CHEMICAL EVOLUTION OF THE GALACTIC INTERSTELLAR MEDIUM: ABUNDANCE GRADIENTS

Manuel Peimbert
Instituto de Astronomía, Universidad Nacional Autónoma de México

Abstract. Recent abundance determinations of galactic H II regions and planetary nebulae are reviewed. The presence of O/H and N/H abundance gradients is well established; there is observational evidence indicating the presence of N/S, He/H and C/H abundance gradients. Some implications of these results are discussed.

1. INTRODUCTION

The presence of abundance gradients of O/H, N/H and N/S in external galaxies is now well established (e.g. 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). Recent observations of the interstellar medium indicate that a similar situation prevails in the Galaxy. It is the purpose of this review to discuss these observations.

2. PLANETARY NEBULAE, PN

A review of PN abundance determinations is presented elsewhere (Peimbert 1978a). Barker (1974, 1978), D'Odorico et al.(1976), Aller (1976), Torres-Peimbert and Peimbert (1977) and Kaler (1978) have studied the presence of abundance gradients in the Galaxy. To study the presence of abundance gradients in the disk of the Galaxy from PN it is necessary to select Type II PN which are of population I and that apparently have not been affected by considerable helium enrichment due to their own stellar evolution (Peimbert 1978a). Based on these considerations the results for PN of Type II by Torres-Peimbert and Peimbert (1977) are presented in Table I and Figure 2.

Kaler (1978) has rediscussed the He/H abundance ratios from a larger sample of PN than those used in previous studies and confirms that there are systematic abundance differences as reported by D'Odorico et al. (1976) and Torres-Peimbert and Peimbert (1977), he finds that the He/H

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abundance ratios diminish with increasing distance above the galactic plane, with increasing radial velocity and with increasing distance to the galactic center. Kaler attributes the radial gradient as due mostly to an excess of population II PN in the anticenter direction and not to the presence of an interstellar gradient.

In the solar neighborhood the N/O abundance ratio in PN of Type II is larger than in H II regions by about a factor of four while the O/H abundance ratio is similar (Torres-Peimbert and Peimbert 1977), this result agrees with the idea that PN are producing nitrogen without affecting their O/H ratio and consequently that their O/H ratio can be used as a tracer of Interstellar medium abundances at the time the parental star was formed. In Figure 2 we present the N/O versus O/H plot for PN of Type II.

There is some controversy regarding the carbon abundance in PN, the faint permitted lines in the visual indicate carbon overabundances with respect to the solar value (Torres-Peimbert and Peimbert 1977, Aller 1978, Shields 1978), while the ultraviolet C III and C IV lines indicate more normal abundances (Bohlin et al.1978, Pottasch 1978). In gas rich regions where star formation has not been appreciable one would expect the C/H and O/H gradients to be similar, as more gas condenses into stars the C/H gradient should become less steep than the O/H gradient because some C is transformed into N, nevertheless if stars like PN are ejecting carbon rich material produced in them then the C/H gradient could be steeper than the O/H one. Panagia et al. (1977), Tinsley (1978) and Mallik (1978) have studied the relevance of the PN enrichment of the interstellar medium under various assumptions regarding the N and C overabundance as well as the rate of PN formation.

3. H II REGIONS

Recently several investigations devoted to the study of abundance gradients across the disk of the Galaxy have been carried out, the results are presented in Table I. We decided to combine the results of all the observers and redetermine the N/H, O/H and N^+/S^+ abundance gradients considering only those objects in which the electron temperature had been determined observationally, the results are presented in Table I and Figure 1. The reduction procedure, that includes ionization correction equations, spatial temperature fluctuations ($t^2 = 0.035$ was adopted) and atomic data, was the same for all the abundance determinations. The logarithmic abundance gradients from this sample were computed and are presented in Table I, equal weight was given to all the points and in those cases where the same object was observed by different groups we considered the results as independent. To compute the N/H gradient the results for NGC 2359 were not considered because the central star, WR of type N5, is losing mass at a very high rate, and this material is probably nitrogen rich.

