INTERSTELLAR AND STELLAR ABUNDANCES ACROSS THE GALACTIC DISK

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Abstract. Observational evidence related to the chemical composition across the disk of the Galaxy is reviewed. The H_2 density distribution derived for the Galaxy is poorly known, consequently it is still not possible to compare theoretical models of the chemical evolution of the Galaxy with the gaseous density distribution. The H_2 density distribution is particularly sensitive to the fraction of carbon atoms embedded in CO molecules and to the possible presence of a C/H abundance gradient.

1. INTRODUCTION

The scarcity of metal-poor stars in the disk (van den Bergh, 1962; Schmidt, 1963) has been the key issue in all the ideas and models on the chemical evolution of the Galaxy. This problem has been discussed at length in the literature (e.g. Pagel and Patchett, 1975) and will not be discussed here. The chemical composition across the disk of the Galaxy should provide us with additional constraints to that provided by the classical G dwarf problem for models of the chemical and dynamical evolution of the Galaxy (e.g. Talbot and Arnett, 1975; Tinsley and Larson, 1977). We will address this review mainly to this problem. The information on this subject is still fragmentary, frequently indirect and comes from many different types of objects. Most of this review will be concentrated on the properties of the disk that can be derived from observations of objects moderately close by, since the large reddening in the plane prevents us from obtaining optical information originating farther away than a few kpc from us.

Recent reviews on the presence of abundance gradients across the disks of spiral galaxies are those by van den Bergh (1975) and Peimbert (1975). Other constraints for models of the chemical evolution of the Galaxy are reviewed elsewhere (e.g. Pagel and Patchett, 1975; van den Bergh, 1975; Audouze and Tinsley, 1976; Mayor, 1976).

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2. STELLAR OBSERVATIONS

It is known that in the Galaxy, M31 and the Magellanic Clouds short-period Cepheids are concentrated towards the outer regions and long-period Cepheids towards the inner regions (Shapley and Mc Kibben, 1940, 1942a, 1942b; van den Bergh, 1958; Baade and Swope, 1965; Fernie, 1968). A possible explanation first advanced by van den Bergh (1958) is that this effect is due to a radial gradient in the chemical composition of these galaxies.

Hartwick (1970) found that the ratio of the number of red to blue supergiants increases with increasing distance from the galactic center as it is the case in M33 (Walker, 1964; Madore, 1971) and suggested that this effect is due to a chemical composition gradient. Janes and Mc Clure (1972), from CN observations of 799 K giant stars, presented evidence for a radial gradient in CN strength. This feature is correlated with [Fe/H] and implies that $d\log(Fe/H)/dR = -0.023 \pm 0.011$ kpc^{-1}, where this result applies in the 5 to 15 kpc range. Grenon (1972) from Geneva photometry of G and K giants and dwarfs found $d\log(Fe/H)/dR = -0.07$ kpc^{-1}.

The most complete work to date on chemical abundance gradients derived from stellar observations is that by Mayor (1976). From an analysis of the kinematic and photometric properties of about 600 F main sequence stars and 600 G and K giants Mayor has derived two values for the metallicity gradient: one for all the objects which includes those with eccentricities in the 0.05 to 0.40 range, and another one for a subset of the statistically younger objects, those with eccentricities in the 0.05 - 0.15 range. Furthermore from the observations by Hansen and Kjaergaad (1971), Mayor has derived sodium abundance gradients corresponding to the two eccentricity groups defined above. Na and Fe gradients are steeper for the younger subset than for the complete samples, see Table I. This result is in agreement with the absence of a gradient for halo stars derived by Grenon (1972) but is apparently in contradiction with the radial metallicity gradient derived from globular clusters that evaluated at the solar neighborhood amounts to $d\log(Fe/H)/dR \simeq -0.1$ (Kinman, 1959; Mayor, 1976).

