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CHEMICAL COMPOSITION OF PLANETARY NEBULAE[†]

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ABSTRACT

Contemporary ideas about the characteristics of Planetary Nebulae are summarized. The chemical composition of the objects are presented in more detail; and the derived information about their progenitor stars is discussed. A description on the influence of intermediate mass stars on the galactic interstellar medium is also given.

RESUMEN

Se presentan brevemente las ideas contemporáneas respecto a las características de las nebulosas planetarias. Se hace énfasis en la composición química y en la información que se deriva de ésta acerca de las estrellas progenitoras. Finalmente se hace una breve relación de la influencia que las estrellas de masa intermedia tienen sobre el medio interestelar galáctico.

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1. INTRODUCTION

The beautiful appearance of Planetary Nebulae (PN) has aroused the interest of sky observers since their discovery. PN have also been a source of considerable scientific knowledge because of their physical conditions that lead to straightforward interpretations of the observations. To date the most complete catalogue of planetary nebulae is the Strasbourg catalogue(1) containing a list of 1455 objects. There are several recent monographs on the subject of PN.(2,3) In Fig. 1 a sample of 4 PN is shown.

PN have been observed to be associated with a blue star at the center called the nucleus of the nebula. It has also been known that the nucleus is the original source of energy powering the nebula. With the advances of the theory of stellar evolution and detailed analysis of observational data it became quite clear that the nuclei of planetary nebulae represent a rather late stage in the evolution of a star not much more massive than the sun. The data also suggested that further evolution of these stars leads naturally to the white dwarf stage. The nature of the precursors to the planetary nebula nucleus was not, however, immediately clear although the early work in the field suggested that red giants and long period variables are the promising candidates. During the last decade considerable progress has taken place in our understanding of these late phases of stellar evolution; the evolutionary connection between planetary nebulae and their immediate precursors, the red giants, seems to have been clearly established.

From spectroscopic measurements of their expansion velocities, and from their increase with time in angular size it is apparent than the nebular expansion lead to the eventual dispersal of the stellar material that forms these shells into the interstellar medium. Since the PN stage occurs late in the life of the stars it is conceivable that part of the material thus returned has undergone the effects of stellar nucleosynthesis. This points out the need to study the role of planetary nebulae on the general scheme of chemical evolution of galaxies. The exact manner in which chemical evolution enrichment has occurred in galaxies is a subject of enormous current interest. Analysis of nebular spectra indicates that