TABLE I

Solar Neighborhood Abundance Gradients*

Object	He/H	C/H	O/H	N/H	N^+/S^+	Objects with observed T_e	Reference
PN	-0.02		-0.06	-0.18		15	(1)
H II					-0.04	0	(2)
H II	-0.02		-0.13	-0.23	-0.09	5	(3)
H II	0.00		-0.04	-0.10	-0.05	5	(4)
H II			-0.11	-0.11	-0.06	4	(5)
H II		-0.09	-0.09	-0.12	-0.05	4	(6)
H II			-0.10	-0.14	-0.05	18	(7)

* Given in d log(X/Y)/dR kpc^{-1}.

(1) Torres-Peimbert and Peimbert 1977, (2) Sivan 1976, (3) Peimbert et al. 1978a, (4) Hawley 1978, (5) Talent and Dufour 1978, (6) Peimbert and Torres-Peimbert 1978, (7) this paper.

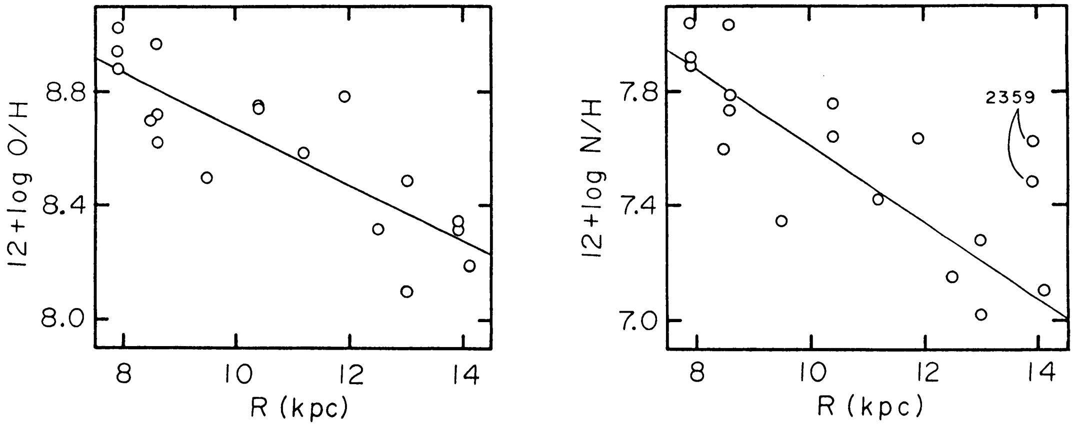

Figure 1. Oxygen and nitrogen abundances versus galactocentric distance for galactic H II regions. The solid lines represent the least-squares solution. For the nitrogen solution NGC 2359 was not included.

There are three possible explanations for the scatter in the abundances at a given R present in Figure 1: a) observational errors due to the faintness of the auroral lines needed to determine the electron temperature, b) inadequate abundance determination procedures, i.e. improper ionization correction factors or temperature distribution scheme, c) real abundance differences. In Figure 1 some of the points represent the same object observed by different groups which implies that the scatter due to observational errors amounts to ∿0.2 dex. We cannot rule out the absence of real abundance differences between H II regions at the same galactocentric distance, these differences, if present, cannot amount to more than a factor of two. Chevalier (1978) has studied the problem of element mixing in the interstellar medium and possible causes for abundance differences at a given galactocentric distance.

If instead of fitting an exponential curve to the observations we do a linear fit with the data presented in Figure 1, it is found that O/H= 0 for R= 15.77 kpc and N/H= 0 for R= 14.25 kpc. These fits are reasonably good and imply that very little star formation activity has taken place at galactocentric distances larger than R= 15 kpc. In this review it has been assumed that $R_\odot$= 10 kpc.