It is possible to obtain a crude estimate of the O/H abundance gradient in the Galaxy by assuming that the O/H abundance derived from H II regions is directly proportional to the Cepheid period, this relationship can be calibrated by means of observations of the Small Magellanic Cloud and the solar neighborhood. Fernie (1968) found for the Galaxy a relation between the galactocentric distance, R, and the Cepheid period given by $\Delta\log P/\Delta R = -0.05$ days kpc^{-1} and an average value of log P= 0.97 days for the Cepheids of the solar neighborhood; Arp and Kraft (1961) found an average value of log P= 0.5 for the SMC Cepheids and Peimbert and Torres-Peimbert (1976) a difference of 0.76 in the log of O/H between the solar vicinity and the SMC H II regions. From these results we obtain

Δ log (O/H)/Δ log P= 1.6 days^{-1} and thus a radial gradient in the Galaxy of d log (O/H)/d R= -0.08 kpc^{-1}. The assumption that the Cepheid periods are related to the metal abundance is strengthened by the results of Gascoigne (1969) and Madore (1974) who found that the SMC Cepheids are 0.1 mag bluer in B-V than the Cepheids in the Galaxy; Bell and Parsons (1972) can explain this difference as due to line blanketing if the metal abundance in the SMC Cepheids is four times smaller than in the solar neighborhood Cepheids.

TABLE I

Stellar Abundance Gradients evaluated at the Solar Neighborhood *

Object	Fe/H	Na/H	O/H
GK, dwarfs and giants	-0.07: (1)	...	...
K giants	-0.023±0.011 (2)	...	...
Intermediate Age Stars (0.05≤e≤0.40)	-0.05 ±0.01 (3)	-0.06±0.02 (3)	...
Young Stars (0.05≤e≤0.15)	-0.10 ±0.02 (3)	-0.15±0.03 (3)	...
Cepheids	...	...	-0.08:(4)

* Given in d log(X)/d R, kpc^{-1}.
(1) Grenon 1972, (2) Janes and Mc Clure 1972, (3) Mayor 1976, (4) this paper.

3. INTERSTELLAR OBSERVATIONS

3.1 H II regions

The presence of abundance gradients in external galaxies derived from interstellar observations is now well established (e.g. Peimbert, 1968; Searle, 1971; Benvenuti et al., 1973; Shields, 1974; Comte, 1975; Peimbert, 1975; Smith, 1975; Sarazin, 1976; Jensen et al., 1976; Collin-Souffrin and Joly, 1976), a similar situation is expected to prevail in the Galaxy.

Sivan (1976) based on the [N II]/[S II] line intensity ratio obtained d log (N^+/S^+)/d R= -0.04 kpc^{-1}. Peimbert et al., (1978) from photoelectric observations of five H II regions, covering a galactocentric range from 8.4 to 13.9 kpc, derived abundance gradients for O/H,N/H, N^+/S^+ and He/H. Hawley (1977) from photoelectric observations of 13 H II regions found smaller gradients in O/H and N/H than those found by Peimbert et al., and no gradients in the He/H,S/H and Ne/H abundance ratios.

These results are presented in Table II.

3.2 Planetary nebulae, PN

A review on the chemical abundances of PN has been presented elsewhere (Peimbert 1978). To study the presence of abundance gradients in the interstellar medium from PN it is necessary to select Type II PN which are of population I and which apparently have not been affected by considerable helium enrichment due to their own stellar evolution (Peimbert 1978). Barker (1974), D'Odorico et al., (1976), Aller (1976) and Torres-Peimbert and Peimbert (1977) have studied the presence of abundance gradients in the Galaxy. In Table II we present the abundance gradients derived by Torres-Peimbert and Peimbert (1977) which we consider to be the most accurate.

TABLE II

Interstellar Abundance Gradients Evaluated at the Solar Neighborhood*

Object	He/H	O/H	N/H	N^+/S^+	
H II Regions	-0.02±.01	-0.13±.04	-0.23±.06	-0.09±.05	(1)
H II Regions	...	-0.05	-0.10	...	(2)
H II Regions	...	...	...	-0.04	(3)
Planetary Nebulae	-0.02±.01	-0.06±.02	-0.18±.04	...	(4)

* Given in d log(X/Y)/dR, kpc^{-1}.
(1) Peimbert et al., 1978, (2) Hawley 1977, (3) Sivan 1976, (4) Torres-Peimbert and Peimbert 1977.