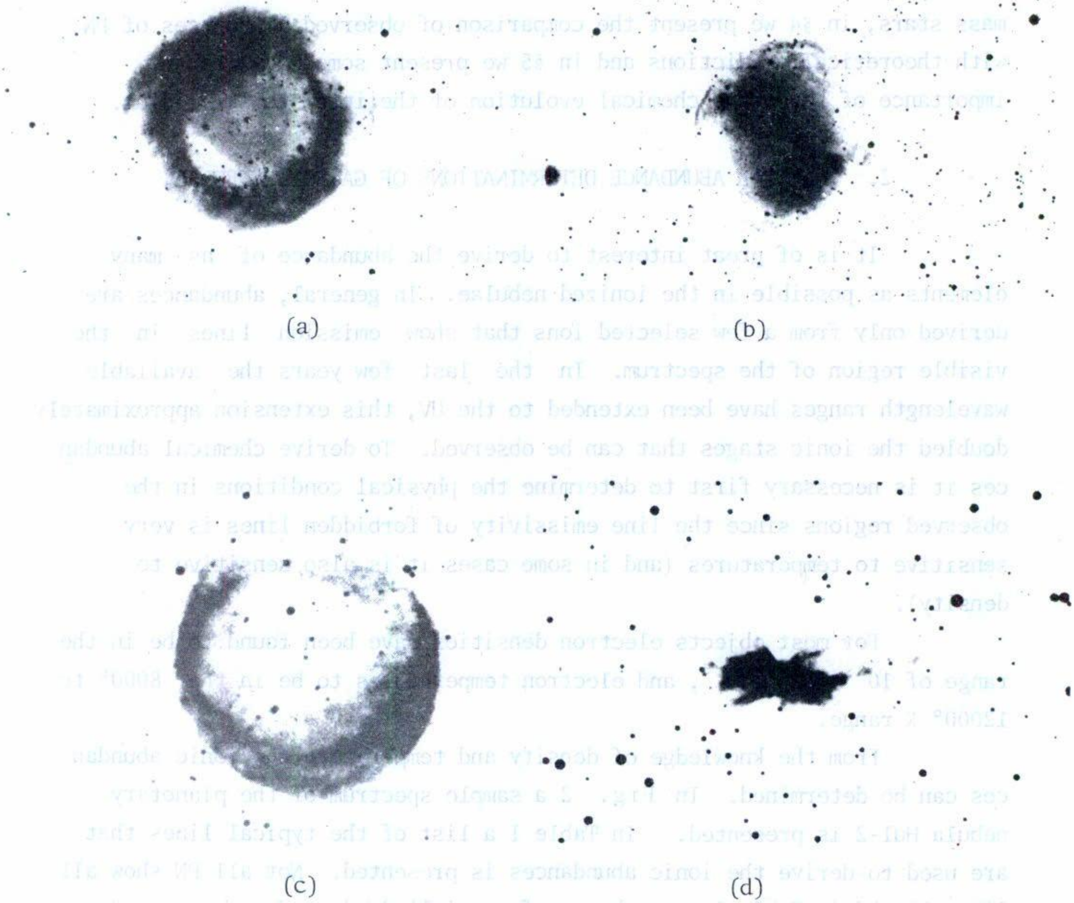

Fig. 1. Direct photographs of planetary nebulae. a) NGC 7293 the Helix Nebula (Anglo-Australian Telescope Board). b) NGC 6853 Dumbbell Nebula (Hale Observatories). c) NGC 6781 in red light.(86) d) NGC 6302 (Anglo-Australian Telescope Board), it is a bipolar nebula of Type I.

PN contribute significantly to this process of enrichment.

The main purpose of this paper is to review the present ideas on the chemical composition and the influence of PN in the chemical evolution of the interstellar medium. To achieve this purpose we present in §2 a description of chemical abundance determinations of gaseous nebulae, in §3 we describe the current theoretical ideas on the evolution of intermediate mass stars, in §4 we present the comparison of observed abundances of PN with theoretical predictions and in §5 we present some ideas on the importance of PN on the chemical evolution of the interstellar medium.

2. CHEMICAL ABUNDANCE DETERMINATIONS OF GASEOUS NEBULAE

It is of great interest to derive the abundance of as many elements as possible in the ionized nebulae. In general, abundances are derived only from a few selected ions that show emission lines in the visible region of the spectrum. In the last few years the available wavelength ranges have been extended to the UV, this extension approximately doubled the ionic stages that can be observed. To derive chemical abundances it is necessary first to determine the physical conditions in the observed regions since the line emissivity of forbidden lines is very sensitive to temperatures (and in some cases it is also sensitive to density).

For most objects electron densities have been found to be in the range of 10^3 to 10^4 cm^{-3}, and electron temperatures to be in the 8000° to 12000° K range.

From the knowledge of density and temperature the ionic abundances can be determined. In Fig. 2 a sample spectrum of the planetary nebula Hul-2 is presented. In Table I a list of the typical lines that are used to derive the ionic abundances is presented. Not all PN show all lines listed in Table I, some show preferentially high or low ionic stages depending on the exciting stellar spectrum and conditions in the nebulae. Also it is known that the spectrum varies with position within the PN, the higher stages of ionization, being in general closer to the central star.

For the interpretation of lines excited by electron collisions it is assumed that the rate coefficient may be written

