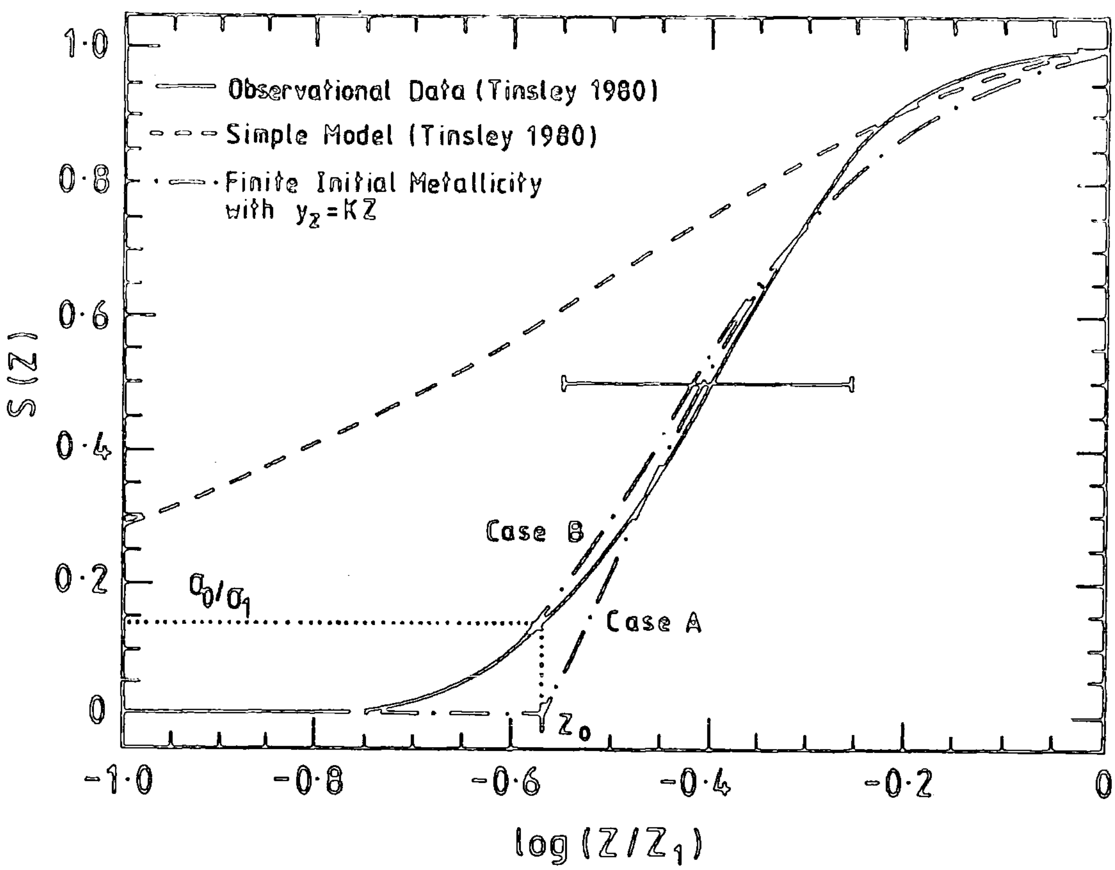


Figure 3.1: The cumulative metallicity distribution for 133 G dwarfs in the solar neighbourhood. The data with errors are represented by the solid curve, reproduced from Tinsley (1980). The abscissa is a measure of the metallicity (Fe/H) inferred from the measurements of UV excess (Pagel and Patchett 1975). The prediction of the simple model, which is far in excess of the observational numbers at lower metallicities, is shown by the dashed line. The model with finite initial metallicity, variable yield and no infall (and also duly corrected for the dark matter fraction) is shown by a dot dashed line. The low-metallicity tail extending beyond the initial metallicity (Z_0) may correspond to the pre-disc population (which is about 5% of the total as indicated by the ratio σ_0/σ_1).

stars leading to a finite initial metal abundance Z_0. As the SFR of Chapter 2 already predicted a finite initial metallicity, the latter solution was followed in our previous work (Paper I; Rana and Wilkinson 1987a, hereafter referred to as Paper IV), where a more extensive discussion is given.

From equation (3.17) the mass fraction of visible stars with metallicity no more than Z is given by

$$S(Z) = \frac{\sigma(Z)}{\sigma_1} = \frac{G' - \exp[G(Z^{1-n} - Z_0^{1-n})/(1-n)]}{(G' - \mu_1)} \quad n \neq 1 \qquad (3.20a)$$

$$= \frac{G' - \mu_0 (Z/Z_0)^{-G}}{(G' - \mu_1)} \quad n=1 \qquad (3.20b)$$

where G' is defined as

$$G' = \mu_0 + \sigma_0 GK \qquad (3.21)$$

and $$(GK)^{-1} = 1 - \frac{(\delta_1 - \delta_0)}{(\mu_0 - \mu_1)} \qquad (3.22)$$

There are now two possible cases.

(i) Case A. This is a special case with $\mu_0 = 1$ which implies that during the formation of the disc, all material was in the form of gas only. Therefore $\sigma_0 = \delta_0 = 0$ and $G' = 1$. For a particular n the problem is reduced to supplying the values of μ_1 and δ_1 and fitting the G-dwarf curve. This will determine G, $Z_1/Z_\odot$, K and the ratio D/(1-R). From dynamical arguments Bahcall (1986c) estimated $\delta_1 = 0.55 \pm 0.10$ and this value for the dark matter fraction has been used. There is now some debate however that this value is an overestimate (e.g. Gilmore and Wyse 1987) and this will be discussed more extensively in Chapter 4. Irrespective of the gas distribution used, best fitting models give $\log_{10}(Z_1/Z_0) \cong 0.57$, implying that the pre-disc metallicity $Z_0 \cong Z_1/4$. A representative plot of the model for n = 1 is shown in Figure 3.1. The n = 0 model is similar to that of Truran and Cameron (1971) with a slightly worse fit than n = 1 at the high metallicity end of the curve.

(ii) <u>Case B</u> The general case with $\zeta_{\odot} \neq 0$ and $\sigma_{\odot} \neq 0$, that is allowing that when the disc formed some matter was already in visible stars or dark matter. There are now essentially five independent parameters for a particular n, namely $\mu_{\odot}$, $\sigma_{\odot}$, μ_{1}, σ_{1} and the ratio $Z_1/Z_{\odot}$ with which to fit the observed G-dwarf curve, allowing a maximum deviation of 5% to 21 points. As the actual scatter in the ordinate and the abscissa is likely to be no less than $\pm$ 15% (Tinsley 1980) then fits for $\chi^2 < 50$ are acceptable. The fraction of visible stars at present in the solar neighbourhood was taken as $\sigma_1 = 0.3 \pm 0.1$ (Bahcall 1986c). The value of $\mu_{\odot}$ was varied between 0.2 and 0.8, while $\sigma_{\odot} = 0 - 0.1$ (Vader and de Jong 1981; Bahcall et al. 1983). The range of μ_1 was chosen to include various estimates of the mass of gas (Chapter 1).

For n = 1, that is variable yield, the best fitting parameters gave $\chi^2 < 21$ with $\sigma_{\odot} = 0.05$, $\log(Z_1/Z_{\odot}) = 0.57 \pm 0.05$ and $G = 1.31 \pm 0.04$ roughly independent of the chosen gas fraction, while G and $\mu_{\odot}$ followed the empirical relationships (Paper I)

$$G' \cong 6.6\mu_1 \qquad (3.23)$$

$$\mu_{\odot} \cong 5.7\mu_1 . \qquad (3.24)$$

Therefore, the constant K in $y_Z = KZ$ is found to be 1.0 or 1.4 while $D/(1-R) \cong 0.25$ or 0.56 for the Bhat et al. or SSS distribution of H_2 respectively.

One may recall from the analysis of the SFR (Chapter 2) that the near constancy of the SFR had suggested two things - little or no infall and a lower bound on the initial metallicity - to be given by $\log_{10}(Z_1/Z_{\odot}) < 0.7$. Both are found to be satisfied here, the first one by choice and the second one from the solution of the G-dwarf problem.

Interesting information is also obtained on $\sigma_{\odot}$, $\mu_{\odot}$ and $\delta_{\odot}$. That $\sigma_{\odot} \approx 0.05$, means that about 5% of the total matter in the solar neighbourhood has metallicity not exceeding $Z_{\odot}$, they are the visible component of the pre-disc population. The observed fraction of metal-poor or halo objects in the solar neighbourhood is in fact about 0.04 - 0.06 (Vader and de Jong 1981; Bahcall et al. 1983). The small tail to the distribution in Figure 3.1 therefore could be due to a pre-disc population. The value of $\mu_{\odot}$ depends on μ_{I} (equation 3.24) and for $\mu_{I} = 0.08 - 0.14$, $\mu_{\odot} = 0.46 - 0.80$ and therefore $\delta_{\odot} = 0.49 - 0.15$. (Note that $\mu_{I} = 0.09 \pm 0.01$ for the Bhat et al. distribution of H_2 and $\mu_{I} = 0.13 \pm 0.01$ for the SSS distribution of H_2). If $Z_{\odot} \approx Z_{I}/3.7$ is required, it is not surprising that the pre-disc population in the solar neighbourhood had to produce $\delta_{\odot} \approx 0.45$, $\sigma_{\odot} \approx 0.05$ with $\mu_{\odot} \approx 0.5$ for $\mu_{I} = 0.09$.

For n = 0, that is a constant yield, the fit to the G-dwarf curve is not as good, best fitting parameters having $\chi^2 > 25$ for $\delta_{I} = 0.55$. However for $\chi^2 < 50$, once again $\log(Z_{I}/Z_{\odot}) = 0.57$, $\sigma_{\odot} = 0.05$ are still satisfied for $\mu_{\odot} > 0.45$. For a particular μ_{I} (e.g. = 0.09) the fit improves as $\mu_{\odot}$ is chosen to be higher. As $\mu_{\odot}$ increases from 0.5 - 0.8, K (and therefore y_Z) increases from 0.020 to 0.028. The ratio D/(1-R) also increases sharply as $\mu_{\odot}$ increases, from 0.24 to 0.56 for the same range in $\mu_{\odot}$. These values for the yield and dark matter fraction will be discussed later in Sections 4.1 and 4.2.

Therefore, for a finite initial metallicity solution to the G-dwarf problem, a yield proportional to metallicity improves the fit but a constant yield case is still allowable. The finite initial metallicity for the best fit (with due regard for $\mu_{\odot} \neq 1$) is $Z_{\odot} \approx Z_0/3.7$. It is now useful to examine briefly whether there is any physical ground for this condition.

Olive (1986) has remarked that provided there exists a mechanism, finite initial metallicity or prompt initial enrichment (PIE) models are the most straightforward perturbations of the simple model. It is recognised that there was some production of metals by pre-galactic star formation but this is restricted to having produced only a tiny fraction of metals in the disc by observations of very low metallicity stars in the spheroid (Hartwick 1983; Bessel and Norris 1984; Beers et al. 1986).

There have been however, many attempts to explain PIE by the pre-disc generation of stars. Truran and Cameron (1971) used an extreme form of variable IMF in postulating only large mass stars form until $Z \approx 0.25\ Z_{\odot}$. It has also been argued that the metal yield was high in low metallicity stars (Matteucci and Tornambè 1985; Tornambè and Matteucci 1985; Jura 1985), and the time-scale fast enough to set up a $Z_{\odot}$. Wyse and Silk (1987) and Olive (1986), on the basis of a bimodal SFR suggested a high rate of massive star formation in the early stages of disc evolution acting as PIE. Initial enrichment of the disc before the commencement of star formation due to prior activity in the halo (e.g. Hartwick 1976) can be taken as a legitimate initial condition for the chemical evolution of the disc on its own (Pagel 1987). Cayrel (1986) from a detailed study of the first stars concluded the disc would be enriched to $Z \approx 0.25\ Z_{\odot}$. Ostriker and Thuan (1975) considered a two component disk-halo model in which matter shed by dying halo stars accumulates in a smaller more rapidly rotating disc. However, Pagel and Patchett (1975) pointed out that the essential feature of these models is the PIE (of $Z_{\odot} \approx Z_{0}/5$) due to enrichment by matter shed in a short initial period from the most rapidly evolving massive stars in the halo while the subsequent inflow of enriched material from small stars of the halo has only a negligible effect. Dynamical collapse models (Schmidt 1975; Larson 1976; Tinsley and Larson 1978) may also lead to a situation which resembles PIE and which may be treated as such for some purposes, but this could be dangerous in problems where time is of importance, for example cosmochronology (Pagel 1987).

Furthermore, recent consideration of the so-called Galactic thick disc metallicity structure provides a physical explanation of the pre-enrichment of the classical thin disc (Gilmore 1984; Gilmore and Wyse 1986; Wyse and Silk 1987). Eggen, Lynden-Bell and Sandage (1962, hereafter ELS) argued on the basis of the correlation of UV excess, orbital eccentricity and z-motions that halo stars formed first, born during free-fall collapse in a short time with little or no dissipation and that the residual gas dissipated energy in a comparable time to form the disc in which the more metal rich stars have been continually forming ever since. The situation now is more complex. Norris et al. (1985) pointed out a kinematic bias in the ELS data and discovered stars with low Z and low eccentricity. Zinn (1985) finds two groups of globular clusters readily distinguished by their distributions in [Fe/H], the group with [Fe/H] > -1 being a flattened population of disc globular clusters with intermediate Z. These observations have been identified with the in situ observations at high Galactic latitudes of Gilmore and Reid (1983) (cf. Bahcall 1986d; Yoshii et al. 1987; Sandage 1987; Norris 1987), who found a stellar component of the Galaxy with kinematics and metallicity distribution intermediate between those of the extreme spheroid and thin disk (Gilmore and Wyse 1985; Wyse and Gilmore 1986). This component has a scale height larger than the already identified thin disc and so is referred to as the thick disc. The ELS picture is now modified, with the halo formed in free fall followed by extended dissipative phases leading ultimately to the present thin disk in which most of the residual or recycled gas is confined, while the bulge, thick disc and halo are fossilized remnants conveying records of a past history. Gilmore and Wyse (1986) have argued that initial enrichment due to rapid infall from the extreme halo alone cannot provide a resolution of the thin disc G-dwarf problem, but that pre-enrichment and then star formation in the thick disc leads to a mean [Fe/H] for the thick disc of -0.6 ± 0.1 which agrees well with the metallicity determined for the oldest, most metal poor G-dwarfs (Gilmore and Wyse 1985), and also the $Z_i/Z_{\odot}$ determined above.

While the above scenario resulting from a fit to the cumulative metal abundance curve for the local G-dwarfs appears to be quite interesting, one must nevertheless be aware of the following limitations. First, the cumulative abundance curve is at present based on a sample of only 133 local G-dwarfs (Pagel and Patchett 1975). There is a possibility (Pagel 1987) that the low metallicity stars have such large scale-heights that they have been missed altogether in the local samples even after weighting by velocity perpendicular to the plane. Secondly, metallicity has been inferred from the UV excesses which are assumed to reflect the relative abundance of iron (Fe/H). The above derivation of $Z_1 / Z_{\odot}$ assumed $Z \propto$ Fe/H, the validity of which is discussed briefly later and in Paper I. Thirdly, G dwarfs constitute only a small fraction of the total mass locked up in visible stars (Σ_s). The validity of the assumption that $\sigma(Z) \propto N_g(Z)$, where N_g = number of G dwarfs sampled, for all Z is highly questionable. Finally, the G-dwarf problem may be a peculiarity of the Sun's position in the Galactic disc and not represent a universal state of affairs. Pagel (1987) has summarised the position with respect to the halo and disc globular clusters (Zinn 1985) and Galactic bulge stars (Rich 1986) and shown that they fit well the predictions of the simple model, so that any proposed solution to the G-dwarf problem must take this into account and not appeal to a universal law. He suggests therefore that inflow is potentially acceptable, but models appealing to a law that true yields are always high at low Z are not.

3.4 THE AGE-METALLICITY RELATION

One can obtain some knowledge of the past evolution of the Galaxy and principally the solar neighbourhood by studying the variation of surface composition of unevolved stars with stellar age, assuming that the surface composition of an unevolved star represents the ISM out of which it is formed. Twarog (1980) showed that disc stars in the solar neighbourhood exhibited a systematic increase of metallicity with the estimated time of their formation, the metallicity having only increased by about a factor of 3 to 4 over the lifetime of the disc, as shown in Figure 3.2. However, determinations of stellar ages and compositions have important uncertainties and Carlberg et al. (1985) have re-analysed part of Twarog's basic data leading to results

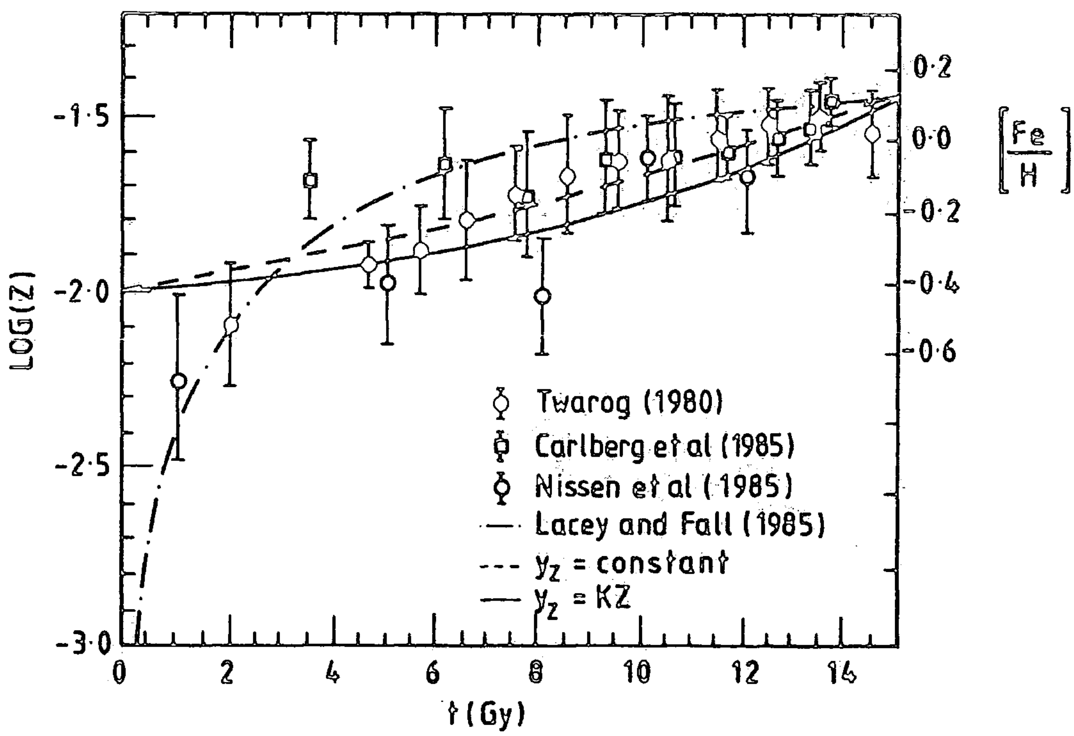


Figure 3.2: The stellar AMR in the solar neighbourhood for disc stars. Observations are from Twarog (1980), the same data recalibrated by Carlberg et al. (1985) and the independent data set of Nissen et al. (1985). The predictions of this work with a constant or variable yield are contrasted with the infall model J of Lacey and Fall (1985).

that are significantly different. Also shown in Figure 3.2 are results from the independent survey of Nissen et al. (1985) which apart from significant scatter seem to follow the trend of Twarog's points. Preliminary results from an extensive uvbyβ photometric survey of F stars also seem to reinforce the Twarog result (Strömgren 1987), and therefore in this work χ^2 will be calculated for the Twarog (1980) points.

Unlike the situation in the G-dwarf problem, the study of the age-metallicity relation (AMR) requires an explicit knowledge of the SFR. Twarog (1980) pointed out that a good fit to the AMR was obtained by a roughly constant SFR. Therefore, previous workers using a SFR proportional to the total gas density have required infall, to keep Ψ_S roughly constant in order to derive the AMR (e.g. Güsten and Mezger 1982; Lacey and Fall 1983). One of the best models of Lacey and Fall (1985) is shown in Figure 3.2 in order to illustrate the additional difficulty of infall models for the region t < 5Gy, especially if the results of Carlberg et al. (1985) are used.

With the SFR of Chapter 2 (equation 3.12) and with a finite initial metallicity Z_0, the AMR relation has already been given in equation (3.18). Its solution is given by,

$$\int_{Z_0}^{Z} \frac{dZ}{Z^{n+kb}\,F(k,G,Z,n)} = J \int_0^t dt \qquad n \neq 1 \qquad (3.25a)$$

$$Z = Z_0 \left(1 - \frac{t}{\tau}\right)^{-1/A} \qquad n = 1 \qquad (3.25b)$$

where the function F(k,G,Z,n) and the constants A, τ^{-1} and J have been defined for convenience as

$$F(k,G,Z,n) = \exp\left[\frac{(1-k)GZ^{1-n}}{(1-n)}\right] \qquad (3.26)$$

$$A = G - k(G - b) \qquad (3.27)$$

$$\tau^{-1} = \frac{A\Sigma_T^{k-1} X^k C(1-R)}{G\mu_0}, \qquad (3.28)$$

and

$$J = \frac{\tau^{-1} F(k, G, Z_\odot, n)}{A Z_\odot^{kb}} \tag{3.29}$$

The constants τ^{-1} and J can of course be alternatively defined from the normalisation when at $t = t_0$, $Z = Z_0$ giving

$$\tau^{-1} = t_1^{-1} \left[1 - \left(\frac{Z_\odot}{Z_0} \right)^A \right] \tag{3.30}$$

$$J = \frac{1}{t_0} \int_{Z_\odot}^{Z_1} \frac{dZ}{Z^{n+kb} F(k,G,Z,n)} \tag{3.31}$$

where t_1 is the age of the disc. In the following t_1 is taken to be 15Gy, which is consistent with recent estimates of the ages of globular clusters (Janes and Demarque 1983; Vandenberg 1983; Ratcliff 1987). In particular, Zinn (1985) found that the most metal rich globular clusters form a disc system whose age as judged by the two prototype disc globular clusters, M71 and 47Tuc is the same as the age of the halo clusters, that is at least 15Gy. Therefore using these equations, with k and b determined from Chapter 2, the set of best fitting parameters (in particular $\log(Z_1/Z_\odot) = 0.57$) are all found to give fits to Twarog's 12 data points with $\chi^2 < 12$. Following Paper I χ^2 has been computed for the standard deviations of Twarog's points. Of course, strictly using standard errors χ^2 will be larger but in the light of possible systematic errors the models give a good fit. This is illustrated in Figure 3.2 where the best fitting n = 0 and n = 1 models are shown. Several comments may be made.

(i) Models with constant yield, that is n = 0 give better fits to the AMR of Twarog (1980) than a yield proportional to metallicity (typically $\chi^2_{AMR} \lesssim 3$ for n = 0, while $\chi^2_{AMR} \lesssim 6.5$ for n = 1). This of course is in contrast to the G-dwarf problem where the opposite is the case, but once again observational uncertainty does not rule out either model at present.

(ii) Marginally better fits are obtained with k and b determined using the Bhat et al. distribution of H_2, but the difference cannot be used to rule out either distribution.

(iii) Models with y_Z = KZ have a more concave AMR than the constant yield model. This is not reflected in the points of Twarog or Nissen et al. (1985) but does appear in the Carlberg et al. (1985) results. However the Carlberg et al. (1985) points have systematically higher metallicities especially when t is small.

(iv) If the data points are taken together, then they suggest that the disc should have an initial metallicity in the range log $(Z_0/Z_\odot) \cong 0.4 - 0.6$ consistent with the requirement needed to solve the G-dwarf problem. However the considerable spread in the points especially at t $\lesssim$ 6Gy does not at present distinguish between the case for infall (Lacey and Fall 1985) and no infall.

(v) The above discussion has assumed $Z \propto$ Fe/H, in that the model predicts $Z_0/Z_\odot$, while the metallicity measurements for the AMR refer to Fe/H. This assumption may be questionable, and more consideration of it is given in Paper I and the next section. However on the basis of this assumption the same set of values which solves the G-dwarf problem solves the AMR within the errors of observation.

Finally from equations (3.26) - (3.31), the returned fraction in the solar neighbourhood may be evaluated independent of its source equation (equation 3.9). One obtains

$$(1-R) = \frac{\Sigma_T G \mu_1^k Z_1^{kb} F(k,G,Z_\odot,n)}{\psi_1 \mu_\odot^{k-1} t_1} \int_{Z_\odot}^{Z_1} \frac{dZ}{Z^{n+kb} F(k,G,Z,n)} \qquad n \neq 1 \quad (3.32a)$$

$$(1-R) = \frac{\Sigma_T G \mu_1^k}{A \psi_1 t \mu_\odot^{k-1}} \left(\frac{Z_1}{Z_\odot}\right)^{kb} \left[1 - \left(\frac{Z_1}{Z_\odot}\right)^{-A}\right] \qquad n = 1 \quad (3.32b)$$

where all values refer to the solar neighbourhood and ψ_1 is the present star formation rate. For numerical computation, $(\Sigma_T)_\odot = 75 M_\odot pc^{-2}$ (SSS 1984) and $(\psi_1)_\odot = 4 \pm 1 M_\odot pc^{-2} Gy^{-1}$ (SBM 1978; Turner 1984; Lacey and Fall 1985). For the range of parameters obtained by fits to the G-dwarf problem and the AMR, the range of resulting R is 0.3 - 0.65, with the Bhat et al. gas distribution giving higher values of R than that of SSS. This is in good agreement with R = 0.35 (Twarog 1980; Chiosi and Matteucci 1983), 0.48 (Tinsley 1980) and 0.5 - 0.8 (Güsten and Mezger 1982). It strongly depends, of course, on $(\psi_1)_\odot$. A larger value of $(\psi_1)_\odot$ implies a larger value of R, otherwise one would expect to see a greater mass in visible stars than implied by $\sigma_1 \Sigma_T$.

Once R is determined, D, the dark matter fraction becomes fixed. Assuming of course $\delta_1 = 0.55$, for n = 0, $D \cong 0.10 - 0.24$, while for n = 1, $D \cong 0.1 - 0.39$, this time higher values of D being favoured by the SSS gas distribution. The consistency of these figures and the consequences for dark matter in the solar neighbourhood will be discussed in Chapter 4.

3.5 THE VARIATION OF THE SFR

The evidence supporting the claim that the SFR has stayed roughly constant over the lifetime of the Galaxy in the solar neighbourhood, as well as in some external spiral galaxies was reviewed in Section 2.2. Olive et al. (1987) have further tried to estimate limits on the SFR by nucleosynthesis data, but conclude that present uncertainties in the yield for massive stars do not allow any rigorous constraints. Studies in nucleocosmochronology which might in principle be used to give information on the history of the SFR are also restricted by uncertainties associated with the input nuclear physics, the meteoritic abundance data, and the nucleosynthesis calculations themselves (Thielemann and Truran 1985; Meyer and Schramm 1986).

However, from the above chemical evolution model it is now possible to study the time evolution of the SFR in the solar neighbourhood. Defining Ψ_0 as the SFR at t = 0, and treating $(\Sigma_T X)$ as a constant (i.e. no infall) equation (3.12) becomes

$$\left(\frac{\Psi_1}{\Psi_0}\right)_{\odot} = \left(\frac{\mu_1}{\mu_0}\right)_{\odot}^{k} \left(\frac{Z_1}{Z_0}\right)_{\odot}^{kb} \qquad (3.33)$$

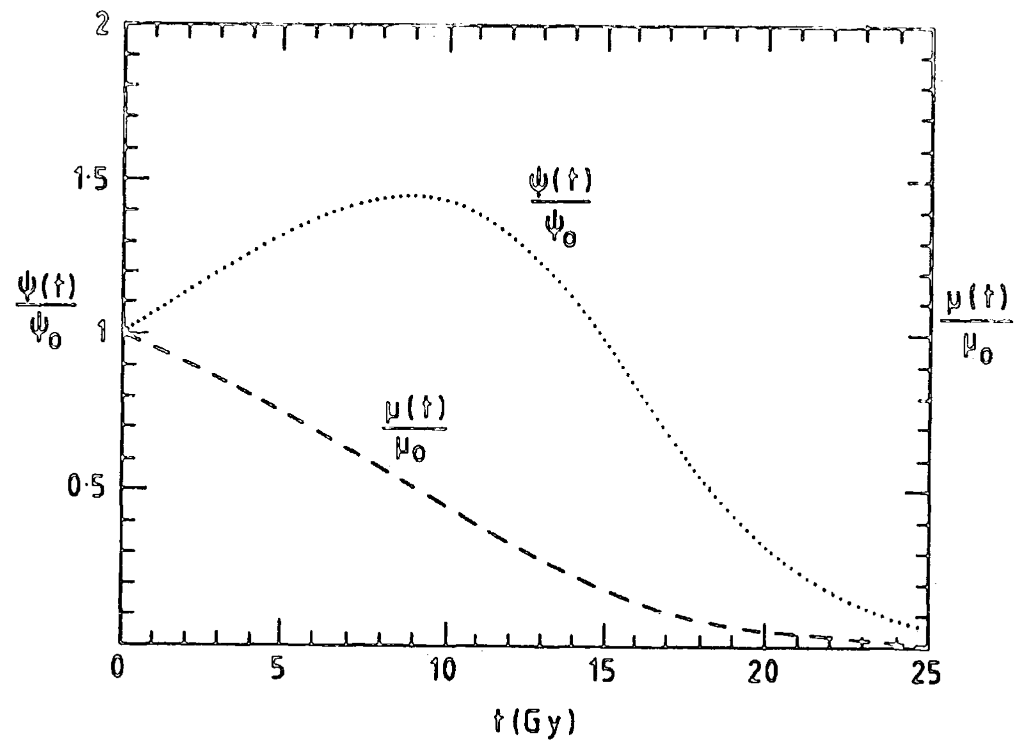
which through equation (3.17) can then be expressed purely as a function of μ or Z and then evaluated as a function of time.

For both n = 0 and n = 1, the range of parameters to fit the G-dwarf problem and AMR give,

$$\left(\frac{\Psi_1}{\Psi_0}\right)_{\odot} \simeq 1.0 \pm 0.5 \qquad (3.34)$$

for the whole range of $(\mu_1)_{\odot}$ defined by the different gas distributions. Therefore, according to the above model the SFR in the solar neighbourhood has not practically changed throughout the age of the disc, which is consistent with the evidence for a constant SFR presented in Section 2.2. Further, infall is now not required to explain the constancy of the SFR in the context of a 'Schmidt' type law of star formation. Larson (1986) in constructing his IMF to fit the observed dark matter fraction with dead stellar remnants requires the total SFR to decrease by a factor of 18 between t = 0 and t = 15Gy. For none of the above parameters is this possible for a SFR given by equation (3.33).

It may be argued that if $(\psi_1/\psi_{\odot})_{\odot}$ has remained practically constant for the past 15Gy, it cannot go on for long as the Galaxy will shortly run out of gas (Larson 1972; Tinsley 1980; Kennicutt 1983b; Pagel 1986b). In fact Larson et al. (1980) in commenting on the short gas depletion timescales inferred from constant SFRs in external spirals, had suggested infall as a possible way out of the situation. This is a possible problem with a $y_Z \propto Z$ model which would predict the Galaxy running out of gas in another 3Gy due to an increasing rate of change of metallicity with time. However, Figure (3.3) shows the time variation of $\psi/\psi_{\odot}$ and $\mu/\mu_{\odot}$ for a model with constant yield (with $\mu_{\odot} = 0.5$, Paper IV). In the region between t = 0 and t = 15Gy, ψ/ψ_0 peaks at around 9Gy but the variation is much less than a factor of 2 and $\psi_1/\psi_{\odot} \simeq 1$. If the AMR is extrapolated to times greater than 15Gy (which may be dangerous due to the breakdown of the instantaneous re-cycling approximation), the model predicts a decreasing SFR with time which flattens out, therefore keeping $\mu/\mu_{\odot} > 0$



<u>Figure 3.3</u>: The fractions $\psi(t)/\psi_\odot$ and $\mu(t)/\mu_\odot$ as a function of time from the formation of the disc of the Galaxy at t = 0, extrapolated to t > 15Gy, the assumed present age of the disc. This is the prediction of a model with constant yield and $\mu_\odot$ = 0.5 (Paper IV).

for times up to 25Gy. Although more detailed modelling is needed, it appears that a star formation rate proportional to the mass of H_2, in a chemical evolution model with constant yield is able to explain a slowly varying SFR in the past and also avoids a 'catastrophic' end to the Galaxy without having to invoke infall.

3.6 THE METALLICITY GRADIENT

Abundance gradients were first detected in nearby spiral galaxies from optical spectroscopy, Searle (1971) interpreting the radial gradients in HII region line strengths ratios as being caused by the decline in the abundance of metals with galactocentric radius. This interpretation has been confirmed and abundance gradients studied in this and other galaxies (e.g. Pagel and Edmunds 1981; McCall et al. 1985; Garnett and Shields 1987). Table A.2.2 (Appendix) lists values derived for the Galaxy of

$$\frac{d\log(Z)}{dR_{G}} = -(0.05 - 0.13)\ \mathrm{dex\ kpc^{-1}} \qquad (3.35)$$

over $R_{G} \simeq 5 - 15$ kpc for least squares fits.

Early attempts to explain these radial gradients involved the SFR following the total mass surface density of the disc (Talbot and Arnett 1975) leading to greater enrichment in the inner parts of the Galaxy, or the effect of spiral arms on the SFR leading to a similar effect (Jensen et al. 1976). This latter explanation has major difficulties, both theoretically (Cassé et al. 1979), and from the observation that some galaxies have metallicity gradients without spiral arms (McCall 1986; Elmegreen 1987c; Section 2.2).

The prediction of the simple model (Schmidt 1963; Searle and Sargent 1972) with constant yield, no infall and $Z_{0} = 0$ gives

$$Z_{1} = y' \ln\left(\frac{1}{\mu_{1}}\right) \qquad (3.36)$$

As Pagel (1987) has re-emphasised, if Σ_{H_2} follows Σ_{T} (as in the distribution of SSS 1984), μ_1 is roughly constant with R_{G} and no metallicity gradient results. It was this apparent failure of the simple model which led to two main modifications in order to explain metallicity gradients.

Firstly, it is claimed a constant yield with vertical infall of gas will produce a metallicity gradient. Tosi and Diaz (Tosi 1982; Diaz and Tosi 1984; Tosi and Diaz 1985) assume temporally and spatially constant infall and vary the

SFR as a free parameter. However, the generation of the metallicity gradient in this model is largely a geometrical effect, the geometry of the disc being such that a uniform infall rate of halo gas per unit area of the disc, having little or no metallicity will cause more dilution of metals at its periphery than near the centre. The main weakness is the assumption of a spatially uniform infall rate as one would expect the rate to increase towards the centre (Hunt 1975; Pagel 1987).

In fact, other workers using more realistic SFRs and infall rates have been unsuccessful in explaining the metallicity gradient (Lacey and Fall 1983; Güsten 1986). The additional factors of radial gas flows (Lacey and Fall 1985) or variable yield (Peimbert and Serrano 1982; Güsten and Mezger 1982) have had to be invoked in addition to infall to solve the problem. Clayton (1987) by studying six different analytic models of galactic chemical evolution has shown that infall models can be characterised by

$$Z(\mu) = \frac{y'}{2}\left\{\ln(1/\mu) + \ln[\ln(1/\mu) + 1]\right\} \qquad (3.37)$$

Both this model and the simple model (equation 3.36) fit reasonably well the observational 12 + log(O/H) versus $\ln(\mu)$ plot for M81 (Garnett and Shields 1987). However, as Garnett and Shields point out, their μ is calculated only using the HI gas, neglecting H_2. If the H_2 follows the distribution of H_2 in similar spirals the observed $Z-\ln(\mu)$ relation will not fit the above models.

The second modification of the simple model used in an attempt to fit the abundance gradient is that of variable yield based on a bimodal or otherwise variable IMF (e.g. Quirk and Tinsley 1973; Güsten and Mezger 1982). Peimbert and Serrano (1982) postulated a yield dependent on the metallicity, while Edmunds and Pagel (1984a) used a yield linear with total mass Σ_T. The situation concerning a variable IMF is far from clear, for example the variable IMF model of Terlevich and Melnick (1984) predicts even flatter gradients than the simple model.

It is immediately obvious however, that with the Bhat et al. (1985) distribution of H_2 for the Galaxy, a gradient exists in μ which through equation (3.36) leads to a gradient in Z (Paper I) therefore allowing the possibility that the simple model could still be applicable to predicting abundance gradients. However, this explanation of the metallicity gradient is essentially phenomenological, that is the variation in Z is derived from a given variation already existing for μ. Even if that is done successfully, it does not explain the existence of a radial gradient in μ_1 starting from an initial assumption that μ_0 and Z_0 are constant with Galactocentric radius at time of formation of the disc. Furthermore, any calculation of a metallicity gradient by this method depends crucially on μ_1 which in turn depends on Σ_{H_2} which is a poorly known observational quantity, especially in external galaxies (Chapters 1 and 2). McCall (1982) and Edmunds and Pagel (1984a) pointed out an observational relationship between 12 + log(O/H) and Σ_T (determined from the rotation curve) of regions in spiral galaxies. As Σ_T can be better estimated than μ_1, it seems reasonable to express the metallicity as a function of Σ_T in order to test any model against observation. It is for these reasons that the following formalism is developed.

Equation (3.18) studies the evolution of metallicity in any region of the Galaxy for which Σ_T is available and the exponents k, b and G are thought to be applicable. Solving this equation with $Z = Z_1$ at $t = t_1 = 15$Gy, the variation of the present metallicity Z_1 for different regions of the Galaxy can be obtained as

$$\int_{Z_\odot}^{Z_1} \frac{dZ}{Z^{n+kb} F(k,G,Z,n)} = J' \Sigma_T^{k-1} \qquad n \neq 1 \qquad (3.38a)$$

$$\log \left(\frac{Z_1}{Z_\odot}\right) = -\frac{1}{A} \log \left(1 - B\Sigma_T^{k-1}\right) \qquad n = 1 \qquad (3.38b)$$

where once again F, A, B and J' have been defined for convenience,

$$B = \frac{CX^k A t_1 (1-R)}{G\mu_o} \qquad (3.39)$$

and

$$J' = \frac{B\ F(k,-G,Z_\odot,n).}{A\ Z_\odot^{kb}} \qquad (3.40)$$

Now the question is, should $Z_\odot$ (and hence $\mu_\odot$) be regarded as constant for all R_G or did the disc have an initial metallicity gradient? This is not improbable as one finds an appreciable metallicity gradient in Fe/H in the radial distribution of globular clusters in our Galaxy and M31 (Sharov and Lyutyi 1984; Pilachowski 1984) although there is some controversy. There is a possibility that consideration of the thick disc metallicity structure could lead to an initial metallicity gradient but further work needs to be done. An initial metallicity gradient however, is not a particularly interesting case because it would partly or wholly explain the present metallicity gradient ab initio, that is, through the choice of initial assumption only. In the first instance therefore $Z_\odot$ will be taken as a constant throughout the disc, and a metallicity gradient will be generated by enrichment in the disc alone.

The constants B and J' can now be evaluated for the solar neighbourhood,

$$B = \left[1 - \left(\frac{Z_1}{Z_\odot}\right)_{\circledcirc}^{-A}\right] (\Sigma_T)_{\circledcirc}^{1-k} \qquad (3.41)$$

$$J' = (\Sigma_T)_{\circledcirc}^{1-k} \int_{Z_{e\circledcirc}}^{Z_{1\circledcirc}} \frac{dZ}{Z^{n+kb} \; F(k,G,Z,n)} \qquad (3.42)$$

and applied to the rest of the disc, assuming that X, the chemical fraction of hydrogen is only a very slowly varying quantity with time and R_G, and hence regarded as a constant.

It can now be seen that the variation of Z_1 with R_G is determined simply by the variation of Σ_T (equation 3.38) which can be determined independently of μ_1. (For the determination of Σ_T see Caldwell and Ostriker 1981 and Bahcall et al. 1983). Furthermore, the value of the parameter k, the index expressing the degree of dependence of the SFR on Σ_{H_2} becomes important in determining the gradient. If k = 1, the gradient vanishes irrespective of whether the yield is variable or not. For k > 1, the metallicity increases towards the Galactic Centre, but for k < 1 the gradient is in the wrong direction.

In order to illustrate this on the compilation plot (Figure 3.4) of metallicity against R_G, the quantity $(Z_1/Z_\odot)_{\circledcirc}$ needs to be represented in terms of 12 + log(O/H). This quantity has been determined for the G-dwarf problem and AMR using Fe/H measurements. Paper I made the assumption that [O/H] = [Fe/H] $\propto$ Z and discussed in detail its validity. We also argued that the spread in

12 + log(O/H) at a particular R_G, was due not only to observational error but also due to the dependence of the metallicity with time of formation of stars and the locking or depletion of metals into grains in HII regions.

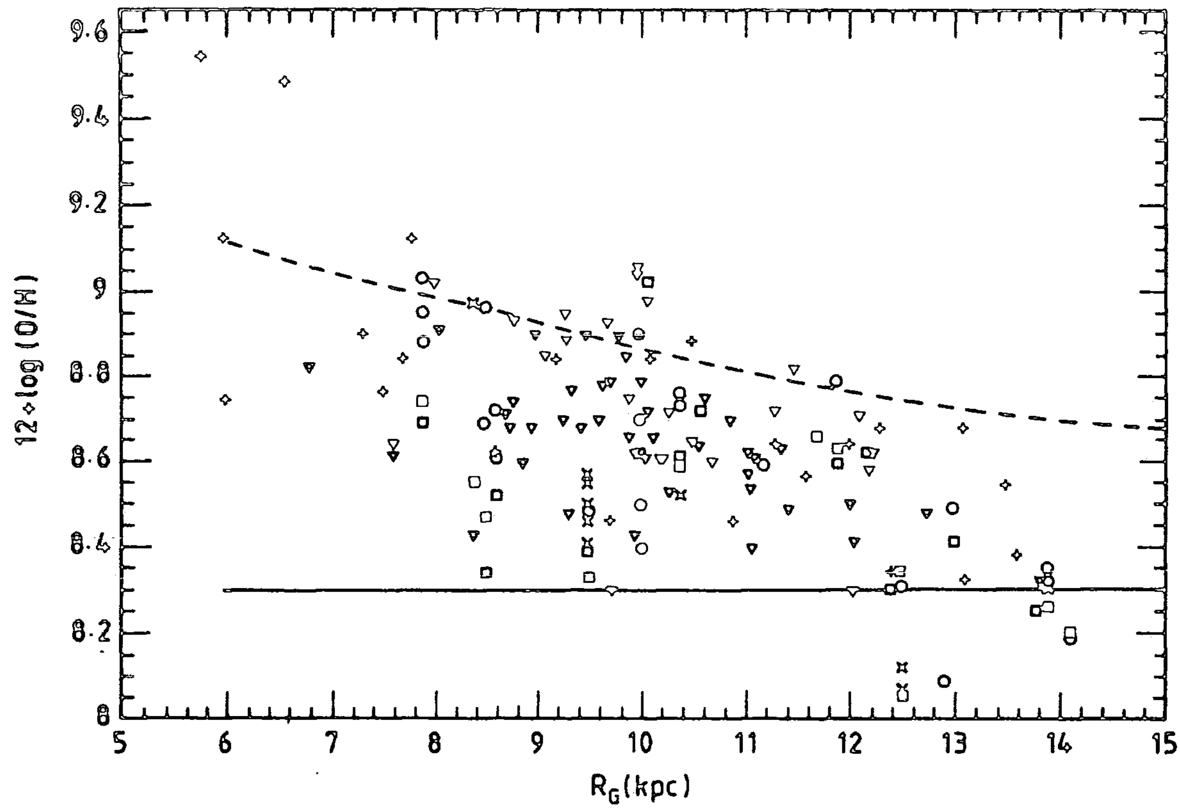


Figure 3.4: The metallicity gradient in the Galaxy shown by (O/H) abundance observations. The sources of data are given in Figure 2.4. Assuming a constant initial metallicity Z_Θ as shown by the solid baseline, a predicted fit to the upper envelope of points for a constant yield model with $d\log(Z_1)/dR_G = -0.06$ dex kpc^{-1} is shown.

