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CHEMICAL ABUNDANCES IN PLANETARY NEBULAE

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Abstract. PN can be divided into four types depending on their chemical composition. In order of decreasing heavy element abundances the types are: I) He and N rich, II) intermediate population, III) high velocity, and IV) halo population. The type II PN are overabundant in N and C relative to the Orion Nebula. Well defined gradients across the galactic disk of He, N and O are derived from type II PN; the oxygen gradient is similar to the metallicity gradient derived from GK giants and F main sequence stars. By comparing the O, Ne and S abundances of PN of types III and IV with the Fe abundances of stars of similar population it is found that the O, Ne and S enrichment in the Galaxy probably took place before the Fe enrichment.

1. INTRODUCTION

Recent reviews and general studies on chemical abundances in PN are those by Aller and Czyzak (1973), Miller (1974), Osterbrock (1974), Barker (1974), Aller (1976) and Torres-Peimbert and Peimbert (1977a, hereunder TPP).

We will restrict this review to galactic PN and to the abundances of H, He, C, N, O and Ne based mainly on photoelectric observations in the visual spectral range. Aller (1977) considers these and other less abundant elements while Kaler (1977) considers Ar and Ne. Recent advances in infrared detectors and UV observations outside the atmosphere have considerably increased the range of emission lines available for the determination of physical conditions. Some of the most important lines detected so far are λ1909 of CIII and λ1549 of CIV, which will be discussed in §2.3, and 12.78μ of NeII which is crucial for the determination of neon abundances in low ionization PN (c.f. Gillett et al.,1973). Abundance determinations based on ionization structure models have been discussed in the recent reviews by Miller (1974), Harrington (1977) and Aller (1977).

The study of chemical abundances in PN is paramount for the under-

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standing of the following problems: a) the effect of evolution of the progenitor star on the chemical composition of the ejected PN envelope; b) the enrichment of the N/O and C/O ratios in the interstellar medium due to PN shells; and c) the determination of the abundances of the interstellar medium, at the time of formation of the progenitor stars, this refers to those elements not affected by stellar evolution in the ejected shells, in particular Ne, S, Ar and possibly O. These problems are related to the study of abundance gradients across the disk of the Galaxy.

2. CLASSIFICATION OF PN

From the range in kinematical properties, galactic distribution, chemical composition and mass of the envelope it follows that PN are a mixed group ranging from Population I to extreme Population II. That is, the masses of the progenitor stars range from several solar masses to less than one solar mass. Osterbrock (1973, p. 404) has suggested that the difference in spectral types of the central stars of PN might be due to differences in the masses of the progenitor stars. Aller and Czyzak (Aller, 1976) find a strong correlation between the spectra of the central stars and the chemical composition of the shells; those stars with continuous and Wolf-Rayet type spectra in general show considerably higher nitrogen and oxygen abundances than those of stars with hydrogen and helium absorption lines. Due to the difference in chemical composition and the different information that can be derived from PN we decided to divide them into four types.

2.1 Type I, helium and nitrogen rich

This is a group of PN which have similar characteristics: a) $N(He)/N(H) \gtrsim 0.14$, b) high nitrogen abundance, and c) extremely filamentary structure. Objects of this type are NGC 6302, NGC 6445, Hu 1-2, Me 2-2, NGC 2440, PB 6 and NGC 2818 (Danziger *et al.*,1973; Aller *et al.*, 1973; Kaler, 1976; Kaler and Aller, 1974; TPP; Dufour and Hack, 1977). The average chemical composition of this type is presented in Table I. Type I PN comprise an extreme subset of Greig's (1971,1972) class B which is defined as having strong forbidden lines of elements in very different degrees of ionization and very conspicuous filamentary structure. Their kinematical properties and galactic distribution place these objects as Population I.

NGC 2818 apparently is a member of the open cluster of the same name which has a main sequence turn-off at about A5 (Tifft *et al.*,1972; Dufour and Hack, 1977) which corresponds to a mass of about 2.1 $M_\odot$ (Allen 1973). The distance to the cluster is of 3.2 kpc which in combination with the observed flux and reddening correction at Hβ (O'Dell, 1963;TPP) yield a M(rms)= 0.80 $M_\odot$ for the shell. This mass is larger than the mean values of 0.50 $M_\odot$ and 0.18 $M_\odot$ derived under the Cudworth (1974) and Cahn and Kaler (1971) distance scales for optically thin PN. It should be noted that the mean values mainly correspond to Type II PN.