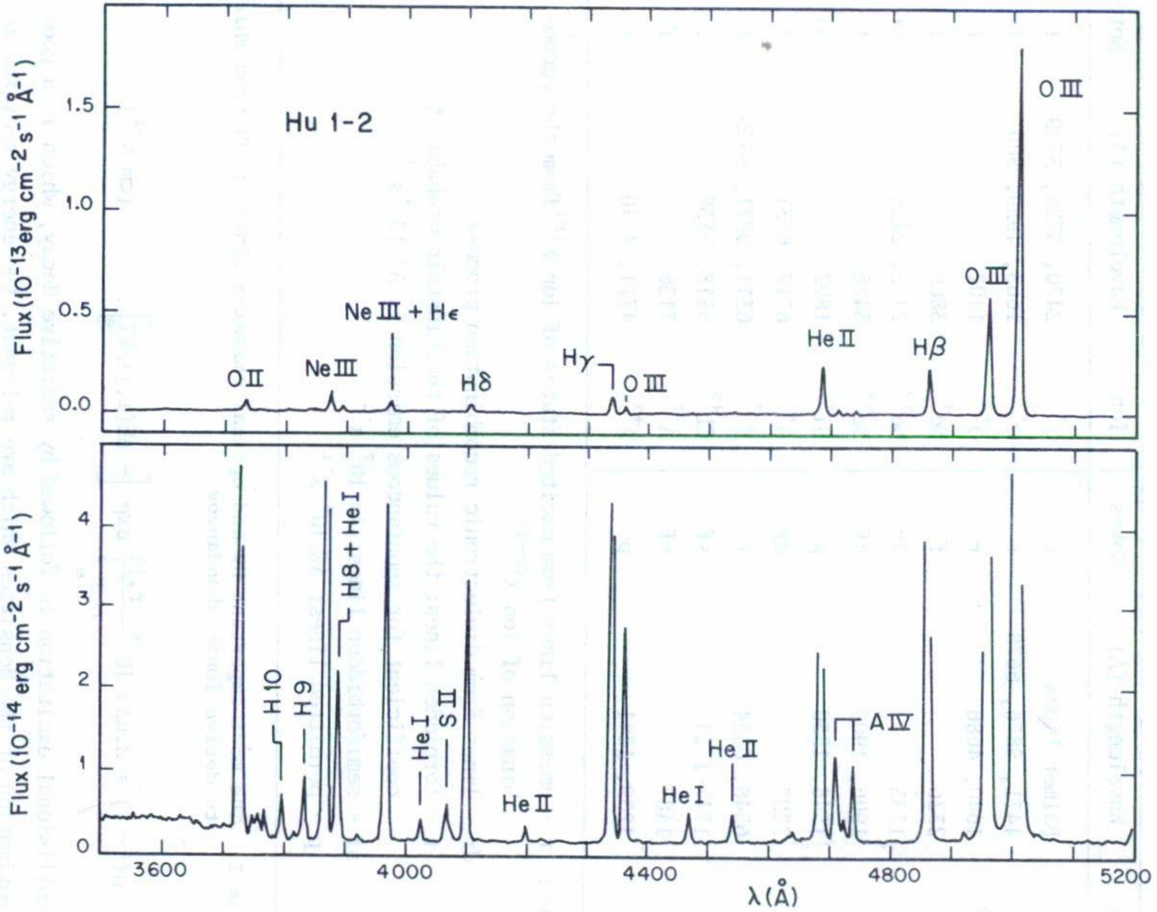

Fig. 2. Blue spectrum of the planetary nebula Hu1-2 obtained by the author. The lower part is the same section of the spectrum as the upper part, that has been amplified to display the weak emission lines. The strongest line is λ5007 Å of O^{++}.

TABLE I

Ion	Wavelength (A)	Notes	Ion	Wavelength (A)	Notes
H^+	Balmer lines	r	O^+	2470, 3726, 3729	f
He^+	4471, 5876, 6678	r	O^{+2}	1663, 4959, 5007	f
He^{+2}	1640, 4686	r	O^{+3}	1402	f
C^+	2326	f	Ne^{+2}	3869	f
C^{+2}	1335	dr	Ne^{+3}	2423, 2425	sf
	1906, 1909	sf	Ne^{+4}	3426	f
C^{+3}	1548, 1550	p	Si^{+2}	1892	sf
	2297	dr	S^+	6717, 6731	f
N^+	6548, 6584	f	S^{+2}	6311, 9071, 9535	f
N^{+2}	1747-1754	sf	Cl^{+2}	5518, 5538	f
N^{+3}	1487	sf	A^{+2}	7136	f
N^{+4}	1239, 1241	p	A^{+3}	4711, 4740	f

Notes: r - emission lines from excited states of ion $X^{(r)}$ from the recombination of ion $X^{(r+1)}$

dr - lines from dielectronic recombination process

f - forbidden lines; the values of the Einstein probability coefficient for spontaneous emission is $A \lesssim 10^{-2} s^{-1}$

sf - semiforbidden lines; $A \sim 10^2 \; s^{-1}$

p - permitted lines; $A \gtrsim 10^6 \; s^{-1}$

Table I. The most important UV and optical emission lines in PN from which to derive ionic abundances

$$q(i \rightarrow j) = 8.63 \times 10^{-6} \frac{\gamma(r,j)}{\omega_i T_e^{\frac{1}{2}}} \exp\left[- \Delta E(i,j)/kT_e\right] \qquad (cm^3 s^{-1}) \quad .$$

If collisional excitation is followed by radiative decay, which is a good approximation at the densities which are relevant, the energy radiated in transitions back to the ground state is

$$N_e N(X^{m+}) \, q\,(i \rightarrow j) \; h\nu_{ij} \qquad (erg\ cm^{-3} s^{-1}) \quad ,$$

where N denotes a number density. This expression may be compared with that for the Hβ line of hydrogen

$$N_e N(H^+)\, \alpha\, (H\beta)\ h\nu_\beta \quad ,$$

where $\alpha(H\beta)$ is the radiative recombination coefficient. Integrating emission along the line of sight, we obtain

$$\frac{I(\lambda_{ij})}{I(H\beta)} = \frac{4861}{\lambda(\mathring{A})} \frac{q(i \rightarrow j)}{\alpha(H\beta)} \frac{N(X^{m+})}{N(H^+)} \quad ,$$

where $I(\lambda_{ij})/I(H\beta)$ is the intensity of the emission line at wavelength λ, relative to Hβ and corrected for interstellar reddening. The line intensity ratio is strongly dependent on the electron temperature, T_e, through the exponential in the expression for the excitation rate coefficient. It follows that the electron temperature must be accurately determined in order to obtain reliable abundance ratios.