Therefore, the present metallicity Z_1 is given approximately by the upper envelope to the points in Figure (3.4). This forced us to draw a baseline for Z_Θ, if possible, without leaving any point below the line, while satisfying the condition of $\log(Z_1/Z_\Theta) = 0.57$ at $R_G = 10$ kpc which also should not exclude any point above Z_1 at the same R_G. Making some compromise on both sides, we preferred to draw the baseline at 12 + log(O/H) = 8.30 as shown in Figure 3.4.

This fixes the present metallicity in the solar neighbourhood as 12 + log(O/H) = 8.87. Since the solar 12 + log(O/H) = 8.80 $\pm$ 0.12 (Rana and Wilkinson 1986c, and references therein) and Edmunds (1984) has adopted 8.92, this upper bound is perhaps justifiable. It is interesting that the spread in (O/H) observations at R_{G} = 10 kpc is very similar to $(Z_0/Z_{\odot})_{\odot}$ determined from the G-dwarf problem and AMR. At R_{G} > 12 kpc there are about half-a-dozen measurements of (O/H) that lie below the baseline. It may be that these objects show an abnormal depletion in the gas phase, possibly because of substantial segregation into grains, or may just be due to observational error. These points could be easily included by the use of a baseline reflecting an initial gradient in $Z_{\odot}$, but in the first instance is unnecessary. The production of a gradient of -0.06 dex kpc^{-1} is shown in Figure 3.4 for the case of a constant yield (Paper IV and a similar plot for variable yield can be found in Paper I). The question of whether Z_1 is represented by the upper envelope of the distribution or the distribution itself is a complex one concerning the value of Z_1 in the solar neighbourhood and the validity of the assumption [O/H] = [Fe/H] (cf. Clegg et al. 1981; Chiosi and Matteucci 1983; Gratton 1985; Laird 1985; Pagel 1987). The important point however is the value of the gradient predicted, that is $d\log(Z_1)/dR_{G}$, and that the gradient of the upper envelope is virtually the same as that of the 12 + log(O/H) distribution itself.

Therefore, in the light of the above discussion, the various gradient determinations in Table A.2.2 (Appendix) and following Lacey and Fall (1985), the observational gradient is assumed to be

$$\frac{d\log(Z_0)}{dR_G} = -0.06 \pm 0.01 \text{ dex kpc}^{-1} \qquad (3.43)$$

Using equations (3.38) - (3.42) and a spatial variation of Σ_T as given in Table A.2.1 (Appendix) the metallicity gradient was evaluated for the parameters which give good fits to the G-dwarf problem. The value of k was then derived by imposing equation (3.43). For n = 1 the required range of k for providing the observed metallicity gradient is $\simeq$ 1.10 - 1.15; but for n = 0, in order to produce the same gradient k = 1.30 - 1.60. The value of k depends also on $\mu_\odot$, the lower the value of $\mu_\odot$, the lower is the required value of k for producing the same gradient. Hence, k increases from $1.36^{+0.09}_{-0.06}$ for $\mu_\odot = 0.5$ to about $1.50^{+0.24}_{-0.14}$ for $\mu_\odot = 0.8$. The value of k is found to be virtually independent of δ_0.

A number of points may be noted from this analysis.
(i) The empirical correlation $\psi_S \propto \Sigma_{H_2}^k$ of Chapter 2 gave k = 1.2 $\pm$ 0.2 for the Bhat et al. (1985) distribution of H_2 in the Galaxy while k = 0.7 $\pm$ 0.2 for the SSS (1984) distribution. Consequently the SSS distribution leads to no metallicity gradient or a gradient in the wrong sense, while the Bhat et al. distribution is able to produce the observed gradient. Although this result was expected on the basis of the simple model, it also applies to models where the yield is proportional to the metallicity. Therefore, it is concluded that the Bhat et al. distribution is superior to that of SSS. In fact the argument may be inverted, and fixing k by the observed metallicity gradient Σ_{H_2} may be derived from the SFR (ψ_S) as a function of Galactocentric radius, independent of the controversial CO surveys. This

will be done in Chapter 4.

(ii) The metallicity gradient has been expressed in terms of Σ_T rather than the uncertain μ_1, and the formalism developed is sufficiently general for its possible application to other spiral galaxies. The existence of abundance gradients in other spirals could be linked to their variation in Σ_T (cf. Talbot and Arnett 1975). A relationship between metallicity and Σ_T is actually observed (McCall 1982; Edmunds and Pagel 1984a; Bothun et al. 1984) and once again this will be examined in detail in Chapter 4.

(iii) Given an initial density profile of the total mass distribution in the disc, it has been shown that with time the Galaxy may naturally develop a radial gradient in the gas fraction (μ_1) and the metallicity (Z_1) even though it begins with a constant initial gas fraction (μ_0) and a constant initial metallicity (Z_0) at all radii, provided the exponent k > 1. This metallicity gradient is not generated by infall or radial gas flows or necessarily variable yield (although this helps). Even for the case of constant yield and no infall a metallicity gradient is produced, the reason being (as noted by Lacey and Fall 1985 and Clayton 1987) the 'efficiency' of star formation (ψ_s/Σ_g) varies as a function of R_G (equation 3.12). This SFR has, of course, been derived empirically rather than adopted to provide the correct result.

This Chapter has shown that using the SFR derived in Chapter 2, using an explicit form for dark matter, a finite initial metallicity of the disc and no infall, problems such as the G-dwarf problem, the AMR, the constancy of the SFR and the Galactic metallicity gradient can be solved quite easily, provided that the H_2 distribution in the Galaxy follows that of Bhat et al. (1985) rather than SSS (1984). In the next Chapter, the consistency and consequences of this model will be examined.

CHAPTER FOUR

GALACTIC CHEMICAL EVOLUTION II – CONSISTENCY AND CONSEQUENCES

4.1 INTRODUCTION

The previous Chapter outlined a model of chemical evolution of the Galactic disc using a form of the SFR, $\psi_s \propto \Sigma_{H_2}^k$, in addition to an explicit dependence for dark matter, finite initial metallicity and no appreciable infall over the majority of the age of the disc. It was shown that with a yield of metals taken to be a constant or proportional to the metallicity, a self-consistent model could be constructed to predict the G-dwarf problem, the age-metallicity relation, the constancy of the SFR in the solar neighbourhood and the Galactic metallicity gradient in good agreement with observations. The aim of this Chapter is to further test the consistency of this model and outline some further predictions.

Firstly, the model will be examined in the light of the available forms for the initial mass function of stars and details of stellar nucleosynthesis, in order to check values of the yield, the dark matter fraction and the returned fraction (Section 4.2). These considerations will then be used to see whether the assumption of a yield proportional to metallicity is justified (Section 4.3). The consequences of these results for the dark matter fraction will be discussed, leading to a consideration of the possible form of dark matter in the disc (Section 4.4). The predictions of the model for abundance gradients in external spiral galaxies will be compared with observation (Section 4.5) and the amount and distribution of H_2 will be examined in detail (Section 4.6). Finally, the evolution of radial gradients in gas, stars and metals will be illustrated (Section 4.7), leading to a possible explanation of the shape of the H_2 distribution in the Galaxy and other spirals.

4.2 THE PRESENT VALUES OF THE DARK REMNANT FRACTION AND THE YIELD

The dark remnant fraction (D) was defined in Chapter 3, in terms of the IMF(ϕ) and its upper and lower mass limits, m_u and m_l, as

$$D(t) = \int_{m_2(t)}^{m_u(t)} w_m \phi(m)\, dm + \int_{m_l(t)}^{m_0} m\phi(m)\, dm \qquad (4.1)$$

where a star of mass m leaves behind a remnant mass w_m, m_2 being the mass above which the star collapses only to a neutron star or black hole but not a white dwarf and m_0 is the mass limit below which the star ends up as a brown dwarf. Similarly the returned fraction R(t),

$$R(t) = \int_{m_1(t)}^{m_u(t)} (m - w_m)\phi(m)\, dm \qquad (4.2)$$

where m_1 is the turn-off stellar mass corresponding to the main sequence lifetime of a star bounded by the running age the disc, and the yield, y_z,

$$y_Z(t) = \frac{1}{(1-R-D)} \int_{m_l(t)}^{m_u(t)} m p_{Zm} \phi(m)\, dm, \tag{4.3}$$

where p_{Zm} is the mass fraction of a star of mass m that is converted to metals and ejected.

In the solar neighbourhood, D,R and y_Z were estimated, independently of the IMF, by solutions to the G-dwarf problem and age-metallicity relation. It was found that for n = 1 (i.e. yield proportional to the metallicity) and for n = 0 (i.e. constant yield),

$$\frac{D}{(1-R)} = \frac{S_1 - S_\odot}{\mu_\odot - \mu_1} = 0.1 - 0.45, \tag{4.4}$$

$$R = 0.3 - 0.6, \tag{4.5}$$

$$y_Z = KZ^n = 0.019 - 0.025 \tag{4.6}$$

assuming S_1 = 0.5 (Bahcall 1986c), $Z_\odot$ = 0.02 and $\psi_{1\odot}$ = $4M_\odot pc^{-2} Gy^{-1}$, the range due to the different assumptions concerning the yield and the uncertainty concerning Σ_{H_2} in the solar neighbourhood. Using different models, R has been calculated to be 0.35 - 0.8 (e.g. Twarog 1980; Tinsley 1981; Güsten and Mezger 1983), in agreement with the above values. The above values of the yield in the solar neighbourhood are somewhat higher than previous estimates y_Z = 0.014 $\pm$ 0.005 (Pagel 1981) and $\gtrsim$ 0.012 (Peimbert and Serrano 1982).

It is now important to compare these values, obtained from model-fitting in the solar neighbourhood, with the values obtained from their definitions (equations 4.1 - 4.3). In order to do this, explicit forms for w_m, ϕ(m), m_2, $m_\odot$ and p_{Zm} need to be critically examined.

4.2.1 The remnant mass function

Previous workers (e.g. Tinsley 1980; Tosi 1982) have represented the function w_m in a very simple way: any star with initial mass lower than $4M_\odot$ will become a white dwarf with $w_m = 0.7M_\odot$ and any star with initial mass greater than $4M_\odot$ becomes a neutron star with $w_m = 1.4M_\odot$. More recently, other workers (e.g. Larson 1986; Rana 1987a) have used

$$w_m = 0.38 + 0.15m \qquad (4.7)$$

which is predicted by stellar evolution calculations assuming a standard mass loss rate (Iben and Renzini 1983).

A crucial part of our understanding of the final fate of stars of differing initial mass concerns recent work on so-called intermediate mass stars (IMS) with the range of mass of 2.3 - $8M_\odot$. Figure 4.1 shows schematically the final fate of such stars. The upper limit for IMS, M_{up}, defined as the limiting mass between degenerate and semi-degenerate C-ignition, marks a sharp discontinuity in the evolutionary behaviour of stars (Renzini 1984). For initial masses $m < M_{up}$, stars experience the asymptotic Giant Branch (AGB) phase and eventually die, either as C-O white dwarfs having failed to ignite C, or ignite C under degenerate conditions thus experiencing a C-deflagration which causes the total disruption of the star (Nomoto 1984a). The latter is termed a supernovae event of type $I\frac{1}{2}$ (Iben 1980).

For stars with $m < M_{WD}$ the final product is a C-O white dwarf remnant. From a theoretical point of view, the value of M_{WD} is uncertain owing to a poor knowledge concerning the mass loss process in stars, but values in the range 4-6 $M_\odot$ have been widely used (Renzini 1977; D'Antona and Mazzitelli 1985). Observations of white dwarfs in young Galactic clusters seem to indicate that all single stars up to (7 ± 1) $M_\odot$ become white dwarfs (Weidemann 1984; Koester and Reimers 1985). However, it has been noted (Iben 1983) that

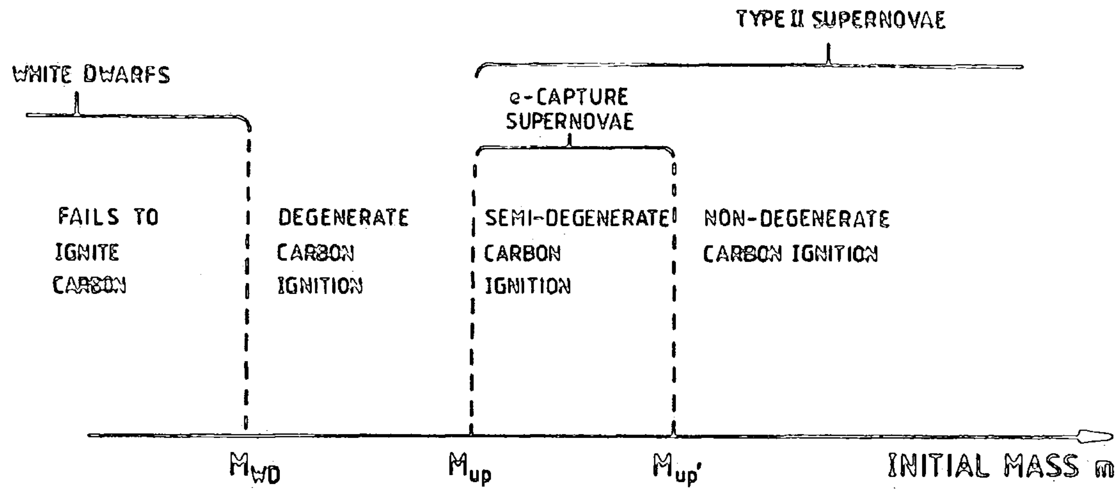


Figure 4.1: The final fate of intermediate mass stars ($\approx 2-12 M_\odot$). M_{WD}, M_{up} and M'_{up} are defined in the text.

M_{WD} may be a function of the metallicity Z, if the mass loss rate is a function of Z.

For stars with $m > M_{up}$, stars ignite carbon either semi-degenerately if $m < M'_{up}$, or non-degenerately thus failing to experience the AGB phase and eventually undergo a core collapse giving rise to a supernova event of Type II, leaving a neutron star remnant (Nomoto 1984b,c; Woosley et al. 1984; Yahil 1984). Although Hillebrandt et al. (1985) suggested that less massive progenitors could lead to this type of collapse, this work follows Tornambè and Matteucci (1985) in identifying supernovae of Type II events with stars of initial mass $m > M_{up}$, thereby fixing the m_2 of equation (4.1) as M_{up}. As with M_{WD}, M_{up} has been proposed to be a function of Z (Becker and Iben 1980; Tornambè 1984; Chieffi and Tornambè 1984; Fujimoto et al. 1984). Recent suggestions (Matteucci and Tornambè 1985; Tornambè and Matteucci 1985; Castellani et al. 1985; Renzini et al. 1985; Bertelli et al. 1986;) indicate that the inclusion of overshooting from convective cores and semi-convection in evolutionary models of IMS limits the mass M_{up} to a value somewhat lower than $8M_{\odot}$ and M_{up} possibly decreases with decreasing Z for log Z $\gtrsim$ -4. In particular, for $Z = Z_{\odot}$, $M_{up} \cong 6M_{\odot}$ whereas for lower metallicities ($Z \cong 10^{-4}$), $M_{up} \cong 4$-$5M_{\odot}$ (Tornambè and Chieffi 1986).

There is one further complication for the remnant mass function, w_m. Calculations of supernova collapse and explosion have shown that supernova explosions are expected for stars with initial mass at least up to $50M_{\odot}$ (Wilson et al. 1986). However, Tornambè and Matteucci (1985), computing a rough estimate of the current Type II supernovae rate by assuming that all stars more massive than M_{up} become Type II require, in order to alleviate discrepancy between the theoretical and observational rates, that stars with initial mass > $50M_{\odot}$ collapse to black holes. In fact, Schild and Maeder (1985) from a consideration of the pulsar distribution, and helium abundance support this view. It is not easy to incorporate this effect into the remnant mass function.

In the light of the above discussion, three possible cases, as described in Table 4.1 are taken. White dwarf

Table 4.1: Parameters for the remnant function, w_m.

Case	M_{WD} ($M_{\odot}$)	M_{up} ($M_{\odot}$)	M_{BH} ($M_{\odot}$)
A	5	6	100
B	6	7	50
C	5	6	100

masses are taken roughly in the region discussed by Weidemann and Koester (1983), linear from $1M_{\odot}$ to M_{WD}. Case

A follows Tinsley (1980) in assuming that for $M > 5M_{\odot}$, $w_m = 1.4M_{\odot}$. Case B increases w_m linearly between M_{up} and M_{BH} where the minimum remnant mass for a black hole is assumed to be $3M_{\odot}$ (McDowell 1985). Case C is the relationship used by Larson (1986) and Rana (1987a), equation (4.7) with M_{WD} and M_{up} as shown in Table 4.1.

4.2.2. The initial mass function

The frequency distribution of stellar masses at birth (IMF) can be estimated from the observed luminosity function if an assumption is made about the time dependence of the SFR (see Scalo 1986 for a comprehensive review). The constraint that the IMF should not show an unphysical discontinuity was used by Miller and Scalo (1979) to argue for a nearly constant SFR and an IMF which is a monotonically declining function of stellar mass. This conventional picture of the IMF has recently been challenged by evidence for a dip at $0.7M_{\odot}$ in the luminosity function (Upgren and Armandroff 1981; Scalo 1986). Larson (1986) has used this and new data compiled by Scalo (1986) to propose a bimodal model of the IMF. This model, where the IMF is double peaked consists of two components of similar form representing separate low-mass and high mass modes of star formation. Using the constraint on the high mass mode that the model should predict enough mass in remnants to account for the Bahcall (1984) amount of unseen matter near the Sun, he finds a reasonable match with Scalo's data if the SFR decays with time as exp(-t/3.4Gy). Rana (1987a) has used a different set of data on the luminosity function, scale heights and main-sequence lifetimes which differ substantially from Scalo (1986). Although his data are

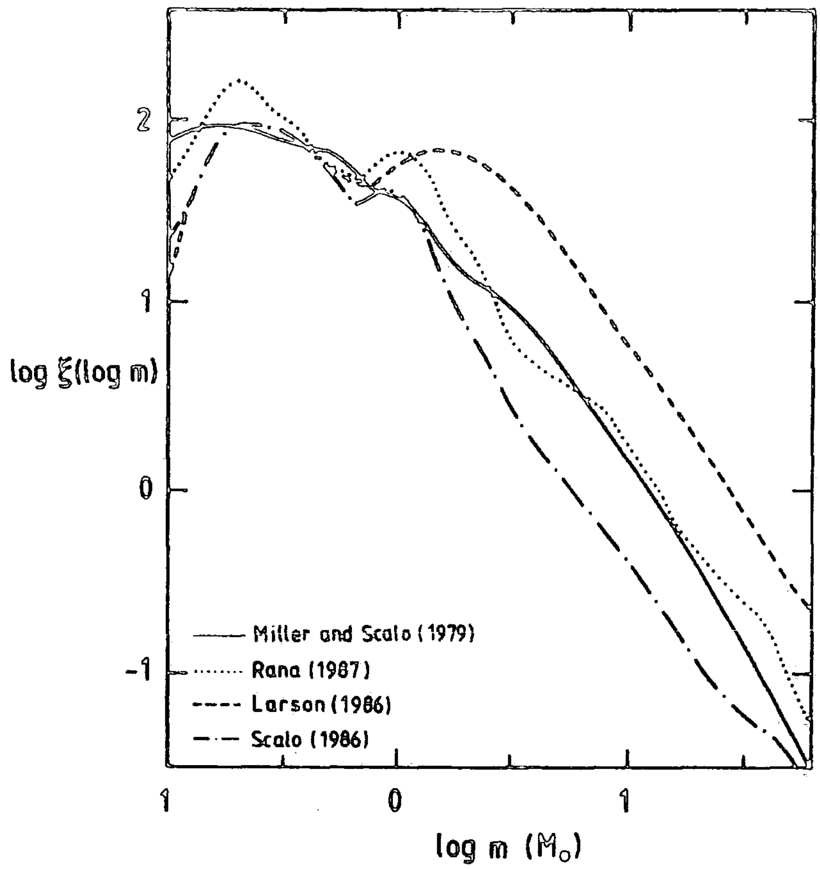


Figure 4.2: The total number ξ(log m) of stars per unit log mass ever formed during the past 15Gy in a column of cross-section 1pc^{-2} through the Galactic plane, for different sets of data, and assumptions about the time-dependence of the SFR. The solid curve is the case of constant SFR for the data of Miller and Scalo (1979). The curve from Rana (1987a) uses a different compilation of data and a SFR from Figure 3.3 of this work. The data of Scalo (1986) are represented by two cases, a constant SFR case and the model of Larson (1986) which has a decreasing SFR with time.

closer to that of Miller and Scalo (1979) he also finds a bimodal, or even multi-modal IMF, which he interprets as possibly evidence of bursts of star formation giving birth to stars of a specific mass range. Due to disagreement concerning the data and the time-dependence of the SFR, four different IMFs, illustrated in Figure 4.2 will be contrasted in the following. With an assumed age of the disc to be 15Gy, the case for a constant SFR is shown for the data of Miller and Scalo (1979). The data of Scalo (1986) are represented by the case for constant SFR and the model of Larson (1986) which has a decreasing SFR with time. The fourth IMF is derived from the data of Rana (1987a) using the SFR for the constant yield case of Chapter 3.

Neglecting the contribution to the dark remnant fraction due to brown dwarfs by setting to zero the second term on

Table 4.2: Dark remnant and returned fractions.

		$m_\ell = 0.1M_\odot$			$m_\ell = 0.007M_\odot$		
$\phi(m)$	w_m	D	R	D/(1-R)	D	R	D/(1-R)
Miller & Scalo(1979)	A	0.030	0.43	0.053	0.060	0.41	0.102
	B	0.014	0.44	0.025	0.045	0.42	0.078
	C	0.038	0.44	0.068	0.068	0.43	0.120
Rana (1987a)	A	0.025	0.43	0.044	0.060	0.40	0.100
	B	0.015	0.43	0.026	0.050	0.41	0.085
	C	0.036	0.44	0.064	0.070	0.42	0.121
Larson (1986)	A	0.050	0.63	0.135	0.051	0.63	0.138
	B	0.025	0.65	0.071	0.025	0.65	0.071
	C	0.068	0.64	0.189	0.068	0.64	0.189
Scalo (1986)	A	0.012	0.30	0.017	0.014	0.30	0.020
	B	0.007	0.31	0.010	0.009	0.31	0.013
	C	0.018	0.32	0.026	0.020	0.32	0.029

the right-hand side of equation (4.1) and integrating using $m_\ell = 0.1M_\odot$ and $m_u = 100M_\odot$ (Terlevich 1982) the resulting R and D for the three cases of w_m and each IMF is shown for $m_\ell = 0.1M_\odot$ in Table 4.2.

In evaluating R, the age of the disc is assumed to be 15Gy, which using the stellar mass-lifetime relation of

Scalo (1986), gives $m_u = 0.91M_\odot$. The value of R turns out to be virtually independent of the three different functions of w_m but varies with different IMFs from $\approx 0.3 - 0.65$. These values are consistent with that determined from fitting the observational problems of chemical evolution.

However, apart from Larson's IMF with w_m functions A and C (which has been constructed of course to give this result) the values shown for D are inconsistent with the predictions from fitting the G-dwarf problem and other parameters in the chemical evolution of the Galaxy. It should be noted that with function B for w_m, which is probably the most physical representation, even Larson's IMF produces too little dark matter. Therefore, the question is can the dark matter fraction be increased by the contribution from brown dwarfs?

4.2.3 Brown dwarfs

Brown dwarfs are stars and planets with masses lower than that required for the onset of nuclear burning (Salpeter 1977). The maximum mass for a 'Jupiter-like' object, $m_\odot$, determined by the onset of nuclear burning is thought to be $0.08M_\odot$ (D'Antona and Mazzitelli 1985; Bahcall 1986b). From theoretical arguments, calculations for the lower limit of the Jeans mass have led to different estimates of m_ℓ, in the range $0.004 - 0.007M_\odot$ (Low and Lynden-Bell 1976; Rees 1976; Silk 1982; Palla et al. 1983). Both $m_\ell = 0.007M_\odot$ and $m_\ell = 0.004M_\odot$ have been examined, but finding little difference the former will be used. In order to perform the calculation for D, including the second term on the right hand side of equation (4.1), the IMF needs to be extrapolated form 0.1 to $0.007M_\odot$. This is not unjustifiable as $m_{\odot}$ is simply the stage at which nuclear burning stops and has nothing to do with cloud fragmentation (Bahcall 1986b).

The column corresponding to $m_{\ell} = 0.007M_{\odot}$ in Table 4.2, shows that even with the contribution from brown dwarf objects, D/(1-R) is still very small compared to the value obtained from fitting the G-dwarf problem. The extrapolation of the IMFs of Larson and Scalo contribute almost no extra dark matter as both decrease very steeply at $m < 2M_{\odot}$. Rana's IMF has some discontinuities at low mass which makes the extrapolation similar to that of Miller and Scalo (1979). Even the form of the Miller-Scalo IMF, which falls off at $m < 0.1M_{\odot}$, means that the classical suggestion of brown dwarfs as dark matter can have a meaning only if the IMF is very different at low masses (Tinsley 1981).

There is however, severe difficulty in estimating the IMF at low masses. The determination of the luminosity function is based on few stars, and it is not clear whether at low luminosity it flattens off, decreases or increases (e.g. Gilmore and Reid 1983; Gilmore et al. 1985; Scalo 1986; Liebert and Dahn 1986; Robin and Crézé 1986; Reid 1987). Recently Hawkins (1986) from a very deep R-band UK Schmidt survey for M stars to low luminosity and an analysis of the R-I colours and proper motion in 15 survey plates, has claimed the first direct detection of very low-luminosity stars. There seems an indication of a steadily increasing population into the regime of substellar masses which would of course increase the dark remnant fraction through brown dwarfs. Further uncertainty in determining the IMF comes through the scale-height to magnitude relation and the mass to magnitude relation (Rana 1987a). In fact, D'Antona and Mazzitelli (1986), adopting the mass-luminosity relation from their models of low mass stars find that there is no decline in the IMF down to $0.1M_{\odot}$, a trend which if continued to lower masses would once again considerably increase D. However, an IMF similar to Miller and Scalo (1979) and not remarkably different at $m < 0.1M_{\odot}$ would leave only the bimodal model of Larson (1986) able to produce the amount of dark matter required by the model of chemical evolution. This question will be discussed in detail in Section 4.4.

4.2.4 Production of heavy elements

The production of heavy elements by massive stars of constant mass has been studied by Arnett (1978) who followed the evolution of He bare cores. More recent studies have included the important property of mass loss (e.g. Maeder 1981, 1984; Prantzos et al. 1986). Transforming y' to y_z (Section 3.2.1), Maeder (1984) evaluating equation (4.3) obtains $y_z = 0.012 - 0.02$ using a Miller-Scalo IMF below $25M_{\odot}$ and that of Garmany et al. (1982) above, and R = 0.17. Chiosi and Matteucci (1984) in fact quote a range of $y_z = 0.0035 - 0.069$ for different stellar IMFs, mass loss rates, overshooting and nucleosynthesis data.

In Figure 4.3, Maeder's (1984) variation of p_{zm} as a function of initial mass, m, is reproduced for the intermediate case of mass loss. The minimum in the metal production at the limit of IMS and massive star models, found by various authors, is thought to be real (Audouze and Tinsley 1976; Mallik 1980, 1981).

With functions A, B and C for w_m and the above values of R and D, the Miller-Scalo IMF gives $y_Z = 0.025$ in good agreement with the value derived for the solar

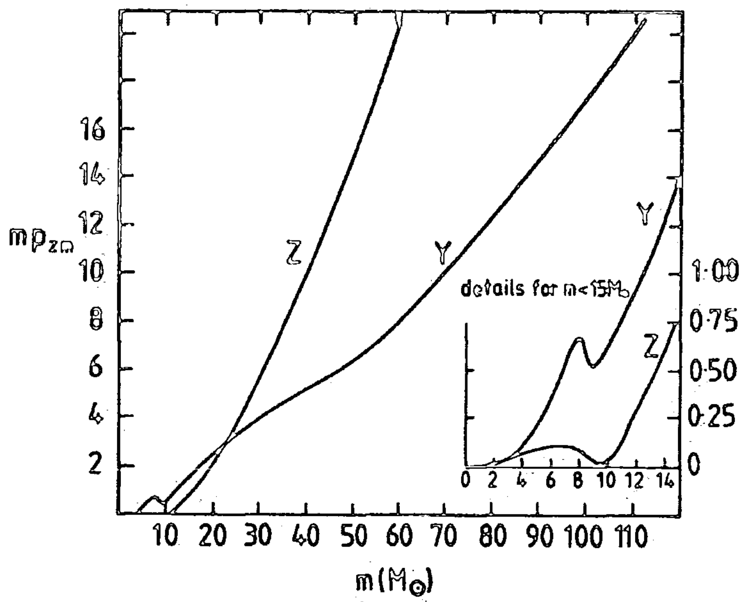


Figure 4.3: The mass of metals, mp_{Zm}, returned to the ISM as a function of the initial mass of the star, reproduced from Maeder (1984). The equivalent curve for helium production is also shown for comparison.

neighbourhood. The IMF of Rana gives a slightly higher yield $y_Z \simeq 0.031$ while that of Scalo gives a low $y_Z \simeq 0.015$. The IMF of Larson (1986) gives a yield four times higher than that of Miller and Scalo. In his model he argues that this is not a constraint as the upper limit of metal production (m_{Zu}) is uncertain. He requires $m_{Zu} \lesssim 16M_\odot$ to give $y_Z \simeq 0.025$. If this is the case then stars more massive than $16M_\odot$ rather than $50M_\odot$ (cf. Section 4.2.1) must evolve directly to black holes with no ejection of metals. Twarog and Wheeler (1982) argued for an upper cut-off of $50M_\odot$ or oxygen would be overproduced in the solar neighbourhood, but Matteucci (1986) has suggested there is no clear evidence requiring m_{Zu} to be much lower than 80-100 $M_\odot$. Although the observed high $\Delta Y/\Delta Z$ ratio (Pagel et al. 1986) may suggest a low m_{Zu} (Peimbert 1986; Pagel 1987), such a low value of $m_{ZW} \gtrsim 16M_{\odot}$ is potentially problematic. Olive (1986) describes the following problems. Arnett (1978) claimed that the typical heavy element producing stars are O stars with masses greater than $26M_{\odot}$. The typical source of metals in Larson's bimodal model is a star of $\approx 14M_{\odot}$. In addition, it has been noted (Truran 1984) that halo stars show abundance patterns which are typical of $40M_{\odot}$. Another potential difficulty, in the context of abundance ratios, is that the bimodal model overproduces Ne and Mg by factors 2 and 4, respectively. Although there are considerable uncertainties in the yields, the new calculations of Woosley and Weaver (1986a,b) make the situation worse. Olive (1986) in order to relax this constraint has shifted the high-mass mode of Larson's IMF to lower mass, which fits the dark matter limit and yield with $m_{ZW} \cong 42M_{\odot}$. Olive et al. (1987) argue that uncertainties at present are too great to place severe constraints on the model.

Therefore, for certain IMFs and assumptions about the upper mass cut-off for metal production the present yield is consistent with that derived from the model of the chemical evolution of the solar neighbourhood. However, is the yield proportional to the metallicity or is it constant?

4.3 IS THE YIELD OF METALS A FUNCTION OF THE METALLICITY?

In many models of the chemical evolution of the Galaxy the yield has been taken to be a constant quantity. However, in order to solve problems associated with the simple model some workers have used a yield varying with

Galactocentric radius (e.g. Güsten and Mezger 1982). Edmunds and Pagel (1984a) argue for some evidence from spiral and irregular galaxies that the yield may be constant in time in any one region but depends on local conditions such as the total surface density. However, they do state (Edmunds and Pagel 1984b) that the yield could be metallicity dependent if the evolution of stars is significantly influenced by metal abundance, for instance through varying mass loss rate.

Peimbert (1984) has contended that a yield independent of metallicity, even with infall, does not agree with the observations of the yield of primary elements derived from HII regions located in spiral, irregular and dwarf galaxies. A yield increasing with the abundance of heavy elements, as proposed by Peimbert and Serrano (1982), better explains these observations than a constant yield. Serrano and Peimbert (1983) also require a yield increasing with metallicity to explain the N/O versus O/H diagram. However, other workers (White and Audouze 1983; Matteucci and Tosi 1985; Diaz and Tosi 1986) have argued that when the actual details of stellar nucleosynthesis are taken into account, a yield independent of Z is consistent with HII region observations for both spirals and irregulars.

Chapter 3 made an ad hoc assumption of $y_z \propto Z^n$ and showed that both n = 0 and n = 1 could give adequate models for the chemical evolution of the Galactic disc. The consequences for the dark matter fraction and the mass of H_2, however, are dependent on the value of n (Paper I and IV). Furthermore, the question still remains, is it reasonable to explain a yield proportional to the metallicity from our present knowledge of the IMF and stellar nucleosynthesis in the Galaxy? The variation of the yield over the lifetime of the Galaxy will be given by the time dependence of the parameters in equation (4.3) namely $\phi(m)$, p_{Zm}, m_{ℓ} and m_{μ}.

4.3.1 Variations in $\phi(m)$

There is much debate concerning whether the IMF is constant in space and time. Garmany et al. (1982) suggested, based on counts of early type stars, that there were spatial variations in the upper IMF. Humphreys and McElroy (1984) subsequently showed that this result was due to a selection effect and the data favour a constant IMF. Observations of the IMF in other galaxies and even in globular clusters (e.g. Berkhuijsen 1982; McClure et al. 1986) do not show a large variation from the Galactic IMF. Terlevich and Melnick (1984, see also Terlevich 1985; Melnick and Terlevich 1986) by studying the properties of a sample of extragalactic HII regions, suggested a dependence of the slope of the IMF (represented by a power law of the mass) on the metal content of such objects given by

$$x = \log Z + 5.05 \quad (4.8)$$

for stars in the mass range $0.1\text{-}100M_{\odot}$. As the metallicity of a galaxy increases with time after the formation of the disc (Twarog 1980) this implies a time-dependence of the IMF. Although the work of Boisse et al. (1981) may be interpreted as implying variations with ambient conditions, Turner (1984) and Scalo (1986) have contended with very different arguments that the IMF is grossly the same everywhere. Furthermore, Matteucci and Tosi (1985) have shown that the Terlevich-Melnick IMF does not reproduce the observed data in dwarf irregular galaxies, suggesting that the IMF dependence on the metallicity, if any, should be much weaker than that given by equation (4.8).

Therefore, significant variations in the IMF may be rare enough for the assumption of a universal function to be a reasonable first approximation (Tinsley 1980; Lacey and Fall 1985). In any case, even if the IMF is variable it is not clear how this variability should be parameterised or how it affects chemical evolution (Pagel 1987). In the following $\phi(m)$ will be assumed to be constant in time, and once again the four IMFs of Section 4.2.2 will be contrasted.

4.3.2 Variations in p_{zm}

The minimum in p_{zm} is at the limit of the IMS and massive star models and therefore corresponds to M_{up}. Any time dependence of M_{up} may affect the shape of the curve. From Figure 2 of Tornambè and Matteucci (1985), M_{up} can be approximated for Z in the range 10^{-3} to 10^{-1} over the age of the Galaxy using the expression

$$M_{up} = 8.0 + 0.8 \log Z \tag{4.9}$$

so that for Z = 0.02, M_{up} = 6.6$M_\odot$(cf. Tornambè and Chieffi 1986). Therefore, the minimum in Maeder's curve (Figure 4.3) should be at 6.6$M_\odot$, not 9.5$M_\odot$ and should move with metallicity. As it would be a very complicated calculation to produce curves of p_{zm} for different Z rigorously, a crude approach is adopted, adequate for our purposes. Fixing points at m = 1$M_\odot$ and m = 50$M_\odot$, the abscissa is then re-scaled to match with the required position of the minimum. If m" corresponds to the mass for a certain p_{zm} given by Maeder (1984), then let m be the corresponding mass for the metallicity-dependent revised curve. Now $M''_{up} = 9.5\ M_\odot$ for Maeder, M_{up} is given by equation (4.9), and a simple transformation is adopted relating m and m" to be given by

$$m = \frac{(M_{up} - 1)(m'' - 1)}{(M''_{up} - 1)} + 1 \qquad m'' < M''_{up} \qquad (4.10a)$$

$$\text{and } m = \frac{(50 - M_{up})(m'' - 50)}{(50 - M''_{up})} + 50 \qquad m'' > M''_{up} \qquad (4.10b)$$

The change of metallicity with time in the Galaxy, changes M_{up}, thereby altering the shape of the p_{zm} curve. It should be stressed that this simple scaling of the yield for different values of M_{up} might be dangerous, since the actual effects of overshooting on the size of the stellar envelope and on the corresponding nucleosynthesis has not yet been computed (Renzini 1984; Greggio and Tosi 1986). However, using this approach in the following, equation (4.9) does not predict a very large effect, that is for Z to increase from ≈ 0.005 to 0.02, M_{up} increases from ≈ 6.2 to $6.6\ M_\odot$. The AMR of Twarog (1980) is taken with log $(Z_1/Z_\odot) = 0.57$ (from Section 3.4) for the Z versus t relation over the lifetime of the disc. This change in M_{up} will have an effect on the remnant mass function, but because the change in M_{up} is small, w_m will remain roughly constant with time. Case A is used for simplicity.

The turn-off stellar mass corresponding to the main sequence lifetime of a star bounded by the age of the disc t, m_1, essentially controls the number of stars which contribute to chemical evolution after the formation of the disc. The mass-lifetime relation from Scalo (1986), has been used to evaluate m_1 as a function of age of the Galactic disc.

4.3.3 Variations in m_ℓ and m_u

The upper mass limit of the IMF, m_u, is assumed to be $100M_\odot$ at present (Terlevich 1982; Humphreys and McElroy 1984). If the contribution of brown dwarfs is neglected, m_ℓ may be taken as $0.1M_\odot$ (Larson 1981). Figure 4.4 shows the variation of y_Z, D and R as a function of time with m_ℓ and m_u constant with time, for each of the IMFs described previously. This results in the yield, the returned fraction and the dark remnant fraction being fairly constant with time. Also plotted is the yield as a function of the metallicity in order to look for a possible relation $y_Z \propto Z^n$ using the AMR of Twarog (1980). If such a relation does exist then the value of n would be quite small, $n \cong 0.0 - 0.1$.

While modelling stellar atmospheres, Kahn (1974) proposed that the upper mass limit m_u could vary with metallicity Z as

$$m_u \propto Z^{-0.5} \tag{4.11}$$

In Figure 4.5, the solid curve shows the results for the Miller-Scalo IMF of keeping m_ℓ constant at $0.1M_\odot$ while m_u is varied as in equation (4.11), once again using the AMR of Twarog (1980) and $\log(Z_1/Z_\odot) = 0.57$. Therefore, m_u decreases from 197 $M_\odot$ when the disc formed to 100 $M_\odot$ at present. The resulting variations are very similar to Figure 4.4, except that the metal yield is slightly increased at early times (less than 5Gy) suggesting an overall $n \cong -0.1$. Because the IMF is falling rapidly at high m, this variation in m_u has little effect. The other IMFs show similar shapes and therefore only the Miller-Scalo IMF will be used to illustrate the following discussion.

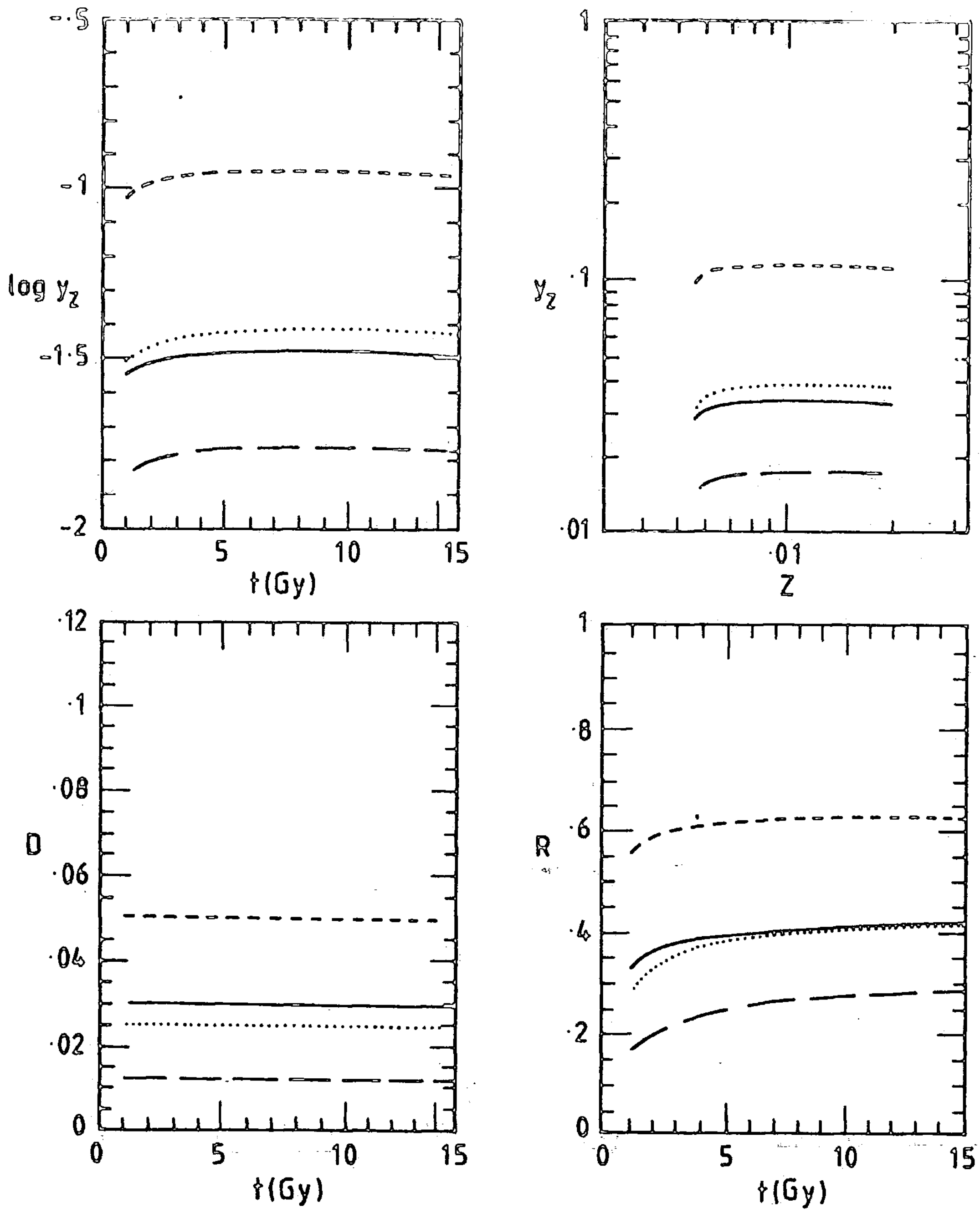


Figure 4.4: The variation of R, D and y_Z with time, and y_Z with metallicity. The case of time independent m_ℓ and m_u neglecting the contribution of brown dwarfs (i.e. $m_\ell = 0.1M_\odot$) for each of the IMFs described in Section 4.2.2. Solid curve: Miller and Scalo (1979); dotted curve: Rana (1987a); short dashed curve: Larson (1986); long dashed curve: Scalo (1986).