The excess helium and nitrogen abundances of Type I PN over the rest of PN are probably due to two causes: a) the more massive nature of their progenitors, which implies that they were formed more recently from a medium presumably richer in helium and heavier elements relative to hydrogen (Pagel and Patchett, 1975;Luck, 1977),and b) a larger contamination of the ejected envelope due to stellar evolution; this envelope is also expected to be more massive than those of the other types of PN.

A careful study of objects of this group should be carried out to find out the extent of the He, N and O enrichment relative to the present chemical composition of the interstellar medium.

2.2 Type II, Intermediate Population I

PN of the solar neighborhood have an average height above the galactic plane of 150 pc which corresponds to progenitors of $M= 1.5\ M_{\odot}$; these values are typical of Intermediate Population I objects (Osterbrock, 1973). Most PN are of Type II, i.e.have been produced by intermediate mass stars. The two following effects are combined to yield a maximum number of PN at intermediate masses: a) the slope of the initial mass function that yields very few objects of large mass, and b) the small fraction of stars of Population II that become PN also yielding few PN in the low mass bracket (van den Bergh, 1973; Alloin et al., 1976).

In TPP the 16 best observed objects (those with the most accurate auroral and transauroral line intensity determinations) have been chosen to derive average abundances of He, N, O and Ne. The values derived would correspond to those of a "typical" PN of Type II. These abundances are presented in Table I and are compared with those for the Orion Nebula, which were derived using the same procedure and atomic parameters, (Peimbert and Torres-Peimbert, 1977) and the Sun (Lambert, 1968; Bertsch et al.,1972). The solar C, N and O values used here are very similar to those in the recent compilation by Ross and Aller (1976). From Table I it is clear that nitrogen has been significantly enriched by stellar evolution in PN shells. Previously other authors had reached the same conclusion (Peimbert and Torres-Peimbert, 1971; Barker, 1974; Boeshaar, 1975; Aller, 1976; Hawley and Miller, 1977).

The value of log N(C)$\sim$9.5 derived in TPP is based on the λ4267 recombination lines observed by Aller and co-workers (Kaler, 1976a). These carbon lines are very weak and their intensities are not as accurate as the photoelectrically measured ones. Alternatively Bohlin et al. (1975,1977) and Panagia et al.(1976), based on the CIV λ1549 and CIII λ1909 lines in NGC 7027 and NGC 7662 derive log N(C)$\sim$8.6-9.0 for these objects which is considerably smaller than the value derived from the recombination lines. This discrepancy should be studied further. Nevertheless these results indicate that the carbon abundance in PN shells is at least normal, if not overabundant. Furthermore Panagia et al. (1976) estimate that in NGC 7027 the amount of carbon embedded in dust grains is similar to that in gaseous form, and TPP argue that the spectra of the central stars of PN are compatible with a carbon overabundance in their photosphere.

TABLE I
Chemical Abundances

	Planetary Nebulae				Orion Nebula	Sun
	I He-N rich	II Interm. Pop.	III High Velocity	IV Halo Pop.		
N(He)/N(H)	0.16	0.11	0.11	0.10	0.10	...
log N(C)	...	{9.5:* 8.8†	...	...	8.5*	8.5
log N(O)	8.8	8.9	8.8	7.7	8.7	8.7
log N(N)	9.0	8.3	8.2	7.4	7.7	7.9
log N(Ne)	8.2	8.3	8.2	7.0	7.9	7.9

* from λ4267 of C II
† from CIII] and CIV UV lines

2.3 Type III, high velocity

Kaler (1970) has defined as Population II PN those objects with $|\Delta v| > 60$ km s^{-1} or $|z| > 0.8$ kpc. We will define as Type III PN those objects with $|\Delta v| > 60$ km s^{-1} that do not belong to the Halo Population. Barker (1974) studied 22 PN that fit Kaler's definition for Population II. In order to have a homogeneous system of abundances we recomputed them with the same mean square temperature fluctuation, $t^2 = 0.035$, and the same atomic parameters used throughout Table I. Most of the difference between the values in Table I and those derived by Barker is due to our use of the cross sections for O^{++} by Eissner and Seaton (1974) instead of those by Eissner _et al_. (1969).

Barker (1974) found similar O/H and Ne/H ratios for PN of Types II and III, the Orion Nebula and the sun. Since a considerable fraction of stars of similar kinematic characteristics to those of Type III PN are Fe poor a similar fraction of Type III PN is expected to be Fe poor. Barker points out that this probably implies that the O and Ne enrichment in the Galaxy took place before the Fe enrichment, this point will be rediscussed in §2.4. At present it is difficult to directly obtain Fe abundances for PN because most of the relevant atomic parameters are not available. Moreover Shields (1975) has estimated that most of the Fe atoms in the shell of NGC 7027 are embedded in dust grains.