That is, forbidden lines are very sensitive to temperature and the accuracy of the interpretation of the line intensities in terms of column density of emitting ions is highly dependent on the accuracy of the temperature determination. On the other hand, in the case of observed lines due to permitted transitions from excited levels that have been reached in the process of recombination, their emissivities have the same dependence on temperature as Hβ; and the derived abundance of the ion which undergoes recombination relative to H^+ is not sensitive to the temperature uncertainty.

It is particularly important to derive the abundance of carbon, since it is the most abundant element heavier than helium. In the optical spectral range there is only one faint carbon line available, the $\lambda 4267$ C^+ line which is produced by recombination of C^{++}; in the ultraviolet range there are lines of C^+, C^{+2} and C^{+3} (see Table I). There has been some question in the literature on whether the 4267 line is produced only by recombination or by some additional mechanism; in the latter case the abundance derived from it would be in excess to the real abundance. The abundances derived from the collisionally excited lines in the ultraviolet, as explained before, are very sensitive to the adopted temperature. In differential studies of PN it has been found that there is a systematically higher C^{++} abundance (by a factor of 1.5) derived from optical studies than from UV work.(4,5,6)

In order to derive total abundances it is necessary to correct for the elements in other stages of ionization which are not available for observation. There are two different approaches to this problem, one is to empirically calculate the abundance of the unseen ions based on the hypothesis that ions with similar ionization potentials have a similar behavior. Another approach is to compute theoretically ionization structures model and adjust the best fit to the observable parameters. In practice a combination of both techniques is the most feasible method. At present more than 100 objects have been analyzed and their chemical abundances have been derived.(2,6,7,8,9,10) The nebular abundances are to a first approximation similar to the so called "cosmic abundance". For most PN the differences are relatively small and for that reason it is difficult to make comparisons among objects that have been analyzed by different investigators.

There are nevertheless certain general features that have been identified. Peimbert(11) proposed a scheme to divide the galactic PN into four types: Type I (He-Ne rich), Type II (intermediate population), Type III (high velocity objects) and Type IV (halo population). From a variety of arguments related to stellar dynamics and stellar evolution it seems that this scheme is not only a chemical composition classification, but that it corresponds to progenitor stars of different masses in the main sequence. There have been several recent reviews dedicated to different aspects of chemical abundance(85) and of this classification.(5,12,13)

In Table II the abundances of planetary nebulae for the different types are presented. Also some of the more accurate abundance determinations for the sun and for galactic and extragalactic H II regions are given in Table II, where the Orion Nebula is representative of the solar neighborhood, and average values for several H II regions in the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). Most of the abundances of Table II were obtained from observations made with ground based optical telescopes; however abundances of carbon and some ions of nitrogen and neon were obtained from observations made with the International Ultraviolet Satellite (IUE).

TABLE II

Type	Element					References
	He	C	N	O	Ne	
			Planetary Nebulae			
$(He-N)_{rich}$	11.18	8.3-9.1	8.6	8.6	7.9	(11,15)
Intermediate	11.04	8.4-9.2	8.1	8.7	8.1	(5,12,13)
Halo	10.99	8.9	6.7-8.3	7.9	6.2-8.0	(14,16)
			Other Objects			
Orion	11.01	8.57	7.68	8.65	7.80	(17,18)
LMC (H II reg)	10.92	7.86	7.03	8.34	7.44	(19,20,22)
SMC (H II reg)	10.89	7.00	6.41	7.89	7.03	(19,21,22)
Sun	...	8.67	7.99	8.92	8.12	(23,24,25)

Table II. Chemical abundances expressed as log N(X) and scaled to N(H) = 12.00.

3. STELLAR EVOLUTION STUDIES OF INTERMEDIATE MASS STARS

The study of PN envelopes allows us to derive information about nucleosynthesis and stellar evolution processes that the progenitors have undergone during their lifetime.

It is thought that asymptotic giant branch stars (AGB), lose their outer layers to form PN and to expose their nuclei which will be responsible for the ionization of the nebular envelopes. The low velocity of expansion of the nebular matter in PN led Shklovsky(26) to suggest that the ejection took place while the parent star was a red giant, moreover, on the basis of the luminosity of the central stars of PN Paczyński(27) suggested that AGB stars undergoing double shell burning are the immediate progenitors of PN.

PN are formed by stellar mass loss in the form of winds and different types of winds have been discussed in the literature, this topic has been reviewed by Iben.(28) It seems that there are at least two different ways to produce PN: by mass ejection at a high rate (superwind) and by mass ejection at a lower rate (ordinary wind) followed by hot wind compression.