Silk (1977) proposed that the lower mass limit could vary as

$$m_{\ell} \propto Z^{-2} \qquad (4.12)$$

Taking the variation of metallicity as before, this means that m_{ℓ} = 1.38 $M_{\odot}$ when the disc formed and 0.1 $M_{\odot}$ at present. This variation is significant because in this region of initial mass the IMF is maximum. The dotted curve in Figure (4.5) shows that R, D and y_Z decrease with time giving a yield roughly inversely proportional to the metallicity ($n \cong -1.0$), which is just the opposite of the usual assumption made for a variable yield (Paper I; Peimbert and Serrano 1982).

However, if the contribution of brown dwarfs is included, with a variation in m_{ℓ} given by (4.12), m_{ℓ} decreases from 0.097 $M_{\odot}$ to the assumed present value of 0.007 $M_{\odot}$. In this range of initial mass the IMF is once again falling off and therefore the m_{ℓ} variation has little effect on R, D and y_Z. The two other plots in Figure (4.5) correspond to the variation in m_u and m_{ℓ} described above but with m_{ℓ} = 0.007 $M_{\odot}$. It is observed that this variation has little effect, except for the absolute value of D.

4.3.4 Other possibilities

It is clear from the above that a 'conventional' variation of the upper and lower mass limits will not justify an assumption of $y_Z \propto Z$. In fact, if a relationship of the form

$$y_Z \propto Z^n \qquad (4.13)$$

exists at all then $n \lesssim 0$ is favoured with $n \cong -1$ for a Silk variation of the lower mass limit of the IMF. Therefore in

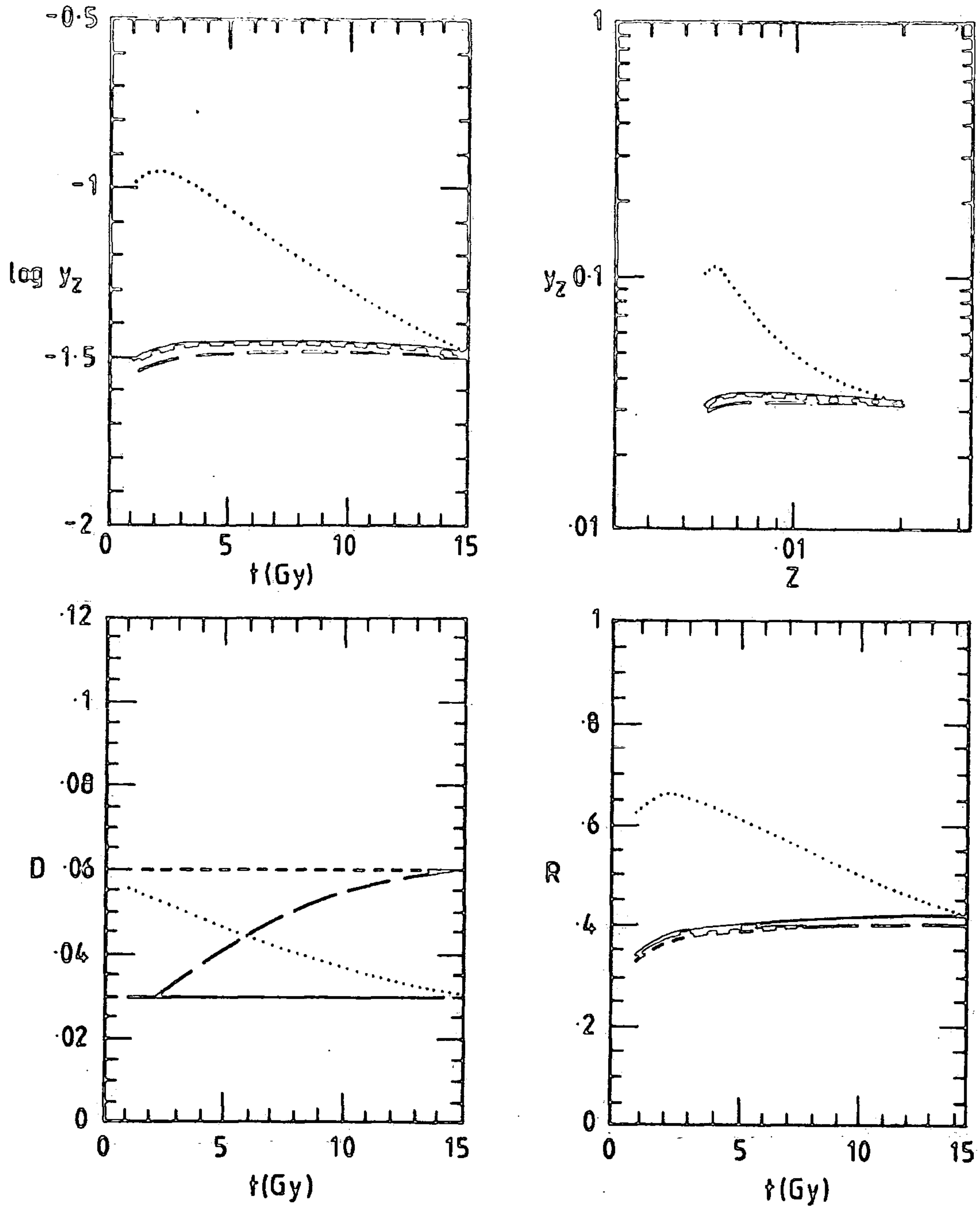


Figure 4.5: The variation of R, D and y_Z with time and y_Z with metallicity. The effect of varying m_l and m_u as a function of metallicity for the Miller-Scalo IMF. Solid curve: $m_u \propto Z^{-0.5}$, $m_l = 0.1M_\odot$; dotted curve: $m_u = 100M_\odot$, $m_l \propto Z^{-2}$; short dashed curve: $m_u \propto Z^{-0.5}$, $m_l = 0.007M_\odot$; long dashed curve: $m_u = 100M_\odot$, $m_l \propto Z^{-2}$ (including brown dwarfs).

order to produce a relationship of the form (4.13) with $n \cong 1$, there must be more radical changes with metallicity either of stellar nucleosynthesis or the IMF.

A yield inversely related to the mass loss rate in massive stars has been shown by Chiosi and Caimmi (1979), but observations seem to indicate that the metallicity increases the mass loss rate (Maeder 1980) that is, again the wrong way, $n = -1$. Mallik and Mallik (1985) by varying the upper cut-off mass in p_{zm} due to the total collapse of stars into black holes have shown that a variable yield with $n \cong 1$ can be achieved. However, this assumption is difficult to justify particularly for low cut-off masses in p_{zm}. Section 4.3.2 showed that recent work on IMS may suggest p_{zm} changes with Z, but a stronger dependence than that given in equations (4.9) - (4.10) is required to give $n = 0$ These remain possibilities but more work needs to be done before firm conclusions are drawn.

Peimbert and Serrano (1982) give two possibilities to change the IMF, either the relative amount of more massive stars increases with Z, or the relative amount of low mass stars decrease with Z. They argue from the work of Lequeux et al. (1980) that the former is not likely and further cannot be important because they claim it would increase the $\Delta Y/\Delta Z$ ratio with Z contrary to observations. Terlevich and Melnick (1984)'s variation of the IMF through equation (4.8) would flatten the IMF at high mass early in the evolution of the Galaxy, that is decreasing the relative amount of low-mass stars with Z. A change in the relative amount of low mass stars is more likely but there are conflicting views concerning how this changes with metallicity. Silk (1977) and Reddish (1978) predict that the relative number of low-mass stars decreases with Z while Larson (1981) predicts exactly the opposite.

The situation concerning the dependence of the yield on metallicity is therefore confused with a possible relation such as (4.13) being valid, but the exponent n having possible values from -1 to 1. However, n = 0, that is a constant yield, seems to be strongly favoured and is probably the best assumption to make at present.

4.4 THE NATURE OF THE DARK MATTER IN THE SOLAR NEIGHBOURHOOD

The suggestion that the Universe contains substantial dark matter, that is mass without corresponding light, is now generally accepted although the two key questions of what fraction of the mass is dark and what is its nature remain controversial (e.g. Rees 1985; Tayler 1986). This so called dark matter problem occurs on a variety of scales; and each scale may provide a distinct problem.

On a cosmological scale, if the cosmological density parameter Ω is believed to be unity (e.g. Guth 1981) then a large fraction of the total mass of the Universe must be non-baryonic since primordial nucleosynthesis requires the fraction of Ω due to baryons < 0.2 (Yang et al. 1984). From virial mass estimates a dark matter problem appears in galaxy clusters (Cowie et al. 1987). The existence of flat rotation curves in the Galaxy and other spirals points towards the halo consisting primarily of dark matter (Faber and Gallagher 1979). Hegyi and Olive (1986) have discussed the observational and physical difficulties with the dark halo mass being in the form of baryons and conclude that the halo dark matter must be primarily non-baryonic (cf. McDowell 1985; Hills 1986). A popular candidate is therefore cold dark matter (Bond and Szalay 1983), a class of weakly interacting Majorana-mass fermions. However, it should be noted that the argument of Hegyi and Olive (1986) against low mass stars or brown dwarfs depends crucially on the assumption that the halo IMF is not substantially different from the present day disc IMF, an assumption which may or may not be true. Stars with very low stellar masses have been suggested for some time for the dark matter in the halo (e.g. Ostriker et al. 1974; Gott 1981). Recently, Carr and Lacey (1987) have examined the possibility of the existence of $10^6 M_\odot$ dark clusters composed of low mass objects in the halo, in order to explain the age-velocity dispersion relation of disc stars. This relation could possibly also be explained by the halo consisting of $\sim 10^6 M_\odot$ black holes (Ipser and Semenzato 1985; Lacey and Ostriker 1985).

Recently the existence of dark matter in the Galactic disc has caused considerable interest. Bahcall (1984) determined the total mass density in the solar neighbourhood by solving for the gravitational potential in the disc and found $(\Sigma_T)_\odot$ may be anything between 65 and 135 $M_\odot pc^{-2}$, but the most preferable value is quoted to be 75 $M_\odot pc^{-2}$. The stellar contribution to this mass density is uncertain (Rana 1987a). Bahcall (1986c,d) suggests that the ratio of the dark to luminous matter, that is $\delta_0/(\mu_1 + \sigma_0)$ lies in the range 0.5 - 1.5, and most of the unseen component must be distributed with a scale height no larger than that for old disc stars.

This dark matter is most probably baryonic, as its concentration towards the Galactic plane suggests that energy dissipation has occurred which is difficult to understand if weakly interacting particles are involved. It is not clear however what form the baryons take. The halo dark matter makes a negligible contribution to the disc (Hegyi et al. 1986; Bloemen and Silk 1987) and observations rule out the dark matter residing as ordinary baryonic gas (Spitzer 1978). Small, solid particles such as dust grains, interstellar meteors or interstellar comets can be ruled out from a variety of arguments (e.g. Tayler 1986; Hills 1986). Hegyi et al. (1986) have argued from X-ray emission and chemical enrichment that the dark matter is not in the form of black holes, which seemed to be consistent with the study of the survival of wide binaries in the solar neighbourhood (Bahcall et al. 1985) implying that the unseen disc objects must have a mass < 2 $M_{\odot}$. This interpretation of wide binaries has been subsequently challenged by Wasserman and Weinberg (1987) who conclude that no useful upper mass limit can be set on the unseen objects as yet. Hills (1977) however, has pointed out that if the dark matter was in the form of massive black holes, exchange collisions would cause conspicuous accumulation in binary stars.

The model of chemical evolution outlined in Chapter 3 and examined in more detail earlier in this Chapter, includes an explicit form for dark matter. In this context, an examination of the possible nature of the dark matter in the solar neighbourhood is now extended. A constant yield will be used, following the results of the previous section, and for ease of presentation the Bhat et al. (1985) value of Σ_{H_2} in the solar neighbourhood will be used, that is $\mu_0 = 0.09$.

The value of the returned fraction R, which is computed in the model independently of the IMF and the remnant fraction w_m (see equation 3.32) is directly related to the residual amount of gas $(\Sigma_g)_\odot$, and the amount of stars formed during the lifetime of the disc if the present rate of star formation continued in the past, that is $(\psi_1)_\odot t_1$, apart from a weak dependence on $\mu_\odot$. The value of $(\psi_1)_\odot$ is not a well-determined quantity ranging between 0.5 $M_\odot pc^{-2} Gy^{-1}$ (Talbot 1980) to 5.0 $M_\odot pc^{-2} Gy^{-1}$ (SBM 1978). Since R cannot be negative, from this present work a lower limit can be placed on $(\psi_1)_\odot$ to be given by $(\psi_1)_\odot > 1.7\ M_\odot\ pc^{-2} Gy^{-1}$ for $t_1 = 15$ Gy. The upper limit to $(\psi_1)_\odot$ depends on how close to unity the value of R can be pushed. Using a Miller-Scalo IMF and the usual forms for w_m, it was shown in Section 4.2.1 that R should be about 0.4, which from equation (3.32) gives

$$(\psi_1)_\odot = 3\ M_\odot pc^{-2} Gy^{-1} \tag{4.14}$$

and this value has been chosen for developing the rest of the present section.

Noting the uncertainty quoted by Bahcall (1986c), a range in the present dark fraction, δ_1, has been taken as 0.2 - 0.7. For each value of δ_1 several values of $\mu_\odot$ have been chosen and k constrained in order to produce the required (observed) metallicity gradient, dlog Z/dR = -0.06 dex kpc^{-1}. Table A.4.1 (Appendix) shows all relevant quantities in the chemical evolution model for certain selected cases, where χ^2_{GD} and χ^2_{AMR} are computed for the G-dwarf problem and AMR as outlined in Chapter 3. Figure 4.6 is a plot of the initial gas fraction μ_0 (= 0.95 − δ_0, as σ_0 = 0.05) versus the present dark matter fraction δ_1. The region corresponding to $\delta_1 < \delta_0$ is

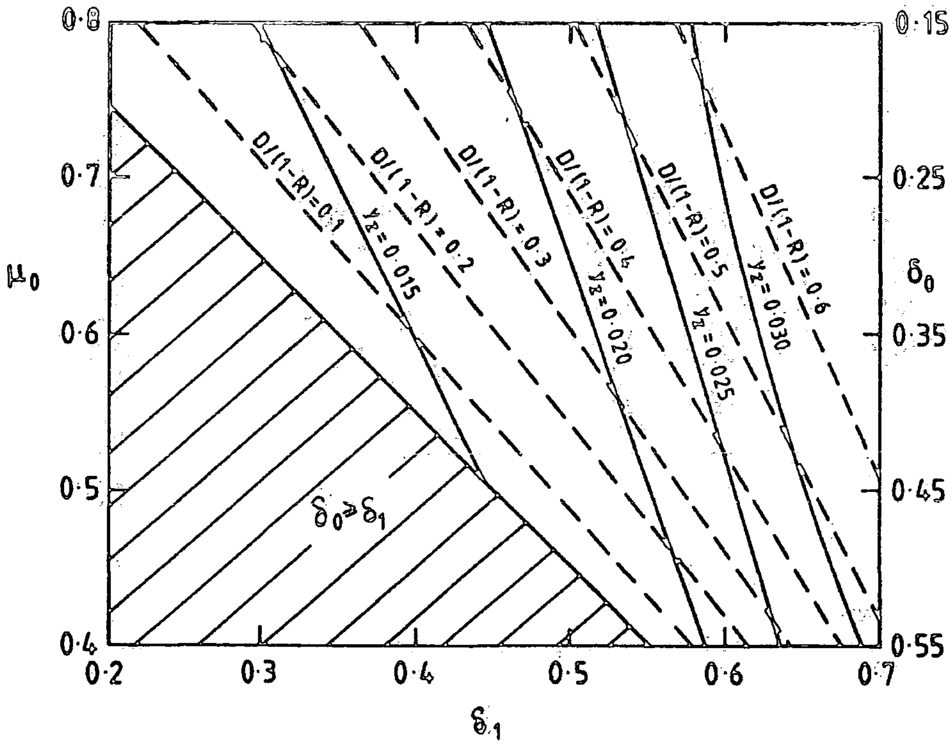


Figure 4.6: The allowed values for μ_0, δ_0 and δ_1 in order to produce a metallicity gradient of −0.06 dex kpc^{-1}. The region $\delta_1 < \delta_0$ is excluded as the dark matter fraction is an increasing function of time in the case of no infall. The solid lines represent the loci of allowed parameters requiring constant yield, y_Z, and the dotted ones represent the required ratio D/(1-R).

excluded, as the dark matter fraction is an ever increasing function of time for a model that does not invoke infall. The solid lines represent the loci of combinations of δ_1 and μ_0 requiring constant yield y_Z, and the dotted areas represent the required ratio D/(1-R). This Figure suggests the following points:

(i) Using Maeder's curve for p_{Zm} and the Miller-Scalo IMF smoothly extended to include brown dwarfs, it has already been found $y_Z = 0.024$ and $D/(1-R)$ can be no larger than 0.1. Now in Figure 4.6, the appropriate curves do not overlap implying from the point of view of chemical evolution, $y_Z \cong 0.024$ is inconsistent with the required value of $D/(1-R)$, which is too high possibly greater than 0.3. They would be consistent if $y_Z = 0.015$ and $D/(1-R) = 0.1$, the former, however cannot be ruled out considering uncertainty involved in evaluating p_{Zm} as a function of m.

The IMF of Rana is even worse. For $D/(1-R) \approx 0.1$, $y_Z \approx 0.03$ which requires $D/(1-R)$ from Figure 4.6 to be ≈ 0.5. For Larson's IMF consistency might be achieved with an upper mass cut-off to metal production less than 16 $M_\odot$ to give $y_Z \cong 0.02$, and $D/(1-R) \cong 0.2$. This would predict $S_1 = 0.57$ and $\mu_0 = 0.47$, but there is every indication that m_{ZU} should be > $16M_\odot$ (Olive 1986). The IMF for the constant SFR case of Scalo (1986) gives too little dark matter compared to Bahcall's value in the solar neighbourhood.

(ii) To satisfy the condition $y_Z = 0.024$ strictly for the Miller-Scalo IMF it would imply the following. Depending on the value of μ_0, S_1 should lie in the range 0.5-0.6. If μ_0 is taken to be somewhat less than unity, say $\mu_0 = 0.65 \pm 0.15$ leaving enough room for producing the initial metallicity by a pre-disc generation, S_1 is found to be 0.55 ± 0.05 which suggests $(\Sigma_D)_\odot = 41 \pm 4\ M_\odot pc^{-2}$ and $(\Sigma_S)_\odot = 30 \mp 4\ M_\odot pc^{-2}$ for $(\Sigma_T) = 75\ M_\odot pc^{-2}$. Since, like the metallicity, the change in S from $S_\odot (\cong 0.25)$ to S_1 during the evolution of the disc is comparable to $S_\odot$, the dark matter in the solar neighbourhood is possibly totally baryonic. The required value of $D/(1-R)$ is then

= 0.4 ± 0.1. This condition can be met with the hypothesis of a large population of brown dwarfs, provided the IMF at the lower mass end is remarkably different from the one suggested by Miller and Scalo. The hypothesis of black holes can hardly do the job without changing R and y_Z appreciably. For brown dwarfs, changes can always be made in the lower end of the mass spectrum (Section 4.2.3) in order to upgrade the ratio D/(1-R) and the revised value of R, if any, can be readjusted with the value of $(\psi_i)_\odot$.
(iii) If y_Z turns out to be $\cong$ 0.015 (calculated from p_{Zm} and the IMF) it would basically support the Miller-Scalo form of the IMF which advocates very few brown dwarfs. This solution will call for similar or somewhat higher values of $\mu_\odot$, but δ_1 has to be less than 0.45. The required value of $\delta_\odot$ is however $\simeq$ 0.35 which must exist prior to the formation of the disc. This implies a remarkably different IMF for the pre-disc population, if $\delta_\odot$ is baryonic. From theoretical derivations of the IMF for zero-metal stars, Yoshii and Saio (1986) suggest that the IMF could be substantially different, but preliminary estimates of dark matter produced by this IMF do not provide the required $\delta_\odot$ (Rana 1987a). It is difficult to imagine how a substantial fraction of $\delta_\odot$ could be non-baryonic because of the difficulty of confining the matter into the shallow potential well of the disc.
(iv) For the more recent IMFs the situation varies. Rana's IMF would follow the above discussion but would require a modest mass cut-off to metal production in order to give y_Z < 0.03. The IMF of Larson (1986) can provide D/(1-R) $\cong$ 0.2 in the form of dead stellar remnants rather

than brown dwarfs. However, a small upper cut-off mass to metal production, < 16 $M_{\odot}$, is needed for consistency in the solar neighbourhood, which as described previously may be unrealistic. A further uncertainty concerns the cooling time of white dwarf remnants (e.g. Olive 1986; D'Antona and Mazzitelli 1986). A modification of Larson's bimodal IMF may overcome these problems (Olive 1986). The IMF of Scalo (1986) with constant SFR cannot provide dark matter in baryonic form to solve the dark matter values given by Bahcall (1986c).

(v) Finally, it should be noted that the actual estimation of $\mathcal{S}_1$ at present is very uncertain. Some estimates of $(\Sigma_{\Upsilon})_{\odot}$ and $(\Sigma_{\mathcal{S}})_{\odot}$ at present in the solar neighbourhood may imply an overestimate of $\mathcal{S}_1$ by Bahcall, suggesting little dark matter at all (e.g. Gilmore and Wyse 1987; Bienaymé et al. 1987). Furthermore, Rana (1987a) in a detailed study of the IMF and an extension of the above discussion, argues that it is possible to satisfy the observational constraints on the local dynamical mass with very little dark matter. If this is the case then bimodal IMFs and other modifications are not necessarily required.

4.5 METALLICITY GRADIENTS IN SPIRAL GALAXIES

The existence of abundance gradients in spiral galaxies provides a good observational test for many theories of the chemical evolution of galaxies. However, the need for high quality data for the observed mass distributions and metal abundances restricts the number of external spirals for which reliable results can be obtained.

It was shown in the previous Chapter, that given an SFR of the form $\psi_S \propto (X\Sigma_T \mu Z^b)^k$, the metallicity gradient is an outcome of $k \neq 1$ and the radial variation of Σ_T for a closed model of the evolution of the Galactic disc. Section 4.3 showed that a constant yield was at present preferable to a metallicity dependent yield, and so y_Z = constant (or n = 0) will be used in the following. The variation of the present metallicity, Z_1 at different R_G was then derived, and is now re-written as

$$\int_{Z_\odot}^{Z} \frac{dZ}{Z^{kb} \exp[(1-k)GZ]} = E' t \Sigma_T^{k-1}(R_G) \qquad (4.15)$$

to show explicitly the time dependence. The constant, E' can be evaluated in the solar neighbourhood at present (t_1 = 15 Gy),

$$E' = \frac{(1-R)CX^k}{G \mu_0 Z_\odot^{kb}} \exp[(k-1)GZ_\odot] \qquad (4.16a)$$

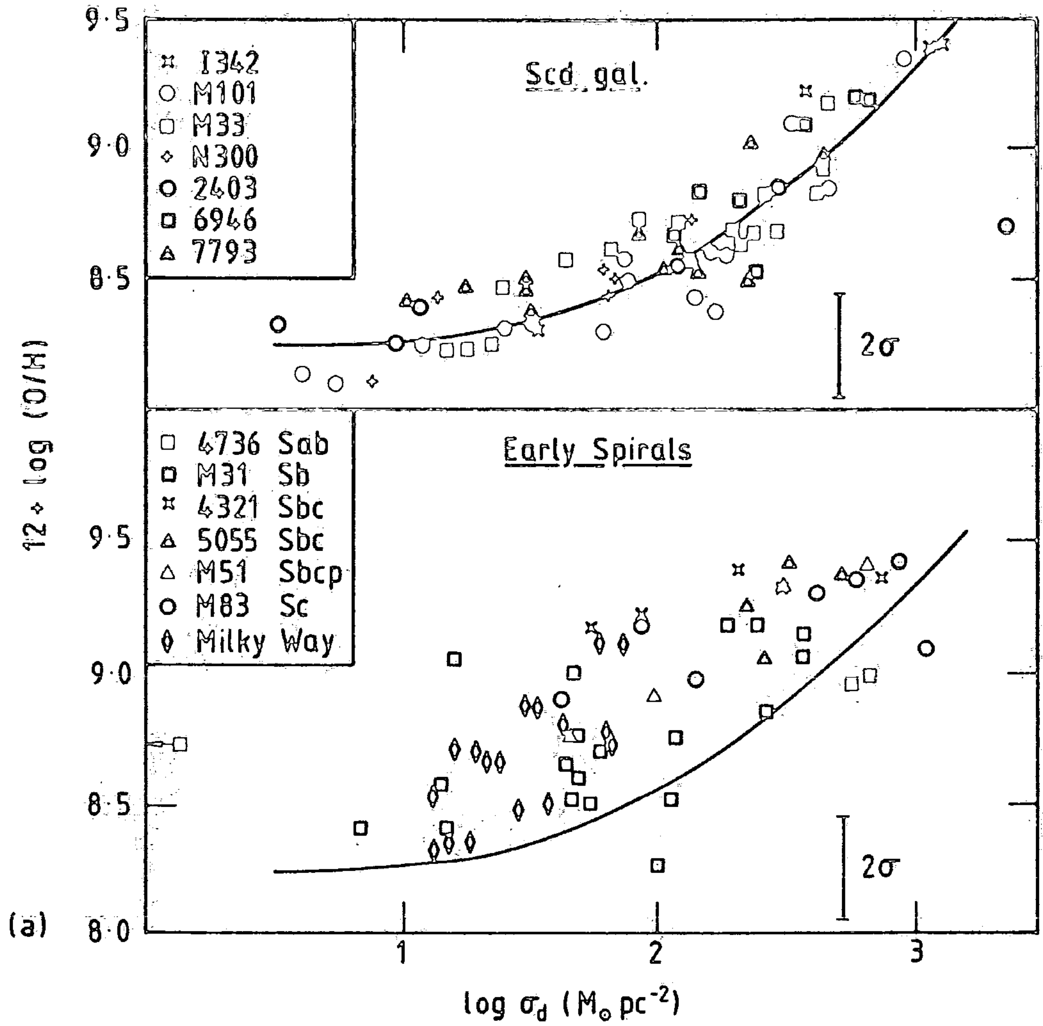
$$= \frac{1}{t_1(\Sigma_T)_\odot^{k-1}} \int_{Z_{0\odot}}^{Z_{1\odot}} \frac{dZ}{Z^{kb} \exp[(1-k)GZ]} \qquad (4.16b)$$

This allows the calculation of the metallicity gradient at any time t during the evolution of the Galactic disc. It was shown that for t_1 = 15 Gy, the present metallicity gradient of - 0.06 dex kpc^{-1} was produced for $k \simeq 1.4$, b = 1.3 (from Chapter 2) and G derived from the fit to the G-dwarf problem (Paper IV and Table A.4.1).

Previous workers have attempted to derive metallicity gradients in spiral galaxies in terms of the gas fraction (e.g. Clayton 1987; equations 3.36 and 3.37). However, this is not particularly satisfactory due to uncertainty in estimating the gas density Σ_g. For a number of galaxies only

Σ_{HI} is available, neglecting the importance of Σ_{H_2}. Even in galaxies that have been mapped in CO, the CO$\rightarrow H_2$ conversion factor is uncertain by a large factor. Therefore, the use of μ to predict abundance gradients must be used tentatively. Tosi and Diaz (1985) in their models which show reasonably good agreement with metallicity gradients in nearby spirals, recognise that these derived gradients are strictly related to the gas fraction and thus depend on the methods employed in the derivation of the gas distributions. Furthermore, the derivation of the metallicity gradient from μ does not illustrate its production from a flat initial metallicity distribution, it simply derives a gradient from an already existing μ gradient. It was for this reason that the form (4.15) was adopted linking the present metallicity to the variation in the better determined quantity Σ_T. Of course the metallicity is related to the gas fraction (equation 3.17), and later Σ_{H_2} will be derived from the observed metallicity gradient rather than vice-versa.

Lequeux et al. (1979) and Kinman and Davidson (1981) found that the abundance of metals in irregular galaxies increased systematically with total mass, in qualitative agreement with equation (4.15) if $k > 1$. Although it has been argued that this holds for only a few low mass irregular galaxies (Hunter et al. 1982), a relationship between metallicity and total surface density across the discs of spiral galaxies has been observed (McCall 1982; Edmunds and Pagel 1984a; Garnett and Shields 1987). In Figure 4.7a, a plot of abundances against surface mass density σ_d of stars in the disc is reproduced from Edmunds and Pagel (1984a). The surface mass densities have been



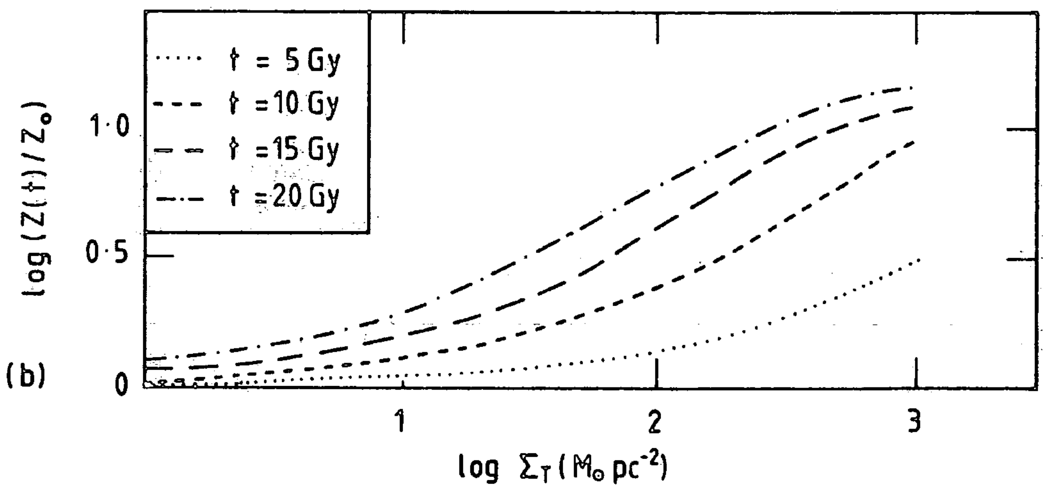


Figure 4.7 (a) Plot of oxygen abundance against surface mass density of stars, reproduced from Edmunds and Pagel (1984a). The eye-fit curve to the Scd data is repeated in the plot for early spirals for comparison.

(b) The metallicity at time t after formation of a galactic disc with initial metallicity $Z_{\odot}$, as a function of the total surface mass density. This is the constant yield model, which gives good fits to the Galactic disc, for k = 1.4.

derived by McCall (1982) following a method due to Monnet and Simien (1977) which assumes that the mass distributions in the bulge and disc follow the corresponding light distributions; with this assumption the rotation curve is fitted with just two parameters, namely the mass-to-light ratios of the bulge and the disc respectively. As Edmunds and Pagel (1984a) point out, this means that the effect of unseen halo material is not explicitly taken into account except through its indirect influence on the derived mass to light ratios. This probably does not impair the physical significance of σ_d because in typical observed spirals there is a nearly unique relation between the surface brightness and total mass surface density (Petrou 1981).

Figure 4.7a shows that there is a well defined average line for Scd galaxies (shown by the eye-fit curve of Edmunds and Pagel 1984a) and that this same line essentially forms a lower envelope to the abundances found in galaxies of earlier morphological type. At a given σ_d early type galaxies appear to have systematically higher abundances than late type galaxies (McCall 1982). Now, the fitting of the G-dwarf problem in the solar neighbourhood at t_1 = 15 Gy implied $\log(Z_1/Z_\odot)$ = 0.57 and assuming $Z_\odot$ was a constant with radius at time of formation of the galactic disc, equations (4.15) and (4.16) give Figure 4.7b where $\log(Z(t)/Z_\odot)$ is plotted against Σ_T for different values of t. This uses parameters determined to give good fits to Galactic chemical evolution. Comparison of Figures 4.7a and 4.7b suggests the following points:

(i) Not surprisingly, since the model is fitted to the Galactic disc, the present trend between metallicity and total surface density is reproduced. This is due primarily to the adopted SFR (Chapter 2) with k = 1.4. The fact that other galaxies follow this trend further suggests that this law of star formation is applicable in external spirals (cf. Section 2.5.2).

(ii) The shape of the Z(t) versus Σ_T relationship is determined by the age of the disc, t. For any particular, Σ_T, Z increases with t, that is the age-metallicity relation of Section 3.4, but the rate of change of Z with time is a function of Σ_T. For t > 15 Gy, Z begins to saturate for high Σ_T, while for t = 10 Gy in the same regime Z is still increasing rapidly. This may provide a tentative explanation of the difference in the relationship for Scd and early spirals. The Scd galaxies follow very well the curve for t $\approxeq$ 10 Gy, which may indicate that these galactic discs formed more recently than the Galaxy. There is much more scatter in the data for early spirals, but there does appear to be a flattening at higher Σ_T indicative of t $\gtrsim$ 15 Gy (for example the galaxies NGC 4321 and M83).

(iii) The spread in metallicities in Figure 4.7a could be therefore due simply to different lengths of time of chemical enrichment. Of course, the large error associated with observation and then calculation of abundances, in addition to poorly known depletion factors will contribute a large amount to the scatter. For example, in some galaxies at a particular σ_d there is a spread in 12+log(O/H) of $\sim$ 0.5 dex. It was argued in Section 3.6, that the upper envelope of metallicity observations in the Galaxy gave the correct distribution of the present metallicity Z_0. This may be also the case in Figure 4.7a, but the situation is far from clear. The problem once again is how to translate the computed value of $Z/Z_{\odot}$ onto the 12+log(O/H) plot. It may be an oversimplification to assume that all of these galactic discs formed with roughly the same initial metallicity. Even so, the adoption of an initial metallicity of 12+log(O/H) = 8.3 taken for the Galaxy, would leave only a few points in the Scd galaxies below this baseline (and within 2σ). It is interesting that both sets of data seem to flatten off as $\sigma_{g} \rightarrow 0$, to 12+log(O/H) $\approx$ 8.3. In these outer parts of spiral discs little star formation (and therefore little chemical enrichment) is observed and therefore observations could be quite close to the initial metallicity. If this were true then the higher 12+log(O/H) at a particular Σ_{T}, the longer that region has been undergoing star formation.

However, there is a second important uncertainty and that is are Σ_{T} and σ_{g} directly comparable? Edmunds and Pagel (1984a) discuss the uncertainty in determining σ_{g} especially in the outer parts of spiral discs where it is low, and suggest that it is possibly underestimated in this region. The value of Σ_{T} is the total mass, that is visible and invisible mass. It is possible to calculate Σ_{S} (the surface density of visible stars) as a function of galactic radius and t from the chemical evolution model (Section 4.7) and the resulting $\log(Z/Z_{\odot})$ versus $\log\Sigma_{S}$ plot shows the same shape as Figure 4.7b with a shift in the x-axis. These difficulties in fixing $Z_{\odot}$ and σ_{g} in Figure 4.7a, mean that Figure 4.7b has not been overlayed. These uncertainties however, do not change the shape of the relationship, which is determined by t.

(iv) Tosi and Diaz (1985) constructed detailed models of nine of these galaxies, and were able to obtain reasonable fits by varying the e-folding time of the SFR and the infall rate (assumed constant and uniform) for each Galaxy. This present work suggests that metallicity gradients in spirals can be explained in the context of a closed model, with a SFR of $\psi_S \propto \Sigma_{H_2}^{1.4}$ simply from the variation of Σ_T. The actual gradient in any one galaxy will depend on a number of factors, but it is tentatively suggested that the age of the disc may be important in determining the shape of the metallicity gradient. Detailed studies and better abundance data of individual galaxies are required before firm conclusions are drawn, but if this is the case, then the relationship between metallicity gradient and total surface density may indicate the age of a galactic disc.

4.6 THE RADIAL DISTRIBUTION OF H_2 IN THE GALAXY

The SFR on the above model is related to the surface density of H_2 by the relationship $\psi_S \propto \Sigma_{H_2}^{k}$, with the index k being independently determined from the required fit to the observed metallicity gradient. So this value of k may then be used to infer either Σ_{H_2} or ψ_S provided the other is known. Using a constant yield, it has already been shown that in order to produce a Galactic metallicity gradient of -0.06 dex kpc^{-1}, k is required to be in the range 1.35-1.48 with the permitted choices for δ_1 and μ_0. This Section assumes k = 1.40 and uses the available radial distributions of the star formation rates ψ_S to derive the corresponding radial distribution of Σ_{H_2} in the Galaxy. This distribution is then compared with the existing controversial estimates of Σ_{H_2} derived from the observed CO emissivity distributions, and implications derived for the universality of the CO$\rightarrow$$H_2$ conversion factor, α_{20}.

4.6.1 A relative distribution of H_2 from SFRs in the Galaxy

In Figure 4.8, available data on the radial distribution of the present SFRs normalised to their respective values in the solar neighbourhood are plotted as a function of Galactocentric radius. Values of ψ_S derived from studies of Lyman continuum emission from HII regions are shown for SBM (1978) and Mezger (1978). The two works sometimes disagree at the 2σ level because of large discrepancies in the individual estimates of the lifetime of HII regions and of dust absorption corrections. (Both sets of data have been included to show the actual uncertainties involved in the estimation of ψ_S from HII regions). Also shown are the SFRs derived from the pulsar distribution (Lyne et al. 1985) and the supernova remnants (Guibert et al. 1978). These surveys are obviously limited mainly to the solar side of the Galaxy, but reasonable models for the pulsar and SNR distributions over the whole Galaxy have been used to infer the SFRs averaged over Galactocentric rings of different radii. However, since the mass ranges of the progenitor stars that lead to the formation of pulsars and SNRs are poorly known, the absolute values of the SFRs cannot be ascertained with certainty, and so radial distributions relative to the value in the solar neighbourhood are used (as suggested by Lacey and Fall 1985).

Now the same plot can be used to represent the radial variation of $\log(\Sigma_{H_2}/\Sigma_{H_{2\odot}})$ provided the relation $\psi_S \propto \Sigma_{H_2}^k$ is valid, except that the ordinate needs to be scaled up by a factor of k. Assuming k = 1.40, the same distribution of

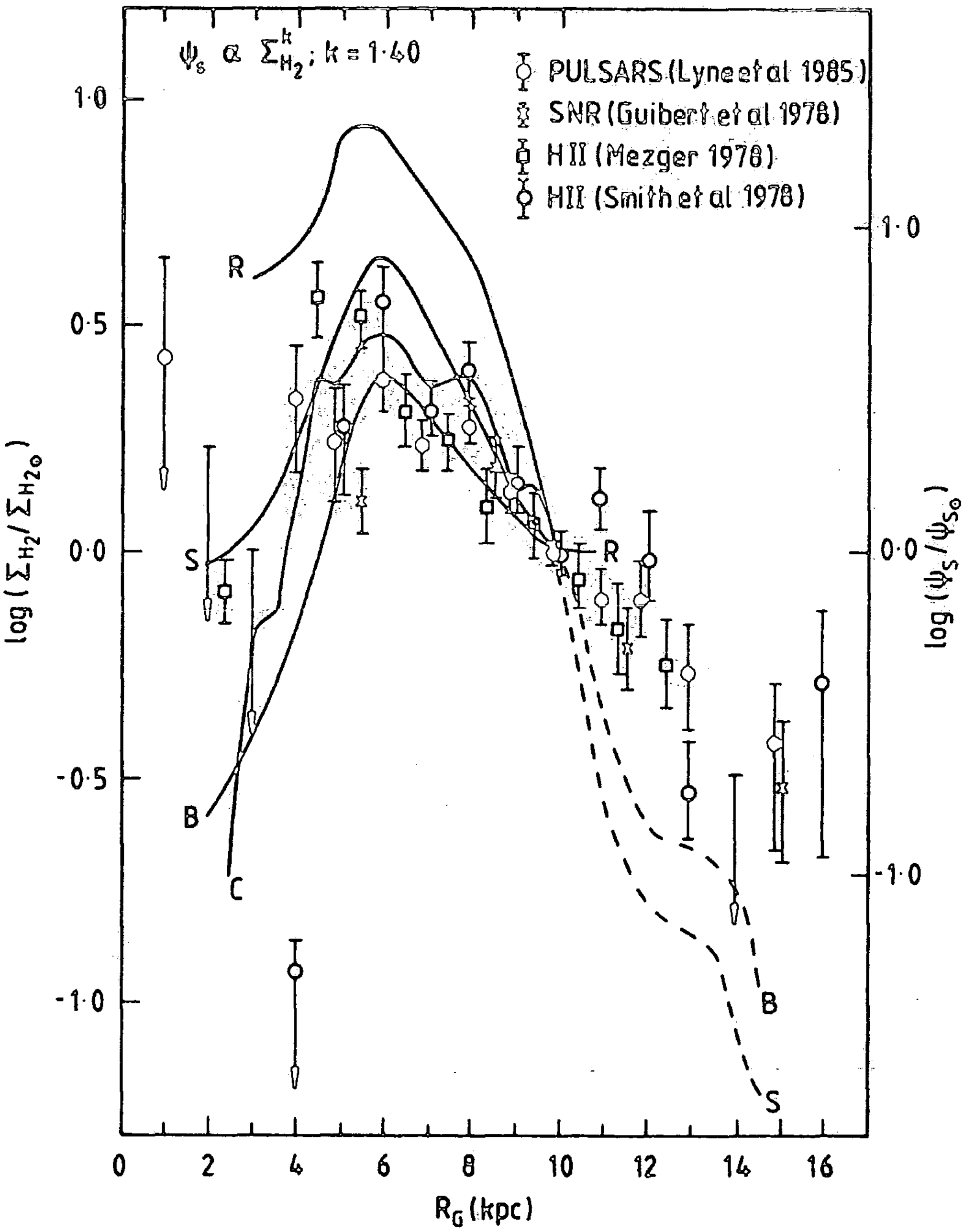


Figure 4.8: The present radial variation of the SFR, ψ_S, normalised to its value in the solar neighbourhood. The same plot can be used to represent the present radial variation of Σ_{H_2}, simply by re-scaling the ordinate by a factor of k, which has been taken to be 1.40. The radial variations of Σ_{H_2} derived from various CO surveys are shown by the family of curves marked B, C, R and S. Dotted lines show where surveys are incomplete.

data points now refers to the predicted radial distribution of Σ_{H_2} in the Galaxy relative to its value in the solar neighbourhood.