It is relatively easy to observationally determine N^+/S^+ abundance ratios in H II regions and therefore to derive its gradient in the Galaxy and other galaxies, this ratio is almost independent of electron temperature, reddening, and instrumental correction. Theoretical models (Peimbert et al. 1974, Hawley and Grandi 1977) predict that in those regions where N is once ionized not only S^+ but also S^{++} is present and consequently to derive the N/S gradient from N^+/S^+ observations it has to be shown that N/S is proportional to N^+/S^+. Since the S/O ratio is almost the same in the Orion nebula, the SMC and the LMC H II regions (Pagel 1978) we would expect the O/H and S/H gradients in the Galaxy to be similar. Consequently the validity of the $d \log (N^+/S^+)/dR = d \log(N/S)/dR$ relation depends on the similarity of the N^+/S^+ and N/O gradients. From Tables I and II it follows that this is indeed the case and that the N^+/S^+ gradient is a good indicator of the N/S gradient.

To obtain the He/H abundance ratio in H II regions it is necessary to estimate the amount of neutral helium present in them. This estimate is based on the ionization degree of other elements that can be observed in several stages of ionization. The best results are obtained from objects of relatively high degree of ionization with a negligible amount of He^0 and from observations of different points with varying degrees of ionization within the same H II region. Peimbert et al. (1978a) have found a $\log(He/H)/dR = -0.02\pm0.01$ while Hawley (1978) does not find such a gradient. Shields and Searle (1978) from their observations and independently from those of Smith (1975) obtained a similar He/H gradient in M101 to that derived by Peimbert et al. for the Galaxy (see Table II). The helium abundance differences found in PN and H II regions in the Galaxy and other galaxies correspond to $2 \lesssim \Delta Y/\Delta Z \lesssim 3.5$.

Based on the λ4267 line of C II, transition $4f\,^2F^0-3d\,^2D$, Peimbert and Torres-Peimbert (1978) have obtained the carbon abundance from three H II regions and derive the gradient given in Table I. It is very difficult to obtain the C/H abundance in H II regions from observations in the optical region since λ4267 is typically about 400 times fainter than Hβ in H II regions of the solar neighborhood.

TABLE II

Abundance Gradients in M101*

He/H	O/H	N/H	N^+/S^+	Reference
	-0.06	-0.09	-0.03	Smith (1975)
+0.01	-0.15	-0.14	-0.04	Hawley (1978)
-0.02	-0.08	-0.15	-0.07	Shields and Searle (1978)

* Given in d log(X/Y)/dR kpc^{-1} and evaluated at a distance comparable to that of the solar neighborhood.

The very large C/N ratio in the solar neighborhood (Peimbert and Torres-Peimbert 1977, Lambert 1968) coupled to the similarity between the C/H and O/H abundance gradients implies that: a) only a small amount of carbon has been converted into nitrogen by a secondary mechanism and b) stars like PN, have ejected to the interstellar medium a small amount of carbon, produced in them, as compared to that ejected by massive stars. Furthermore the C/H abundance gradient implies that if the fraction of carbon embedded in CO molecules is the same in all the Galaxy the estimated amount of H_2 molecules for the Galaxy based on the CO distribution should be reduced by a factor of two to three (Gordon and Burton 1976, Peimbert 1978b).

In Table II we present the abundance gradients for M101 they are in good agreement with the galactic ones particularly those derived by Shields and Searle (1978). From an analysis of radio recombination lines Churchwell and Walmsley (1975) and Churchwell et al. (1978) have found a positive electron temperature gradient in the Galaxy extending from 5 to 13 kpc, from their model calculations an increase in Z of about a factor of 2 from R= 13 to R= 5 kpc is required; this variation corresponds to d log(O/H)/dR $\sim$ -0.03 which is in good agreement with the results by Hawley (1978) but is significantly smaller than the other values given in Table I. Considerable work has been done on CNO isotopic variations in the interstellar medium (see Linke 1977 and references therein), significant differences have been found mainly between the solar neighborhood and the galactic center but no clear-cut results on isotopic abundance distributions across the disk of the Galaxy have been found with the exception of a practically constant $^{12}C/^{13}C$ ratio. Audouze et al.(1976) have computed simple models of galactic chemical evolution that are in agreement with the $^{12}C/^{13}C$ observations and that predict a substantial N/O gradient.