General descriptions(30) of the evolution of the surface abundances of He, C, N and O intermediate mass stars ($1 \leq M/M_{\odot} \leq 8$) from the main sequence until the ejection of the PN envelope or until ignition of C in the core are available.(29,30,31) They take into account two processes affecting the surface composition:

i) three phases of convective dredge-ups and

ii) nuclear burning in the deepest layers of the convective envelope.

The predictions are for an increase of H and N and C in the surface of the stars during their evolution; the exact amount depending on the mass of the star.

The computations by Renzini and Voli(29) have been made considering two parameters: $\alpha = \ell/L$, the ratio of the mixing length to the pressure scale height, and η, which multiplied by the Reimers' rate(35) gives the mass loss rate during the AGB phase. The computations were made for $\eta = 1/3$ and $2/3$ and $\alpha = 0$, 1, 1.5 and 2, with most of them for $\eta = 1/3$ and $\alpha = 0$ and 1.5. The values of α and η are not well known and they may vary with stellar evolution stage, initial stellar mass and chemical composition. Values of α and η can be obtained by comparing the stellar evolution predictions with observed abundances in AGB stars and PN, as well as with observed abundances in the interstellar medium that depend on models of galactic chemical evolution. It has been estimated semiempirically that η is in the 1/3 to 3 range and that for stars with $M < 2\ M_{\odot}$ it is in the 1/3 to 1/2 range (*e.g.*,references 34,28 and references therein).

4. CHEMICAL COMPOSITION OF PLANETARY NEBULAE

a) *Type I Planetary Nebulae*

They have been defined as those objects with $He/H > 0.125$ or $N/O > 0.5$ (where both ratios are given by number). Most He and N rich PN are very filamentary and show a bipolar structure (class B). In general their spectra present very strong forbidden lines ranging from [O I], [N I] and [S II] up to [Ne V].

Only a few central stars of Type I PN have been located in the HR diagram, and in general their locations correspond to tracks of more massive cores than those of most PN nuclei.(8) Méndez and Niemela(38) have classified PN central stars in the WR sequence and it is found that most objects of spectral type classified in the WC2-WC4 range are of PN of type I, while Heap(39,40) concludes that central stars of PN with WC spectra may be among the most massive stars of the sample of central stars of PN studied with the IUE. Grieg(41) based on the galactic kinematical properties of Class B PN found that these objects have the most massive progenitors of all PN and that they are of Population I. Acker(42,43) from the study of He rich PN found that their spatial and kinematical parameters correspond to $M_i \sim 3\ M_{\odot}$.

A substantial fraction of type I PN shows bipolar structures consisting of low density material with filaments, lobes and ansae along the major axis and of higher density material along the minor axis. Several ideas have been proposed in the literature to explain this configuration. In what follows some of them will be briefly described: i) two phases of wind ejection by a single star,(39,44) ii) two phases of wind ejection by a binary system,(45,46,47) iii) stellar rotation and gravitational braking.(48) The first two mechanisms need a thick toroid that acts as a focussing element for the stellar wind, as that included in the model by Cantó.(49) Calvet and Peimbert(44) noted that main sequence stars with $M > 2.4\ M_{\odot}$ have high rotation velocities and that a large fraction of their angular momentum can be lost on the AGB phase by mass loss. A slow stellar wind with preferential ejection along the equatorial plane then creates a toroidal circumstellar envelope. When the central star evolves to the PN nuclei phase a fast stellar wind is generated that interacts with the circumstellar envelope previously formed and that shapes a bipolar nebula along the axis of rotation.

A similar idea was developed by Heap(39) to explain the bipolar morphology present in most PN with WC central stars. The idea is that the rotationally enhanced ejection would result in a nebula initially concentrated in a plane and the fast wind phase no longer rotationally dominated would enhance the asymmetry by pushing out most effectively the less dense polar regions. Heap(51) has found that if angular momentum in red giants is conserved, and the core spins-up, then the PN central star would rotate at very high velocity for a 3.5 $M_\odot$ star, while it would be very slow for a 1.5 $M_\odot$ star; in this case rotationally enhanced ejection may be important in PN with massive progenitors.

An alternative suggestion has been the possibility of forming bipolar nebulae by binary systems(45,46,47) during the evolution of the primary to the red giant branch. The proposed mechanisms are different but in any case the ejected matter should be concentrated to the orbital plane at the time of ejection and as the nebula ages another less massive nebular component produced by the wind, and moving at a somewhat higher speed, is expected in the direction of the orbital axis. It has not yet been proven whether or not both mechanisms, the single star one and the close binary one, proposed to explain the morphology of type I PN are in operation. For either case, detailed models of the nature of the ejection are yet to be computed.