Superimposed on this plot are curves representing some of the different estimates of the distribution of Σ_{H_2} derived from the CO emissivity measurements in the Galaxy. Each distribution has been normalised to its quoted value in the solar neighbourhood. This naturally eliminates the existing differences in the absolute values of $(\Sigma_{H_2})_{\odot}$ arising partly from differences in the absolute values of the CO emissivity and partly from differences in the adopted values of the CO$\rightarrow H_2$ conversion ratio (Chapter 1). In this plot, only the shapes of various radial distributions of Σ_{H_2} are relevant. The four continuous curves labelled B, C, S and R refer to H_2 distributions in the inner Galaxy averaged for the north and south (that is, averaged along the Milky Way on either side of the centre of the Galaxy), respectively given by Bhat et al. (1985), Cohen et al. (1985), SSS (1984) and Robinson et al. (1984). These distributions were chosen to illustrate and encompass the range of the many other published distributions. The last three distributions are derived independently of one another, each group using an independent CO survey of its own. The Bhat et al. distribution uses the CO survey of SSS (1984), adopts a lower $\alpha_{2\odot}$ in the solar neighbourhood and applies a differential metallicity correction to $\alpha_{2\odot}$. The observations for the outer Galaxy (that is, for $R_G > 10$ kpc), are fewer and are shown by dotted lines where the sampling is incomplete. Only SSS give an observational distribution of Σ_{H_2} for the outer Galaxy as far as 14.5 kpc but for the northern declinations only. Using a metallicity correction to α_{20}, Bhat et al. suggest values that are represented by the dotted curve. Robinson et al. give values for the average of north and south which extend only up to R_G = 11 kpc. Now with reference to Figure 4.8 the following points may be noted:

(i) Within the solar circle, almost all of the data points lie within the bounds of all CO-based estimates thereby justifying the result of $\psi_S \propto \Sigma_{H_2}^{k}$ with $k \approx 1.40$. In fact, since the vertical spread of the SFR data is considerably narrower than that found among the different CO surveys, these results may further be used to constrain them.

(ii) Outside the solar circle, the agreement between the SFR data and those from the CO-surveys is rather poor. This is probably due to an underestimate of Σ_{H_2} in the outer Galaxy from the CO-surveys, for a number of reasons. The CO survey data in the outer Galaxy is incomplete whereas the observed SFRs derived from the pulsars, SNRs and HII regions include the regions the SSS CO survey does not (ℓ = 170-330°). When the CO survey data is complete, there is a possibility that the average of the north and south will rise to the level required by the observed activity of star formation in the ring as a whole. In fact, the trend of Robinson et al.'s measurement of the north and south beyond the solar circle suggests such a possibility.

Kutner and Mead (1981) had argued for a similar underestimate of H_2 in the outer Galaxy due to the large molecular complexes being shifted upwards from the plane, but their analysis was questioned by Solomon et al. (1983b). However, there is still reason to believe an underestimate may be due to uncertainties in α_{20}. Bhat et al. (1985)'s use of a metallicity correction still underestimates Σ_{H_2} in Figure 4.8, but they point out that this could still be an underestimate because in the quiescent clouds in the outer Galaxy a large fraction of CO would be locked into grains. van Dishoeck and Black (1987) further point out that strong CO line emission is excited efficiently only if the density exceeds a certain critical value. If the mean cloud densities are low in the outer Galaxy, there may be significantly more H_2 than is suggested by the weak CO line emission. The underestimate of H_2 may also be linked to a Galactocentric temperature gradient affecting α_{20} (Maloney and Black 1987).

Therefore, whether the H_2 is underestimated because of incomplete CO surveys, or because of an even larger α_{20} in the outer Galaxy than adopted by Bhat et al. (1985), at the moment this will be left as a prediction.

(iii) Among the four CO-based H_2 distributions for the inner Galaxy, the SFR data seem to favour the Cohen et al. and Bhat et al. distributions in the inner Galaxy. The data however fails to be consistent with the shape of Robinson et al.'s distribution, but marginally fits the SSS distribution.

(iv) If, in view of the above point, the CO distribution of Cohen et al. (1985) is correct, the shape of their H_2 distribution is such that their values do not require any appreciable radial gradient corrections for α_{20} such as metallicity or temperature gradients. On the other hand, if the CO survey of SSS is correct, they would require a gradient correction, either in metallicity and/or temperature in order to make their distribution fully compatible with the SFR data. For example, a metallicity correction may be introduced by assuming

$$\alpha_{20} \propto Z^{-n'} \tag{4.17}$$

where Bhat et al. (1985) have used n' = 1. If n' were to be determined from the requirement of compatibility with the SFR data in the inner Galaxy, the SSS CO distribution would require $n' \cong 0.8 - 0.9$. Upon the same consideration, Robinson et al.'s curve would require a metallicity correction with $n' > 1.5$. Similarly, a suitable radial gradient for the gas temperature T_k following

$$\alpha_{20} \propto T_k^{-1.3} \tag{4.18}$$

(Kutner and Leung 1985) may also be studied for each distribution leading to different values of the exponent. It must be stressed that at present it is difficult to distinguish between the metallicity correction and that of the temperature variation. Either or both factors may be responsible. At present all that can be said is that some radial gradient in α_{20} is needed for the SSS and Robinson et al. CO-surveys in deriving H_2, assuming that the value k = 1.40 is reasonably accurate.

(v) Previous work (Rana and Wilkinson 1986b) carried out a similar analysis to the above, but in the context of a variable yield model of Galactic chemical evolution which required k = 1.12. The conclusions were the same as those given above except that a smaller metallicity correction to the SSS data was required, i.e. $n' \cong 0.7$. However, it has been previously argued that the case of constant yield is preferable and therefore a higher value of n'.

4.6.2 <u>A tentative distribution of H_2 in the Galaxy</u>

Apart from the shape, it is also possible to predict an absolute distribution of Σ_{H_2} from the SFR data in Figure 4.8, provided the value in the solar neighbourhood, $\Sigma_{H_2\odot}$ is known. Chapter 1 summarised the uncertainties in the CO emissivities and the determination of the local value of $\alpha_{2\odot}$. In view of this controversy, we therefore prefer to estimate $\Sigma_{H_2\odot}$ independently of the CO surveys.

It has long been realised that the Galaxy appears to contain too much gas than could be observed from the present SFR in the Galaxy (Turner 1984). If large gas clouds are primarily responsible for star formation, they would gravitationally collapse on a time-scale of 10^6 y, and in that case (in order to fit the observed SFR of $\sim 5\ M_\odot y^{-1}$) there should not be more than about $10^7\ M_\odot$ of gas in the Galaxy in the form of large clouds. Now the central question is, how much H_2 is there in the Galaxy? The original CO surveys (Scoville and Solomon 1975) had claimed a huge amount of H_2 in the Galaxy, $M_{H_2} \sim 5.10^9\ M_\odot$ and SSS (1984) still claim it to be $> 3.6.10^9\ M_\odot$ in spite of the fact that from the γ-ray analysis and other arguments, Bhat et al. (1985, 1986) could hardly allow for $M_{H_2} > 10^9\ M_\odot$.

Theoreticians trying to understand the process of star formation in the Galaxy had to face the problem of stabilising GMCs against self gravitation. If the average lifetime of a GMC is typically a few times 10^7 y, this would imply an SFR of $\sim 100\ M_\odot\ y^{-1}$ for the whole Galaxy if the SSS (1984) M_{H_2} is assumed to be correct. Turner (1984) however showed that under some circumstances a GMC may break up into smaller molecular clouds which may once again be recycled through the Galactic spiral density waves on time-scales $\approx 2.10^8$ y to form more GMCs. Having delayed the star formation this way, he obtains a theoretical SFR of $\cong 20\ M_\odot y^{-1}$ for $M_{H_2} = 4.10^9 M_\odot$, which he took from SSS. If Turner's model of Galactic star formation is a viable one, the present observed SFR of $5\ M_\odot y^{-1}$ would suggest that $M_{H_2} \cong 1.10^9 M_\odot$. Interestingly enough, a recent study (Rengarajan 1984, 1986) of the star formation efficiency in molecular clouds from the FIR observations also independently supports the above ratio of ψ_s to M_{H_2}.

Now suitably binning the data points in Figure 4.8 and estimating the integral for the total amount of H_2 in the Galaxy up to 16 kpc, it is found that $(\Sigma_{H_2})_\odot = 1.30 \pm 0.20\ M_\odot pc^{-2}$ for a tentative value of $M_{H_2} = 10^9 M_\odot$. Recently, Dame et al. (1987) have obtained the same value by summing the masses of the largest clouds within 1 kpc of the Sun but assuming $(\alpha_{20}) = 5.4$. The value derived from the SFR analysis is independent of the value of α_{20} but can be used in comparison with the CO to determine $(\alpha_{20})_\odot$. When applied to the CO data of SSS (1984), $(\alpha_{20})_\odot = 2.5 \pm 0.5$, which is close to the value advocated by Bhat et al. (1985) from the γ-ray analysis.

Using $(\Sigma_{H_2})_\odot = 1.30\ M_\odot pc^{-2}$, Figure 4.9 presents a radial distribution of Σ_{H_2} derived exclusively from the SFRs in the Galaxy. Error bars are derived from the spread of the values of ψ_s derived from different indicators. Of course the true distribution is subject to change by a constant factor for all R_G, for any revision of the normalisation in the solar neighbourhood. It should be noted that Güsten and Mezger (1982) have claimed a Galactic SFR of $7.5 - 11\ M_\odot y^{-1}$ which in the above argument would raise $(\Sigma_{H_2})_\odot$ by a factor of two. However, their radial distribution appears not to follow the other indicators of star formation such as the pulsars and SNRs. Furthermore, Chapter 6 will show that a lifetime of H_2 of a few times 10^8 y is probably an upper

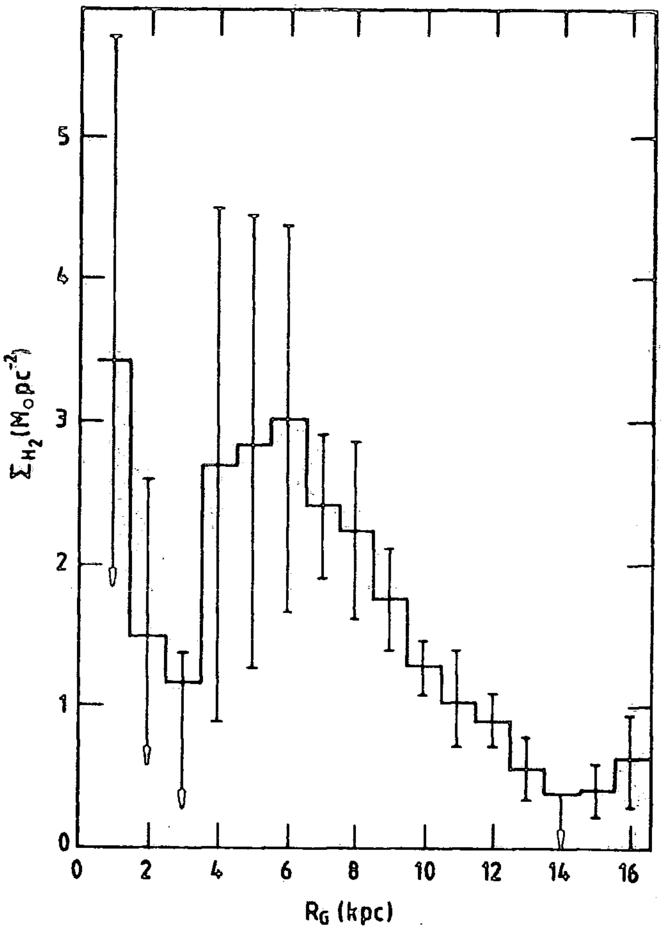


Figure 4.9: A tentative radial distribution of Σ_{H_2} as suggested by the present work. The value of Σ_{H_2} in the solar neighbourhood has been so adjusted that the total mass of H_2 in the Galaxy between R_G = 1 and 16kpc corresponds to $10^9 M_\odot$ for the present SFR of $5M_\odot y^{-1}$. The true distribution of Σ_{H_2} is of course subject to change by a constant factor for all R_G for any revision of the above normalisation.

estimate. The use of a constant yield leading to k = 1.40, does not affect the results of this analysis greatly. A variable yield with k = 1.12 leads to $(\Sigma_{H_2})_\odot$ = 1.15 $M_\odot pc^{-2}$, $(\alpha_{20})_\odot$ = 2.2 and a radial distribution very similar to Figure 4.9 (Paper II).

With the above reservations, this method gives a possible way of estimating Σ_{H_2} in the Galaxy independent of the controversial CO surveys. Of course, it depends on a model of the SFR as $\psi_S \propto \Sigma_{H_2}^k$ and the fixing of k by the observed metallicity gradient, but Chapters 2-4 have argued for the validity of these points.

4.7 RADIAL GRADIENTS IN GAS, STARS AND METALS

In the previous section, the radial distribution of H_2 has been derived from the observed SFR through $\psi_S \propto \Sigma_{H_2}^k$, fixing k by the required metallicity gradient. As in the case of the metallicity gradient, this does not illustrate the evolution of the SFR radial distribution (and therefore the H_2 distribution) with time. It may be further argued that due to uncertainties in the SFR itself, especially in external spirals, it would be helpful to see whether the gas distributions can be derived directly from the total surface density, Σ_T, (in a similar manner to the metallicity gradient) so that specifying this quantity for any galaxy will predict its distribution of metals, stars and gas.

The chemical evolution model, described above, is used with the simplest of assumptions, that is, constant yield and no infall. The case n = 0, δ_0 = 0.5, $\mu_\odot$ = 0.6, b = 1.3 and k = 1.40, described in Table A.4.1 (Appendix) is used in the following.

The radial distribution of Σ_T is shown in Figure 4.10a and taken from Table A.2.1 (Appendix) following SSS (1984) between R_G = 3 and 15 kpc. The assumption is then made that the initial metallicity ($Z_\odot$) and gas fraction ($\mu_\odot$) are constant with R_G. In reality this may not be strictly true, but for simplicity it is a good approximation. The metallicity gradient is then derived using equations (4.15)-(4.16) and shown in Figure 4.10b, each line representing a time step of 5 Gy after formation of the disc at t = 0. Of course k has been chosen to give the observed metallicity gradient of -0.06 dex kpc^{-1} at t = 15 Gy, and the present metallicity in the solar neighbourhood has been taken as 12+log(O/H) = 8.90 to normalise the plot.

The value of k is now fixed by the observed metallicity gradient, b is determined by the empirical correlation between p_{z} and Z (Section 2.4) and all other parameters are fixed by the model of chemical evolution in the solar neighbourhood. Therefore, the radial distribution of SFR, gas, density of stars and dark matter can now be predicted.

The SFR shown in Figure 4.10c is given by equations (3.12) and (3.17) as

$$\psi_s = CX^k \left[\Sigma_T \left(\frac{Z}{Z_\odot}\right)^b \exp\,[G(Z_\odot - Z)]\right]^k \qquad (4.19)$$

where X has been taken as a constant. The value of CX^k can then be evaluated in the solar neighbourhood at t_1 = 15 Gy,

$$CX^k = \frac{(\psi_1)_\odot}{(\Sigma_T)_\odot^k} \left(\frac{\psi_0}{\psi_1}\right)_\odot \qquad (4.20)$$

where $(\psi_1)_\odot$ = 3 $M_\odot pc^{-2} Gy^{-1}$ and $(\psi_1/\psi_0)_\odot$ is taken from Table A.4.1 (Appendix).

The total gas density, Σ_g , is shown in Figure 4.10d and derived using equation (3.17), that is

$$\Sigma_g = \mu_0 \Sigma_T \exp[G(Z_\odot - Z)] \qquad (4.21)$$

The surface densities of visible stars and dark matter are then given by

$$\Sigma_s = \sigma_0 \Sigma_T + \frac{(1-R-D)}{(1-R)} (\mu_0 \Sigma_T - \Sigma_g) \qquad (4.22)$$

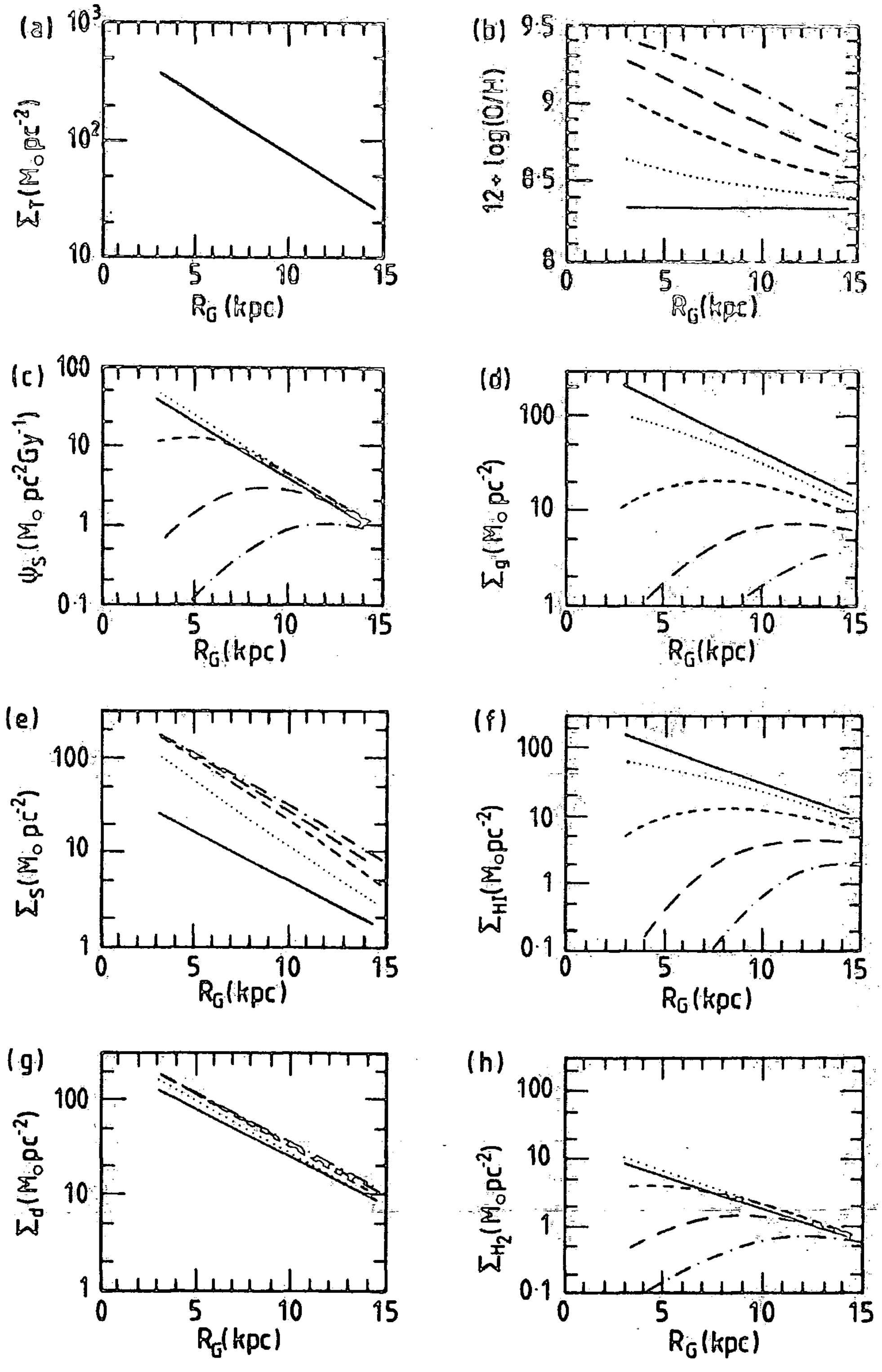


Figure 4.10: Radial and time evolution of the Galaxy in a model with no infall, constant yield and $\psi_S \propto \Sigma_{H_2}^k$. Shown are curves corresponding to times t after disc formation.

t = 0
t = 5Gy
t = 10Gy
t = 15Gy
t = 20Gy

and
$$\Sigma_d = \Sigma_T - \Sigma_s - \Sigma_g , \qquad (4.23)$$

and shown in Figures 4.10e and 4.10g. Finally, Σ_{H_2} can be derived from ψ_s by

$$\Sigma_{H_2} = \left(\frac{\psi_s}{\psi_{s\odot}} \right)^{1/k} (\Sigma_{H_2})_\odot \qquad (4.24)$$

where for the solar neighbourhood $(\Sigma_{H_2})_\odot = 1.30\ M_\odot pc^{-2}$ has been taken at present. The value of Σ_{HI} then follows

$$\Sigma_{HI} = \Sigma_g X - \Sigma_{H_2} \qquad (4.25)$$

These radial distributions shown in Figure (4.10) suggest the following points:

(i) The metallicity gradient is a direct indicator of age for any exponential disc with no initial metallicity gradient (cf. Section 4.4).

(ii) The surface density of star formation ψ_s is exponential for the first 7-8 Gy, slightly increasing, but then declining for t > 10 Gy, especially in the central parts. The total SFR for the Galaxy has been estimated between R_G = 3 kpc and 15 kpc,

$$\psi_T = \int_{3kpc}^{15kpc} \psi_s\ 2\pi R_G\ dR_G \qquad (4.26)$$

and is shown as a function of time in Figure 4.11. It can be seen that between t = 0 and t = 15 Gy, the SFR has stayed practically constant, declining from its original value by less than a factor of three at t = 15 Gy. This is consistent with the work of Kennicutt (1983b) and Gallagher et al. (1984) which suggests a roughly constant SFR in late-type spiral galaxies.

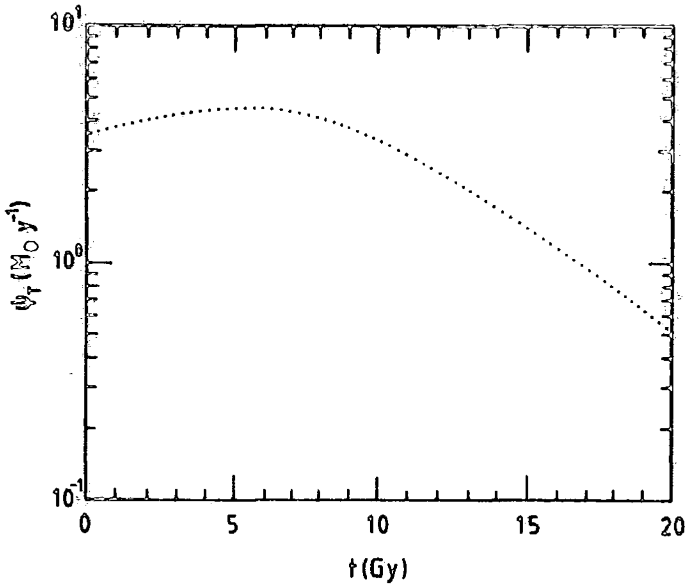


Figure 4.11: The total SFR in the disc of the Galaxy as a function of time after formation of the disc.

(iii) The model reproduces quite nicely the presently observed radial distributions of ψ_s, Σ_g, Σ_{HI} and Σ_{H_2} (that is a Bhat et al. type of H_2 distribution), though not perfectly. The predicted peak of the ψ_s and Σ_{H_2} distributions occurs at $\approx$ 8 kpc whereas observations suggest closer to 6 kpc. However, the fact that such an extra-ordinarily simple model predicts a molecular ring for spirals is quite important. The apparent 'hole' in the H_2 and total gas distributions in this and other galaxies has been difficult to reproduce in other models of chemical evolution. For example, Lacey and Fall (1985) find it extremely difficult using infall and radial gas flows to produce this hole. Only with a $\psi_s \propto \Sigma_g^2$ and with the inflow velocity rising sharply close to the centre of the Galaxy is it possible. Young and Scoville (1982a) had suggested that the hole was due to either orbital disruption at the inner Lindblad resonance (cf. Stark and Blitz 1978) or to gas having been exhausted in the nuclear bulge. Young (1985a) concludes that the nuclear bulge hypothesis is favoured by data on CO distributions in external galaxies. Sanders (1977) had earlier suggested that the hole was due to gas inflow into the central 600 pc of the bulge, and Jog and Ostriker (1987) have more recently suggested an inward drift of clouds due to viscous interaction thus depleting gas within 3 kpc. The chemical evolution model, described in this work, however, produces a central hole in the gas distributions quite naturally without the effect of the bulge being taken into account. It is simply due to a high SFR in the central parts.

Furthermore, there have been a number of attempts to explain the relative radial distributions of HI and H_2 using, for example, density waves (Roberts and Burton 1976), spiral arms (Wyse 1986) or stochastic self propagating star formation (Seiden 1983a,b). The present work re-asserts that these distributions can be understood in the context of a simple model of Galactic chemical evolution with $\psi_s \propto \Sigma_{H_2}^k$ and the fraction of gas in molecular form simply controlled by the metallicity.

(iv) Pagel (1987) pointed out a possible problem with $\psi_s \propto \Sigma_{H_2}^k$, and the Bhat et al. (1986) distribution of Σ_{H_2}, arguing that if Σ_g was roughly constant with R_G at present, while ψ_s was highest in the 4-6 kpc ring the gas in that ring will not last much longer. If the gas is not replenished from an outside source, he predicted a 'wave' of gas exhaustion spreading out from the central regions. This is seen clearly in plots (d), (f) and (h) of Figure 4.10. However, it is not clear why this should be a problem. It can be seen that there is still a sizeable amount of total gas remaining up until 15 Gy. The presently observed hole could be an indication of this gas exhaustion moving out through the Galaxy. If Σ_g presently followed the shape of Σ_T, as contended by the H_2 distribution of SSS (1984), then gas would remain in the 4-6 kpc ring for a longer time, but it then would be unclear as to what the reason for the < 4 kpc hole was.

(v) The surface densities of visible stars and dark matter remain roughly exponential in shape at all times.

Finally, one may ask can this model be used to describe the evolution of other spirals. A detailed discussion of this is outside the scope of the present work, but some initial remarks may be made. As a first attempt, one could simply use the different total surface mass distributions and keep all the other parameters (determined for the Galaxy) the same. Of course, the normalisation of quantities may be different, but the shapes of the radial distributions will be determined by Σ_T and t. Total surface mass densities have been taken from Diaz and Tosi (1984) and Tosi and Diaz (1985) for three galaxies, M51, M31 and NGC6946 as examples. Determining the metallicity gradient between R_G = 6 and 14 kpc after t_1 = 15 Gy, the predicted and observed metallicity gradients are compared in Table 4.3.

Table 4.3: Predicted and observed metallicity gradients.

	$d\log(Z)/dR_G$		
	Predicted	**Observed**	**Reference**
M51	-0.067	-0.081±0.027	Tosi & Diaz (1985)
M31	-0.050	-0.030±0.010	Diaz & Tosi (1984)
NGC6946	-0.068	-0.077±0.047	Tosi & Diaz (1985)

As can be seen the agreement is reasonable considering the uncertainty in observations.

The surprising result however, is that for each of these galaxies, the predicted Σ_{H_2} distribution exhibits a central hole, similar to the Galaxy. The observed CO distributions (Scoville and Sanders 1987) show only a central hole for M31, while M51 and NGC6946 have CO distributions increasing towards the centre. Although a metallicity correction as proposed by Bhat et al. (1985) flattens the observed H_2 distribution, it does not produce central holes. Therefore, either the above model is too simple to apply to other galaxies, or the CO does not successfully trace the H_2 distribution. No doubt such a simple model will need some modification, but the fact that the metallicity gradients are reproduced could reinforce the growing feeling that the use of a constant conversion factor α_{20} in external spirals is not valid (e.g. Bhat et al. 1986; Lo et al. 1987a; Maloney and Black 1987). Chapter 6 will further examine the issue of α_{20} in external galaxies.

CHAPTER FIVE

PERTURBATIONS OF THE OORT CLOUD AND TERRESTRIAL MASS EXTINCTIONS

5.1 INTRODUCTION

The subject of mass extinctions of organisms has aroused interest for many years, and recently has been linked to the existence and properties of giant molecular clouds (e.g. Clube and Napier 1984a,b; Rampino and Stothers 1984a). It is the intention of this Chapter to re-examine this link in an attempt to constrain the masses of GMC.

Possible links of mass extinctions and other terrestrial geological events with astronomical phenomenon were postulated centuries ago (see the reviews of Clube and Napier 1982c and Bailey et al. 1986) but it is only fairly recently that a specific hypothesis and a particular astronomical phenomenon - cometary or meteoritic impacts - has come to the fore (Öpik 1958; Urey 1973; Clube 1978; Hoyle and Wickramasinghe 1978; Napier and Clube 1979; Hoyle 1981; Hills 1981; Rampino and Stothers 1984a).

In particular, Alvarez et al. (1980) showed that deep sea limestones showed a marked increase in iridium concentration above the background level at precisely the time of the mass extinctions associated with the K-T boundary, which included the extinction of dinosaurs. This they ascribed to the impact of a 10km diameter extra-terrestrial body, injecting about sixty times its own mass into the atmosphere and so affecting photosynthesis and food chains. This iridium layer has now been detected worldwide (Hsu 1980; Saito et al. 1986; Alvarez 1987) with other signatures of explosions such as microspherules and shocked minerals (Keller et al. 1983; Smit and Kyte 1984; Bohor et al. 1984). There has even been a claim of a global layer of graphite at the K-T boundary, due to the impact igniting worldwide fires (Wolbach et al. 1985). Similar iridium layers have also been claimed, associated with 3 other periods of mass extinctions (Ganapathy 1982; Alvarez et al. 1982; Playford et al. 1984; Xu et al. 1985) suggesting other impacts as causes of terrestrial mass extinctions.

Although the evidence for coincidence of apparent impact signatures with extinction events is extremely impressive (Jablonski 1986) a number of doubts with the above picture have been expressed. Some impact signatures are found mid-extinction and there is difficulty in the dating of palaeobiological data in order to derive coincidences (Crawford 1985; Padian and Clemens 1985). Furthermore, detailed studies of environmental change at the time of major extinctions may suggest gradual changes rather than the expected abruptness of an impact event (Stanley 1984; Clemens 1986; Sloan et al. 1986; Norman 1986; Donovan 1987). Officer et al. (1987) have recently reviewed the alternative case for volcanic activity being the cause of mass extinctions.

Luck and Turekian (1983) in examining osmium isotope ratios at the K-T boundary suggested comet showers rather than a single impact being the cause. It is these comet showers that have further been invoked to explain a possible periodicity seen in the terrestrial record.

5.1.1 Periodicity in the terrestrial record

Traditionally it was thought that each mass extinction event was essentially unique and could be explained independently by changes in climate, continental configurations, global habitat area, orogenic activity, oceanic or atmospheric chemistry and even extra-terrestrial phenomenon. However, Raup and Sepkoski (1982, 1984) using extinctions in marine invertebrates demonstrated an apparently regular 26 My periodicity in the pattern of extinctions, a feature which had long been suspected in the geological record (e.g. Holmes 1927; Fischer and Arthur 1977; McCrea 1981). Figures 5.1 and 5.2 are taken from the recent work of Sepkoski and Raup (1986) from which they derive a period of 26.2 $\pm$ 1.0 My. The significance of this result, if correct, is that extinction events are ultimately due to a single forcing agent rather than a plethora of individual causes (McClaren 1983).

This rough 30 My periodicity, in phase with the extinction events, has since been shown to apply to a wide range of geological indicators, as summarised by Table A.5.1 (Appendix). In particular, the discovery that episodes of mass extinction appear to correlate with the ages of dated terrestrial craters (e.g. Seyfert and Sirkin 1979; Alvarez and Muller 1984) indicates that cometary impacts could play a major role. These comet showers, in addition to causing mass extinction, could possibly trigger geomagnetic reversals (Pal and Creer 1986) and volcanic activity (Pandey and Negi 1887; Rampino 1987), although the details of this process are far from clear.

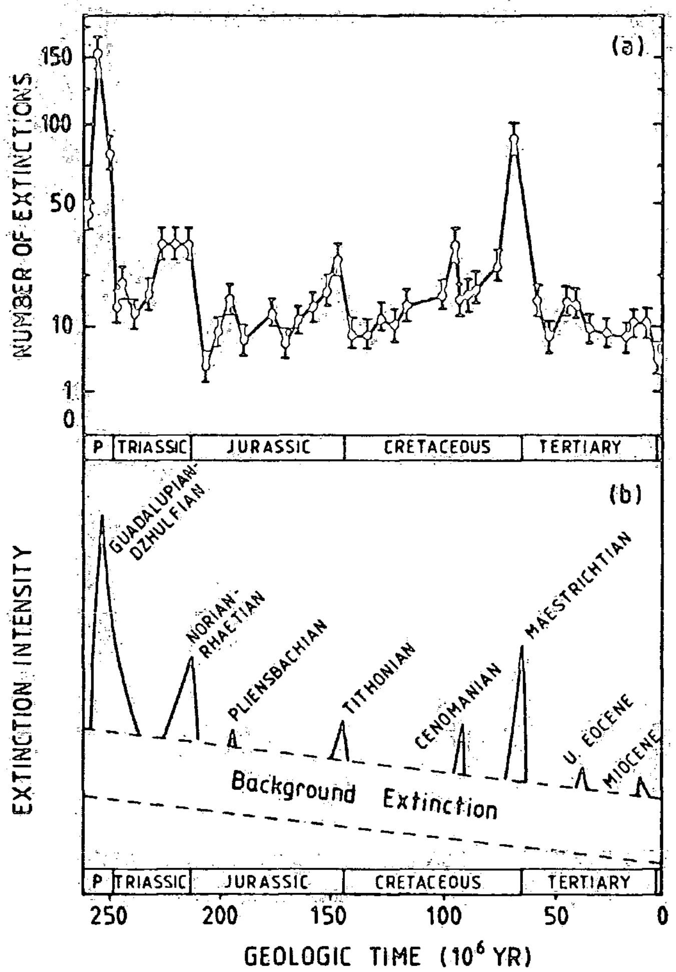


Figure 5.1: (a) The number of extinctions for marine animal families through 43 stages as measured by simple numbers of extinction per stage over the last 270My (Sepkoski and Raup 1986).
(b) A model of extinction intensity from Sepkoski and Raup (1986). Background extinction, the intensity of normal intervals of time, is shown as a decreasing function of time. The heights of the 8 extinction peaks (which are left unscaled) reflect the relative magnitudes of the events at familial and stage levels.

It is important, before outlining methods for the production of periodic comet showers, to be clear about the uncertainties in the above periodicity analysis. Periodicity in mass extinctions ultimately depends on difficult decisions concerning the absolute dating of stratigraphical boundaries, the culling of the database and the definition of a mass extinction (e.g. Dingus and Sadler 1982; Stigler 1985; Hoffmann 1985, 1986; Jablonski 1986;

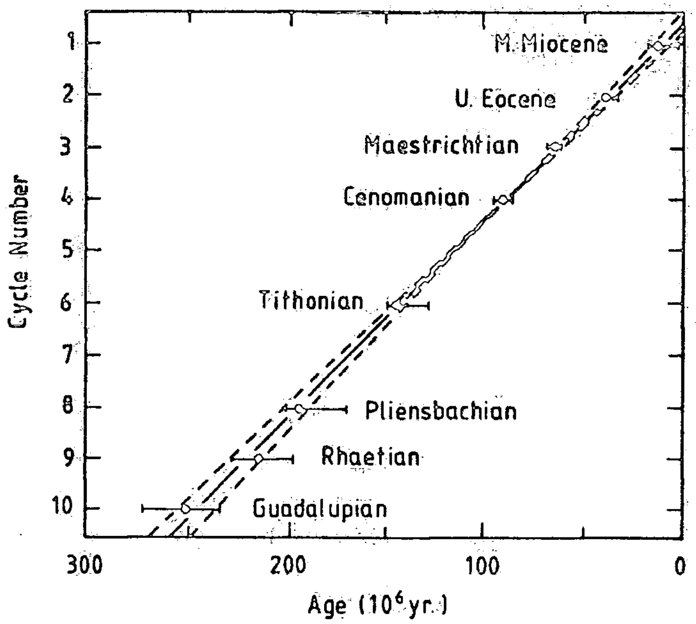


Figure 5.2: The cycle number against age relationship is shown for 8 significant extinction events. The solid line is a least squares fit with slope corresponding to a period of 26.2 My, while the dashed lines show the range in slopes for solutions which pass through the error bars of all points. (After Sepkoski and Raup 1986).

Tremaine 1986). Some workers (e.g. Patterson and Smith 1986) using the same data find no evidence for periodicity. Furthermore, although the record of mass extinctions may statistically show periodicity, it is possible that this might arise even if the extinctions themselves are not periodic (cf. Kitchell and Pena 1984). This point is illustrated in Figure 5.3, in which the distribution of time intervals between successive mass extinctions is compared with the exponential distribution expected for a random process. At first sight there is a clear inconsistency with the random hypothesis, the observed interval distribution resembling two delta functions broadened by noise, such as would be expected from genuine periodicity with timing errors and occasional missing cycles. However, the disparity could be illusory if an extinction event is

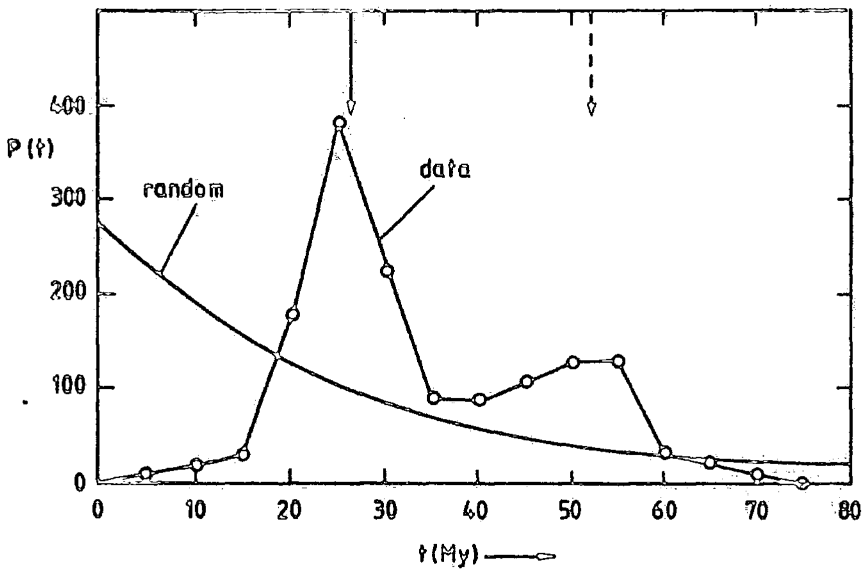


Figure 5.3: The frequency of the intervals between successive extinctions detailed by Sepkoski and Raup (1986). The quoted errors on the extinction dates have been allowed for in an approximate way. The arrows indicate where peaks would be expected for a 26 My periodicity (the peak at 52 My occurs when cycles are missed). The exponential curve marked 'random' relates to the expectation for a purely random process. The experimental data appear clearly to favour periodicity.

followed by a 'dead time' in which surviving species are more hardy and less prone to extinction, while new susceptible species develop more slowly (e.g. Stanley 1984). In this way, a nearly random distribution of extinction triggers might produce an apparently periodic extinction record, though the period would correspond to the dead time and the required frequency of potential extinction causes would have to be higher.

This hypothesis would not, of course, naturally explain detected periodicity in other geological indicators. However, periodicity in these other indicators is still controversial. Uncertainties in the cratering record include its incompleteness, age determinations and the fact that not all structures used to suggest periodic comet showers are produced by the same type of body (Weissman 1985; Grieve et al. 1986; Jacobs 1986). Doubt has also been cast on the periodicity in geomagnetic reversals (Lutz 1985; Raup 1985b; Jacobs 1986).

However, Sepkoski and Raup (1986) have reconsidered some of these questions and still believe the mass extinction record shows evidence for periodicity. The present work re-examines the case for periodicity of cometary impacts, following the suggestion of McClaren (1986) that 'surely the burden of proofs rests, now, firmly on the shoulders of those who would deny the existence of this violent phenomenon, and for them the proof must be ... evidence and argument leading to the denial of Earth-crossing asteroids and their periodic arrival on Earth'. Whilst, of course, the existence of asteroids in Earth-crossing orbits cannot be denied, this work will show that periodic 30 My variations in the cometary flux cannot be caused by encounters of the Solar System with GMCs, that is the so-called 'Galactic' model.

5.1.2 The Galactic model of terrestrial mass extinctions

It seems very unlikely that any 30 My periodicity in the terrestrial record could be due to processes in the Earth surface and atmosphere or to deep Earth processes as these have characteristic periods 10^{0} - 10^{5} y and 10^{8} - 10^{9} y respectively (McCrea 1981). However, the fact that the 30 My cyclicity is identical, within the errors, to the mean interval between Galactic plane crossings by the Solar System (Innanen et al. 1978; Bahcall and Bahcall 1985) has been a major argument implicating external astronomical processes as a primary cause of mass extinctions (Hatfield and Camp 1970).

In principle, a heightened flux of comets through the inner planetary system could produce significant climatic deterioration, leading to mass extinctions either by the direct effects of cometary impacts or by the passage of the Earth through streams of debris from the break up of a large comet (Clube and Napier 1986a,b,1987). It has been suggested (Clube and Napier 1984a,b; Rampino and Stothers 1984a) that the required change in cometary flux could be caused by passages of the Solar System past molecular clouds, modulated by the Solar System oscillation, thus significantly disturbing the orbits of comets in the Oort Cloud. According to the view developed by Clube and Napier (1984a, 1986a) the present parabolic flux is primarily the result of such an event and the Oort Cloud (cf. Kresák 1977; Yabushita 1979) is regarded as an unstable system which is intermittently replenished in rare episodes of comet capture associated with the passage of the Sun through a dense molecular cloud containing comets (see Section 5.5). Alternatively, the Oort Cloud may be assumed to be primordial, with comets at large radii ultimately originating in a hypothetical dense inner core of the system, which is calculated to be stable for the lifetime of the Solar System (Hills 1981; Bailey 1983a,b,c,1986a; Shoemaker and Wolfe 1984a; Weissman 1986). Following the suggestion of Hills (1981), a major disturbance of the orbits in the inner core would produce a short-lived, intense 'shower' of comets passing through the inner planetary system. Provided that the encounters deflect enough comets and the encounter rate and degree of modulation agree with the observations, either theory in principle provides a good working hypothesis for the explanation of extinctions.