4. DISCUSSION

A relationship of the type $[N/O] = \alpha[O/H]$ with $\alpha= 1$ is predicted by simple models with instant recycling approximation assuming nitrogen to be of secondary origin (Talbot and Arnett 1973). In Figure 2 we show the N/O versus O/H plot for the galactic H II regions, the data show a value of α close to 0.4 in poor agreement with the theoretical prediction. Furthermore a very poor fit is provided by more precise models that drop the instant recycling approximation (Talbot and Arnett 1974) presented in Figure 2.

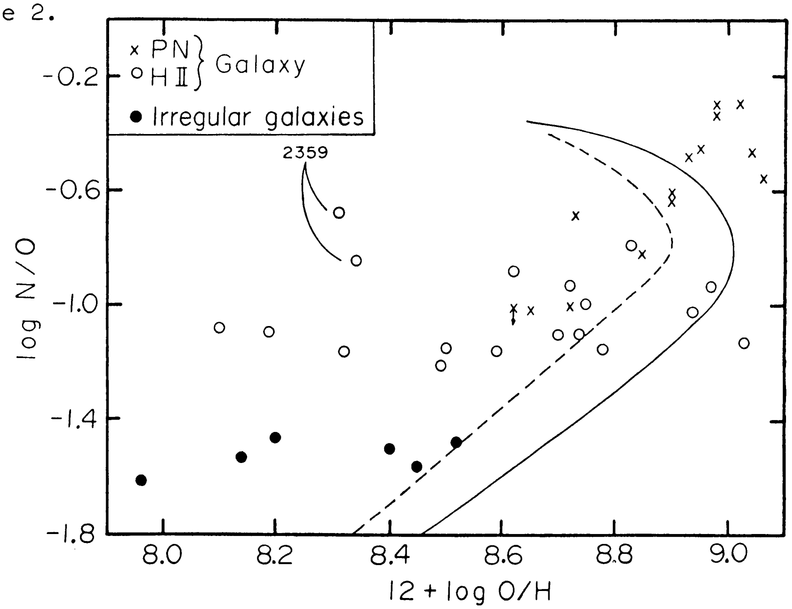

Figure 2. Relative nitrogen abundance N/O versus oxygen abundance. Broken and full curves show theoretical predictions by Talbot and Arnett (1974) for MESF and simple models respectively.

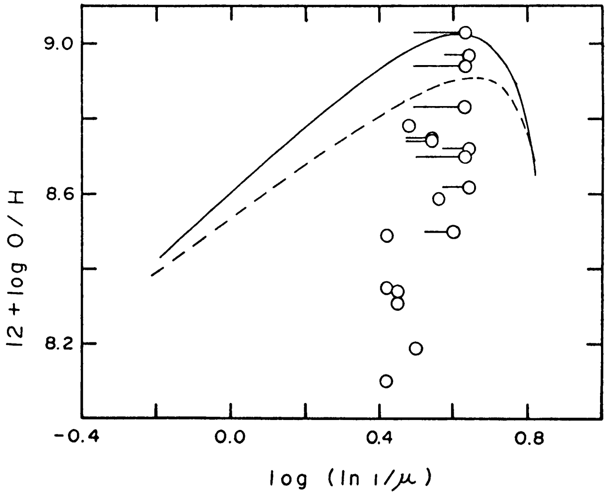

Figure 3. Oxygen abundances plotted against the astration parameter, log(ln 1/μ), for H II regions in the Galaxy. Horizontal bars represent the correction for H_2 molecules after Gordon and Burton (1976). Broken and full curves show theoretical predictions by Talbot and Arnett (1974) for MESF and simple models respectively.