A crude estimate of the mass of the progenitors of Type I PN have been made for some objects; these are NGC 3132, NGC 2346 and NGC 2818.(49,52,53,54) The average mass for these objects is 2.4 $M_\odot$. Since NGC 3132 and NGC 2346 are mild examples of He-N enrichment, the lower mass limit for which the process is expected to take place is around 2.4 $M_\odot$. In their study of stars of intermediate mass Renzini and Voli(29) predict that the He and N rich PN are those that have undergone substantial 2nd dredge-up and that they correspond to progenitors with $M > 3\ M_\odot$. The above mentioned additional evidence is also in agreement with this idea.

The N/O, C/O compared to He/H abundances from Peimbert and Torres-Peimbert(55) and the prediction from(29) are presented in Fig. 3. In this figure there is a very satisfactory agreement between the observed values and the predicted ones from models that allow hot burning at the base of the convective envelope (α = 1 and 2 of(29)). The agreement corresponds to progenitors in the 3.3-8 $M_\odot$ range.

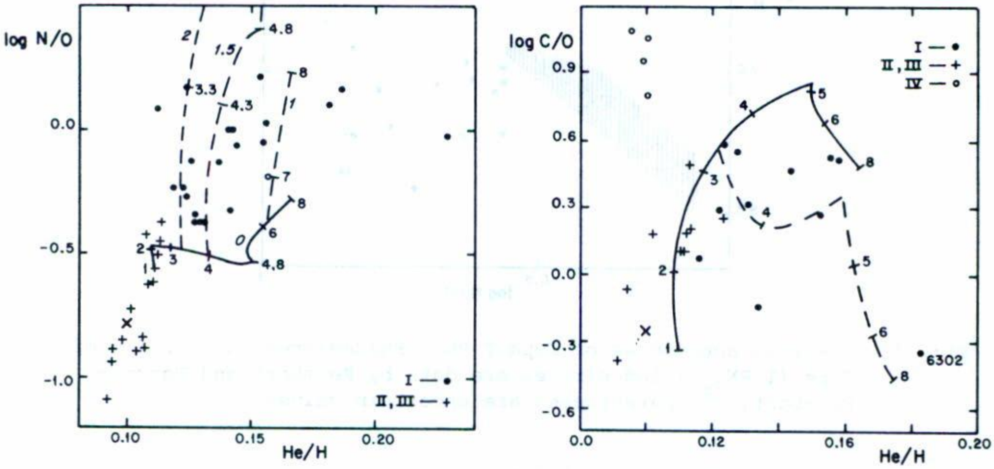

Fig. 3. Observed abundances of PN. Filled circles are abundances of individual Type I objects (55) + symbols are Type II PN (52). Predicted surface abundances of intermediate mass stars (29): solid lines correspond to models with no nuclear burning at the base of the convective envelope: dashed lines correspond to models for different values of the mixing length $\alpha = 1, 1.5, 2$; numbers along the tick marks are the masses of the main sequence parent stars. The cross correspond to initial composition of stellar models.

For PN of Type I there is an anticorrelation between the O/H and the N/O observed ratios that seems to be real. It is presented in Fig. 4. This anticorrelation cannot be explained with the available models. The O depletion reaches factors of 2 to 3 while the most favorable theoretical models produce depletions of a factor of 1/3.$^{(29,34)}$ That is, the O/H versus N/O anticorrelation implies that most of the N is of secondary origin but that it comes from O and not from C. This result is very important for metal-poor galaxies where the C/O ratio is considerably smaller that in the solar vicinity.

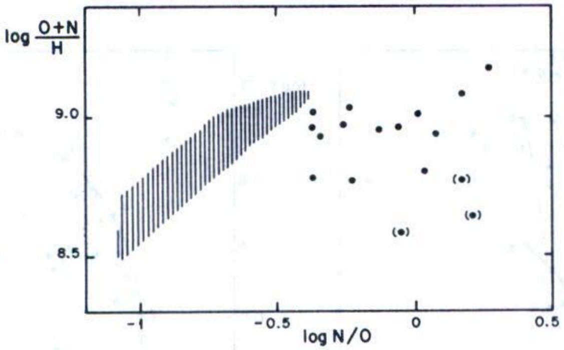

Fig. 4. Observed abundances of Type I PN. Shaded area is location of Type II PN, filled circles are data by Peimbert and Torres-Peimbert,(55) parentheses are uncertain values.

b) *Type II and III Planetary Nebulae*

Type II PN are intermediate-population objects with a distance to the galactic plane, z, smaller than 1 kpc and a peculiar radial velocity, V_{pr}, smaller than 60 km s^{-1}; while Type III PN are population II objects with $|z| > 1$ kpc or $|V_{pr}| > 60$ km s^{-1} that do not belong to the halo population. In many cases, it is difficult to differentiate whether a PN is of Type II or III, since this distinction is very sensitive to distance determinations. For the purpose of this discussion we will group Type II and Type III PN together.