However, this (Galactic) explanation for periodic comet showers has been challenged on two grounds. First, the width of the molecular cloud layer may be too great in comparison with the amplitude of the solar motion about the Galactic plane to allow a statistically significant 30 My periodicity to be extracted from what is only a small number of dated events in the terrestrial record (Thaddeus and Chanan 1985; Thaddeus 1986). This criticism has been discussed by Stothers (1985), who holds that a Galactic signal could still be detectable in the geological record, even with the Sun's present small amplitude of oscillation. The theory might, of course, be restored by assuming that encounters between the Solar System and molecular clouds were more strongly modulated in the past, due to the amplitude of the solar motion being greater previously than now (e.g. Thaddeus 1986; Clube and Napier 1986a; Bailey et al. 1986).

The second criticism of the Galactic explanation for comet showers is that the present phase of the solar orbit does not agree with the theory's simplest predictions (Schwartz and James 1984; Davis et al. 1984). According to expectations, mass extinctions should mostly occur when the Sun is close to the Galactic plane (i.e. close to its present position, e.g. Mihalas and Binney 1981), whereas the evidence of the terrestrial record (Raup and Sepkoski 1984) indicates that we are now almost halfway between extinctions. This phase discrepancy could be attributed to the partly stochastic nature of the extinction record, but it nevertheless does remove some of the theory's initial attraction.

In addition to examining these two problems, this Chapter will also examine the more fundamental problem, that of obtaining a large enough signal itself. Section 5.2 presents a definition of an 'extinction' shower and estimates the critical semi-major axis above which the comet velocities must be randomized in order to produce a shower which might register in the geological record. Section 5.3 then considers constraints on the masses and mass densities of perturbers, in particular GMCs capable of producing showers of sufficient strength and frequency to explain the results on mass extinctions, while Section 5.4 returns to the signal-to-noise and phase problems. Finally, Section 5.5 examines the question of the survival of the Oort Cloud over the lifetime of the Galaxy.

There are, of course, alternative astronomical suggestions for the cause of periodic mass extinctions such as Nemesis (Davis et al. 1984; Whitmire and Jackson 1984) and Planet X (Whitmire and Matese 1985). Nemesis is a postulated unseen solar companion in a highly eccentric orbit that periodically enters the Oort Cloud and perturbs comets, but such a theory has difficulties concerning irregularities in the period of revolution and dynamical instability (Hut 1984; Hills 1984; Torbett and Smoluchowski 1984; Clube and Napier 1984c; Weissman 1984). Planet X is a similar idea, with this time a planet creating comet showers whenever its perihelion passes close to the inner disc of the comet cloud, but it seems that there are major difficulties in the planet having enough mass to scatter enough comets (Kerr 1985; Tremaine 1986). At the present time, neither of these alternatives appears to be a viable explanation for the 30 My periodicity of comet showers and so will not be considered further.

5.2 THE DEFINITION OF AN EXTINCTION SHOWER

Long-period comets entering the planetary system from the Oort Cloud are removed from their original orbits by planetary perturbations, either by ejection into interstellar space or by capture into short period orbits where they quickly decay. The flux of new comets from the Oort Cloud thus represents a steady loss of low angular momentum long period comets, which is described in velocity space by a loss cylinder in the comets' velocity distribution at large heliocentric distances. Comets with velocities inside the loss cylinder, i.e. with perihelion distances $q \leqslant q_{lc} \simeq$ 15AU (Bailey 1984) are effectively removed from the Oort Cloud within one orbital period. Provided that perturbations (e.g. due to stars or the Galactic tidal force) are strong enough to replenish these losses occurring on an orbital timescale with comets lying on neighbouring low angular momentum orbits, the loss cylinder is kept filled and a more or less steady influx of long period comets will result. For smaller semi-major axes, however, the orbital period and the effectiveness of external perturbations are both reduced, and at some value of the semi-major axis the loss cylinder will not be kept steadily filled (Oort 1950; Bailey 1977; Hills 1981).

Occasional close, exceptionally strong perturbations may still fill the loss cylinder, however, and it is these intermittent encounters which lead to the possibility of comet showers, the instantaneous influx of long period comets being then much greater than the steady-state value. Therefore to link mass extinctions to the nature of the perturbers, the proportion of shower to background comets above which a mass extinction may be expected to occur must be estimated. Then the critical semi-major axis, a_{crit}, down to which the loss cylinder must be filled in order for such a shower to occur may be evaluated.

5.2.1. The proportion of shower to background comets

The mechanisms by which comet showers affect the Earth are poorly understood. They range from explosions, caused by collisions of large bodies (Napier and Clube 1979; Alvarez et al. 1980), to the possibly more important long-term environmental and climatic effects brought about by interactions of the Earth with interplanetary debris on a variety of scales (e.g. Clube and Napier 1986a,b). Discussions of these questions may be found in the volumes edited by Roddy et al. (1977), Silver and Schultz (1982), Holland and Trendall (1984) and Smoluchowski et al. (1986). In fact the link between impact and biological change is far from clear (Heissig 1986; Clemens 1987), and may provide another major difficulty for comet showers as the cause of mass extinctions.

However, according to the Galactic comet shower hypothesis under consideration, the showers of comets cause mass extinctions and also an enhanced cratering rate on the Earth, this being the cause of the apparent correlation between the ages of dated craters and times of mass extinctions (e.g. Shoemaker and Wolfe 1984b). The relative number of craters which appear to be associated with showers may thus be used to give a rough indication of the required ratio of shower to background comets necessary to cause a mass extinction.

Observations of terrestrial craters (Grieve 1982) show that the rate of production of craters, for example with diameter > 10 km, integrated over the whole earth is $(7 \pm 3) . 10^{-6}\ y^{-1}$. Observations of dated craters indicate that about 70% occur bunched in time as if associated with comet showers (Muller et al. 1984). The ratio of shower to background craters is thus ≅ 70/30, and if crater-forming projectiles arise from the long-period comet flux, a ratio of shower to background comets (R_{sh}) on the order of 70/30 ≅ 2 would be implied. However, if a significant proportion of terrestrial craters are caused by projectiles having an unmodulated source, such as the asteroid belt, the required modulation of the comet flux would be much greater.

Although estimates concerning the cratering record have large uncertainties, it is generally agreed that most craters can be explained as a result of impacts with bodies derived from the observed population of Earth-crossing asteroids (Grieve and Dence 1979; Shoemaker 1984). Barely 5% of the total cratering rate can be attributed to the present long period comet flux (Weissman 1982; Olsson-Steel 1987). If Earth crossing asteroids predominately arrive as a result of collisions or gravitational interactions in the asteroid belt (Wetherill and Shoemaker 1982; Wetherill 1985), a R_{sh} of about 50 would be required in order to explain the cratering data. Alternatively, observed Earth-crossing asteroids may originate from the break up or decay of short period comets (e.g. Bobrovnikoff 1931; Öpik 1963; Shoemaker 1977; Clube and Napier 1982b,1984a,b,1986a,b), thus the terrestrial cratering record reflects changes in the population of short period comets, some of which certainly derive from the isotropic near-parabolic flux. If all short period comets originated from this flux, the cratering record might in principle be explained by $R_{sh} \cong 2$. But if some (possibly the majority e.g. Fernández and Ip 1983a,b; Bailey 1986b) originate from a hypothetical inner core to the Oort Cloud, a presumably unmodulated source not directly connected to the long period flux, the required variation in the latter would obviously be greater.

Therefore, to explain the apparent periodicity in the cratering record the comet shower hypothesis ought to predict $R_{sh} > 2$. Depending on the ultimate source of Earth-crossing asteroids, it may be that the required value of R_{sh} should have to exceed 2 by more than an order of magnitude, placing a correspondingly stronger constraint on the theory.

5.2.2 The critical semi-major axis

The critical semi-major axis, a_{crit}, is defined as the value for which a single filling of the loss cylinder down to a_{crit} ensures that the proportion of shower to background comets during a time interval $T \cong 30$ My will exceed the required value $R_{sh} > 2$.

Following Bailey (1983a,b), a spherically symmetrical model for the comet cloud is defined so that the number

$N(E)dE$ of comets with orbital energies per unit mass E in the range E, E + dE is given by

$$N(E) = K(E/\hat{E})^{-\gamma}, \qquad E_{min} \leqslant E \leqslant E_{max}$$
$$= 0 \qquad \text{otherwise} \qquad (5.1)$$

where $E = -GM_{\odot}/2a$, $\hat{E} = -GM_{\odot}/2R_{\odot}$, $E_{max} = -GM_{\odot}/R_{\odot}$ and $E_{min} = -GM_{\odot}/2a_{\odot}$, K being a constant defined in terms of the observed near parabolic flux and other parameters of the model, a is the semi-major axis of the orbit, $R_{\odot} \simeq 2.10^{5}$ AU is the outer radius of the comet cloud and $a_{\odot}$ is the semi-major axis corresponding to the inner boundary of the cloud. For the Oort (1950) model of the comet cloud $\gamma = 5/2$ but for the arguably more plausible models (Hills 1981; Bailey 1983b,1986a) we generally expect $-2 < \gamma < 0$. Thus the cloud is centrally condensed having most of its mass in relatively tightly bound orbits with $a \leqslant 10^{4}$ AU

It has recently been shown that the dominant source for the quasi-steady background comet flux into the inner planetary system is the tidal force of the Galactic disc (Torbett 1986a,b; Morris and Muller 1986; Heisler and Tremaine 1986; Byl 1986; Delsemme 1987), although random stellar perturbations are still required to replenish the low angular momentum orbits on which the tide can operate. Following Heisler and Tremaine (1986), the semi-major axis a_t above which the tide keeps the loss cylinder steadily filled may be written (Bailey 1986b)

$$a_t = \left(\frac{3\sqrt{2}}{40\pi} \frac{M_{\odot}}{\rho_0} q_{lc}^{1/2} \right)^{2/7} \qquad (5.2)$$

where ρ_0 is the total mid-plane density of Galactic material. In this approximation the solar orbit about the Galactic plane obeys simple harmonic motion with the interval between successive Galactic plane crossings

$$T = \frac{\pi}{(4\pi G\rho_{\odot})^{1/2}} \qquad (5.3)$$

Assuming T = 30 My gives $\rho_{\odot} = 0.194\ M_{\odot}pc^{-3}$ (cf. Bahcall and Bahcall 1985), so that

$$a_t = 3.208.10^{4} q_{15}^{1/7} \text{ AU} \qquad (5.4)$$

where $q_{15} = q_{lc}$ /15AU.

Bailey (1986b) has shown that the injection rate per unit semi-major axis by the Galactic tide, for comets with $a > a_t$ and perihelia q distributed uniformly in the range $0 \leq q \leq q_{lc}$ is

$$F_{lc,t}(a) = \frac{K}{4\pi} (GM_{\odot})^{1/2} R_{\odot}^{-\gamma} a^{\gamma-9/2} J_{lc} \qquad (a > a_t) \qquad (5.5)$$

where

$$J_{lc} = (2GM_{\odot} q_{lc})^{1/2} \qquad (5.6)$$

is the specific angular momentum of a nearly parabolic orbit on the loss cylinder.

Setting $x = a/a_t$, $x_R = R_{\odot}/2a_t$ and integrating (5.5) over $a \geq a_t$, the background injection rate of new comets into the planetary system ($a \geq a_t$ and $q \leq q_{lc}$) becomes

$$\mathring{N}_{qs} = \frac{KR_{\odot}^{-\gamma}}{2\pi} (GM_{\odot})^{3/2} q_{lc} a_t^{\gamma-7/2} \int_1^{x_R} x^{\gamma-9/2} dx \qquad (5.7)$$

and the number of background comets injected during a time interval T is simply

$$N_{qs,T} = \mathring{N}_{qs} T. \qquad (5.8)$$

Now the number of shower comets injected as a result of filling the loss cylinder down to a semi-major axis $a_{crit} < a_t$ can also be calculated. From (5.1) the total number of comets in the cloud per unit semi-major axis is

$$N(a) = K \left(\frac{R_\odot}{a}\right)^{-\gamma} \frac{GM_\odot}{2a^2} \qquad (a_\odot \leqslant a \leqslant R_\odot/2) \tag{5.9}$$

and if a strong perturbation causes the loss cylinder to become filled down to a_{crit}, the fraction of such comets with perihelia less than q_{lc} is $\cong 2q_{lc}/a$. Hence the number of shower comets may be written

$$N_{sh} = KR_\odot^{-\gamma} GM_\odot q_{lc}\, a_t^{\gamma-2} \int_{x_{crit}}^{1} x^{\gamma-3} dx \tag{5.10}$$

where $x_{crit} = a_{crit}/a_t$. Combining (5.7), (5.8) and (5.10) the ratio of shower to background comets is obtained.

$$R_{sh} = \frac{N_{sh}}{N_{qs,T}} = \frac{P(a_t)}{T} \frac{\int_{x_{crit}}^{1} x^{\gamma-3} dx}{\int_{1}^{x_R} x^{\gamma-9/2} dx}, \tag{5.11}$$

where $P(a_t) = 2\pi(GM_\odot)^{-1/2} a_t^{3/2}$ is the period of an orbit with the semi-major axis a_t. Figure 5.4 shows R_{sh} as a function of x_{crit} and the power law index γ of the adopted model of the Oort Cloud. Setting $R_{sh} = 2$ then defines the value of a_{crit} (for a particular value of a_t) below which the loss cylinder must temporarily be filled in order to cause an extinction shower. It can be seen that the original non-centrally condensed model of Oort (1950), having $\gamma = 2.5$, is unable to produce any significant comet showers at all; and secondly if R_{sh} is required to be greater than 2 on average, the loss cylinder must be filled down to

$$a_{crit} < 2.10^4 \text{AU} \tag{5.12}$$

for $a_t = 3.2.10^4$ AU.

Of course, the above discussion depends on the assumption (equation 5.1) that the Oort Cloud model can be described by a simple power law with constant index γ. It

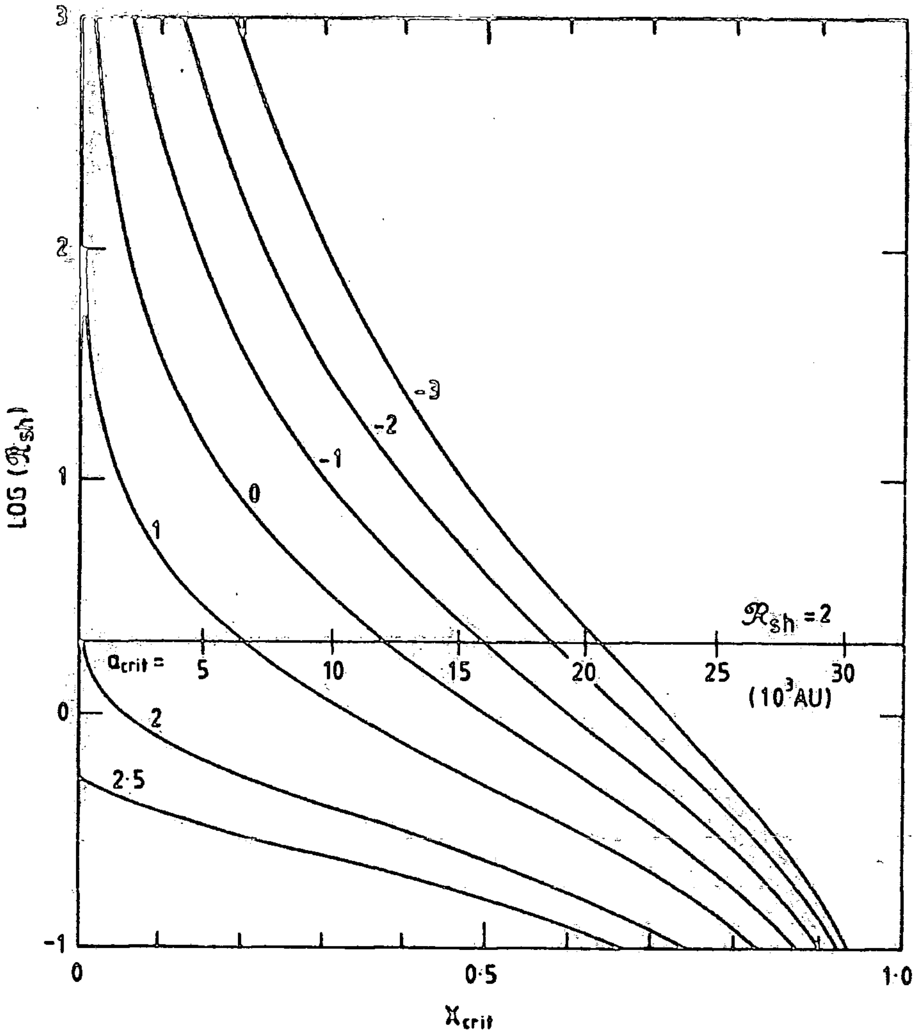


Figure 5.4: The ratio of shower to background comets $R_{sh} = N_{sh}/N_{\gamma s,T}$ as a function of $x_{crit} = a_{crit}/a_t$. The curves are labelled by the corresponding spectral index, γ, of the power law distributions for cometary energies (equation 5.1). A value of $R_{sh} > 2$ is required to produce an 'extinction' shower. (A value of $a_t = 3.208 . 10^4$ AU has been used).

may be that Oort Cloud models are not characterised by a single value of the slope of the energy distribution (e.g. Delsemme 1977; Bailey 1983b, 1986a) or even that γ may be time dependent (Kresák 1977; Yabushita 1979; Bailey 1984; Clube and Napier 1984a, 1986; Clube 1987a). We have discussed these possibilities in detail elsewhere (Bailey et al. 1987, hereafter referred to as Paper VI) and concluded that there is little effect on the above value of a_{crit}. It is this value from the condition $R_{sh} > 2$ that puts extremely tight constraints on the nature of any perturbers capable of causing extinction showers with a mean interval as short as 30 My.

5.3 THE SIGNAL PROBLEM

Sepkoski and Raup (1986) appear to have obtained an almost complete sequence of mass extinctions every $\cong$ 30 My during the past $\cong$ 270 My, specifically at least 8 events out of 10 (Figures 5.1 and 5.2). If these are due to comet showers, the bodies which disturb the Oort Cloud must have a space density and mass such that they trigger a death shower with almost unit probability during each 30 My interval. Assuming a mean mass density $\rho \equiv nM$ for the perturbers and a relative velocity V to the Solar System, both averaged along the solar orbit about the Galaxy, during the time between Galactic plane crossings we expect an average of one encounter with impact parameter

$$b < b_1 = (\pi n V T)^{-1/2} \tag{5.13}$$

The probability distribution of minimum impact parameters, b_{min}, which occur during each cycle is

$$P(b_{min})\, db_{min} = \frac{2b_{min}}{b_1^2} \exp\left(-\frac{b_{min}^2}{b_1^2}\right) db_{min} \tag{5.14}$$

so that the fraction f of cycles in which b_{min} exceeds a value b_f is given by $f = \exp(-b_f^2/b_1^2)$. The fact that less than 1/5 of the cycles are missing from a complete sequence of extinctions therefore indicates that encounters with impact parameters up to

$$b_{1/5} = \sqrt{\ln 5}\, b_1 = \left(\frac{\ln 5}{\pi} \frac{M}{\rho V T}\right)^{1/2} \tag{5.15}$$

must be able to trigger an extinction shower. The question is, now, is this possible for astrophysically plausible perturbations of the Oort Cloud?

For a given encounter with impact parameter b, the semi-major axis down to which the loss cylinder is filled depends on whether the impulse approximation is valid or not, and, if it is, on whether the perturber passes at a large distance or close enough to the Sun to pass directly through the Oort Cloud. Long period comets with semi-major axes a, lie at mean heliocentric distances on the order of 3a/2. Following Fernández and Ip (1987), if the impulse approximation is valid and $b < 3a/2$, then the loss cylinder will be filled down to a shower semi-major axis, a_{sh}, given by

$$a_{sh} = b \left[\frac{2}{3} \frac{q_{lc} V^2}{GM_\odot} \left(\frac{M_\odot}{M} \right)^2 \right]^{1/2} \qquad \left(b < \frac{3a}{2} \right) \qquad (5.16)$$

For more distant impulsive perturbations, Hills (1981) obtained

$$a_{sh} = b \left[\frac{8}{27} \frac{q_{lc}}{GM_\odot} V^2 \left(\frac{M_\odot}{M} \right)^2 \right]^{1/4} \qquad \left(\frac{3a}{2} < b < b_{max} \right) \qquad (5.17)$$

where b_{max} is the impact parameter beyond which the impulse approximation breaks down.

At large values of the impact parameter, the duration 2b/V of the encounter becomes long compared with the orbital period $2\pi (GM_\odot)^{-1/2} a^{3/2}$ of the perturbed comet with semi-major axis a. This yields a rough estimate of the maximum impact parameter b_{max} above which (5.17) breaks down, i.e. $b_{max} \simeq V(a^3/GM_\odot)^{1/2}$. In this situation, a_{sh} may be estimated from equation (5.2) with the factor $4\pi\rho_0$ replaced by M/b^3 (Byl 1983) which gives

$$a_{sh} = \left(\frac{3\sqrt{2}}{10} \; q_{1e}^{1/2} \; b^3 \; \frac{M_\odot}{M}\right)^{2/7} \qquad (b > b_{max}) \qquad (5.18)$$

The continuity of equations (5.17) and (5.18) at $b = b_{max}$ gives

$$b_{max}(a) = \sqrt{\frac{400}{243}} \; V \left(\frac{a^3}{GM_\odot}\right)^{1/2} \qquad (5.19)$$

Equations (5.16) - (5.18) determine the value of a_{sh} down to which the loss cylinder is filled by a single encounter with impact parameter b. Setting $b = b_{1/5}$ gives values of a_{sh} for which bodies with parameters M, ρ and V are able to fill the loss cylinder down to a_{sh} during a specified time interval T in 80% of cycles. These equations with equation (5.15) thus become

$$a_{sh}\,(AU) = 5.659.10^4 \, q_{15}^{1/2} \, V_{20}^{1/2} \, T_{30}^{-1/2} \, \rho_{05}^{-1/2} \left(\frac{M_\odot}{M}\right)^{1/2} \qquad (M < M_1) \qquad (5.20)$$

$$a_{sh}\,(AU) = 3.171.10^4 \, q_{15}^{1/4} \, T_{30}^{-1/2} \, \rho_{05}^{-1/2} \qquad (M_1 \leqslant M \leqslant M_2) \qquad (5.21)$$

$$a_{sh}\,(AU) = 2.670.10^4 \, q_{15}^{1/7} \, V_{20}^{-3/7} \, T_{30}^{-3/7} \, \rho_{05}^{-3/7} \left(\frac{M}{10^4 M_\odot}\right)^{1/7} \qquad (M > M_2) \qquad (5.22)$$

where M_1 and M_2 are given by

$$\left(\frac{M_1}{M_\odot}\right) = \left(\frac{3 q_{1e} V^2}{2GM_\odot}\right)^{1/2} = 3.184 \; q_{15}^{1/2} \; V_{20} \qquad (5.23)$$

and

$$\left(\frac{M_2}{M_\odot}\right) = 3.331.10^4 \; q_{15}^{3/4} \; V_{20}^{3} \; T_{20}^{-1/2} \; \rho_{05}^{-1/2} \; , \qquad (5.24)$$

with $V_{20} = V/20 \text{ kms}^{-1}$, $T_{30} = T/30$ My and $\rho_{05} = \rho/0.05\ M_\odot pc^{-3}$. As emphasised by Fernández and Ip (1987), equation (5.20) should be used whenever the mean mass of the perturbers is less than M_1, that is for perturbations by typical stars and by hypothetical smaller bodies such as brown dwarfs.

These expressions show that a_{sh} is least when M lies in the range $M_1 \leqslant M \leqslant M_2$ and that for this broad range of masses the value of a_{sh} is independent of both M and V. Equation (5.12) means that $a_{sh} \lesssim 2.10^{4}$ AU in order for a shower to register in the terrestrial record, and therefore perturbers, in order to produce mass extinctions at 30 My intervals, must have a mean mass density $\rho > 0.1\ M_{\odot}pc^{-3}$ averaged along the solar orbit (equation 5.21). This depends on the assumption that $R_{sh} \approx 2$ for detectable showers; if the required value of R_{sh} is larger, then a_{crit} will be lower and the minimum mass density of perturbers even higher. Since the limit on the perturber density is already close to the maximum allowable local density of all Galactic material (i.e. $\rho_0 \approx 0.2\ M_{\odot}pc^{-3}$, from stellar observations and in order that the mean time between Galactic plane crossings should be $\cong$ 30 My), it is clear that the Galactic model cannot produce shower-to-background ratios much greater than 2 for 30 My comet showers.

The above conclusions depend on the use of (5.11) to calculate the ratio of shower to background comets. Fernández and Ip (1987) call this contribution to a shower the 'halo' component, since it comprises comets coming into the planetary system from all directions, distributed more or less isotropically about the Sun. However, comets whose orbits lie close to the path of the perturber may also be strongly affected, thereby possibly constituting a second 'clustered' contribution to a comet shower. Assuming that comets with semi-major axes a lie at heliocentric distances close to r = 3a/2, encounters with an impact parameter b will thus only affect comets in a clustered sense if a > 2b/3. Thus, as noted by Fernández and Ip (1987), a non-zero clustered contribution will be associated with relatively low mass perturbers, i.e. $M < M_{\rm I}$, or (equation 5.23) less than or equal to the mass of a typical star. Since molecular clouds have $M \gg M_{\rm I}$, a full derivation of this topic will not be given here, but can be found in Paper VI. It is shown there that the cluster shower to background ratio is given for various models of the Oort Cloud by

$$
\begin{aligned}
R_{clus} &= 0.09\, q_{15}^{-1/2}\, V_{20}^{-1}\, T_{30}^{2}\, \rho_{o5} \left(\frac{M}{M_\odot}\right) && (\gamma = 0) \\
&= 0.17\, q_{15}^{-5/14}\, V_{20}^{-1/2}\, T_{30}^{43/14}\, \rho_{o5}^{3/2} \left(\frac{M}{M_\odot}\right)^{1/2} && (\gamma = -1) \qquad (5.25) \\
&= 0.32\, q_{15}^{-3/14}\, T_{30}^{58/14}\, \rho_{o5}^{2} && (\gamma = -2) \\
&= 0.57\, q_{15}^{-1/14}\, V_{20}^{1/2}\, T_{30}^{73/14}\, \rho_{o5}^{5/2} \left(\frac{M_\odot}{M}\right)^{1/2} && (\gamma = -3)
\end{aligned}
$$

These expressions show that if the Oort Cloud is only moderately centrally condensed (i.e. $\gamma > -2$), the maximum value of R_{clus}, reached for high densities and $M \simeq M_{\rm I} \simeq 3M_\odot$, is of order unity. Therefore for such models, showers of clustered comets at 30 My intervals will be too weak to register in the terrestrial record. If, however, the Oort Cloud is extremely centrally condensed, $\gamma = -3$, R_{clus} rises as the mass of the perturbers decreases, which could lead to very large values of R_{clus} for small masses. For example, one could postulate a model in which $\gamma = -3$ (corresponding to a cloud with density $n_c(r) \propto r^{-7}$) and assume that all the missing mass in the Galactic disc, resided in low mass brown dwarfs, i.e. $\rho \simeq 0.1\ M_\odot pc^{-3}$ and $M \simeq 0.01\ M_\odot$. This would imply $R_{clus} \simeq 30$. Thus showers of clustered comets might affect the terrestrial record if (i) the missing mass in the

Galactic disc is composed entirely of low mass bodies with $M \simeq 10^{-2} M_\odot$ (cf. Stothers 1984) and (ii) the Oort Cloud itself is extremely massive > $10^{4} M_\odot$ and centrally condensed. This latter condition presents great difficulty and may prove prohibitive (Paper VI).

In summary, for the Galactic hypothesis to produce significant variations in the cometary flux (i.e. $R_{sh} \gtrsim 2$) on a regular 30 My timescale, the perturbers must have a high mass density > $0.1 M_\odot pc^{-3}$, and large masses $M > 3M_\odot$. The local density of molecular clouds ($\simeq 1$-$3.10^{-2} M_\odot pc^{-3}$; e.g. SSS 1984; Bhat et al. 1985; Dame et al. 1987; Section 4.6), even considering the uncertainty in α_{20}, is much too small to impose a recognizable 30 My modulation of the cometary flux, periodic or otherwise (cf. Thaddeus 1986; Scoville and Sanders 1986). In fact, $\alpha_{20} \simeq 28$ would be needed to account for 30 My comet showers! Such a large value of α_{20} is inconsistent with reasonable estimates from γ-rays and other methods (Chapter 1). In addition such large GMC masses implied by such a large α_{20} would have catastrophic consequences for the survival of the whole of the Oort Cloud (Section 5.5). Therefore, no useful constraint can be derived on the mass density of GMCs from 30 My periodicities in the terrestrial record. The suggestion that known molecular clouds produce the perturbations leading to 30 My comet showers (Clube and Napier 1984a; Rampino and Stothers 1984a,1986; Stothers 1985) cannot be valid, irregardless of arguments concerning the value of α_{20}, scale heights or phase problems. Comet showers however, with a much longer characteristic interval may still be produced by known bodies, for example

200 - 500 My for molecular clouds or stars (cf. Morris and Muller 1986).

The mass density of perturbers necessary on the Galactic model exceeds any which can be associated with known bodies. The total visible mass observed in the solar neighbourhood is $\approx$ 0.1 $M_{\odot} pc^{-3}$ (Hill et al. 1979; Stothers 1984). The possibility, however, that the perturbations are by massive dark bodies is difficult to rule out completely, as the density limit is just within the maximum allowed for the dark matter in the solar neighbourhood (Bahcall 1984, 1986a). However, Section 4.4 has reviewed evidence for the nature of the dark matter and concluded that the dark matter (if it exists at all) is probably in the form of low mass stars (Bahcall 1986b). Observations of the existence of wide binaries in the solar neighbourhood may even place an upper limit of $\approx 2M_{\odot}$ on the masses of the dark bodies (Bahcall et al. 1985), ruling out the idea of $> 3M_{\odot}$ perturbers altogether (but see Wasserman and Weinberg 1987).

It has been suggested (Clube 1987a,b) that the required dark matter may reside in the GMCs themselves, as 'primary condensations' such as brown dwarfs and giant comets. Clube (1987c) further suggests that this could explain why the mass of H_2 from virial analysis appears to be greater than derived from γ-rays (Table A.1.1). However, Bhat et al. (1986) have argued that there is essentially little discrepancy between virial masses and γ-ray masses when the more appropriate optically thinner lines are used. If all of the dark matter resided in GMCs (i.e. $\rho \approx 0.1 M_{\odot} pc^{-3}$), using the virial mass arguments even of SSS (1984), it is difficult to see how this could occur without significantly increasing their internal velocity dispersion above that observed. It is also difficult to see how such a large population of brown dwarfs could be confined to GMCs close to the plane.

Low mass perturbers may constitute the dark matter, but are ineffective unless their masses are extremely small ($M < 10^{-2} M_{\odot}$ for $\rho \cong 0.1 M_{\odot} pc^{-3}$) and the Oort Cloud model is both exceedingly massive and centrally condensed. Hills (1985, 1986) has considered possible limits to the space density of low mass perturbers in the Galactic disc, but for bodies with masses $\approx 10^{-2} M_{\odot}$ the available constraints are extremely weak. However, such a massive and centrally condensed Oort Cloud seems unlikely.

Wc thus conclude that it is most unlikely that the required perturbations of the Oort Cloud can be provided by missing mass in the Galactic disc. Whether large mass or low mass perturbers, ρ is required to be greater than $0.1 M_{\odot} pc^{-3}$. This value is marginally consistent with estimates of the dark matter mass density made by Bahcall (1984, 1987), but is far greater than more recent estimates made by other workers (e.g. Gilmore and Wyse 1987; Bienaymé et al. 1987; Rana 1987a). Even if the dark matter can provide $\rho > 0.1 M_{\odot} pc^{-3}$ with suitable perturbers, the next section describes two further difficulties for the Galactic explanation of periodic comet showers: the signal-to-noise problem and the phase problem.

5.4 THE SIGNAL-TO-NOISE AND PHASE PROBLEMS

According to the Galactic hypothesis, mass extinctions are most likely to occur when the Solar System is close to the Galactic plane. This is where the space density of perturbers is greatest, and where the likelihood of a close encounter is highest. Following Thaddeus and Chanan (1985), the assumption is made in this Section that the cometary influx is simply proportional to the rate of encounters with perturbers, which are taken to be material with gaussian scale height $h_{P} = \xi h_{C}$, where h_{C} is the corresponding scale height of known molecular clouds. (The assumption of a gaussian distribution fits the large scale CO surveys and is generally accepted by radioastronomers; the following analysis is not sensitive to this assumption and remains essentially unchanged if an exponential or other plausible form is taken). Observations of molecular clouds in the solar neighbourhood and in the region presumably covered by the Solar System during the last 270 My indicate that the half-width half maximum of the distribution is $z_{1/2} = 85 \pm 20$pc (Sanders 1981; Dame and Thaddeus 1985; Bronfman et al. 1987). In particular, Dame et al (1987) find $z_{1/2} = 87$pc from local measurements which are independent of assumptions concerning the distance to the Galactic Centre. Thus, recent measurements do not favour the value of $z_{1/2} = 60$ pc advocated by Stothers (1985). In general, whatever the nature of the perturbers, their scale height h_{P} must be at least as great as that of the young stars and molecular clouds in the Galactic disc, so $\xi > 1$.

The approximation of Thaddeus and Chanan (1985) favours the Galactic modulation model, because by ignoring the more or less steady background flux of comets due to distant stellar perturbations and the Galactic tide, it artificially enhances any periodic signal in the cometary influx. It also implicitly assumes that encounters are short range, the effect of long range encounters is to reduce the modulation. Nevertheless despite these biases to greater signal-to-noise ratios, it has proved difficult for the Galactic hypothesis to achieve a signal-to-noise ratio in the encounter rate with molecular clouds as high as that observed in the terrestrial record of mass extinctions ($\approx$ 2). This difficulty arises because the present amplitude, $z_\odot$, of the solar motion perpendicular to the Galactic plane is comparable or less than the scale height of the proposed perturbers.

A related difficulty, the so called phase problem, arises because although the record of mass extinctions is essentially complete over the past $\approx$ 270 My and the Sun's present position is close to the Galactic plane, we now seem (unexpectedly on the model) to be roughly halfway between extinctions (Raup and Sepkoski 1984).

A possible solution to both problems is to assume (e.g. Thaddeus 1986; Bailey et al. 1986) that the required encounters between the perturbers and the Solar System were more strongly modulated in the past than now. This may be justified because the amplitudes of oscillation of stars as old as the Sun are mostly significantly greater ($\approx$ 250pc, Wielen 1977; Fuchs and Wielen 1987) than the present solar value ($z_\odot \approx$ 80pc). Clube and Napier (1986a) have therefore argued that over the past $\approx$ 270 My the Sun's amplitude of oscillation might have been more typical of other G stars of its age and that a recent close encounter with another body, for example Gould's Belt (Napier 1986) has reduced its velocity to the present value, simultaneously changing the orbital phase.

In order to study this possibility, the solar motion is assumed to be approximately harmonic perpendicular to the plane, that is

$$z(t) = z_{\odot} \sin [w(t + t_{\mathbb{C}})] \quad (5.26)$$

where t = 0 denotes the present time, w is the angular frequency and $t_{\mathbb{C}}$ is the time of the last crossing of the Galactic plane. If the present z-position and z-velocity of the Sun are taken to be ≅ 8pc north of the plane and ≅ 8 kms^{-1} away from the plane (Mihalas and Binney 1981; Stothers 1985) then $t_{\mathbb{C}}$ ≅ 1 My. It should be noted that other studies especially those in relation to young stars (de Vaucouleurs and Malik 1980) suggest a present z-position of ≅ 20-30 pc, but this has little effect on the conclusions.

Now, if a close encounter with another body occurred at a time $t = -t_{e}$, leading to a strong perturbation of the solar orbit, this itself would also produce an intense comet shower and an episode of mass extinction. According to the data of Raup and Sepkoski (1984), t_{e} ≅ 11 My, but an exact determination of the date of the most recent extinction event is difficult and other estimates cover a wide range (Napier 1986). In what follows, although this is not a crucial assumption, $3 \leqslant t_{e} \leqslant 17$ My is taken.

The orbit of the Sun prior to the encounter is therefore

$$z(t) = z_{i} \sin [w(t + t_{e}) + \S] \quad (5.27)$$

where $z_{i} > z_{\odot}$ is the prior amplitude of oscillation and § is a phase factor introduced to describe the distance of the

Sun from the plane at the time t_e of the encounter.

Therefore from (5.26) and (5.27)

$$z_e = z_\odot \sin [w(t_c - t_e)] = z_* \sin\delta \qquad (5.28)$$

or $$\sin \delta = \frac{z_\odot}{z_*} \sin\phi \qquad (5.29)$$

where $\phi = w(t_c - t_e)$. (5.30)

The pre and post-encounter velocities of the Sun can also be derived,

$$\dot{z}_e \; (-t_e^-) = wz_* \cos\delta \qquad (5.31)$$

and $$\dot{z}_e \; (-t_e^+) = wz_\odot \cos\phi \qquad (5.32)$$

The required impulse Δv_z in the z direction is therefore,

$$\Delta v_z = wz_\odot \cos\phi - wz_* \cos\delta \qquad (5.33)$$

or $$\frac{\Delta v_z}{wz_\odot} = \cos\phi \pm (r_*^2 - \sin^2\phi)^{1/2} \qquad (5.34)$$

where $r_* = z_*/z_\odot$. The solution for Δv_z as a function of $z_*/z_\odot$ thus has two branches, depending on whether the encounter merely slows the Sun down or actually reverses its direction of motion. Now for T = 30 My, the range in ϕ corresponds to the range in t_e, that is $-1.6 \leqslant \phi \leqslant -0.2$. However, whatever the exact phase, it is readily verified that the solutions for $\Delta v_z/wz_\odot$ are bounded for all ϕ by solutions corresponding to $\phi = 0$, i.e. $\Delta v_z = wz_\odot (1 \pm r_*)$. Since $r_* > 1$ (because $z_* > z_\odot$), the encounter must produce an impulse in the z direction whose magnitude $|\Delta v_z| > wz_\odot(r_* - 1)$.

Thaddeus and Chanan (1985) showed that a minimum r_* value of $\gtrsim 3$ was necessary in order to achieve a signal-to-noise ratio of 2 in the encounter rate with molecular clouds. In order to be extremely conservative, it will be assumed that $r_* \gtrsim 3/2$ will produce a sufficient signal-to-noise ratio in the terrestrial record. Thus, allowing any other perturbers to have a scale height ξ times that of molecular clouds, for $z_{\odot} \cong 80$ pc, the initial amplitude of the solar motion prior to the hypothetical massive encounter must be $z_i \gtrsim 120\xi$ pc. For $\xi = 1$, since the present mid plane velocity, $wz_{\odot} \cong 8$ kms^{-1}, the minimum z-velocity change necessary to produce the required change in amplitude is $V_{min} \cong 4$ kms^{-1}. Therefore, for an encounter with a point mass M, impact parameter b and relative velocity V, the total impulsive velocity change Δv must satisfy

$$\Delta v = \frac{2GM}{bV} > |\Delta v_z| \gtrsim \xi V_{min} = wz_{\odot}(r_i - 1)\xi = 4\xi \text{kms}^{-1} \quad (5.35)$$

This inequality places stringent limits on the likely mass of the body encountered. A constraint is obtained by requiring that the intensity of the accompanying comet shower should not be too great, since the evidence of the terrestrial record does not suggest that the most recent event was particularly extreme (Figure 5.1). This probably requires $a_{sh} > 10^4$ AU (cf. Figure 5.4), and so combining equations (5.35) and (5.17),

$$\frac{M}{M_{\odot}} > 1.681.10^5\, q_{15}^{-1/2}\, \xi^2\, V_{20} \left(\frac{V_{min}}{4\text{kms}^{-1}}\right)^2 \left(\frac{a_{sh}}{10^4\text{AU}}\right)^2 \quad (5.36)$$

Therefore, if the Solar System has indeed been recently decelerated in the z-direction as required for the Galactic hypothesis to satisfy the signal-to-noise and phase constraints of the terrestrial record, the body which caused the impulse must have had $M >> 1M_{\odot}$. The mass range implied, suggests that a sufficiently massive GMC may have caused such a perturbation (e.g. Clube and Napier 1986a), although if $\xi > 3$ (corresponding to a dark matter scale height comparable with that of the stellar disc) the required mass of the cloud is excessively large. Using the CO data of Dame et al. (1987), observations of molecular clouds in the solar neighbourhood (< 350 pc) do not show the existence of any sufficiently massive centrally condensed body in the right direction and in any case the required impact parameter would probably correspond to a penetrating encounter of the cloud with attendant reduced net effect. The data of Taylor et al. (1987) on Gould's Belt show it to be too large a structure and not massive enough to provide the required impulse. If the halo is composed of massive black holes (Lacey and Ostriker 1985) or dark clusters (Carr and Lacey 1987), then their mass of $\sim 10^6 M_\odot$ is of the required order, but the relative velocity as they pass through the disc is ~ 250 kms^{-1} (Ipser and Semenzato 1985), which rules them out as suitable candidates. Moreover, as ξ increases the required change in velocity of the Sun becomes quite prohibitive.

Unless the scale height of the hypothetical perturbers is less than 200 pc (i.e. $\xi < 3$), the signal-to-noise and phase problems are most unlikely to be overcome by postulating a recent close encounter of the Solar System with a GMC. Currently accepted values for the scale heights of dark matter tend to be larger than this (e.g. Bienaymé et al. 1987).

Lastly, two further difficulties for the Galactic explanation of mass extinctions by periodic comet showers need to be mentioned. First, interactions with perturbers of any kind will inevitably change both the amplitude and phase of the solar orbit about the Galactic plane, so that the extent to which strict periodicity is present in the geological record imposes a tight constraint on the theory. In general, an astronomical hypothesis of the kind considered here will not predict a constant signal-to-noise ratio or phase over a very extended period of time. Secondly, the geometry of the astronomical model naturally predicts that a few encounters will have much smaller impact parameters than the rest, and this will be reflected in the distribution of values of a_{sh} (equations 5.20 - 5.22) which scales roughly in proportion to b. Since the Oort Cloud must be centrally condensed on the model (Figure 5.4), this implies a rapidly falling frequency distribution of individual shower intensities which is not matched at all by the terrestrial record of mass extinctions (Figure 5.1). Neither of these difficulties can be accurately quantified with present knowledge (the first because the nature of the perturbers is still unknown, the second because the link between the comet flux and the mass extinction rate has not been firmly identified), although both appear to militate against a direct astronomical link with periodic mass extinctions.