3.3 Neutral and molecular hydrogen

To obtain the total gas density it is necessary to estimate the amount of HI and H_2 molecules which comprise most of the interstellar matter. Gordon and Burton (1976) have estimated the amount of HI and H_2 as a function of galactocentric distance. Their results are presented in Tables IV and V where N(HI) and $N(H_2)$ are the volume densities at the plane and σ(HI) and $\sigma(H_2)$ are the projected surface densities. The differences between the N/σ ratios are due to the larger scale height for HI than for H_2 (Baker and Burton, 1975; Burton and Gordon, 1976). The corresponding density gradients are presented in Table III.

Gordon and Burton (1976) derived the H_2 distribution directly from the CO distribution and point out (see also Burton 1976) that the distributions of giant H II regions (Burton et al.,1975), γ rays (Strong, 1975), H 166α (Lockman, 1976) and supernova remnants (Kodaira, 1974) are quite similar to that of CO and that they differ essentially from the N(HI) distribution. Hayakawa et al., (1977) find that the overall dis-

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tribution of infrared sources in the Galaxy derived from observations at 2.4 μm is also similar to that of CO. In Table III we also present the gradient of the SN remnants derived from the distribution by Kodaira (1974) and the gradient of the dust to gas ratio derived by Puget et al. (1977) from observations in the anticenter direction.

TABLE III

Other Gradients Evaluated at the Solar Neighborhood*

N(HI)	N(H)	σ(HI)	σ(H)	SN	Ω-Ωp	σ_t	N_d/N(H)
-0.02	-0.17	+0.03	-0.08	-0.12	-0.11	-0.12	-0.08
(1)	(1)	(1)	(1)	(2)	(3)	(4)	(5)

* Given in d log(X)/dR, kpc^{-1}
(1) Gordon and Burton 1976, N(H)= N(HI)+2N(H_2); σ(H)= σ(HI)+ σ(H_2), (2) Kodaira 1974, supernovae,
(3) Ω from Schmidt 1965, Ωp= 13.5 km s^{-1} kpc^{-1} (Lin 1971),
(4) σ_t= total surface density, Innanen (1973), (5) Puget et al.(1977).

4. DISCUSSION

The O/H abundance gradient given by H II regions is steeper than that given by PN (see Table II). This difference, if real, could be due to at least three causes: a) a different O/H distribution of the interstellar medium at the time of formation of the PN parent stars, b) a different O/H in the shell from that of the original cloud from which the PN formed, and c) the effect of non circularity of the PN orbits around the center of the Galaxy. The Fe/H and Na/H gradients derived from intermediate age stars (see Table I) are similar to the O/H gradient derived from PN which supports possibility a). On the other hand there is some observational evidence that suggests that the rate of enrichment of Fe has been different to that of O, S and Ar and consequently that the Fe/H and O/H gradients are not directly comparable (Peimbert, 1973; Barker, 1974; Chevalier, 1976; Chevalier and Kirshner, 1977). Furthermore based on the observational evidence Chevalier has suggested that the Fe enrichment is due to SN of type I, while that of O, S and Ar is due to SN of Type II.

The data from Tables I and II indicate that the abundance gradients are steeper for the younger objects. In what follows we will consider O as being representative of primary mechanisms of element formation, alternatively N seems to have been formed both by primary and secondary mechanisms (e.g. Peimbert and Torres-Peimbert, 1971; Smith, 1975; Peimbert et al., 1978).