These objects have a mean distance above the galactic plane, $\langle z \rangle$, of $\sim$190 pc (adopting the distance scale by Cudworth(56)), which corresponds to the spatial distribution of stars of $\langle M \rangle \sim 1.4\ M_\odot$. As explained in §3, theory predicts that only the first dredge-up and a modest amount of the third dredge-up, have taken place in these objects; consequently that N and C have been moderately enriched and that He/H has increased by about 0.01 by number.

From the comparison between the theoretical predictions and the observed composition in PN of types II and III presented in Table II, it is seen that in general their composition agrees well with those objects for $M > 3\ M_\odot$. This limiting mass is higher than that observed from kinematic properties, possibly indicating a higher efficiency in the dredge-up processes, than predicted. There are well established positive correlations between the He/H and N/O ratios and the O/H and N/O ratios. These correlations are in agreement with a secondary production of N and with different initial He, C and N abundances produced by galactic chemical evolution and galactic abundance gradients.

It is predicted that the surface chemical composition for O and heavier elements has not been affected by stellar evolution, and therefore the composition of the galactic interstellar medium at the time of formation of the parent stars may be traced from the PN results. In particular radial galactocentric gradients for O, A and S can be derived from PN. Gradients from PN have been reported in the literature by several authors(5,7,9,52,57,58). The reported O/H gradients are in agreement with those derived from H II regions.(59,60,61)

c) *Type IV Planetary Nebulae*

The abundances of halo PN can be more easily interpreted because their initial chemical composition has not been substantially affected by galactic chemical evolution. On the one hand, there are the chemical elements that have not been altered by the progenitor nuclear evolution and that help establish the conditions of the interstellar medium at the time of formation of the precursor stars, namely: S, Ar and possibly O; and on the other hand, there are those elements whose abundances have been modified on the surface of the star during its lifetime: He, N and C.

At present, there are four known PN which are extreme population II objects (Type IV) one of them K 648, in the globular cluster M15, the rest are isolated objects. From their kinematic properties it follows that the masses of the progenitor stars of these objects are of $\cong 0.8\ M_{\odot}$.

A compilation of their chemical abundances is presented in Table III. This table can be compared with the solar neighborhood abundances presented in Table II. It can be seen that S, Ar, and O are underabundant relative to population I objects, as is to be expected from population II objects. However, the abundance of O and Ne relative to Ar and S seem to be larger than in the solar neighborhood. For extreme population II objects He is expected to correspond to the pregalactic abundance of

He/H = 0.07 and since it is higher, it is consistent with the prediction that there has been He enrichment in the PN itself. N/O is higher than in Orion which is to be expected from the first dredge-up phase in which both He and N are increased. It is also seen that C has been substantially enriched, moreover the total abundance present of C/H is as large as solar.

TABLE III

	H	O	C	N	Ne	S	A	References
K648	11.00	7.67	8.73	6.5	6.7	5.15	4.26	(26,59)
H4-1	10.99	8.36	9.31	7.75	6.70	5.20	4.29	(50,66)
BB-1	10.98	7.90	9.09	8.34	8.00	5.70	4.59	(69,61,66)
DD-1	11.00	8.03	8.83	8.30	7.32	6.46	5.58	(62)

Table III. Chemical composition of Halo PN. Given in log X by number where log H = 12.00.

That is, in these objects He, C and H have been enriched. This can be understood in terms of the first and third dredge-ups to have occurred.

The theoretical situation for the low mass limits for the 3rd dredge-up to take place is not well established. For such low mass stars Renzini and Voli(29) do not predict any 3rd dredge-up episode to proceed. However, Iben and Renzini(62,63) have succeeded in bringing C to the surface of a star of initial mass 0.7 $M_\odot$, of Z = 0.001; this result is very sensitive to the opacities used in the computations.

The excess C found in H4-1, BB-1 and DD-1 is based on observations of λ4267 recombination line, while the C values presented for K648 were obtained from IUE data;(16) that is, the C/O excess is not based only in the recombination observations but also in the collisionally excited UV lines.

K648, H4-1 and BB-1 show a similar pattern in their A and S behavior in that they have an underabundance of 1.7 to 2.3 dex relative to solar. The underabundance of O is 0.6 to 1.3 dex while that of Ne is of

0.1 to 1.6 dex. DD-1 shows a uniform underabundance of A, S, O and Ne of 0.8 dex. On the other hand in all 4 halo PN the ratio C/O is 10 while that of Ne/O is essentially solar (although with large scatter). Two possibilities have been advanced in the literature: a) that the enrichment of O and Ne in the interstellar medium proceeded earlier in the evolution of the galaxy than that of A, S and Fe, and b) that the O and Ne excess relative to A, S and Fe, are a product of the progenitors of the PN themselves.(64,65,67,69,70). The constancy in the C/O ratio supports the second possibility.