In conclusion, if the strong 30 My periodicity apparent in the geological record is confirmed, direct astronomically induced processes can be paradoxically almost certainly be ruled out, as no known observed or dark matter candidates have sufficient mass density or small enough scale height. This suggests that any periodicity, especially in the cratering record is probably spurious (c.f. Shoemaker and Wolfe 1986; Tremaine 1986). The claim that an apparent 30 My periodicity in volcanic activity is induced by cometary showers (Pandey and Negi 1987), irregardless of the uncertain link between comets and induced volcanism (Rampino 1987), must also be incorrect. Apart from the cratering record, periodicities in the other terrestrial indicators must then be ascribed to processes intrinsic to the Earth.

If the evidence for periodicity in the geological record is shown to be false, it may still be possible to attribute global mass extinctions to a weakly modulated rate of arrival of very massive comets in near-Earth orbit, as previously suggested for periodic extinctions (Clube and Napier 1986a). The mean interval between mass extinctions would then depend, among other things, on the mass distribution of the largest comets (large enough to cause a significant terrestrial trauma), and the biological reaction to such events.

The claimed 30 My periodicity can therefore not be used to constrain the masses of GMCs. Finally, the next section briefly reviews one more aspect of the interaction of GMCs with the Oort Cloud which has in the past been used to constrain GMC masses.

5.5 THE SURVIVAL OF THE OORT CLOUD

It has been suggested that very close encounters with GMCs over the lifetime of the Solar System would lead to a complete stripping of comets from the Oort Cloud (Clube and Napier 1982b; Napier and Staniucha 1982). If this is correct, then a presently observed Oort Cloud implies replenishment of comets from some source. It is well known that comet capture from interstellar space is an inefficient process, even taking into account three body encounters with planets (Valtonen and Innanen 1982; Torbett 1986c). Clube and Napier (1982a, 1984a) therefore suggested a three body process using GMCs. There are some arguments for believing that there exists a high space density of comets in molecular clouds (Clube and Napier 1982a, 1985; Bailey 1987), and in an encounter of the Solar System with a GMC, it was postulated that the Oort Cloud as well as being disrupted was then replenished with new comets. On this picture, although the Solar System may have had a primordial comet cloud, the presently observed comets are of interstellar origin. There are, however, many problems with this view including whether GMCs can confine comets for a long enough time (van den Bergh 1982) and whether this replenishment can occur often enough (Torbett 1986c).

If the Oort Cloud was not totally stripped over the lifetime of the Solar System, then of course there would be no need for comet replenishment. Bhat et al. (1986) pointed out that if the median mass of clouds was $1.3.10^5 M_\odot$ rather than the conventional $5.10^5 M_\odot$ (SSS 1984) a significant fraction of the Oort Cloud should in fact remain intact up to the present day, removing the need for Oort Cloud replenishment (cf. Hut and Tremaine 1985). This may be interpreted, in the light of problems with the replenishment mechanism as evidence once again for a lower α_{20} than advocated by SSS (1984).

However, there is another alternative, and that is to postulate a massive inner core to the Oort Cloud which is stable to even the very close encounters (Hills 1981; van den Bergh 1982; Bailey 1983a,b). The disrupted outer Oort

Cloud is then replenished with comets from the inner core. It may be that constraints on such a model can be provided by the total mass of the Oort Cloud, effect on planetary orbits and the short period comet flux (Bailey 1983a, 1986b; Paper VI) but at present such constraints only argue against extreme centrally condensed models of the Oort Cloud (Section 5.3). A model with $\gamma \simeq -2$ would mean that a significant fraction of the Oort Cloud would survive even with the higher values for the masses of GMCs.

Therefore, if the model of the Oort Cloud can be better specified then the survival of the Cloud may be used to constrain GMC masses. However, considerable uncertainty in how centrally condensed the Oort Cloud is, means that at present the higher masses of SSS (1984) cannot be totally ruled out by this argument.

CHAPTER SIX

THE LIFETIME OF GIANT MOLECULAR CLOUDS AND H_2 IN THE VIRGO CLUSTER SPIRALS

6.1 INTRODUCTION

The early surveys of CO in the Galaxy, adopting a large value of α_{20}, had indicated a large amount of H_2 in the inner Galaxy, > 5 times the mass of HI at the peak of the molecular ring (e.g. Solomon, Sanders and Scoville 1979). From this result Scoville and Hersh (1979) argued that H atoms would usually be in the form of H_2 rather than HI which suggested that the lifetime of GMCs > 10^8 - 10^9 y. In fact, early estimates of the growth of 10^5 - $10^6 M_{\odot}$ clouds also indicated lifetimes $\approx 10^9$ y which seemed to confirm this picture.

However, work on the chemical evolution of the Galaxy (Section 4.6) and the γ-ray data (Bhat et al. 1985; Strong et al. 1987) has suggested that the mass of H_2 in the inner Galaxy is roughly equal to the mass of HI, the conversion factor α_{20} being $\simeq 3$ in the solar neighbourhood and varying as a function of Galactocentric radius. This would indicate that the lifetime of GMCs $\lesssim 10^8$ y (Blitz and Shu 1980). It is the intention of this Chapter to ask whether this is consistent with current estimates of the lifetime of GMCs. The argument can of course be inverted and evidence for 'short' GMC lifetimes may indicate lower H_2 estimates in the inner Galaxy.

The question is quite complex and so Section 6.2 re-examines the argument of Scoville and Hersh (1979) and its various assumptions. Evidence is presented that it is the radial dependence of the lifetime of the HI phase which controls the mass ratio of H_2/HI. Previous arguments for a long lifetime of GMCs are shown to be no longer valid and evidence favouring a short lifetime is presented.

It is against this background that recent CO surveys of galaxies in the Virgo cluster have been used to claim GMC lifetimes $\gtrsim 10^8 - 10^9$ y (Kenney and Young 1986; Stark et al. 1986). As the possibility of making an estimate of the lifetime of the molecular gas (or even putting a lower limit to it) is clearly attractive and important for the mass of gas in the inner Galaxy, these claims are critically examined in Section 6.3.

This leads on to a consideration of α_{20} in the Virgo spiral galaxies. The conventional approach in estimating the mass of H_2 in external galaxies has been to assume that the value of α_{20} determined locally, applies universally (e.g. Young and Scoville 1982a; Dickman et al. 1986). Section 6.4 suggests that the cluster environment in Virgo changes α_{20} with respect to isolated galaxies and uses evidence from SFRs and IR results to confirm this claim. Finally, the consequences of these results for the evolution of the Virgo galaxies are briefly described.

6.2 THE LIFETIME OF GIANT MOLECULAR CLOUDS

6.2.1 The mass of H_2 in the inner Galaxy

Scoville and Hersh (1979) proposed that if the ISM constantly cycles gas through the H_2, HI and HII phases, and the relative abundances are maintained in steady state, continuity demands that the mass flow rate out of the H_2 phase (M_{H_2}/τ_{H_2}) must equal the flow rate out of the HI and HII phases into H_2 (M_{HI}/τ_{HI}), that is

$$\frac{M_{H_2}}{\tau_{H_2}} = \frac{M_{HI}}{\tau_{HI}}. \tag{6.1}$$

The time scale for a typical low density atomic or ionised hydrogen region to exist is $\simeq 10^8$y, so that if $M_{H_2} > M_{HI}$ then $\tau_{H_2} > \tau_{HI}$. The quantity τ_{H_2} was directly identified with the GMC lifetime.

However, since GMCs have different masses, the definition of their lifetime as a group, τ_{H_2}, depends on the time scale of evolution of a cloud as a function of its mass, t(m) and on the mass distribution of clouds

$$f(m)\,dm = m^{-\nu'}dm \tag{6.2}$$

where $\nu' \simeq 1.5$ (Stark et al. 1987). If GMCs are produced from HI behind shocks (e.g. Bash et al. 1977) then τ_{H_2} is unambiguous, being the average mass weighted period between cloud formation and disruption. However, if GMCs are formed by cloud-cloud collisions, with larger molecular clouds growing at the expense of smaller ones, τ_{H_2} includes both the time span of the giant cloud (τ_{GMC}) and the time taken for smaller clouds to grow to that mass. Therefore, in the following τ_{H_2} will be termed the lifetime of the molecular phase with $\tau_{H_2} \geqslant \tau_{GMC}$.

At the peak of the molecular ring, the estimate of H_2 presented in this work (Figure 4.9) gives $M_{H_2}/M_{HI} \sim 1.0$ which implies by equation (6.1) $\tau_{H_2} \simeq 10^8$y. In contrast, the distribution of SSS (1984) gives $M_{H_2}/M_{HI} \sim 5$ and therefore $\tau_{H_2} \simeq 5.10^8$y. It is important to be clear about the uncertainties in this analysis. The first is the assumption that the relative abundances of HI and H_2 are maintained in a steady state. This is not strictly true as gas is continually depleted due to star formation, some of the gas being returned to the ISM but some being locked up in long lived stars or dead stellar remnants. The aspect of star formation may be examined crudely in the following way. The rate of change of H_2 is given by

$$\frac{dM_{H_2}}{dt} = -\frac{M_{H_2}}{\tau_{H_2}} + \frac{M_{HI}}{\tau_{HI}} . \qquad (6.3)$$

Assuming that all H_2 cycles back to HI through stars, which lock up a fraction $(1-\alpha)$, then

$$\frac{dM_{HI}}{dt} = -\frac{M_{HI}}{\tau_{HI}} + \frac{\alpha M_{H_2}}{\tau_{H_2}} . \qquad (6.4)$$

Scoville and Hersh (1979) assumed $\alpha = 1$ and $dM_{H_2}/dt = dM_{HI}/dt = 0$ in order to obtain equation (6.1). In Section 2.4, the fraction of molecular gas to the total hydrogen was shown to be empirically correlated with the metallicity Z, such that

$$\frac{M_{H_2}}{(M_{H_2} + M_{HI})} = AZ^{-b} \qquad (6.5)$$

where $b \cong 1.3 - 1.4$. This expression yields

$$\frac{1}{M_{H_2}}\frac{dM_{H_2}}{dt} = \frac{1}{M_{HI}}\frac{dM_{HI}}{dt} + 2.3b\left(\frac{d\log Z}{dt}\right)\left(\frac{M_{H_2}}{M_{HI}} + 1\right). \qquad (6.6)$$

Substituting equations (6.3) and (6.4) into (6.6) gives

$$\frac{1}{\tau_{H_2}}\left(\frac{M_{HI} + \alpha M_{H_2}}{M_{H_2} + M_{HI}}\right) = \frac{1}{\tau_{HI}}\left(\frac{M_{HI}}{M_{H_2}}\right) - 2.3b\,\frac{d\log Z}{dt} \qquad (6.7)$$

which reduces in the limit $\alpha \rightarrow 1$ and $d\log Z/dt \rightarrow 0$ to equation (6.1). From Figure (4.10), dlogZ/dt over the past 5Gy at R_G = 6kpc may be estimated to be $\cong 10^{-10}$ dex y^{-1} which over 10^8y makes a negligible contribution if $M_{HI}/M_{H_2} \sim 1$. Section 4.2 estimated the returned fraction as 0.4 - 0.6, but α will be effectively much higher as not all the H_2 will form stars (say 50%). We therefore conclude that the effects of the relative abundances not being constant will only alter lifetimes derived from equation (6.1) by at most 20%.

On the basis of this, we may now go on and examine equation (6.1) in the context of variation with Galactocentric radius. In Figure 6.1 the variation of M_{H_2}/M_{HI} has been derived as a function of R_G, using the H_2 distributions of SSS (1984) and the present work (Figure 4.9). Assuming that each disc annulus is closed (i.e. there are no significant gas flows), this variation also represents τ_{H_2}/τ_{HI}, which varies by at least an order of magnitude over the disc of the Galaxy.

Present theories of cloud formation, whether by large scale gravitational instability or cloud-cloud collisions are not dependent on whether the gas is H_2 or HI, and in fact the observation that the size spectrum of molecular clouds both in the inner and outer Galaxy is very similar to the HI size spectrum as measured in the solar neighbourhood (Tereby et al. 1986) indicates that the formation mechanism is the same. The problem is therefore, why does M_{H_2}/M_{HI} vary by over an order of magnitude. Elmegreen and Elmegreen (1987b) have found a similar trend in individual 'superclouds' of mass $\simeq 10^7 M_\odot$. The total cloud mass appears to be constant as a function of R_G (Grabelsky et al. 1987) but molecular cores become less massive and atomic envelopes become more massive with increasing R_G. Figure 6.1 suggests that the increase of M_{H_2}/M_{HI} with decreasing R_G could be due to either increasing τ_{H_2} in the inner Galaxy or decreasing τ_{HI}.

If molecular clouds were held up from collapse longer in the inner Galaxy then τ_{H_2} could be higher. However,

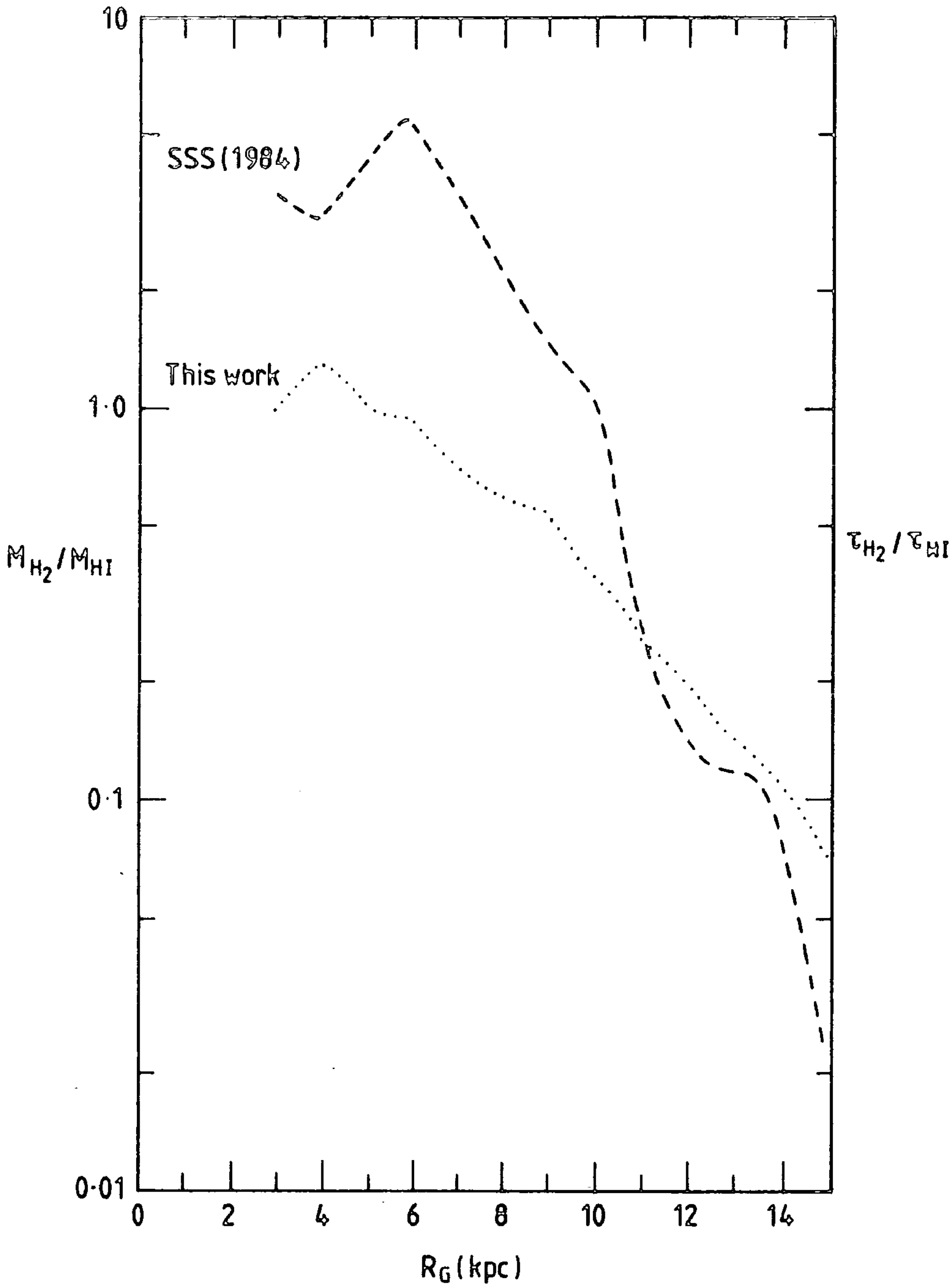


Figure 6.1 : The ratio of the mass of H_2 to the mass of HI as a function of Galactocentric radius. HI values have been averaged from Table A.2.1 (Appendix) while H_2 has been taken from SSS (1984) and the present work (Figure 4.9). Following the argument of Scoville and Hersh (1979) this variation also represents the ratio of the lifetime of the molecular and atomic phases.

firstly if τ_{H_2} were responsible for the variation, a value of $\tau_{H_2} \simeq 10^8$y at the 6kpc ring would imply $\tau_{H_2} \lesssim 10^7$y in the outer Galaxy. If GMCs are built up from cloud-cloud collisions (Section 6.2.2), the time-scale for forming $10^5 - 10^6 M_\odot$ clouds is > 10^7y, implying that the size spectrum of molecular clouds in the outer Galaxy would be very different. However, observations of the size spectrum show no such effect (Tereby et al. 1986). This suggests that τ_{H_2} may be roughly constant with radius.

Secondly, evidence for a roughly constant τ_{H_2} may be derived from the observed SFR. The rate of flow of H_2 into HI must be connected to the SFR (Chapter 2). The SFR (ψ_S) will be approximately given by

$$\psi_S \simeq \eta \frac{M_{H_2}}{\tau_{H_2}} \qquad (6.8)$$

where η is the efficiency of star formation, or essentially the amount of H_2 that forms stars. The results of Section 2.3.1 showed a correlation in the disc of the Galaxy of $\psi_S \propto M_{H_2}^k$ with k close to unity. Equation (6.8) therefore implies $\tau_{H_2} \propto \eta$ as a function of R_G. Myers et al. (1986) have recently estimated the stellar content of molecular clouds in the inner Galaxy from the far-IR and Lyman α luminosities. The mass of stars (M_S) derived in this way represents only the stars currently present in the molecular cloud and for the total mass of stars it must be multiplied by a factor R'> 1 in order to account for stellar production during the whole of the cloud lifetime. There is no way to reliably estimate R' for each cloud, but using the ratio of M_S to the cloud mass (M_C) may give some indication of the trend of η ($\propto M_S/M_C$) with R_G.

Following Myers et al. (1986), deriving M_C from the CO data of Dame et al. (1986) using $\alpha_{20} = 4$, the quantity M_S/M_C is shown as a function of Galactocentric radius in Figure 6.2. There is considerable spread, but there is no evidence

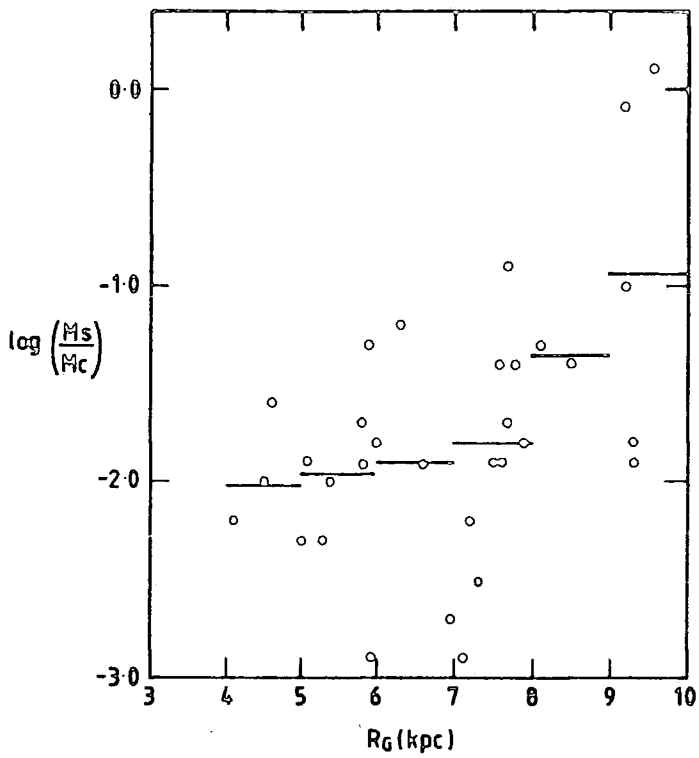


Figure 6.2 : The ratio of the stellar mass in molecular clouds, estimated from far-infrared and Lyman α luminosities, to the mass of the cloud as a function of Galactocentric radius. Data are taken from Myers et al. (1986) following their adoption of $\alpha_{20} = 4$ for the estimate of M_C. The horizontal bars represent mean values.

for M_S/M_C (and hence η) decreasing with increasing R_G, which would be needed to explain ψ_S if a τ_{H_2} variation is responsible for the M_{H_2}/M_{HI} variation. In fact the trend in Figure 6.2 is in the opposite sense. It is interesting in this context to explore the effect of a metallicity correction to α_{20}. Using the metallicity measurements of Figure 2.5, the difference in mean metallicity between R_G = 10kpc and R_G = 6kpc is $\cong$ 0.4 dex. If α_{20} were inversely proportional to metallicity (Bhat et al. 1985), this would decrease the estimated cloud mass and therefore increase $\log(M_S/M_C)$ by $\cong$ 0.4dex at 6kpc compared to 10kpc, thus flattening out any gradient. It therefore appears a variation in τ_{H_2} cannot account for the M_{H_2}/M_{HI} variation, and if a metallicity correction to α_{20} is used, τ_{H_2} and the star formation efficiency (assuming that this is represented by M_S/M_C) are constant with R_G.

Returning to Figure 6.1, the variation of M_{H_2}/M_{HI} must then be due to a variation in τ_{HI} as a function of R_G, that is, the lifetime of the molecular phase is fairly constant, but the rate of conversion of $HI \rightarrow H_2$ increases with decreasing R_G. This is consistent with the suggestion of Section 2.4 that in a region of more grains per cm^{-3} more HI evolves into H_2. Assuming that the catalytic process for $H + H \rightarrow H_2$ is completely efficient for all H atoms arriving at a grain surface, then the rate of formation of H_2 is

$$\frac{dn(H_2)}{dt} = \frac{1}{2}\, n(H)\pi a^2 n_g V_H \qquad (6.9)$$

for grains of radius a, number density n_g and where V_H is the probable velocity of H atoms (Dyson and Williams 1980). Of course for a mass M_{HI} to be all converted to H_2, $dn(H_2)/dt \propto (M_{HI}/\tau_{HI})$ and therefore

$$\tau_{HI} \propto \frac{1}{n_g} \qquad (6.10)$$

If τ_{H_2}, a and V_H are roughly constant with R_G, then the decrease in τ_{HI} from R_G = 10kpc to 6kpc required to give M_{H_2}/M_{HI} for the radial distribution of M_{H_2} advocated in this work (Figure 6.1) is $\approx$ 2.5. This is roughly the increase in metallicity over the same region, which is consistent with the grain density following the metallicity. (Section 2.5

and Appendix A.2.5 have argued that the dust-to-gas ratio is proportional to the metallicity, but the total gas is roughly constant over this region). The variation for SSS (1984) can also be explained by an increase in metallicity combined with an increase in total gas.

The situation concerning individual clouds will no doubt be more complex. Elmegreen and Elmegreen (1987b) suggest that superclouds of mass $\approx 10^7 M_\odot$ could form by gravitational instabilities in the ambient interstellar gas (Elmegreen 1987d) while molecular clouds inside form differently by agglomeration of smaller clouds. They ascribe the variation in molecular fraction per cloud as due to the variation in average pressure in the disc of the Galaxy, arguing that greater pressure implies greater density and therefore molecular line shielding being more important. However, it may be simply that the dust-to-gas ratio controls the molecular fraction, not only by enhancing evolution of $HI \rightarrow H_2$ but also by increasing opacity. Franco and Cox (1986) have shown that any of the proposed mechanisms to agglomerate interstellar clouds will be effective in the molecularization of the ISM as long as they can generate column densities above

$$N_T \approx 5.10^{20} \left(\frac{Z_\odot}{Z}\right) cm^{-2} \qquad (6.11)$$

where the metallicity has been taken proportional to the dust-to-gas ratio. Thus for higher metallicities, it is easier to form molecular clouds, as dust grains provide the opacity necessary to prevent the external UV radiation flux from penetrating.

We tentatively suggest therefore that the observed variation in M_{H_2}/M_{HI} with R_G, both in disc annuli and individual superclouds can be understood in terms of the variation in τ_{HI} due to the variation in metallicity and hence dust-to-gas ratio. It should be noted that this mechanism does not differentiate between the two different H_2 distributions until τ_{H_2} is fixed by other means. However, caution is needed in any application of equation (6.1) as τ_{HI} is a function of Galactocentric radius. Any derivation of M_{H_2} from this equation probably needs as much care with evaluating τ_{HI} as with τ_{H_2}.

Nevertheless, we take $\tau_{HI} \simeq 10^8$y at 6kpc and now consider the evidence concerning an estimate of τ_{H_2}.

6.2.2 The formation and growth of GMCs

One of the main arguments for a lifetime of the molecular phase > 10^8 - 10^9y came from initial estimates of the time needed to 'grow' GMCs by cloud-cloud collisions (Scoville and Hersh 1979; Kwan 1979). The time required to build up clouds of 10^5 - $10^6 M_{\odot}$ simply by random cloud-cloud collisions of smaller clouds is 2.10^8 - 10^9y implying of course, τ_{H_2} at least greater than these values.

However, these models neglected the tendency of spiral arm gravitational fields to enhance substantially the number density of clouds and thereby increase cloud-cloud collisions. Recent numerical simulations have shown that much shorter formation times are possible when a spiral potential is imposed (Tomisaka 1986; Combes and Gerin 1987). Kwan and Valdes (1983) found that the rate of growth of massive clouds near a potential minimum such as a spiral arm was enhanced by a factor 3-6 over the simple random case, large GMCs forming within 4.10^7y. Mutual gravitational attraction between neighbouring clouds can also increase the rate of coalescence. Kwan and Valdes (1987) modelled the local gravitational interaction between clouds closer than 400pc and found the rate of coalescence of larger clouds increased by a factor of 3. Large scale gravitational interactions have yet to be modelled, but once again it is thought that the rate of coalescence will be increased (Roberts and Steward 1987). Elmegreen (1987a) has also shown that growth times can be reduced to $\lessapprox 6.10^{7}$y, simply by taking account of the effect of magnetically enhanced collision cross-sections.

An allied argument concerns the cloud-cloud velocity dispersion of molecular clouds. Stark (1979, 1983, 1984) found that the velocity dispersion of clouds was roughly constant over the cloud mass range $10^{2} - 10^{5.5}$ $M_{\odot}$. Equipartition of the random kinetic energy of the clouds, due to the clouds surviving several cloud-cloud collision times would predict the velocity dispersion proportional to $M_{c}^{-1/2}$. Since equipartition is not observed, mechanisms other than cloud agglomeration must dominate the kinetic energy of the cloud ensemble. This may be taken as evidence that clouds do not form by agglomeration or that there exists some process which injects kinetic energy into larger clouds. Jog and Ostriker (1987) have suggested that the gravitational scattering of massive clouds off each other in the differentially rotating Galactic disc constitutes an effective gravitational viscosity which could be such a process. Clouds with mass $\gtrsim 10^{5} M_{\odot}$ do show a velocity dispersion consistent with equipartition (Stark 1983; Scoville et al. 1987). However, the relevance for cloud lifetimes is that although early calculations had suggested that equipartition through cloud-cloud collisions could be achieved only in $\gtrsim 10^8 - 10^9$ y, recent calculations indicate that equipartition can be achieved in $\gtrsim 5.10^7$ y (Scoville et al. 1987; Jog and Ostriker 1987). In fact these recent calculations do not include the effects of gravitational focusing or the effect of spiral arms, both of which would shorten this timescale even further.

If the velocity dispersion of molecular clouds, (or clouds $<10^5 M_{\odot}$) can be taken as evidence for formation mechanisms other than cloud-cloud collisions, these formation mechanisms have even shorter timescales. The Parker instability (Mouschovias et al. 1974; Blitz and Shu 1980) where cloud formation proceeds due to magnetic instabilities in the gas layer has a growth time of $\cong 2.10^7$ y (Elmegreen 1982), while formation of clouds due to large scale gravitational instability also has a growth time of $\cong 2.10^7$ y (Cowie 1981; Elmegreen 1987d).

We therefore conclude that earlier values of $\tau_{H_2} \cong 10^8 - 10^9$ y from a consideration of the growth of GMCs are no longer valid; there is still no general agreement on the mechanism of growth, but all current mechanisms favour growth times $< 10^8$ y.

6.2.3 Spiral arms

The question of whether GMCs are confined and formed in spiral arms has been used to argue for both long and short lifetimes, the argument being that if GMCs are confined to spiral arms, then their lifetime must be $< 4.10^7$ y otherwise they will diffuse into the inter-arm region (e.g. Turner 1984).

Consequently, there have been extensive searches for spiral structure with conflicting results (Liszt 1985). Solomon and Sanders (1980) from the early CO surveys claimed no spiral pattern but these observations provided little information because of random and systematic motions (Blitz and Shu 1980). On the other hand, Cohen et al. (1980) claimed GMCs were only found in spiral arms, consistent with a short lifetime.

The picture at present is much more complicated, large-scale surveys of the Galactic plane showing two distinct cloud populations, (i) clouds with warm cores (> 10K) constituting ≈ 25% of the total population and ≈ 50% of the total emission, clearly associated with HII regions and Galactic spiral arms, and (ii) clouds with cold molecular cores (< 10K) constituting ≈ 75% of the total number and ≈ 50% of the total emission, distributed uniformly throughout the disc (Sanders 1981; Solomon et al. 1985; Scoville et al. 1986, 1987). Recent observations of external spiral galaxies confirm this picture (Rydbeck et al. 1985; Lo et al. 1987b). It appears that the size spectrum of clouds is not greatly different between arm and interarm regions (Scoville et al. 1987) although there is clear evidence for clustering of clouds with warm cores into aggregates (Rivolo et al. 1986). The estimation of the mass of the two populations is complicated by the temperature effect, but virial theorem mass estimates by Scoville et al. (1987) essentially show no difference between the two populations (but see Section 1.2 for uncertainties in this analysis).

Early theories of cloud formation had suggested GMCs were formed in spiral arms from HI and launched from them in ballistic orbits (Bash et al. 1977). Stark et al. (1987) have challenged this view that molecules form from interarm atomic gas in a spiral density wave. From a study of external spiral galaxies, there appears to be no obvious correlation between the surface brightness of CO and that the arm class, which suggests that density waves are not required to form molecules. A simple interpretation therefore is that molecular clouds form throughout the disc, and that spiral density waves merely organise the existing clouds (and other galactic material) into a spiral pattern. This is consistent with molecular clouds being found in the interarm regions, an interarm/arm contrast for HI (Elmegreen and Elmegreen 1987a) and the observation that the average SFR per unit area of a galaxy is relatively independent of the presence of an obvious wave mode (Elmegreen and Elmegreen 1986).

The clustering of clouds into aggregates could explain some results that molecular clouds are brighter in density wave spiral arms (Dame et al. 1986). It is a well known property of spiral galaxies that particle orbits have a tendency to linger in spiral arms in response to the gravitational attraction toward the local potential minimum in the arm. As a result individual cloud particles will often take as much time to move across spiral arms as in between. In addition, neighbouring particle trajectories tend to converge as they enter a spiral arm. This orbit crowding phenomenon has been shown in the numerical simulations of Roberts and Steward (1987) to allow larger clouds to assemble from smaller clouds and is the primary mechanism which underlies the organisation of GMC complexes along spiral arms. These complexes are loosely associated and are dissociated upon exciting the arm through the postarm divergence in the system's velocity field. Roberts and Steward (1987) point out on the basis of their results, determination of individual cloud lifetimes is difficult, as the individual clouds in their computed models live forever and yet they show strong concentrations in spiral arms. This counters earlier arguments that molecular clouds must be long lived because of the lack of spiral structure as well as the counter arguments that molecular clouds are short lived because they are observed primarily in spiral arms.

However, if the scenario is that clouds form throughout the disc and are built up into the largest complexes by orbit crowding in spiral arms, what does this mean for the lifetime of the molecular phase? Kwan and Valdes (1987) in detailed numerical simulations have studied this process and modelled the fragmentation of clouds. In order to fit the observed mass spectrum of clouds they find $\tau_{H_2} \lesssim 2.10^8$ y, a value also found by Turner (1984) in his similar examination of the SFR in the Galaxy. This upper limit is a little higher than the $\tau_{H_2} \simeq 10^8$y required for the M_{H_2} in the inner Galaxy advocated by this work, but well below the $\tau_{H_2} \simeq 5.10^8$y required by the M_{H_2} of SSS (1984).

A number of questions are still unclear, for example the significance of warm cloud cores. In the numerical simulations, giant cloud complexes are clearly confined to spiral arms but when compared to the warm core cloud population of Solomon et al. (1985) appear to have a different distribution along the arm, suggesting that the warm cores may not trace out the spiral arms uniformly. Nevertheless, once again we see that early arguments for long lifetime GMCs from the spiral arm distribution (e.g. Solomon and Sanders 1980) are not well founded, the evidence favouring $\tau_{H_2} \lesssim 2.10^8$ y.

6.2.4 Other considerations

There are a number of additional arguments to the ones previously outlined which suggest short lifetimes, $\lesssim 5.10^7$ y, certainly for GMCs and possibly τ_{H_2}. Many are well known, but here we briefly review them for completeness.

The gravitational binding energy of a cloud of mass $\approx 2.10^5 M_\odot$, and diameter $\approx$ 40pc is $\approx 10^{50}$ ergs. Blitz and Shu (1980) showed that $\approxeq 10^{51}$ ergs was available from OB star formation inside the cloud (assuming a small efficiency of $\approx 10^{-3} - 10^{-2}$ in converting radiant energy into expansion) over 10^7 y to disrupt the parent cloud. Even if OB star formation is slow in beginning after GMC formation, clouds would still be disrupted in a few x 10^7 y (Turner 1984). For clouds with mass < $10^4 M_\odot$, Mazurek (1980) calculated a disruption time-scale of $\simeq 4.10^6$ y. Therefore it seems very unlikely that GMCs where stars are forming can exist $\gtrsim 5.10^7$ y.

It is now well established that GMCs appear to be loose associations of smaller clouds or clumps (e.g. Blitz and Stark 1986; Blitz 1987). Random collisions between these clumps, at rates determined by their observed random motions, will ensure that they must coalesce into a centrally condensed cloud structure in $\approx 10^7$ y (Blitz and Shu 1980). Elmegreen (1985) has re-examined this point and added into the calculation the effect of the magnetic fields of the clumps to obtain a timescale of $\lesssim 2.10^{7}$ y. The observation that such centrally condensed structures are not seen in general, with the one exception of the ρ Oph cloud, once again suggests that GMCs have lifetimes of a few 10^{7} y.

An additional problem for longer lifetime GMCs ($\gtrsim 2.10^{8}$ y) is a suitable mechanism to support these clouds against collapse. The problem for theoreticians has always been to prolong GMC lifetimes for much longer than the free fall timescale ($\approx 10^{6}$ y). It has been suggested that this could be done by magnetic fields (Mouschovias 1976a,b), rotational support (Field 1978), the winds of T-Tauri stars (Norman and Silk 1980) or supersonic turbulence within the clouds (Scalo and Pumphrey 1982), but each of these mechanisms can be shown not to have enough energy to support clouds for longer than $\lesssim 4.10^{6}$ - 1.10^{7} y (Blitz and Shu 1980; Turner 1984; Elmegreen 1985). Even when global turbulence originating from galactic rotation provides a fresh input of energy (Henriksen and Turner 1984), GMCs can only be supported for a few x 10^{7} y before forming stars.

Finally, theoretical arguments and laboratory data support the suggestion that CO and long chain molecules can stick easily to grain surfaces at the low temperatures prevailing in GMCs (Allen and Robinson 1977; Leger 1983). If GMCs are long-lived in comparison with the time scale for absorption onto grain surfaces ($< 10^{7}$ y), it is surprising that larger depletions of such molecules are not seen. In order to have much longer GMC lifetimes, efficient mechanisms must be found to return molecules back to the gas phase, which may be difficult (Williams 1985; van Dishoeck and Black 1987).

In summary, therefore, present observational and theoretical evidence from the formation of GMCs, spiral arm structure and other considerations favour $\tau_{GMC} \lesssim 5.10^7$ y with the lifetime of the molecular phase $\tau_{H_2} \lesssim 2.10^8$ y. From the continuity argument of Scoville and Hersh (1979), this is consistent with the H_2 distribution in the inner Galaxy proposed in Section 4.6 of this work, much lower than the H_2 distribution of SSS (1984). It is in the light of this result, that claims have been made from CO observations of the Virgo cluster of galaxies for a much longer lifetime of GMCs and the molecular phase. In the following we critically examine these claims.

6.3 THE LIFETIME OF THE MOLECULAR PHASE FROM GAS STRIPPING IN THE VIRGO GALAXIES

Recent CO surveys of galaxies in the Virgo cluster (Young 1985b; Kenney and Young 1985, 1986; Stark et al. 1986) have led to the claim that the lifetime of the molecular phase, τ_{H_2}, is $\gtrsim 10^8 - 10^9$ y. Specifically, Stark et al. (1986, hereafter referred to as S) and Kenney and Young (1986, hereafter referred to as KY) studied total galaxy contents of HI and CO as a function of angular distance from the centre of Virgo, assumed to be coincident with M87. The interesting results found were that the ratio of CO/HI increased towards the cluster centre, as did the ratio of the CO 'diameter' to that of HI. S found no evidence for differences in results for early-type galaxies (Sab and earlier) and late-type (later than Sab). These results were explained in terms of HI being removed preferentially, compared with H_2, by ram pressure due to the intercluster medium (ICM). The argument then proceeds that if HI is removed from the inner disc, the molecular gas must survive for at least the cluster crossing time (3.10^8 - 10^9)y, since conversion from $H_2 \rightarrow HI$ would have led to its disappearance, in view of HI being swept away rather readily.

This argument for long molecular lifetimes is crucially dependent on the nature of gas stripping and on the assumption that α_{20} is not affected by the cluster environment. In this Section, we examine gas stripping and in Section 6.4 the value of α_{20} in the Virgo spirals.

6.3.1 The HI deficiency

It was suggested some time ago (Davies and Lewis 1973) that galaxies in the Virgo cluster are deficient in total HI mass with respect to field galaxies of the same morphological type. Although there have been some doubts (e.g. Tully and Shaya 1984) a majority of authors now arrive at the same conclusion that a significant number of Virgo spirals are depleted of HI (e.g. Chamaraux et al. 1980; Haynes et al. 1984; Haynes 1985; Guiderdoni and Rocca-Volmerange 1985; Huchtmeier 1985; Warmels 1986). Haynes and Giovanelli (1986) found that for galaxies less than 2.5° from the centre of the cluster, 75% of the observed galaxies are HI deficient. Between 2.5° and 5° the deficiency is still observed, but the fraction falls, disappearing at $\gtrsim 5^{\circ}$. This deficiency has been attributed to galaxy formation in the cluster environment, or the stripping of the gas by tidal encounters or interaction with the ICM. HI deficiency has been shown to be a phenomenon in some other clusters such as A262, A2147 and Coma but is by no means universal (Bothun et al. 1982; Giovanelli and Haynes 1985), the gas removal mechanism being efficient in some environments but not in others. The correlation of HI deficiency and cluster X-ray luminosity, rather than local galaxy density, suggests the predominance of galaxy-ICM interaction as the cause (Giovanelli and Haynes 1983; Haynes and Giovanelli 1986).

In addition, it has also been shown that HI discs of galaxies within 5° of the centre of the Virgo cluster are smaller compared to isolated galaxies of the same optical size (e.g. van Gorkom and Kotanyi 1985; Warmels 1985; Haynes and Giovanelli 1986). Giovanardi et al. (1983) and Giovanelli and Haynes (1983) further claimed that the gas was depleted in such a way that the surface density remained roughly constant. Using the data of Giovanelli and Haynes (1983), Figure 6.3 illustrates this, plotting the 'surface density' of HI (M_{HI}/D_{HI}^2) for galaxies Sab and later as a function of the angular distance (Θ) from M87. We have also plotted the isolated galaxy sample of Hewitt et al. (1983). The surface density appears to be roughly constant, although the statistics are poor at the smallest values of Θ, where for $\Theta < 2^{\circ}$ there might be a small reduction. A similar analysis has been carried out for the independent sample of Helou et al. (1984) and the trend confirmed. This sample is not strictly directly comparable in absolute surface densities to Giovanelli and Haynes (1983) because of a different definition of D_{HI}. This result strongly indicates that if HI is removed, it is taken from the outer parts of galactic discs, thereby decreasing

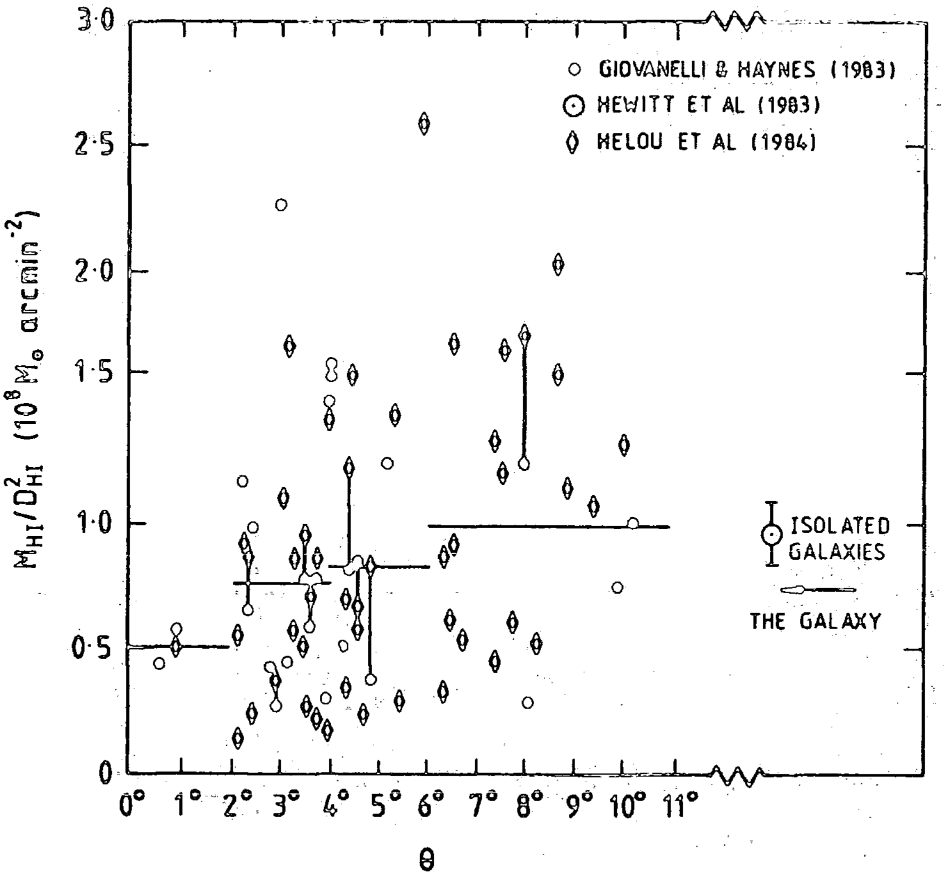


Figure 6.3 : The surface density of HI ($M_{HI}/(D_{HI})^2$) in spiral galaxies (Sab and later) as a function of angular distance form M87 (◉). The data of Giovanelli and Haynes (1983) and Hewitt et al. (1983) define D_{HI} as twice the distance from the galactic centre within which the best fit model contains 70% of its total HI mass. Helou et al. (1984) define D_{HI} as twice the distance from the galactic centre where the HI flux falls to 1/e of the peak value. These measures are strictly not directly comparable, however for galaxies in common, $\langle D_{HI}$ (Giovanelli and Haynes) $/D_{HI}$ (Helou et al.)$\rangle = 1.09$ with a standard deviation of 0.14. Common galaxies are linked by vertical bars. Horizontal lines represent median values. For comparison, the isolated galaxy sample of Hewitt et al. (1983) is shown with an assumed distance to Virgo of 15Mpc.

both M_{HI} and D_{HI}.