2.4 Type IV, Halo Population

There are three known PN that belong to the Halo Population: K648 in M15 (Peimbert, 1973), H 4-1 (Miller,1969) and 108-76°1 (Boeshaar and Bond 1977). K648 and 108-76°1 have N(He)/N(H)∼0.10, while H 4-1 have N(He)/N(H)= 0.09 (Torres-Peimbert and Peimbert,1977b); that is, Type

IV PN do not show excesses in helium, on the contrary they appear to have a slight deficiency of this element relative to the other PN.

Due to the almost normal chemical abundance of the shells of PN and the enriched appearance of the spectra of the central stars it is thought that most of the hydrogen rich convective envelope, present during the red giant phase, is ejected to form the PN shell; furthermore the mass in the hydrogen rich envelope increases with stellar mass (Paczynski and Ziolkowski, 1968; Harm and Schwarzschild, 1975). Therefore the result by Peimbert (1973) of M(rms)= 0.018 $M_\odot$ for the shell of K648 and the M(rms)= 0.80 $M_\odot$ value for NGC 2818 provide another argument in favor of a range of masses for the progenitor stars.

K648 has about one order of magnitude less O and Ne relative to Population I objects; while the red giant stars have at least two orders of magnitude less Fe (Peimbert, 1973; Butler, 1975). As in the case of PN of Type III there are two possible explanations for this result: that the ejected shell has been contaminated by O and Ne and it does not represent the stellar original abundances or, more likely, that indeed the O and Ne enrichment in the Galaxy took place before the Fe enrichment.

Observations of the Cas A SN remnant provide additional evidence in favor of a different rate of enrichment of Fe relative to the rates for O, S and Ar. While O, S and Ar are overabundant by at least two orders of magnitude relative to H in the fast moving knots (Peimbert and van den Bergh, 1971; Peimbert, 1971; Chevalier and Kirshner, 1977), Fe is underabundant relative to O, S and Ar (Chevalier and Kirshner). This result indicates that this type of SN can be responsible for the O, S and Ar enrichment of the interstellar medium but not of the Fe enrichment. Based on these and other arguments Chevalier (1976) has suggested that the Fe enrichment is due to SN of Type I. This would explain the different rates of enrichment of O, S and Ar relative to Fe.

3. ABUNDANCE GRADIENTS

To study the presence of abundance gradients in the interstellar medium of the Galaxy it is necessary to select Type II PN which have nearly circular orbits and are located at galactocentric distances similar to those of their birthplace. Type I PN have probably been affected by considerable helium enrichment due to their own stellar evolution, while objects of Types III and IV in general originated at very different galactocentric distances from their present location. The expected gradients are rather flat, their determination is complicated by the relatively large errors introduced by the emission line intensity measurements. Therefore we will study the gradients determined from the best observed objects in TPP. Previous work on abundance gradients has been done by other authors: Barker (1974) found negative gradients of He, N and O based on a smaller sample of Type II PN than that in TPP but no gradients from Type III objects; D'Odorico et al.(1976) found negative gradients of He, N and O on a smaller sample of Type II PN than that in TPP; and Aller (1976) found moderate negative gradients of He and N but not of O from a mixed sample of PN types, mostly of Type II.

3.1 Oxygen, nitrogen and helium

The values for the abundance gradients derived in TPP are presented in Table II. For the optically thick PN Cudworth's (1974) distance scale, which is very similar to that of Minkowski (1965), has been used. For the optically thin PN both Cudworth's as well as Cahn and Kaler's (1971) distance scales have been used. The results for both distance scales are not very different because only 6 out of the 16 objects are optically thin. The gradients are uncertain not only due to the errors in the line intensity measurements and in the abundance determination procedure but also due to the statistical nature of the individual distances. The detection of the abundance gradients, based on objects with very different ionization structure, indicates that the errors introduced by the abundance determination procedure are small. The rest of the PN not included in the best observed sample by TPP show a larger scatter in their correlation of abundances with galactocentric distance than the best observed objects. This indicates that a considerable fraction of the scatter is due to errors in the line intensity determinations and not to errors in the abundance determination procedure.