Some support for the galactic result is given by Smith (1975) who obtained a value of $\alpha \sim 0.5$ for the H II regions in M33 and M101, however Shields and Searle (1978) find $\alpha = 0.8 \pm 0.3$ for M101. In Figure 2 we have also plotted the H II region values derived for the irregular and dwarf blue galaxies: NGC 6822 V, LMC, SMC, II Zw40, II Zw70, and NGC 4449 (Peimbert and Spinrad 1970, Peimbert and Torres-Peimbert 1974, 1976, Dufour 1975, Dufour and Harlow 1977, Aller et al. 1977, Pagel et al. 1978, Peimbert et al.1978b). The N/O versus O/H relationship is almost flat with $\alpha \sim 0.2$ again in disagreement with the predictions for simple models. A possible explanation, not the only one, is that in these objects nitrogen is mostly of primary origin with a primary production close to log N/O ~ -1.7. This is a very modest ratio about 1/5 of the Orion nebula value.

Another interesting difference present in Figure 2 is that H II regions in irregular and dwarf blue galaxies have a smaller N/O ratio for a given O/H ratio than galactic H II regions. A possible explanation is that the galactic initial mass function (IMF) is different to those of irregular and dwarf blue galaxies or that infall in the Galaxy of material with pregalactic abundances has reduced the O/H ratio of regions with substantial amounts of nitrogen produced by secondary mechanisms.

An excellent discussion on the implications of abundance gradients for galactic enrichment models has been made by Pagel et al. (1978). They have tested simple models of galactic chemical evolution in the instantaneous recycling approximation (Schmidt 1963, Talbot and Arnett 1971, 1973, Searle and Sargent 1972, Pagel and Patchett 1975, Audouze and Tinsley 1976) by means of the equation

$$\log Z = \log p + \log(\ln 1/\mu) \qquad (1)$$

where it has been assumed that gas changes into stars according to a constant IMF in an isolated zone, Z is the mass-fraction of heavy elements in the interstellar gas, p the yield and μ the ratio of the remaining mass of gas to the total mass of the zone. Pagel et al. find that equation (1) is not in contradiction with the observations of the Magellanic Clouds, on the other hand for the H II regions in the Galaxy observed by Peimbert et al. (1978a) they find that the fit is very poor since for very different O/H ratios μ is almost the same.

In Figure 3 we present the O/H ratio versus log(ln $1/\mu$) for those H II regions in Figure 1 and Table I. The values of μ were obtained from Gordon and Burton (1976) and Innanen (1973), in the galactocentric range of interest the correction due to molecular hydrogen is small. The additional data confirms the result of Pagel et al. (1978) that the O/H ratio is independent of μ and that there is no agreement with simple models of galactic chemical evolution.

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DISCUSSION

Tinsley: You showed a plot in which O/H does not vary with $\ell n(1/\mu)$ in the way simple models predict, and you mentioned that infall could solve the problem. It is true that with infall there need be no correlation between abundances and gas fraction. However, in order to get an abundance spread, some parameter must vary from region to region. One possibility is that the IMF varies, and another possibility is that the ratio of star formation rate to infall rate varies. In particular, infall leads to a limiting abundance of a given element which is the product of its yield (dependent on the IMF) and the ratio (star formation rate)/(infall rate).

Wollman: As one moves toward the center, is there a preferential settling of heavier material into the plane? Might this account for an abundance gradient? The abundance of neon within the central parsec of the Galaxy is apparently not more than about three times the adopted solar abundance.

Peimbert: Since the observations come from HII regions that are located very close to the galactic plane, $<|z|> \sim$ pc, the effect that you mention will produce a negative gradient. I think that theoretical quantitative predictions should be carried out considering at least the following elements: H, He, C, N, O, Ne and S. The optical results are not in contradiction with the results for the galactic center. There are theoretical models of the chemical evolution of the Galaxy that predict a maximum in the O/H ratio in the 2 to 6 kpc range. More observations in the infrared are needed to obtain the galactocentric distribution of chemical abundances.