Of possible gas removal mechanisms, galaxy-galaxy interactions (Spitzer and Baade 1951; Icke 1985) can be shown to be not frequent enough in Virgo (Giovanelli and

Haynes 1983) while galactic winds (Matthews and Baker 1971) preferentially deplete the central galactic regions so increasing D_{HI} rather than the observed decrease. Although the details are complex, two mechanisms, ram-pressure stripping (Gunn and Gott 1972) and thermal evaporation (Cowie and Songaila 1977) both predict stripping of the outer regions and therefore a decrease in D_{HI}. As both S and KY have suggested ram-pressure stripping in order to explain their results, the next section examines the likelihood of this mechanism in the Virgo spirals.

6.3.2 The likelihood of ram-pressure stripping

Since the original suggestion of Gunn and Gott (1972), ram-pressure stripping has been studied theoretically by a number of workers (Gisler 1976; Lea and de Young 1976; Kent 1980; Farouki and Shapiro 1980; Shaviv and Salpeter 1982). In its simplest form it predicts that galactic gas will be removed if its density is below n_{ISM} where

$$n_{ISM} \simeq \left(\frac{V_g}{V_{esc}}\right)^2 \cdot n_{ICM} \qquad (6.12)$$

V_g being the velocity of the galaxy with respect to the ICM (the component perpendicular to the galactic plane), V_{esc}, the escape velocity from the galaxy at the point in question and n_{ICM} the density of the intercluster medium.

A number of observations have suggested its occurrence in galaxies in the Virgo cluster. As described above, the existence of a radial deficiency in HI despite damping projection effects coupled with smaller HI discs can be explained in principle by ram-pressure stripping. In the core of the cluster there appears to be a marginal correlation of HI deficiency with velocity (Giovanelli and Haynes 1983) although a larger sample (Haynes and Giovanelli

1986) shows no significant correlation. Deficient spirals seem to be on radial orbits (Dressler 1986; Giraud 1986) while the non-deficient are on more circular orbits and therefore avoid the high density ICM. Warmels (1985) found asymmetric HI distributions in the Virgo core which are expected for ram-pressure stripping. However, Haynes and Giovanelli (1986) found that dwarf galaxies which have a lower restoring force were not more HI deficient than spirals contrary to expectation.

Stark et al. (1986) evaluated expression (6.2) to obtain $n_{ISM} = 0.6\ cm^{-3}$ and concluded that a major part of the ISM was stripped. However, this is due to what appears to be an overestimate of both n_{ICM} and V_g. The value used for the ICM, $n_{ICM} = 3.10^{-2}\ cm^{-3}$ (Stark 1987b) is even higher than the density reasonable models would predict right at the centre of Virgo. Taking the model of Fabricant and Gorenstein (1983) for the X-ray surface brightness distribution about M87, n_{ICM} may be evaluated as

$$n_{ICM}(\theta) = (n_{ICM})_{o} \left[1 + \left(\frac{\theta}{a}\right)^2\right]^{-0.65} \qquad (6.13)$$

where the core radius a = 1.6'. At $\theta \simeq 2^{o}$, $n_{ICM} \simeq 10^{-4} cm^{-3}$ (Gorenstein et al. 1977; Forman et al. 1979) which gives $(n_{ICM})_{o} \simeq 2.7.10^{-2} cm^{-3}$. A more realistic average value for $\theta < 2^{o}$ therefore would be at least an order of magnitude lower than that quoted by S. Secondly, S use $V_g = 1800 kms^{-1}$ which is again too large for Virgo. The usual velocity dispersion is quoted to be 720-800kms^{-1} (Ftaclas et al. 1984; Huchra 1985) which gives $V_g \simeq 1300 kms^{-1}$ (i.e. $\sqrt{3} \times 760$).

Using $V_{esc} \simeq 400 kms^{-1}$ (for a typical galactic position equivalent to that of the Sun in our own Galaxy),

$V_g \lesssim 1300\ kms^{-1}$ and $n_{ICM} \lesssim 3.10^{-3}\ cm^{-3}$ in equation (6.12) gives

$$n_{ISM} \lesssim 0.032\ cm^{-3} \lesssim 7.7\ 10^{-4}\ M_{\odot} pc^{-3} \qquad (6.14)$$

Although Bosma (1981a) has argued that V_{esc} may be an upper estimate as the total mass density of the Galaxy may be higher than the total mass density found at comparable radii in many other galaxies, this effect will be less than a factor of 2.

Therefore the fact that it is only densities $\lesssim 10^{-2} cm^{-3}$ that are susceptible to ram-pressure loss indicates that it is only the extreme outer parts of galaxies in the sense of large galactocentric radius that are at risk. In order to illustrate this, we have taken the CO and HI radial profiles (Young 1985b; Warmels and van Woerden 1985) for the spiral galaxy NGC4254, and calculated the total gas as a function of galactocentric radius. If it were within 1^{θ} of the centre of the cluster, equations (6.12) and (6.13) imply that only gas with radius > 15 kpc will be swept by ram-pressure stripping. (As the CO falls off exponentially, even a high value of $\alpha_{20} = 8$ for the conversion of $CO \rightarrow H_2$ does not affect this result). The inner regions of galaxies, where the value of V_{esc} will be higher by ~ 2 and therefore n_{ISM} still lower by a factor 3-4, should be safe. It is this fact which has important consequences for the understanding of the CO results.

6.3.3 Comparison of the CO and HI results

The detailed time evolution of HI and H_2 and their inter-relation is quite a complex process (Chapter 2 and Section 6.2) and there is thus an attraction in studying the Virgo galaxies, if due to gas stripping, the $HI \rightarrow H_2$ process has been turned off. As S note, if this is correct and there is no environmental effect on the CO luminosity, then the process $H_2 \rightarrow HI$ can be studied in near-isolation.

S and KY argue that, in contrast to the HI deficiency, the CO contents are roughly normal. Further, Young (1985b) presents CO profiles as a function of galactocentric radius which are similar to the profiles of nearby spirals in that the bulk of the CO is found within 10 kpc of the galactic centre following a roughly exponential distribution.

Figure 6.4 reproduces from KY the ratio of the CO disc

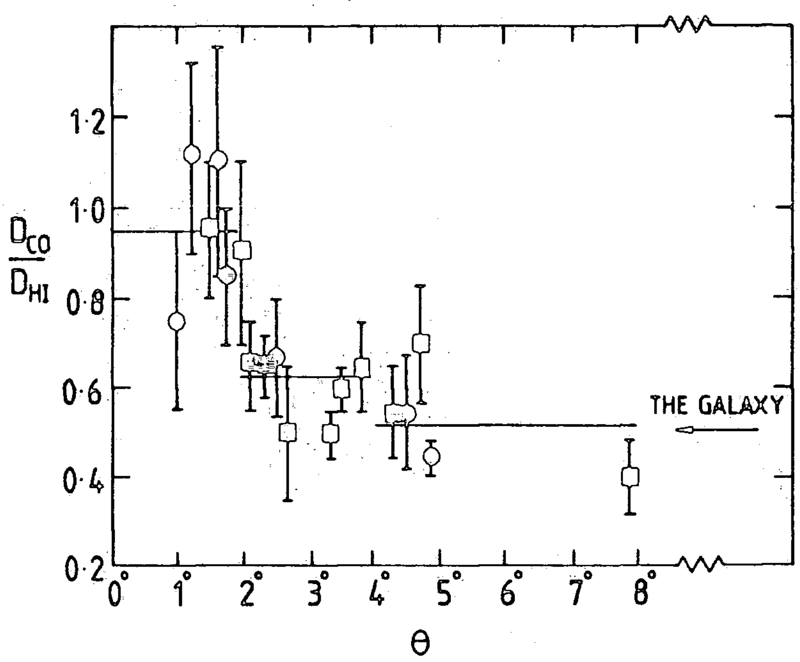
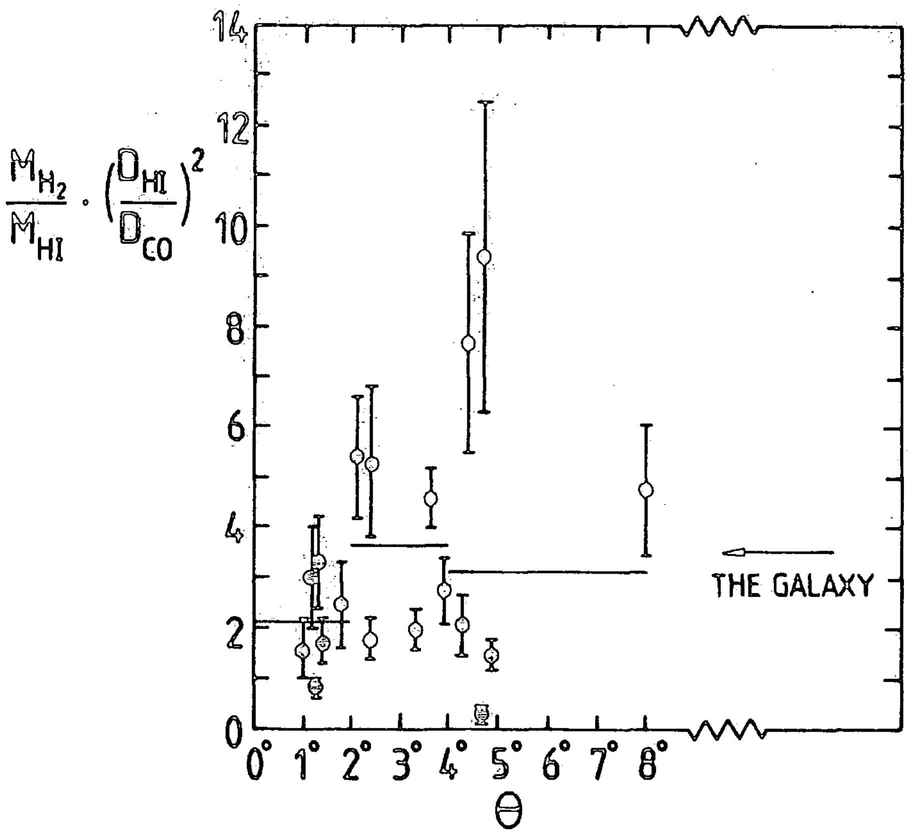


Figure 6.4 : The ratio of angular diameter for CO (D_{CO}) to that for HI (D_{HI}) for spiral galaxies in Virgo versus angular distance to the centre of the cluster, reproduced from Kenney and Young (1986). The horizontal lines represent median values. Squares denote types Sbc-Sc, circles denote Sab-Sb. D_{HI} and D_{CO} are the diameters at which HI falls to a surface density of 5.10^{19} atoms cm^{-2}, and H_2 (using $\alpha_{20} = 8$) falls to 4.10^{20} molecules cm^{-2}.

to the HI disc as a function of Θ. The increase in this quantity may be explained as D_{CO} being constant while D_{HI} falls closer to the cluster centre. This is consistent with ram-pressure stripping removing HI from the outer disc, with the CO, which is concentrated in the inner parts, being left alone. It is to be noted that if this explanation is correct, nothing can be inferred concerning the $H_2 \Longrightarrow HI$ process and H_2 lifetimes as both HI and H_2 are unaffected in the inner parts of a galaxy. Only if HI is removed from the whole of the disc, as KY point out, do the arguments for a long lifetime of H_2 hold.

In a more detailed examination of this problem, the ratio of mean surface density of H_2(CO) to that of HI has been derived by the present author as a function of Θ and this is given in Figure 6.5. If HI were being swept out



<u>Figure 6.5</u> : Ratio of surface densities of 'H_2' and HI against angular distance from the centre of the Virgo cluster. The data are taken from Kenney and Young (1986) and M_{H_2} is calculated using their constant value of $\alpha_{20} = 8$. The horizontal lines represent median values.

rather uniformly in the inner parts of the galaxies while the GMCs were left unaffected due to their higher density

(Kent 1980; Kritsuk 1983) this ratio would be expected to rise with decreasing Θ. In fact, the ratio is roughly constant, and may even fall somewhat below $\Theta < 2^{\Theta}$. A possible reason for this is advanced in the next section.

Therefore, the arguments favouring lifetimes of the molecular phase larger than $(3-10).10^{8}$ y are not well founded. In deriving these long lifetimes it is also assumed that there is no environmental effect on α_{20}. The next section shows that this assumption may also be questionable.

6.4 THE CO→H_2 CONVERSION FACTOR IN THE VIRGO GALAXIES

6.4.1 The effects of the inter-cluster wind on GMC

Implicit in the arguments advanced elsewhere, and by this Chapter so far, is the assumption that the intercluster wind has no effect on the GMC. Whilst it is true that ram pressure has probably a negligible effect on the tightly bound clouds (Kent 1980; Kritsuk 1983) its effect on the dust grains, and the thermal properties of the clouds may be quite considerable. As the ^{12}CO lines are optically thick, only effects in the outer layers of the GMC would be enough to change the CO/H_2 ratio. Two effects are likely, partial evaporation of grains returning more CO into the gas phase, and an increase in gas temperature which would affect α_{20}, as $\alpha_{20} \propto T_k^{-1.3}$ (Kutner and Leung 1985).

It has not proved possible to evaluate the magnitude of these effects, detailed modelling of GMCs (e.g. van Dishoeck and Black 1986) being outside the scope of this work. However, it is apparent that both effects result in an apparent increase in the CO signal for the same amount of H_2. If true, Fig. 6.5 would indicate an even greater loss of H_2 at $\Theta < 4^{\circ}$. A consequence would be that the formation of GMC was inhibited by the ICM as an increased loss of H_2 by way of short-life clouds which cycle to HI which is then lost, cannot be invoked, without also losing the HI in the denominator of the ordinate of Fig. 6.5.

Whatever the details it appears that one should expect a lower α_{20} for many galaxies in the Virgo cluster than for isolated galaxies. Both optical and IR information are now used to examine this effect.

6.4.2 The star formation rate

Direct measurements of the SFR from Hα fluxes show that for a given morphological type, the SFR in late type spirals within 6° of the centre of Virgo is less than in equivalent field galaxies by a factor of approximately 2 (Kennicutt 1983a, 1985).

This seems to be supported by the lack of high surface brightness disc galaxies (Phillips and Disney 1986) and smaller stellar discs (Peterson et al. 1979) again within 6° of the Virgo core. The observation that nuclear Hα emission (Stauffer 1983) and nuclear IR emission (Devereux et al. 1987) do not appear to be significantly depressed in spirals in the same region seems to indicate once again that the cluster environment has preferentially affected the outer regions of the galaxies. The deficiency of HI is correlated with UV colours (Giovanelli and Haynes 1983), galaxies being fainter than those with normal HI contents.

The colours of spirals within 6° of the core are redder than those in the field but are normal relative to field galaxies of the same HI content (Kennicutt 1983a; Stauffer 1983). Kennicutt (1983a) has used this to argue against recent gas stripping as this would make galaxies anomalously blue relative to their HI content. However, in understanding the SFR, it is the H_2 rather than HI that is important, the SFR (ψ_S) being well correlated with the mass of H_2 (Chapter 2). Using the recent CO data, a comparison of these two quantities is much more useful in giving information about the Virgo environment.

CO data have been compiled from KY and Knapp et al. (1987) and M_{H_2} has been derived using a datum value of $\alpha_{20} = 8$ (following KY) in the first instance. Following Kennicutt (1983b), the Hα data of Kennicutt and Kent (1983) have been used to derive ψ_S. This process involves estimating extinction and the use of an IMF and the result is uncertain to at least 50%. Figure 6.6 shows the ratio ψ_S/M_{H_2} as a function of angular distance from M87 for galaxies Sab and later.

Turner (1984) has shown that under some circumstances a GMC may break up into smaller molecular clouds which may once again be re-cycled through galactic spiral density waves on timescales $\simeq 2.10^8$y to form more GMCs. Having delayed star formation in this way he obtains a theoretical ratio $\psi_S/M_{H_2} \simeq 5.10^{-9}y^{-1}$. It can be seen that all of the Virgo spirals are lower than this, on average by a factor of 3.5. This is consistent of course, with the claim that the SFR is lower (Kennicutt 1983a) while the H_2 content is approximately normal (Young 1985; K; S).

It has been argued that for some spirals the SFRs estimated from Hα could be underestimated, the SFRs only

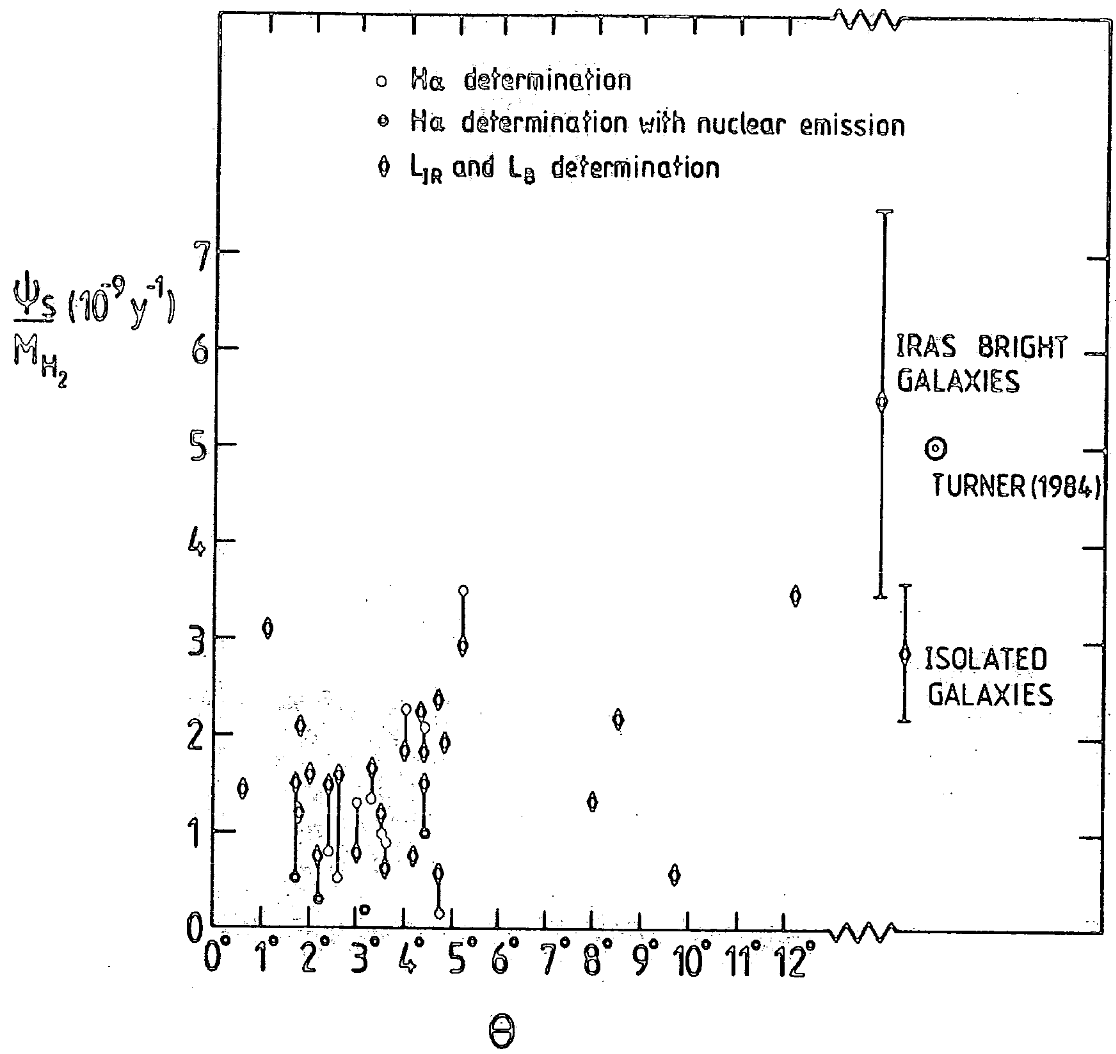


Figure 6.6 : The ratio of the SFR to the mass of H_2 (calculated using $\alpha_{20} = 8$) as a function of angular distance from M87 for galaxies Sab and later. The SFR has been determined in two independent ways as outlined in the text. Also shown for comparison are the IRAS bright galaxies and the isolated galaxies of Young et al. (1986a,b) and the theoretical ratio for Ψ_S/M_{H_2} of Turner (1984).

being correct for blue galaxies with large equivalent widths (Lonsdale-Persson and Helou 1987). Unfortunately, very few of the isolated galaxies in the Hα data of Kennicutt and Kent (1983) have CO measurements, so it is at present impossible to see whether this may be the reason for the above result.

However, an independent check of this can be made using

IRAS data for the Virgo galaxies. Knapp et al. (1987) give the 60μm and 100μm fluxes taking into account extended emission. Following equations (2.12) and (2.13) of Section 2.5.1, an estimate can be made of the SFR of O, B and A stars from the IR and blue luminosity (derived from RC2). The distance to Virgo has been taken to be 15Mpc. SFRs derived in this way are also shown in Figure 6.6, the same galaxies being joined by a vertical bar to their Hα determination. The trend suggested by the Hα determination is confirmed, with some scatter as expected.

It may be argued that the uncertainties in deriving in these ways make direct comparison with the value of Turner (1984) meaningless. Equation (2.12) obviously does not account for either the formation of low mass stars or the re-cycling of gas in the ISM, although to some extent these effects may balance. In addition, although IR emission is often associated with star formation (e.g. de Jong et al. 1984; Telesco et al. 1986) the situation may be quite complex. The IR emission may be only partially associated with star formation, a second contribution associated with the interstellar radiation field heating of diffuse material, and this fraction may vary considerably amongst galaxies (e.g. Pajot et al. 1985; Cox et al. 1986; Sekiguchi 1987; Lonsdale-Persson and Helou 1987; Walterbos and Schwering 1987; Wainscoat et al. 1987). However, it is encouraging that in Figure 6.6 the Hα and IR determinations show good agreement.

Furthermore, using exactly the same method as described above for the IR determination, we have also derived ψ_s/M_{H_2} for 27 IRAS bright galaxies of Young et al. (1986a) and 13 galaxies taken from the Karachentseva Catalogue of Isolated Galaxies (1973) presented by Young et al. (1986b). The average values of each of these samples are also plotted in Figure 6.6.

If the SFR can reasonably be derived from equations (2.12) and (2.13), and if Turner's (1984) model of star formation is viable, this immediately suggests that the use of $\alpha_{20} = 8$ for even the isolated galaxies is an overestimate by a factor of approximately two. If $\alpha_{20} \lessapprox 4$ were used then the IRAS bright galaxies would have a higher efficiency of star formation, a result to be expected as many are interacting systems (Kennicutt et al. 1987), and the isolated galaxy sample would be consistent with the model of Turner (1984). Due to the uncertainties involved, this may not be true, but what does seem clear is that the galaxies within 5° of the centre of the cluster have on average a much lower ψ_S/M_{H_2} compared to isolated galaxies of the same type.

This last result indicates either of two things. If the H_2 contents are 'normal', that is, there is no environmental effect on the conversion factor α_{20}, then the efficiency of star formation is reduced in the Virgo galaxies. The other possibility, as suggested in Section 6.4.1 above, is that α_{20} decreases because of the ICM and so a low H_2 mass appears to be 'normal', i.e. the use of the same α_{20} for the Virgo and isolated spirals overestimates M_{H_2} and so decreases ψ_S/M_{H_2}.

Concerning the first possibility, most of the theoretical studies suggest an enhancement in ψ_S rather than a lower efficiency (e.g. Dressler and Gunn 1983). Bothun and Dressler (1987) argue that the ram-pressure phenomenon, as well as stripping HI, could enhance star formation. Using Jura's (1976) relation involving the minimum mass required for cloud collapse as a function of external pressure, it appears that this mass is 20-30$M_{\odot}$ for rich clusters like Coma, which is 10-100 times less than the minimum collapse mass induced by the passage of Galactic density waves or supernovae shocks (Shu et al. 1972; Turner 1984). As the external pressure increases with decreasing θ, one should see a greater enhancement closer to the core. Therefore, in clusters with high ICM densities, ram pressure induced star formation is a real possibility. Of course, Virgo is not such a rich cluster as Coma, n_{ICM} being lower by a factor of $\sim$3 (Shanks 1987). Repeating the same calculation for Virgo, we obtain minimum masses of 35-50$M_{\odot}$ which shows that even in Virgo, induced star formation is still a possibility.

In reality, of course, the situation is likely to be much more complicated and difficult to model. If ram pressure is very effective in removing the HI medium, replacing it with a hot, but thin ICM, then cold GMC may rapidly evaporate. At present the theory of thermal evaporation (e.g. Balbus and McKee 1982) does not adequately describe the effects on cold dense clouds with a hot ICM, although Section 6.3.3. argued that ram pressure was not able to remove HI in the regions of GMC. Kent (1980) speculates that the molecular clouds could even experience a drag force which causes them to collect in the centre of the Galaxy. He also shows that if a hydrodynamical code is used to model the interaction, a bow shock forms at the interface of the galaxy with the ICM which facilitates the flow of material around rather than through the disc. This may even inhibit the excitation of cloud collapse, but it is unlikely that this would reduce the efficiency of star formation as compared to isolated galaxies.

Apart from the above uncertainties, the general view seems to be that the ICM should increase the efficiency of star formation rather than reduce it. Compression of gas in the inner portion of the galaxy may induce star formation while the outer disc is stripped of HI (Haynes and Giovanelli 1986). Therefore, the reason that ψ_S is low in the Virgo galaxies is because the H_2 content is low. To explain this low value, then within $\Theta = 5^{\circ}$,

$$\alpha_{20}\,(\text{Virgo}) \simeq 0.5\,\alpha_{20}\,(\text{isolated galaxies}) \qquad (6.15)$$

In fact, if the ICM does increase the efficiency of star formation with decreasing Θ, α_{20} (Virgo) would be even lower. More data on CO contents and SFRs as a function of Θ, as well as a greater theoretical understanding of the efficiency of star formation, could even lead to an evaluation of α_{20} as a function of Θ. We would expect α_{20} to be lower for smaller Θ, but the data at present do not allow such an analysis. In particular, more CO observations are needed for galaxies in the range $\Theta = 6 - 12^{\circ}$. The next section, further examines the IR evidence for a low α_{20}.

6.4.3 IR results

Figure 6.7 shows the ratio of the total FIR luminosity (40 - 300μm) as calculated above (equation 2.13) to M_{H_2} (with $\alpha_{20} = 8$), as a function of angular distance from M87. The mean of the isolated galaxy sample (Young et al. 1986b) is calculated in the same way. Rengarajan and Verma (1986)

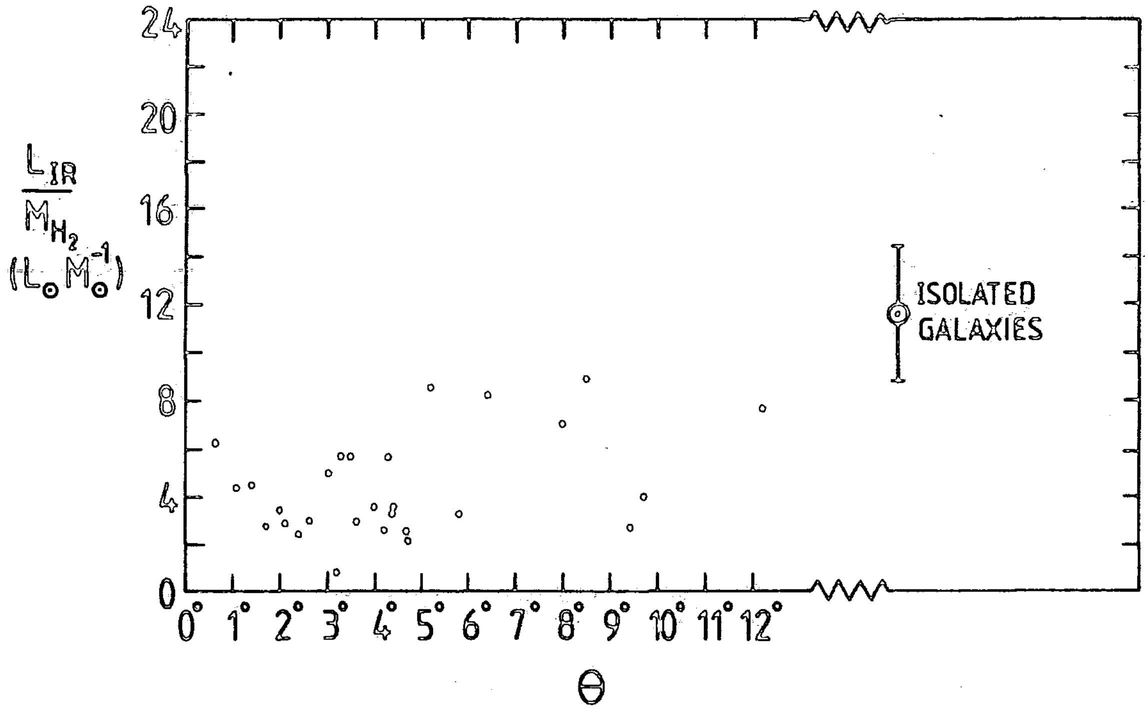
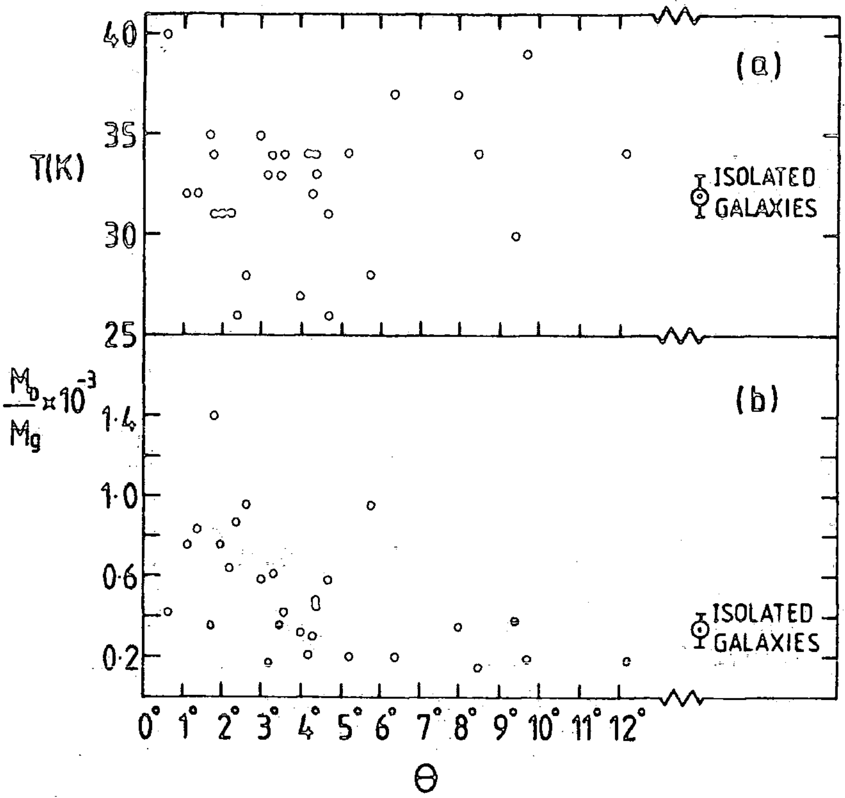


Figure 6.7 : The ratio of total IR luminosity to mass of H_2 as a function of angular distance from the centre of Virgo. The isolated galaxy sample is that of Young et al. (1986b). M_{H_2} in both cases has been calculated using $\alpha_{20} = 8$.

earlier had found $L_{IR}/M_{H_2} \simeq 13$ (correcting their value to $\alpha_{20} = 8$) for a sample of interacting and isolated galaxies. It can be seen that galaxies with $\theta < 5°$ are on average well below the value for the isolated galaxies.

Young et al. (1986a) found that for IRAS bright galaxies L_{IR} depended roughly on the first power of the H_2 mass and a temperature defined from the ratio of the 60μm and 100μm fluxes. Tacconi and Young (1987) from CO surveys of dwarf irregular galaxies extend this relationship over three more orders of magnitude. Assuming a λ^{-1} emissivity law, the 'dust temperature' as defined by Young et al. (1986a,b) has been derived for the Virgo galaxies using the 60/100μm flux ratios of Knapp et al. (1987) and the IRAS Extragalactic Catalogue (Lonsdale et al. 1985). Although the physical interpretation of T for a galaxy is far from clear (e.g. Thronson et al. 1987b), there appears to be no real difference between the Virgo sample and the isolated galaxy sample (Figure 6.8a). A similar result for a much larger



<u>Figure 6.8</u> : (a) Temperature derived from the ratio of the 60μm and 100μm fluxes assuming a λ^{-1} emissivity law, as a function of angular distance from the centre of Virgo, compared to the isolated galaxy sample of Young et al. (1986b).
(b) Ratio of 'warm' dust (calculated from the 100μm flux) to total gas as a function of angular distance from the centre of Virgo, compared to the isolated galaxy sample of Young et al. (1986b). M_{H_2} is calculated from the CO data using $\alpha_{20} = 8$.

sample of Virgo spirals within 6° of the core has also been found by Leggett et al. (1987a). In addition, Bicay and Giovanelli (1987) also found similar dust temperatures to the ones calculated above in galaxies in seven other rich clusters.

Therefore, in the absence of any temperature difference, if L_{IR} is correlated with M_{H_2}, Figure 6.7 indicates once again that particularly within $\theta = 5°$, M_{H_2}

has been overestimated. There have been a number of recent claims that the IR properties of the Virgo galaxies are 'normal' or indistinguishable from field galaxies (e.g. de Jong 1985; Devereux et al. 1987; Leggett et al. 1987a), which would appear to contradict the above picture. Leggett et al. (1987b) have even used this and the apparent 'normal' H_2 contents (KY;S) to argue that the far IR flux in disc galaxies is dominated by emission from dust associated with molecular gas. However, it is important to be clear about what is meant by the IR properties of Virgo galaxies being normal. For example, Devereux et al. (1987) compare the average L_{IR} of galaxies with $\Theta < 9^{\circ}$ with field galaxies and find no real difference. As any effect on α_{20} is likely to occur for $\Theta < 5^{\circ}$, any gross average over 9° will smooth out any differences. Leggett et al. (1987a,b) have considered galaxies with $\Theta < 6^{\circ}$. They find that (S_{100}/S_{60}) and (L_{IR}/L_B) are similar to field galaxies, and that relationships between these two quantities and L_{IR} are similar to those found in the field galaxy sample of Rieke and Lebofsky (1986). However, the spread in absolute values of L_{IR} is so large that any comparison with the absolute value of L_{IR} for field galaxies is difficult. Young et al. (1986b) had in fact noticed in their study of isolated and interacting galaxies that the ranges in L_{IR} for the two galaxy samples had sufficient overlap that selection on L_{IR} alone would not distinguish between the samples. The distinction between the two samples was shown clearly by L_{IR}/M_{H_2}, the interacting galaxies having a mean value 6 times that of the isolated sample. The important indicator for comparisons is therefore not a gross average of L_{IR}, but the quantity

L_{IR}/M_{H_2}. For galaxies within $\Theta \cong 5^{\circ}$, this quantity is found to be lower than that for isolated galaxies. We do not expect any theoretical reason for a lower L_{IR} as compared to M_{H_2} for $\Theta < 5^{\circ}$ (unlike the situation for interacting galaxies where a greater efficiency of star formation is expected), which leads once again to the conclusion that α_{20} is lower for $\Theta < 5^{\circ}$ than for isolated galaxies.

In addition to the total luminosity, the IR flux densities can be used to estimate the mass of warm dust in each galaxy. Using equations (2.15) and (2.16) of Section 2.5.3, the 100μm fluxes and T from Figure 6.8a, Figure 6.8b shows the dust-to-gas ratio (M_D/M_g) as a function of Θ. HI and H_2 masses have been taken from KY and Knapp et al. (1987) using $\alpha_{20} = 8$. There appears to be an enhancement in M_D/M_g for the Virgo galaxies over the isolated galaxies but this is to be expected due to the well known HI deficiency (Section 6.3.1).

As was noted in Section 2.5.3, the 100μm flux only samples the warm dust and so underestimates the total amount of dust present. For four galaxies in the Virgo sample, NGC4254, NGC4321, NGC4501 and NGC4527, Chini et al. (1986) have obtained 1300μm fluxes. This wavelength samples dust of all temperatures and so a total dust-to-gas ratio can be computed, but only for the central 90" of the galaxies sampled by the 1300μm beam. Young (1985b) shows that the CO distribution in the Virgo galaxies is roughly exponential, so following Section 2.5.3 assuming that the HI surface density is approximately constant with galactocentric radius while the CO follows an exponential distribution with scale length 5kpc (Young et al. 1985) allows the total M_D/M_g in the central 90" to be calculated. Using the 1300μm flux and temperature T in equation (2.16) gives a range for the four galaxies as

$$\frac{M_D}{M_g} \approx (2-6).10^{-3} \qquad (6.16)$$

compared to the canonical value for the solar neighbourhood of 10.10^{-3}. This result at face value is consistent with the idea that H_2 has been overestimated especially noting the fact of the HI deficiency.

However, the major uncertainty in the above analysis is the use of a temperature derived simply from the 60/100μm flux. Chini et al. (1986) argue that their observations cannot be explained by dust emitting at a uniform temperature and adopt a warm and cold component model with corresponding temperatures T_W and T_C. The use of T_C as given by Chini et al. (1986) increases M_D by a factor 2-3 over M_D calculated using T. This marginally brings M_D/M_g to the solar neighbourhood value, but it is difficult to increase it any more, except of course by reducing M_g. In fact, if the dust-to-gas ratio follows the metallicity of a region (Appendix A.2.5) as the metallicity increases with decreasing galactocentric radius, M_D/M_g should be > 10.10^{-3} in the central regions of a galaxy. Therefore, although there are large uncertainties, the IR data seem to indicate a lower α_{20} in galaxies within 5° of the Virgo core than in the solar neighbourhood and isolated galaxies.

Recently, Knapp et al. (1987), by comparing the CO and HI fluxes and 100μm fluxes for galaxies with $\theta < 12^{\circ}$, and assuming a constant dust-to-gas ratio concluded that $\alpha_{20} = 12.6 \pm 7.0$ in the Virgo spirals. However, as pointed out above, the 100μm flux is not a good indicator of the total dust content and variations in the dust-to-gas ratio could greatly affect this result.

It could be argued that the low dust-to-gas ratio in Virgo was due not to an overestimate of α_{20} but that the Virgo galaxies may have an intrinsically small dust-to-gas ratio. Although Section 6.4.1 suggested that evaporation of grains in the outer envelopes of GMC could be caused by the ICM; this effect is not expected to affect the whole of the galactic dust content (Dyson 1987). As Knapp et al. (1987) point out, it will be observations at longer wavelengths that will constrain α_{20} from the IR data.

6.4.4 <u>The evolution of galaxies in the Virgo cluster</u>

It has been argued in this Section, that although the CO observations are normal relative to galaxies of the same morphological type (Young 1985b), α_{20} and therefore M_{H_2} are lower in galaxies within 5° of the Virgo core. This means that the Virgo spirals in that region are deficient in H_2 as well as HI.

Ram-pressure stripping could be responsible for the HI deficiency, but cannot be responsible for any H_2 deficiency as the H_2 is concentrated in the inner regions and is much denser (Kent, 1980; Kritsuk 1983). The possible variation in α_{20} with Θ however means that Figures 6.4 and 6.5 cannot be at present interpreted as evidence for a stripping mechanism of H_2. A consideration of thermal evaporation or turbulent viscous stripping (Cowie and Songaila 1977; Nulsen 1982) in relation to molecular clouds is beyond the scope of this work, although both processes could be involved.

Finally, there is always the possibility of a primordial origin for the gas deficiency. Phillips (1987) has shown that HI deficient galaxies have a lower surface brightness which he interprets as galaxies having been deficient in HI for a significant fraction of their lifetimes and may favour a primordial deficiency. If the cluster environment affects the formation of galactic discs in some way so that HI is deficient (e.g. Dressler 1980), this in turn would lead to smaller H_2 masses and smaller integrated SFRs (Section 4.7). HI could also be subsequently stripped from the outer regions by ram-pressure stripping, the deficiency in H_2 in the inner regions being of primordial origin. This 'primordial' deficiency picture, however, may not be consistent in Virgo with the kinematic evidence that the cluster is relatively young, late type spirals only arriving in the core some $\approx$ 6Gy ago (Tully and Shaya 1984; Guiderdoni 1987; Binggeli et al. 1987).

Whatever the mechanism for the gas deficiency, the result that α_{20} is affected by the ICM environment is important in relation to the rest of this thesis. The standard assumption that the α_{20} determined locally applies universally (e.g. Young and Scoville 1982a), appears to invalid for galaxies within 5° of the Virgo core. Of course, the low SFR, L_{IR}/M_{H_2} and dust-to-gas ratio might be explained by other independent reasons, but a consistent and perhaps the simplest interpretation is that M_{H_2} and therefore α_{20} has been overestimated.

CHAPTER SEVEN

CONCLUSIONS

7.1 SUMMARY OF THE PRESENT WORK

A quantitative description of the evolution of spiral galaxies is a complex problem requiring a wide ranging synthesis of observation and theory. This thesis has attempted to understand the key role played by molecular hydrogen in that evolution, in areas such as star formation, chemical evolution and the relationship between the Galaxy and the Solar System. The goal of this work was not only a description of the global physics of H_2 in galaxies, but also to use that physics to constrain the mass and radial distribution of H_2, a problem of much contemporary debate.