The density wave theory has been proposed to explain the formation of early type stars and giant H II regions across the galactic disk. From this theory it is expected that the ratio of newly formed stars to gas should be proportional to Ω-Ωp, the rotation frequency minus the pattern frequency. The observed distribution of giant H II regions relative to that of H I is similar to that of Ω-Ωp. This correlation has been mentioned as supporting evidence for the density wave theory (Mark, 1971; Lin, 1971; Shu, 1973; Roberts, 1975). However it is not obvious whether Ω-Ωp should be compared to the distribution of giant H II regions relative to H I or to the total gas density given by HI+H_2. When the second comparison is made (see Table III) the correlation disappears, the discrepancy is even larger if we assume that Ω-Ωp should be multiplied by a density compression factor that is expected to increase as Ω-Ωp increases (Shu, 1973).

Combes et al., (1977) have obtained a partial radial distribution of carbon monoxide emission in M31. The CO emission is correlated with dark areas, on the inner side of H I spiral arms. This observation can be explained within the frame of the density wave theory of spiral structure in the sense that the compression produced by the density wave induces the formation of molecular clouds and consequently that $N(H_2)/N(H\ I)$ is proportional to Ω-Ωp.

It is clear that to be able to compare the predictions of the density wave theory a very accurate H_2 density distribution is needed. The H_2 density distribution by Gordon and Burton (1976) was obtained under the following assumptions: a) $N(C)/N(H)= 6\times10^{-4}$; b) $T^*(^{12}CO)/T^*(^{13}CO)= 3$; c) 10% of the carbon atoms are embedded in CO; and d) N(C)/N(H) is independent of galactocentric distance.

Dickman (1975) and Tucker et al., (1976) find $^{13}CO/H_2= 3.0\times10^{-6}$ which combined with a value of 40 for the ratio $^{12}CO/^{13}CO$ (Wannier et al.,1976) implies that the fraction of carbon in CO is about 20%. In Table VI we show the gaseous density gradient derived under the assumption that 20% of carbon is in the form of CO. The density gradient is not as steep as that derived under the 10% assumption.

Another correction to the H_2 density distribution can be made if we assume that the CO/H_2 ratio is not uniform but that in the solar neighborhood it decreases with galactocentric distance. The CO/H_2 ratio should be proportional to the C/H variation since carbon is the least abundant of the two elements that constitute the CO molecules. Torres-Peimbert and Peimbert (1977) found that in planetary nebulae carbon and nitrogen were enriched by factors of 9 and 5 relative to those of H II regions, and from the results by Tinsley (1978) it follows that a considerable fraction of carbon in the interstellar medium has been produced by PN. Therefore the C/H abundance gradient should be steeper than the O/H gradient and might be intermediate between the N/H and the O/H gradients. In what follows, based on the results by Peimbert et al.,

TABLE IV

Radial Distribution of Volume Densities at b= 0°(cm^{-3})

R (kpc)	N(HI)	$2N(H_2)$	$2N(H_2)$	$2N(H_2)$
7.5-8.0	0.38	2.22	1.11	0.39
8.0-8.5	0.36	1.48	0.74	0.33
8.5-9.0	0.32	0.62	0.31	0.17
9.0-9.5	0.29	0.92	0.46	0.32
9.5-10.0	0.38	0.72	0.36	0.32
10.0-10.5	0.40	0.74	0.37	0.41
10.5-11.0	0.25	0.26	0.13	0.19
11.0-11.5	0.23	0.28	0.14	0.25
11.5-12.0	0.32	0.18	0.09	0.20
12.0-12.5	0.36	0.02	0.01	0.03
	(1)	(1)	(2)	(3)

(1) Gordon and Burton 1976, (2) 20% of C in CO, CO/H_2= constant, (3) 20% of C in CO, d log $(CO/H_2)/dR$= -0.20 kpc^{-1}.