TABLE II

Solar Neighborhood Abundance Gradients (kpc^{-1})

	PN (C)	PN (CK)	H II Regions
$\frac{d \log(He/H)}{dR}$	-0.02±.01	-0.03±.01	-0.02±.01
$\frac{d \log(O/H)}{dR}$	-0.06±.02	-0.08±.02	-0.13±.04
$\frac{d \log(N/H)}{dR}$	-0.18±.04	-0.21±.04	-0.23±.06

3.2 Comparison with H II regions and stars

In Table II we also present the abundance gradients derived by Peimbert et al.(1977) from galactic H II regions. The helium gradient is similar for both types of objects. The oxygen gradient is flatter for PN, and while the O/H ratios are similar at the solar neighborhood at larger galactocentric distances the O/H ratio is higher in PN than in H II regions;this difference might be significant. The nitrogen gradient is similar for PN and H II regions, however the N/H ratios are from 4 to 5 times larger in PN than in H II regions, supporting the secondary origin of nitrogen in PN.

Mayor (1976) has found, for a sample of 600 F main sequence and 600 GK giant stars, a value of d log(M/H)/dR= -0.05 kpc^{-1}, where M stands for metals. For a subset of his sample comprising the youngest objects he found d log(M/H)/dR= -0.10 kpc^{-1}. The PN oxygen gradient is similar to the metal gradient derived from the FGK stars which is in agreement with the intermediate population characteristics of both types of objects.

4. RELATIVE ENRICHMENT OF NITROGEN OXYGEN AND HELIUM

The study of abundance gradients from PN is affected by the lack of reliable individual distances to the objects and by the various ages of the PN involved. It is thus important to study distance independent correlations like the relative enrichments of N, O and He.

4.1 Nitrogen and oxygen

Boeshaar (1975) found that in general the earlier the population type of PN the more abundant in nitrogen. Aller (1976) found [N/O]= 0.32 for Greig's B and [N/O]= 0.15 for his C nebulae, where the square brackets refer to the usual logarithmic notation,which is in agreement with Boeshaar's result. In TPP a tight correlation between nitrogen and oxygen is found, with a slope of $\Delta[N/H]/\Delta[O/H] = 2.5$. Smith (1975) from observations of H II regions in spiral galaxies found a slope of $\Delta[N/H]/\Delta[O/H] \sim 1.5$. Peimbert <u>et al</u>.(1977) from observations of galactic and Magellanic Clouds H II regions find values in the 1.1 to 1.7 range for this ratio. The large $\Delta[N/H]/\Delta[O/H]$ ratio in PN also points to a nitrogen enrichment in the ejected shell produced by mixing of nucleosynthesis products to the surface of the star prior to the ejection of the envelope.

4.2 Helium and oxygen

Kaler (1970) found a fairly steep inverse correlation between helium and oxygen abundances in PN, also Barker (1974) found an almost flat inverse correlation. On the other hand, TPP found a fairly steep positive correlation between He and O abundances. The observational errors are smallest for the objects in TPP and largest for the objects in the work by Kaler. The reasons are that most of the line intensity determinations used by Kaler are photographic while those used in the other two studies are photoelectric, and secondly that the objects in TPP are in general brighter than those observed by Barker. The inverse correlation can be explained as due to overestimates by varying amounts of the weak line intensities. For example the larger the overestimate the higher the He/H ratio, the higher the electron temperature derived from forbidden lines and the lower the derived O/H ratio.

By adopting oxygen as representative of the heavy elements and by assuming a factor of proportionality such that Z= 0.01 for log O/H= -3.41 (Peimbert and Torres-Peimbert 1974) in TPP it is found that the slope of the helium to metals correlation is ΔY/ΔZ= 2.4 and extrapolating for Z= 0 it corresponds to Yp= 0.244. These results are in fair agreement with those derived from the Orion Nebula and the Magellanic Clouds H II regions as well as with those derived from galactic H II regions (Peimbert and Torres-Peimbert, 1977;Peimbert et al., 1977). He and O could have been contaminated in PN by their own stellar evolution, however since the agreement of these correlations with those derived from H II regions is good, it follows that for PN of Type II the enrichment of He and O has not been considerable, and that the He and O gradients derived from PN of Type II indeed are related to the gradients of the interstellar medium at the time of formation of the progenitor stars.

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DISCUSSION

Miller: Did you attempt any tests of significance, like chi-squared tests, for those lines in those figures that gave slopes?

Peimbert, M.: The plus or minus comes mainly from the accuracy of the helium determination. It's not a chi-squared test.

Dufour: I noticed that extrapolation of your log O vs. log N for planetary nebulae goes across the values for SMC and LMC HII regions, while the line for galactic HII regions does not. Does this tell us anything about differences in the chemical evolutionary history of the Clouds and the Galaxy or about differences in the initial mass function of stars in the Clouds and the Galaxy?

Peimbert, M.: The difference is of the order of a factor of 2 or so which is close to being significant. It probably means that the amount of material that has been processed in the Clouds is relatively smaller than the amount that has been processed in the galaxy for objects with similar chemical abundance.