The relationship of molecular hydrogen to the star formation rate (SFR) in galaxies has been examined. Although it is now well established observationally that star formation takes place primarily in the molecular gas, previous parameterisations of the SFR had not explicitly taken this into account. Following Talbot (1980), from a comparison of the radial distribution of the SFR, H_2 and HI in the Galaxy, it is concluded that the SFR (ψ_s) seems to be better correlated with the surface density of molecular hydrogen (Σ_{H_2}) than the total gas or atomic hydrogen, such that

$$\psi_s \propto \Sigma_{H_2}^k \qquad (7.1)$$

with k determined empirically to be 1.2 ± 0.2 for the Bhat et al. (1985) distribution of H_2, or 0.7 ± 0.2 for the SSS (1984) distribution of H_2. Between surface or volume densities of gas, the data at present do not make a sharp distinction. We therefore suggest that it is the amount of molecular hydrogen, as opposed to the total amount of gas, in any particular region which determines the SFR. Spiral arms merely re-organise matter within discs and do not determine the SFR, in agreement with recent observational results from external spiral galaxies (Elmegreen and Elmegreen 1986).

The molecular fraction of the gas (p_2) is found to be correlated with the metallicity Z of a region with $p_2 \propto Z^b$, $b \cong 1.3$. In its simplest form this relationship can be understood in terms that a region of higher metallicity will have more grains and consequently more evolution of $HI \rightarrow H_2$. In addition, metals themselves could be important in the formation of molecular clouds, acting as coolants and increasing opacity. We suggest therefore that variations in the mass ratio of H_2/HI as a function of Galactocentric radius and from galaxy to galaxy are controlled by the metal abundance (assumed to be proportional to the dust-to-gas ratio), rather than the volume densities (Tacconi and Young 1986, 1987) or spiral arms (Wyse 1986). Tacconi and Young (1987) have since suggested this qualitatively from their study of dwarf irregular galaxies. This picture is consistent with recent observations of external spirals that suggest that density waves do not trigger molecular cloud formation (Stark et al. 1987).

The problem for models of galactic evolution has always been to describe the time evolution of Σ_{H_2} and Ψ_S. Using the above correlations derived from the radial distributions in the Galaxy, a more explicit form of the SFR is obtained in terms of the total gas fraction μ and metallicity,

$$\psi_S \propto (\Sigma_T X \mu Z^b)^k \qquad (7.2)$$

where Σ_T is the total surface density of matter and X is the chemical fraction of hydrogen in the ISM. The time dependence of this modified 'Schmidt law' of the SFR explains quite naturally the production of a metallicity gradient and the constancy of the ψ_S over the lifetime of the disc, without the requirement of infall of gas from the halo.

A preliminary study of external spirals seems to support the general nature of the above 'law'. The total SFR of a galaxy is shown to be correlated with its total H_2 content, although uncertainty concerning the $CO \rightarrow H_2$ conversion factor, α_{20}, in these galaxies means that this result must be interpreted at present with care. Compiling radial distributions of HI, H_2 and Z for nine other spirals, we confirm the same correlation $p_2 \propto Z^b$ as observed in the Galaxy. In a further attempt to study this correlation, the mass of dust in a galaxy has been calculated from the 60μm and 100μm IRAS fluxes and this 'warm' dust-to-total gas ratio is shown to be correlated with the total p_2 of a galaxy. The 100μm flux however does not sample the total mass of dust in a galaxy and so 1300μm observations have been used in order to derive the total dust-to-gas ratio of a galaxy. This analysis can only be at present carried out for the central 90" of galaxies and there are large uncertainties concerning the temperature of the dust and the radial distribution of the gas. No correlation of this dust-to-gas ratio with p_2 is found. However, there is evidence that the dust-to-gas ratio and/or α_{20} varies from galaxy to galaxy.

Using the above form for the SFR, a self-consistent model of the chemical evolution of the Galaxy is proposed and compared with observations. This model is presented in terms of the instantaneous recycling approximation and includes an explicit form for dark matter. Due to the observational and theoretical uncertainty concerning the existence of infall of gas to the disc, we assume gas flows to have negligible effect on the chemical evolution of the disc, and evolve each disc annulus as a closed system. The yield of metals is taken as $y_Z = KZ^n$ to study both the constant yield case (n = 0) and variable yield. The formalism is developed for any value of n, but results are computed for n = 0 and n = 1.

The G-dwarf problem in the solar neighbourhood is solved by the requirement that the initial metallicity of the disc $Z_0 \simeq Z_1/3.7$ (Z_1 being the present metallicity) which finds recent support from consideration of the thick disc of the Galaxy (Gilmore and Wyse 1986). The age-metallicity relation of stars in the solar neighbourhood (Twarog 1980) is well reproduced by the same model. The case of constant yield provides a better fit to the AMR, while variable yield provides a better fit to the G-dwarf metallicity distribution, but considering present observational uncertainties neither case is ruled out. The returned fraction R is found to be in the range 0.3 - 0.65 depending on the value of n and the gas fraction in the solar neighbourhood.

For both constant and variable yield, the ratio of the present SFR (ψ_1) to the SFR when the disc formed (ψ_0) is found to be approximately unity in the solar neighbourhood, consistent with observational determinations of the past history of the SFR. For n = 1, the gas at present in the solar neighbourhood will be depleted to zero in a short timescale of $\approx$ 3Gy, while for the constant yield case the SFR decreases rapidly after $\approx$ 10Gy and $\mu > 0$ for Galactic lifetimes > 20Gy.

Given an initial density profile of the total mass distribution in the disc, it is shown that with time the Galaxy may naturally develop a radial gradient in the gas fraction and the metallicity even though it begins with a constant initial gas fraction and constant initial metallicity at all radii. The present observed metallicity gradient can be generated simply from the radial distribution of Σ_T, provided that the exponent k > 1. The metallicity gradient is not generated by infall or radial gas flows or necessarily variable yield (although this helps). We conclude therefore that a consistent model of the chemical evolution of the disc of the Galaxy is possible without invoking infall or radial inflow of gas.

To further examine the consistency of this model, we have studied the returned fraction R, the dark matter fraction D and the yield of metals y_Z from the IMF and details of stellar nucleosynthesis. With the IMF of Miller and Scalo (1979), the usual remnant fraction and the fraction of ejected metals from Maeder (1984), we find $R \cong 0.42$, $D \cong 0.05$ and $y_Z = 0.024$. It seems very difficult to simulate a case where $y_Z \ll Z$ from current knowledge of the IMF and stellar nucleosynthesis, the case of y_Z = constant is much more likely.

The consequences of this constant yield model of

Galactic chemical evolution for the nature of the dark matter in the solar neighbourhood have been discussed. If from the details of stellar nucleosynthesis the yield is $\lessapprox$ 0.015, the required value of D/(1-R) is $\lessapprox$ 0.1 which is consistent with the form of the IMF of Miller and Scalo (1979) extended down to 0.004 $M_{\odot}$. However, if $y_Z \lessapprox$ 0.025, D/(1-R) is $\lessapprox$ 0.4 for which the Miller-Scalo IMF is inadequate and a separate population of brown dwarfs are needed. The IMF of Larson (1986) can provide D/(1-R) $\lessapprox$ 0.2 in the form of dead stellar remnants rather than brown dwarfs but requires a small upper mass cut-off to metal production, < 16$M_{\odot}$, which may be unrealistic. The IMF of Rana (1987a) derived using the SFR of equation (7.2) requires a large population of brown dwarfs and an upper cut-off < 100$M_{\odot}$. The IMF of Scalo (1986) with a constant SFR cannot provide dark matter in baryonic form to solve the dark matter problem in the disc.

Assuming the applicability of the chemical evolution model to other spirals, abundance gradients in external spirals are examined. For a constant yield, no infall and k = 1.4 the trend between Z and Σ_T of Edmunds and Pagel (1984a) is reproduced, the shape of the relationship depending on the age of the disc. We suggest that for spiral galaxies with constant $Z_{\odot}$ as a function of radius, the metallicity gradient may be a direct indicator of the age of the disc. The evolution of radial gradients in stars, gas and metals are illustrated. It is shown that ψ_S is exponential with radius for the first 7-8 Gy of a galaxy's lifetime and the total galactic ψ_S remains roughly constant. A central hole in the gas distribution is shown to arise quite naturally without invoking gas flow into the bulge. More detailed observations and modelling for other spirals are required but these initial results are encouraging.

The relationship of the molecular gas in the Galaxy and other Galactic properties to the evolution of the Solar System has been studied, in particular the hypothesis that the observed 30My periodicity in the record of mass extinctions has a Galactic cause, namely perturbations of the Oort Cloud by known or unknown bodies in the Galaxy. Our principal result is that comet showers are not produced either with sufficient frequency or intensity by individual known bodies, whether stars or molecular clouds. If showers do occur with a mean interval of 30My, it may be possible to modify the Galactic hypothesis by invoking perturbations of the Oort Cloud by hypothetical dark matter, but only if the dark matter has a mean density > 0.1 $M_{\odot}$ pc^{-3} and is confined closely to the plane, both conditions being very unlikely. Therefore, if there is indeed an apparent 30 My periodicity in the mass extinction and geological records, we argue that astronomically induced processes are unlikely to be the primary cause.

Finally, we have examined the question of the lifetime of GMCs showing that previous arguments favouring long GMC lifetimes are no longer valid. We suggest that the lifetime of the molecular phase is constant with Galactocentric radius while the lifetime of the atomic phase is determined by the metallicity. This explains the previous correlation of p_2 and Z and possibly the molecular fraction of 'superclouds' (Elmegreen & Elmegreen 1987b). A consistent and comprehensive picture of the formation, evolution and dispersal of GMCs is still required, but it is concluded from a number of arguments that the lifetime of the molecular phase has an upper limit of 2.10^8y.

Arguments favouring lifetimes of the molecular phase > $(3-10).10^8$y as deduced from the Virgo spirals are shown to be not well founded. These arguments depend on HI being stripped throughout the whole of the galactic disc, whereas in Virgo HI stripping occurs (if at all) predominantly in the outer regions of the disc.

From a study of CO, HI, optical and IR observations of late type spirals in Virgo, the effect of the intercluster medium on the CO$\Rightarrow H_2$ conversion factor has been examined and it is shown that α_{20} is lowered in these galaxies with respect to its value in the solar neighbourhood and in isolated galaxies.

7.2 IMPLICATIONS FOR THE $H_2 \rightarrow$ CO CONVERSION FACTOR AND THE MASS OF H_2 IN THE GALAXY.

Chapter 1 reviewed the current controversy surrounding the CO$\rightarrow H_2$ conversion factor (α_{20}) and the mass and radial distribution of H_2 in the Galaxy. The debate centres on the value of α_{20} locally and whether it varies as a function of Galactocentric radius and from galaxy to galaxy. Methods to determine α_{20} empirically have large uncertainties and have led to conflicting results. SSS (1984) from extinction and virial mass estimates determined $\alpha_{20} = 7.2$ locally and throughout the Galaxy. Although more recent work has reduced this value to $\cong 6.0$ (Solomon and Rivolo 1987), such a high and constant value of α_{20} means that H_2 is the dominant gas component in the inner Galaxy. Bhat et al. (1986) from the cosmic γ-ray evidence and other arguments claim a value of $\alpha_{20} \cong 3.0$ in the solar neighbourhood, decreasing towards the inner Galaxy. This variation in α_{20}, ascribed to either metallicity or temperature effects results in the mass of H_2 in the inner Galaxy to be only one-fifth of that claimed by SSS (1984).

The intention of this thesis was to use the global physics of H_2 in the Galaxy in order to constrain its radial mass distribution and hence α_{20}.

In the models of the SFR and Galactic chemical evolution (Chapters 2 and 3) the H_2 surface mass distributions of SSS and Bhat et al. were compared. It was found that both gave good correlations with the SFR (equation 7.1), but leading to different values of the exponent k. The Bhat et al. values of Σ_{H_2} led to $k = 1.2 \pm 0.2$ while for SSS $k = 0.7 \pm 0.2$. This difference in k, and different values of the gas fraction μ in the solar neighbourhood led to marginally better fits to the AMR and higher values of the returned fraction for the Bhat et al. distribution. However, uncertainty in the AMR and returned fraction means that neither H_2 distribution can be ruled out by these considerations.

The real distinction between the two H_2 distributions came in computing the Galactic metallicity gradient in a closed model of chemical evolution. We have shown that the predicted metallicity gradient depends crucially on the value of k. Only if $k > 1$ will the metallicity increase towards the Galactic centre as observed. Therefore, in such a model only the Bhat et al. H_2 distribution can produce the observed gradient. Of course, a more complex chemical evolution model with infall and radial gas flows may be able to generate a metallicity gradient even with the SSS distribution of gas. It is not possible at present to rule out the existence of infall, although we have argued (Section 3.2) that current observations do not favour its occurrence in the later stages of Galactic evolution. However, in this work we have argued that infall is not required in order to give a consistent model of the chemical evolution of the Galaxy. The Bhat et al. H_2 distribution allows the adoption of a simple closed model with $\psi_S \propto \Sigma_{H_2}^k$.

In fact, compiling data on the radial distributions of the SFR in the Galaxy, and fixing k ≅ 1.4 by the observed metallicity gradient, a radial distribution of H_2 has been derived independently of the CO and γ-ray surveys. Using Turner's (1984) model of star formation we tentatively derived a surface density of H_2 in the solar neighbourhood to be $1.3 \pm 0.2\ M_\odot pc^{-2}$. When compared to the CO data of SSS (1984) this value gives $(\alpha_{20})_\odot = 2.5 \pm 0.5$, consistent with the value advocated by Bhat et al. (1985) from the γ-ray analysis. It is also close to $\alpha_{20} = 3.6$ derived recently by Maloney and Black (1987) using chemical modelling techniques.

The radial distribution of H_2 suggested by the present work is shown in Figure 7.1 in comparison with the other distributions. In the outer Galaxy, we claim a small underestimate of H_2, even by Bhat et al. (1985), possibly due to the incompleteness of the CO survey. In the inner Galaxy we find good agreement with Bhat et al. (1985). As

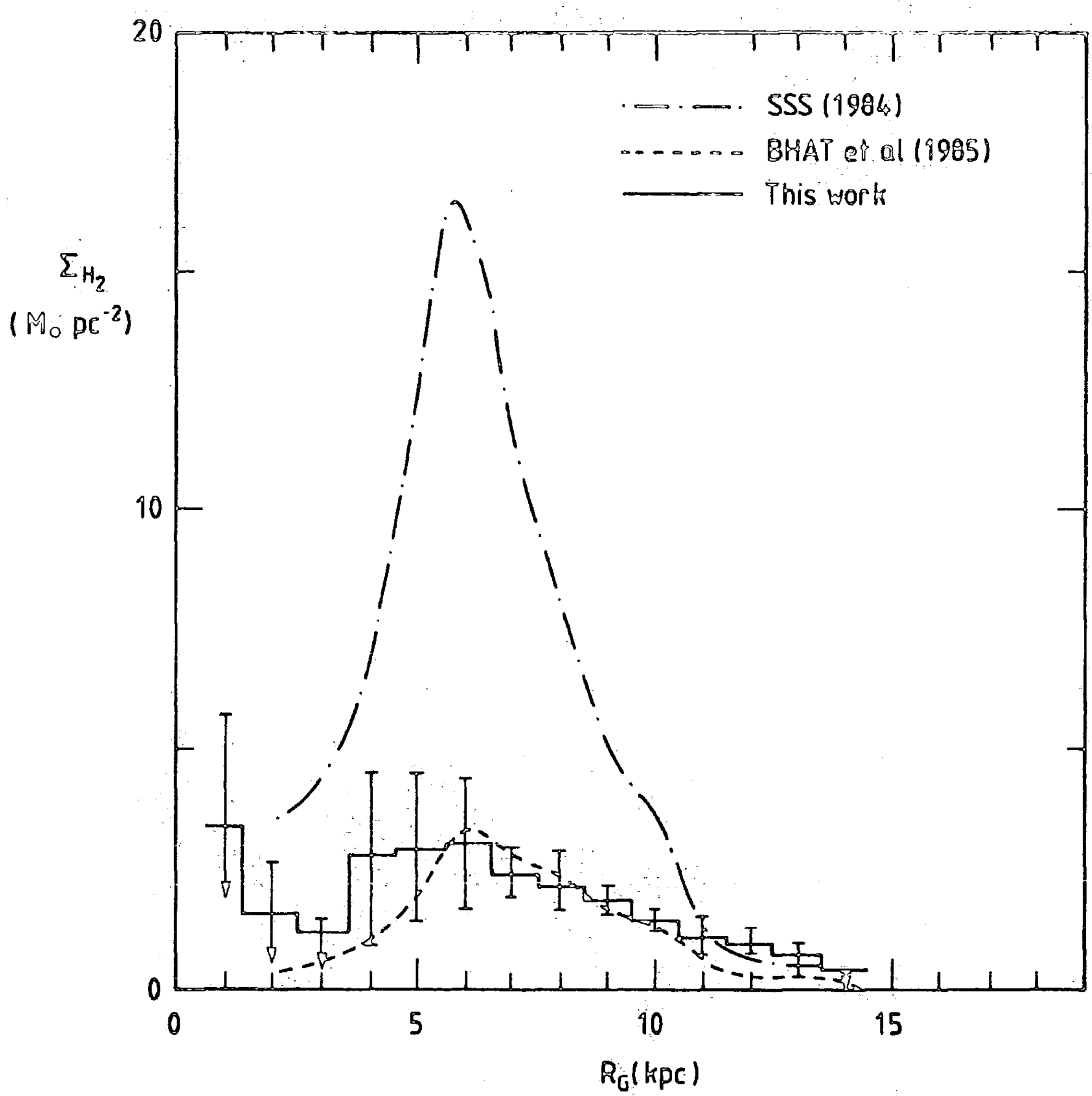


Figure 7.1 : The radial distribution of Σ_{H_2} in the Galaxy. The H_2 distributions of SSS (1984) and Bhat et al. (1985) are contrasted with the distribution derived in this work from the SFRs and observed metallicity gradient.

pointed out in Section 1.2, this is also in good agreement with the γ-ray analysis of the Columbia/COS B group (Bloemen et al. 1986; Strong et al. 1987), who use an $\alpha_{20} = 5.6$ but refer to a different CO radial profile.

This means that the masses of HI and H_2 are roughly equivalent in the inner Galaxy. From a study of the lifetime of the molecular phase, we conclude that $\tau_{H_2} < 2.10^8$y which also leads to roughly equivalent amounts of HI and H_2. Arguments favouring a much larger τ_{H_2} and therefore larger M_{H_2} in the inner Galaxy, in particular those from the Virgo spirals, are shown to be not well founded. Perturbations of the Oort Cloud of comets by GMCs are shown not to provide any useful constraints on their mass density.

Thus, evidence from chemical evolution and GMC lifetimes seems to confirm evidence from γ-rays and other arguments (Bhat et al. 1986) that the mass of H_2 in the inner Galaxy is roughly one fifth that claimed by SSS (1984).

Comparing the radial distribution of H_2 in Figure 7.1 with the CO radial profile of SSS (1984) indicates that α_{20} varies as a function of Galactocentric radius. If this is due to metallicity such that $\alpha_{20} \propto Z^{-n'}$, then we estimate $n' \simeq 0.8$-0.9 as compared to Bhat et al.'s $n' = 1$. From a theoretical point of view it is still not clear whether metallicity and/or temperature will produce a radial gradient in α_{20} (e.g. Kutner and Leung 1985; Williams 1985; van Dishoeck and Black 1987), but nevertheless an assumption of a constant α_{20} (e.g. Young and Scoville 1982a; SSS 1984) seems to be incorrect.

Maloney and Black (1987) have recently used sophisticated modelling techniques to study the effect of variations in the gas temperature, mean density and CO abundance on α_{20}. They model the CO emission from galaxies taking into account cloud-cloud shielding, specifying the H_2 distribution a priori, and examine the effect of variations on I_{CO}. They conclude that the use of a constant α_{20} between galaxies will give very misleading results because of these variation effects. We have used IRAS and 1300μm observations of spiral galaxies to suggest that the dust-to-gas ratio and/or α_{20} may vary by an order of magnitude between galaxies. We suggest that the effect of the ICM on GMCs in the Virgo spirals is to lower α_{20} with respect to the value in the solar neighbourhood and in isolated galaxies. If the IR and Hα properties truly describe the current SFR, and if Turner's (1984) model of star formation is correct we predict $\alpha_{20} \lesssim 2$ in the Virgo spirals. Therefore any estimates of H_2 in external galaxies from CO using a constant α_{20} must be treated with caution.

7.3 FUTURE WORK

The present work has opened up a number of questions and avenues for further study. For example, although we have attempted to present a consistent model of Galactic chemical evolution, much work still needs to be done. As Pagel (1987) has pointed out, the subject is in a confused state, attempts to build a unique quantitative picture hampered by ambiguities in the data which lead to great freedom in theory and assumptions. Better and more comprehensive abundance data are required for both this and other galaxies. Theoretical understanding of stellar evolution, in particular the effect of binary evolution (e.g. Matteucci and Greggio 1986; Iben 1987), and the IMF (e.g. Scalo 1986; Rana 1987a) is crucial to models of galactic chemical evolution.

Perhaps the crucial parameter for chemical evolution and certainly the SFR is the mass of H_2. Empirical determinations of α_{20} (Solomon et al. 1987a; Strong et al.

1987; Richardson and Wolfendale 1987) and theoretical work on cloud chemistry (van Dishoeck and Black 1986; Maloney 1987) and CO emission from galaxies (Maloney and Black 1987) are at present in progress. However, if α_{20} depends on metallicity, then radial abundance data of galaxies are essential if the correct H_2 masses are to be inferred from the CO data. If α_{20} depends on gas temperature effects, then it is necessary to obtain information on the excitation of CO, from the ratio of higher transitions (Maloney and Black 1987). The use of radial 1300μm observations in addition to an understanding of how the dust-to-gas ratio varies may provide an independent way of estimating H_2 in external galaxies.

We finally mention two other areas where H_2 seems to play a key role and where further study is required. Open clusters in the disc of the Galaxy are disrupted by mutual gravitational interactions between stars in the cluster, the stationary tidal field of the Galaxy and also by GMCs. van den Bergh and McClure (1980) and Lyngå (1982) suggested qualitatively that the prevalence of massive clouds of H_2 in the inner Galaxy could be responsible for the fact that open clusters in the outer parts of the Galaxy have longer lifetimes than those in the inner parts.

Wielen (1985) has considered quantitatively the problem of encounters of open clusters with GMCs, deriving an analytic way of dealing with these encounters. The effect of GMCs in the solar neighbourhood is shown to give fairly good agreement with the age distribution of clusters, the reduction in lifetime depending on the volume density ρ_{H_2}. We have used his formalism, examined the dependence on ρ_{H_2}

and also find a dependence on cloud mass and radius. In the solar neighbourhood the difference between the H_2 distribution of SSS (1984) and this work would lead to a factor of ≈ 2 in total lifetime. If we naively insert the values for ρ_{H_2} at $R_G \cong 6$kpc where the difference is more appreciable, we would predict a factor of 5 difference in lifetime.

Therefore, as a consequence of the shape of the H_2 distribution one should expect the age distribution of open clusters to vary as a function of R_G. This has been suggested qualitatively but never shown quantitatively. The work on the solar neighbourhood will need to be extended by a study of the variation of the Galactic tidal field and mass and size of GMCs in order to predict open cluster lifetime as a function of R_G. The use of an open cluster catalogue (e.g. Lyngå 1985) will give the age distribution of open clusters as a function of R_G, giving due care and attention to other variables affecting age such as radius, mass, z-dependence and possibly metallicity. The comparison of predictions with observations should lead to constraints on the radial distribution of H_2, especially the volume densities at 6 kpc. Apart from acting as a test of dynamical theories of open clusters, this will allow H_2 to be estimated independently of the controversy surrounding the CO and γ-ray data. The observation that clusters in LMC have much longer lifetimes than in the Galaxy (Elson and Fall 1985) may also provide a constraint on the mass of H_2 there.

An associated problem is the interaction of GMCs with wide binaries in the solar neighbourhood. Weinberg et al.

(1987) have recently studied the time evolution of wide binaries by stochastic encounters with field stars and GMCs in the solar neighbourhood with a hybrid Monte Carlo scheme. They find that if the molecular cloud density is different by a factor of 2, the half-lives for disruption change by a factor of 1.4. However, not only is the disruption process sensitive to cloud density, the cloud's internal structure will have a significant effect. Observations of wide binary separations may therefore constrain the mass density and internal structure of GMCs in the solar neighbourhood and also could provide constraints on the dark matter in the disc (Bahcall et al. 1985).

In conclusion, the role of H_2 in galaxies is crucial for many processes. We have attempted to outline various areas but many more await detailed study.

APPENDIX

Table A.1.1 : Recent values of the CO to H_2 conversion factor, α_{20}, published in the literature.

$$\alpha_{20}(\text{atoms cm}^{-2}\,\text{K}^{-1}\,\text{km}^{-1}\,\text{s}) = 2N(H_2)/\int T(CO)\,dv.$$

Determination and Authors	α_{20}	Notes
Visual Extinction (local region)		
Dickman (1975)	4.4	$A_V < 4$
Gordon & Burton (1976)	4.6	
Dickman (1978)	3.6	
Blitz (1978)	15.0	
Blitz & Thaddeus (1980)	15.0	
Blitz & Shu (1980)	2.0	
Frerking, Langer & Wilson (1982)	3.6	ρ Oph
Frerking, Langer & Wilson (1982)	9.6	Taurus
Young & Scoville (1982a)	8.0	
Liszt (1982)	10.0	ξ Oph, $A_V > 5$
Thaddeus (1983)	3-4	
SSS (1984)	7.2	$A_V > 5$
Lebrun & Huang (1984)	2.2	Oph-Sagittarius
Bhat, Mayer & Wolfendale (1986)	2-4	
Richardson & Wolfendale (1987)	3.0	
Virial theorem		
SSS (1984)	9.2	
Sanders, Scoville & Solomon (1985)	5-9	

Scoville et al. (1986)	5-9	
Bhat, Mayer & Wolfendale (1986)	3.0	
Solomon et al. (1987a)	6.0	
Scoville et al. (1987)	6.1	
γ-rays		
Li et al. (1983)	2.3	local clouds
Hermsen & Bloemen (1983)	5.2	Orion complex
Bloemen et al. (1984)	5.2	Orion complex
Houston & Wolfendale (1985)	3.7	Orion complex
Bhat et al. (1985)	2.7	local clouds
Lebrun et al. (1983)	2-6	inner Galaxy
Bhat et al. (1984,1985,1986)	2.7 †	
Bloemen et al. (1986)	5.6	inner Galaxy
Strong et al. (1987)	4.6	inner Galaxy
Other methods		
Solomon, Sanders & Scoville (1979)	12.0	radiative transfer
Rickard et al. (1985)	4.6	standard cloud method
Kutner & Leung (1985)	4.0	theoretical models
Bhat, Mayer & Wolfendale (1986)	3.8 †	X-ray absorption
Bhat, Mayer & Wolfendale (1986)	2.7	galaxy counts
Parkinson et al. (1987)	3.9	IR analysis

† Value shown is the local value, but is found to be a function of Galactocentric radius.

Table A.1.2 : Total Galactic H_2 mass estimates for $2 < R_G < 10$ kpc.

	M_{H_2} $(10^9 M_\odot)$	
Gordon & Burton (1976)	2.1	
Scoville & Solomon (1975)	1-3	
Solomon, Sanders & Scoville (1979)	3.9	Mass-Stony Brook
SSS (1984)	2.6	
Solomon et al. (1987a)	2.0	
Lebrun et al. (1983)	0.4-1.2	
Dame (1984)	0.7	Columbia/COSB
Thaddeus & Dame (1984)	0.7	
Bronfman et al. (1987)	1.2	
Bhat et al. (1984,1985)	0.6	
Bhat, Mayer & Wolfendale (1986)	0.6	Durham
Parkinson et al. (1987)	0.9	

(cf. $M_{HI} = 0.9.10^9 M_\odot$; Henderson, Jackson & Kerr 1982; Bloemen et al. 1986)

Table A.2.1 : Basic data for gas distributions and star formation rate in the Galaxy.

R_G (kpc)	Σ_{HI} ($M_\odot pc^{-2}$) (1)	(2)	(a) h_{HI} (pc) (3)	Σ_{H_2} ($M_\odot pc^{-2}$) (4)	(5)	(b) h_{H_2} (pc) (5)	(c) Σ_T ($M_\odot pc^{-2}$) (5)	ψ_s ($M_\odot pc^{-2} Gy^{-1}$) (6)
3	0.6	1.1	150	0.5	4.2	44	371	
4	1.6	1.5	150	0.9	6.6	46	296	0.2
5	2.9	2.3	150	2.0	11.8	56	235	12.0
6	3.7	2.8	150	3.4	16.5	71	187	30.0
7	4.4	2.4	150	2.8	12.2	73	149	14.0
8	5.1	2.8	150	2.5	8.5	61	119	18.0
9	3.8	2.5	150	1.6	5.1	65	94	7.9
10	3.5	2.7	150	1.4	3.8	70	75	5.0
11.5	4.9	2.7	240	0.3	0.7	70	53	6.0
12.5	5.5	3.9	300	0.3	0.6	70	42	2.8
13.5	5.8	2.8	360	0.3	0.5	70	34	
14.5	5.8	1.2	420	0.1	0.2	70	27	0.05

(1) Li et al. (1982)

(2) Burton & Gordon (1978)

(3) Kulkarni et al. (1982)

(4) Bhat et al (1985)

(5) SSS (1984)

(6) SBM (1978)

(a) Scale height of HI distribution

(b) Scale height of H_2 distribution

(c) Total surface density with $\Sigma_T(R_G)_\odot = 75\ M_\odot pc^{-2}$ (cf. Bahcall et al. 1983), which is also similar at $R_G > 4$ kpc to the double exponential model of Caldwell & Ostriker (1981).

Table A.2.2 : Determinations of the metallicity gradient, $d\log(Z)/dR_G$ (dex kpc^{-1}), for the Galaxy.

Objects	Range of R_G	(Fe/H)	(O/H)	(Z)	References
HII regions (electron temp.)	8-14		-0.08		Mezger et al. (1979)
	4-17		-0.05		Wink et al. (1983)
	4-13		-0.06†		Garay & Rodriguez (1983)
(optical spectra)	8-14		-0.04		Hawley (1978)
	8-13		-0.13		Peimbert et al (1978)
	8-14		-0.09		Peimbert & Torres-Peimbert (1979)
	8-14		-0.11		Talent & Dufour (1979)
	8-14		-0.10		Peimbert (1979)
	6-15		-0.07		Shaver et al. (1983)
Planetary Nebulae	7-14		-0.06		Torres-Peimbert & Peimbert (1977)
	8-12		-0.04		Peimbert & Serrano (1980)
	7-13		-0.07		Faúndez-Abans & Maciel (1986)
Open Clusters	8-14	-0.05			Janes (1979)
	8-12			-0.10	Panagia & Tosi (1980, 1981)
	8-14	-0.13			Lyngå (1985)
	8-13	-0.11			Cameron (1985)
Cepheids (from periods)	5-15			-0.07	Harris (1981)
	5-14			-0.07	Harris & Pilachowski (1984)
Supergiants	9-12	-0.13			Luck (1982)
A and F stars	8-15	-0.08			Christian & Smith (1983)
Old disc stars	9-12	-0.04			Mayor (1976)
Young disc stars	9-12	-0.10			Mayor (1976)
All stars	9-12	-0.05			Mayor (1976)
		-0.05			Marsakov & Suchkov (1982)

† using the calibration of O abundance of Shaver et al. (1983).

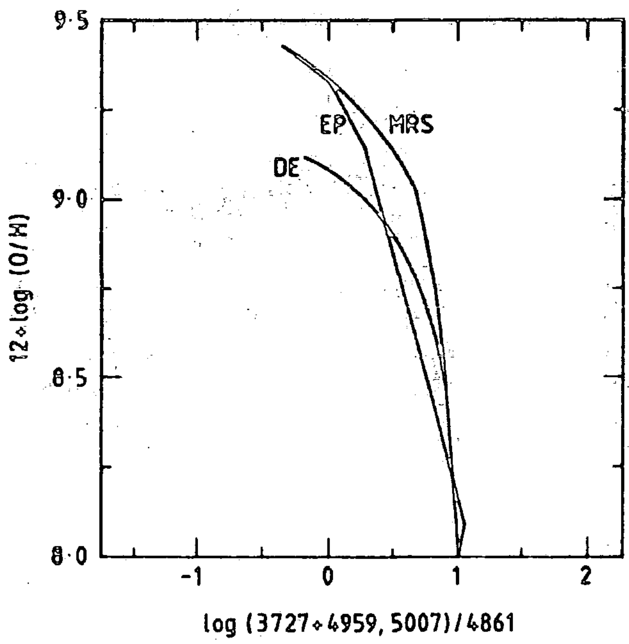
Table A.2.3 : Sources of data for Figure 2.8 (Section 2.5.2).

	HI	CO	(O/H)
The Galaxy	1	2	1
M51	3	4,5	6
IC342	7,8	9,10	6
NGC6946	8	10	6
M100	11	12	13
M101	8,14	15	16
M31	17	18	16
M33	19	16	16
M83	20,21	12,22	16
NGC2403	8	23	6

References.

1. This work
2. SSS (1984)
3. Weliachew & Gottesman (1973)
4. Scoville & Young (1983)
5. Rydbeck et al. (1985)
6. Tosi & Diaz (1985)
7. Newton (1980b)
8. Rogstad & Shostak (1972)
9. Morris & Lo (1978)
10. Young & Scoville (1982a)
11. van der Kruit (1972)
12. Young & Scoville (1982b)
13. McCall et al. (1985)
14. Bosma et al. (1981)
15. Solomon et al. (1983a)
16. Diaz & Tosi (1984)
17. Gottesman & Davies (1970)
18. Coombes et al. (1977)
19. Newton (1980a)
20. Allen et al. (1986)
21. Rogstad et al. (1974)
22. Coombes et al. (1978)
23. Young (1985a)

Figure A.2.4: The calibration curve of oxygen abundance against the observed ratio ([OII] + [OIII])/Hβ for HII regions. Shown are the curves given by Edmunds and Pagel (1984), McCall, Rybski and Shields (1985) and Dopita and Evans (1986) from which the Figure is taken.



Appendix A.2.5 : Is the dust-to-gas ratio a function of the metallicity?

It is a widely accepted assumption that the relative amount of dust is correlated with the metal abundance of a region (e.g. Koornneef 1985; Section 2.4). Both observation and theory tend to reinforce this assumption, but the situation is still far from clear.

Campbell et al. (1986) found that HII galaxies with lower abundances had less optical reddening, a trend expected if the dust content decreased with decreasing metallicity (Z). On the basis of this picture, these low abundance galaxies should not be strong IR sources. Gondhalekar et al. (1986) from a study of the IRAS data from three low metallicity HII galaxies found this to be the case. Estimating the mass of gas (M_g) simply from the HI flux and the mass of dust (M_d) from the 100μm emission, they found $M_g/M_d \gtrsim 10^5$ as compared to $\approx 10^2$ in the solar neighbourhood. No CO observations were available for these galaxies so H_2 has been neglected, and of course the 100μm emission does not sample all of the dust, but nevertheless the dust-to-gas ratio is very low, in line with what would be expected for low metallicity.

Viallefond et al. (1982) found a correlation between the dust-to-gas ratio and metallicity in HII regions in M101, the higher the metallicity the higher the dust-to-gas ratio. The gas was estimated using both HI and CO (using a constant α_{20}), the dust mass being estimated from optical and radio extinction.

The main observational evidence however for $M_d/M_g \propto Z$ comes from a study of the SMC and LMC. The amount of gas in dust grains cm^{-3} can be written

$$\langle\rho_d\rangle = \frac{4\pi}{3} a^3 \rho_d n_d = Z f_d \, m n_T \qquad (A.1)$$

where a is the radius of the dust grains, ρ_d is the actual mass density within the grain, f_d is the fraction of heavy elements in dust grains, m is the gas mass per proton and n_T is the proton number density (Franco and Cox 1986). Therefore the dust-to-gas ratio is given by

$$\frac{\langle\rho_d\rangle}{m n_T} = Z f_d, \qquad (A.2)$$

and if the 'efficiency' of dust formation (f_d) is roughly constant then the dust-to-gas ratio will be $\propto Z$. Relative to the solar neighbourhood, the dust-to-gas mass ratio (Zf_d) is smaller by a factor of 4 in the LMC (Koornneef 1982) and by a factor of 8 in the SMC (Bouchet et al. 1985) whereas the heavy element abundances are smaller by factors of 4 and 10 in the LMC and SMC respectively (Dufour 1984). Thus, in spite of the large differences in heavy element abundances between the SMC, LMC and solar neighbourhood, the value of $f_d \approx 0.5$ remains about constant for all three systems (Clayton and Martin 1984; Bouchet et al. 1985; Franco and Cox 1986). The above analysis of the LMC and SMC uses extinction in the visible and near IR towards particular stars, to estimate the dust mass, and the profile of the Lyman α interstellar absorption line along the same line of sight to estimate the column density of N_{HI}. This analysis is done for lines of sight where there is little CO emission. If in the SMC and LMC there is considerably more H_2 because of a higher α_{20} (Bhat et al 1984) the dust-to-gas mass ratio would be even lower.

Not only does metallicity vary from galaxy to galaxy, it also varies as a function of galactocentric radius (R_G). If the dust-to-gas ratio is determined by the metallicity, we may expect M_D/M_g to increase towards the centre of a galaxy. For our own galaxy, it is difficult to interpret the variation of the IRAS 100μm flux as an indication of dust mass because of the possible variation of the dust temperature with galactocentric radius (Burton et al. 1986; Burton and Deul 1987). However, Sodroski et al. (1987) assuming that all of the dust along a given line of sight is at a single temperature have used the 60μm, 100μm, HI and CO fluxes in an attempt to study the Galactocentric variation of $M_{\mathfrak{D}}/M_{\mathfrak{g}}$. The mass of H_2 is calculated from the Columbia CO data using a constant $\alpha_{20} = 4$. Deriving the dust temperature from the ratio of the 100μm and 60μm fluxes, it appears to be essentially constant ($\approx$ 24K) with $R_{\mathfrak{G}}$. The $M_{\mathfrak{D}}/M_{\mathfrak{g}}$ ratio however decreases from the inner to outer Galaxy by a factor of $\approx$ 3 which is similar to the change in Z over the same region. This may indicate that $M_{\mathfrak{D}}/M_{\mathfrak{g}} \propto Z$, but care is needed if IRAS has primarily sampled the warm component of Galactic dust and the fraction of dust in this component varies with $R_{\mathfrak{G}}$. Detailed observations at longer wavelengths ($\approx$ 1300μm) are needed to decide between these possibilities.

In a similar study for M31, Walterbos and Schwering (1987) have shown that the dust temperature is also relatively constant with $R_{\mathfrak{G}}$. It is then shown that the ratio of the IR optical depth at 100μm to the column density of HI increases with decreasing radius for $R_{\mathfrak{G}} < 15$ kpc. Taken at face value, this result suggests a significant variation in the dust-to-(atomic) gas as a function of $R_{\mathfrak{G}}$. One may ask whether this gradient is due to neglecting the contribution of H_2. Star formation, and hence probably H_2 (Chapter 2) is concentrated in a ring around $R_{\mathfrak{G}}$ = 10kpc, indicating that there is not much molecular material internal to this ring, and so the neglect of H_2 is unlikely to be the dominant cause of the gradient. By examining the role of small grains, Walterbos and Schwering conclude that the variation in $M_{\mathfrak{D}}/M_{\mathfrak{g}}$ is in the range of the observed metal abundance variation (Blair et al. 1982) and also consistent with the upper limit to the variation of $M_{\mathcal{D}}/M_{g}$ derived in an independent analysis of optical data (Walterbos and Kennicutt 1987).

Observationally therefore the dust-to-gas ratio is correlated with the metallicity. We might also expect this from theoretical considerations. Although the details of the formation and evolution of dust in galaxies are not yet fully understood, we know that the formation rate of icy mantles is largely controlled by the abundance of the CNO group of elements and by the gas density (Crézé and Isobe 1974). The most probable source of graphite grains is the atmosphere of low and intermediate mass red giants, while silicate grains are probably produced from type II supernova (Gondhalekar et al. 1986). Therefore, it is reasonable to believe that the amount of dust in the ISM will increase with the age of a galaxy, as does the metallicity. In a particular region stellar processing not only acts to increase the metal abundance, but it also depletes the mass of total gas. Even if the mass of dust stays constant, the dust-to-gas ratio will increase with metallicity.

Thus, to a first approximation we assume that

$$\frac{M_{\mathcal{D}}}{M_{g}} \propto Z \qquad (A.3)$$

Observations of abundances and IR measurements at longer wavelengths are needed to confirm this relationship.

Table A.4.1 : Best fitting model parameters for different sets of δ_1 and μ_0.

$n=0$, $\mu_1=0.09$, $\sigma_0=0.05$, $\log(Z_1/Z_0)= 0.57$, $\psi_1= 3 M_\odot pc^{-2} Gy^{-1}$.

$d\log(Z_1)/dR_G = -0.06$ dex kpc^{-1}

δ_1		0.4			0.5			0.6	
μ_0	0.5	0.6	0.8	0.5	0.6	0.8	0.5	0.6	0.8
G	-	72.1	83.0	-	72.1	83.0	65.2	72.1	83.0
χ^2_{GD}	-	36.1	28.7	-	31.2	24.6	29.2	25.0	19.5
δ_0	-	0.35	0.15	-	0.35	0.15	0.45	0.35	0.15
D/(1-R)	-	0.098	0.35	-	0.29	0.49	0.37	0.49	0.63
y_Z	-	0.015	0.018	-	0.019	0.024	0.024	0.027	0.033
χ^2_{AMR}	-	2.8	2.9	-	2.8	2.9	2.7	2.8	2.9
$(\psi_1/\psi_0)_\odot$	-	0.76	0.49	-	0.76	0.49	0.99	0.76	0.49
R	-	0.41	0.40	-	0.41	0.40	0.44	0.41	0.40
D	-	0.054	0.202	-	0.163	0.282	0.193	0.272	0.363
k	-	1.40	1.48	-	1.40	1.48	1.37	1.40	1.48

Table A.5.1 : Short term periodicities claimed in the terrestrial record.

Phenomenon	Period (My)	Source
Climatic and sea-level changes	≃30	Dorman (1968)
	≃32	Leggett et al. (1981)
	≃30	Fischer & Arthur (1977)
	≃33	Rampino & Stothers (1984b)
Volcanic activity	≃33	Pandey & Negi (1987)
Tectonic cycles	≃30	Holmes (1927)
	≃32	Rampino & Stothers (1984b)
Mass extinctions	≃32	Fischer & Arthur (1977)
	26-30	Raup & Sepkoski (1984)
	30±1	Rampino & Stothers (1984a)
	26±1	Sepkoski & Raup (1986)
Geomagnetically disturbed epochs	32-34	Negi & Tiwari (1983)
	≃30	Raup (1985a)
	≃30	Stothers (1986)
	≃30	Pal & Creer (1986)
Ages of craters	≃27	Seyfert & Sirkin (1979)
	31±1	Rampino & Stothers (1984a)
	32±1	Rampino & Stothers (1984b)
	≃28	Alvarez & Muller (1984)

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