TABLE V

Gaseous Surface Density Distribution ($M_\odot$ pc^{-2})

R(kpc)	σ(HI)	$\sigma(H_2)$	$\sigma(H_2)$	$\sigma(H_2)$
7.5-8.0	2.85	6.87	3.43	1.22
8.0-8.5	2.65	4.58	2.29	1.03
8.5-9.0	2.34	1.92	0.96	0.54
9.0-9.5	2.17	2.85	1.42	1.01
9.5-10.0	2.93	2.23	1.11	0.99
10.0-10.5	3.39	2.29	1.14	1.28
10.5-11.0	2.29	0.80	0.40	0.56
11.0-11.5	2.31	0.87	0.43	0.77
11.5-12.0	3.38	0.56	0.28	0.62
12.0-12.5	4.12	0.06	0.03	0.08
	(1)	(1)	(2)	(3)

(1) Gordon and Burton 1976, (2) 20% of C in CO, CO/H_2= constant, (3) 20% of C in CO, d log $(CO/H_2)/dR$= -0.20 kpc^{-1}.

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(1978) for N and O we will adopt the value d log(C/H)/d R= d log(CO/H_2)/d R= -0.20 kpc^{-1}. The gaseous density gradients derived under this assumption are presented in Table VI.

TABLE VI

Gaseous Density Gradient (kpc^{-1})

$\frac{d \log CO/H_2}{d R}$	$\frac{d \log N(H)}{d R}$ (1)	(2)	$\frac{d \log \sigma(H)}{d R}$ (1)	(2)
0.00	-0.17	-0.13	-0.08	-0.04
-0.13	-0.10	-0.08	-0.03	-0.01
-0.20	-0.06	-0.05	-0.01	+0.00

(1) 10% of C in CO, (2) 20% of C in CO.

The H_2 distributions derived under the various assumptions are presented in Tables IV and V. In Table VI we also present the density gradients computed under the assumption that d log(CO/H_2)/d R= -0.13. From Tables IV to VI it follows that the gaseous density distribution is very uncertain and that it is still premature to compare it with theoretical models.

Jensen *et al.*,(1976) have argued that for star formation the primary abundance, represented by O/H, should be proportional to (Ω-Ωp). In Table III it can be seen that the O/H and the Ω-Ωp gradients are very similar. For a flat velocity curve O/H α v_{rot} T(1/R - 1/R_c), where $v_{rot} \approx$ 250 km/sec for the solar neighborhood, T is the age of the Galaxy and is about a Hubble time, and R_c is the corotation radius. In this case R_c is related to the solar neighborhood O/H gradient by

$$R_c/R_\odot = \left[1 + \frac{1}{2.303\, R_\odot \frac{d \log O/H}{d R}} \right]^{-1} . \qquad (1)$$

This equation together with the O/H gradient for H II regions derived by Peimbert *et al.*, (1978) (see Table II) yields R_c= $15.0^{+4.3}_{-1.6}$ kpc where a value of $R_\odot$= 10 kpc was adopted. This result is in reasonable agreement with those derived from dynamical considerations and constitutes a consistency check for the arguments of Jensen *et al.* Under the same framework it is found that the increase of O/H per spiral passage is about 6×10^{-6}. The observations indicate that O/H α Ω-Ωp however, there is no simple theoretical explanation for this result since the observed O/H value reflects the integrated effect over the history of the Galaxy and many conditions that regulate the chemical evolution of the disk have to be considered e.g. infall of processed or primeval material, variation of $\Omega-\Omega p$ with time, etc.

5. CONCLUSIONS

The presence of abundance gradients in the Galaxy is well established.

The O/H gradient derived from H II regions is proportional to $\Omega-\Omega p$.

To be able to discriminate among models of chemical evolution of the Galaxy it is paramount to obtain an accurate gaseous density distribution. Progress could be made in this direction by deriving the C/H abundance gradient and a more accurate determination of the fraction of carbon atoms embedded in CO molecules.

From the observed O/H and N/H gradients it follows that a C/H negative gradient exists. This gradient together with the possibility that the fraction of C embedded in CO molecules is larger than 10% reduces considerably the predicted amount of H_2 present in the Galaxy.

The enrichment of Fe is probably due to SN of Type I and that of O to SN of Type II, consequently theoretical predictions of the rates of enrichment should take this into account.

There is some evidence that in the disk the abundance gradients have become steeper with time. This result is still preliminary and should be analyzed further.

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