5. INTERSTELLAR MATTER AND CHEMICAL EVOLUTION

The chemical composition of the interstellar medium can be determined by studying the emission line spectra of gaseous nebulae. Hydrogen, helium, carbon, nitrogen, oxygen, and neon are the six most abundant elements in our galaxy and in those galaxies for which accurate abundances have been determined. The relative abundance of these elements in the interstellar medium can be derived from H II regions, planetary nebulae, and supernova remnants. A review of this topic has been given by Peimbert *et al.*(71)

Accurate abundance determinations of H II regions have made possible to find small differences in the abundance of elements among various galaxies and among different regions of the same galaxy. These small differences occur because material produced in stellar interiors and rich in elements heavier than hydrogen has been injected into the interstellar medium. The enrichment of the interstellar medium is due to loss of mass from massive stars that explode as supernovae and from stars of intermediate mass that become planetary nebulae before turning into white dwarfs.

It has been argued(69,70) that galaxies are formed with hydrogen and helium by mass in the proportion of 77% and 23% respectively and almost no heavy elements.

The theory of stellar evolution predicts that in the lifetime of the galaxy, only stars more massive than ∿1 $M_\odot$ have evolved and ejected material that has modified the chemical composition of the interstellar medium. The stars more massive than ~8 $M_{\odot}$ produce supernovae that enrich the interstellar medium with oxygen and heavier elements such as neon, sulfur, argon, iron, and nickel. The intermediate mass stars produce planetary nebulae that enrich the interstellar medium with helium, nitrogen, and carbon; this can be seen by comparing the abundances of these elements in $(\mathrm{He\text{-}N})_{\mathrm{rich}}$ and intermediate PN of the solar neighborhood with the Orion Nebula values (see Table II). Moreover, these stars are responsible for most of the carbon and nitrogen and a substantial amount of the helium enrichment of the interstellar medium.(74,75,76)

Models of the evolution of the chemical comparition of galaxies have been constructed to explain the observed abundances in the interstellar medium of our galaxy and other galaxies;(19,77-80) in general the abundance at a given time in a region of a galaxy depends on (i) the initial mass function, that is the distribution of stars of different mass, (ii) the birth rate of stars and the chemical composition of mass lost by the stars during their evolution, and (iii) any large-scale mass flows, like infall from the halo or radial flows across the disk of a galaxy. Since these physical parameters are not generally known in galaxies, the observed abundances can be used as constraints of the galactic chemical evolution models.

In closed models, in which there are no mass flows, the total mass (gas plus stars) is conserved and abundances depend only on the fraction of the initial mass of the galaxy that has been converted into stars independently of the details of the birth rate function.(81) This result holds as long as the time scale for gas consumption in the galaxy is much longer than the lifetime of the stars that produce predominantly a given element: this is the Instantaneous Recycling Approximation (IRA). Such simple model (closed plus IRA) predicts that the heavy element abundance increases logarithmically with the decrease of gas fraction, $M_{\mathrm{gas}}/M_{\mathrm{total}}$. All information about the contribution of individual stars is condensed in the "yield", which is the mass of the newly formed elements that stars eject to the interstellar medium in units of the mass that is never returned to it (mass permanently trapped in "remnants"). The yield is defined for a stellar generation and weighted by the initial mass function, and it depends only on the assumed stellar mass loss composition.

In the simple model, there is a clear distinction between primary and secondary elements, where primary elements are those that are directly synthesized from hydrogen and helium, and secondary elements are those synthesized from heavy elements that were already present in the star when it was formed. The assumption of IRA breaks down for nitrogen because the average star that produce nitrogen has a smaller initial mass (around 3 $M_\odot$) than the average star that produces oxygen (around 25 $M_\odot$). Since the life time of a star is a strongly decreasing function of its mass, this means that there is a delay in the injection of nitrogen into the interstellar medium with respect to the injection of oxygen. Moreover, there are usually no strong gradients of N/O across disks of spiral galaxies, whereas O/H usually shows well-defined gradients. This led to the suggestion that nitrogen is primary, so that each region in a given galaxy is represented by a constant N/O while O/H may vary considerably and that there is a spread in N/O caused by the effect of delays in the ejection of nitrogen.(82)

It has been found that the observed N/O vs. O/H relation for all galaxies is best explained by models with (i) accretion of uncontaminated gas,(ii) secondary nitrogen,and (iii) a yield increasing with O/H.(83) Each of these three assumptions is necessary otherwise: if nitrogen were primary there would be galactic regions with high O/H and low N/O; if each region behaved like the closed models there would not be a variation of N/O for a given O/H and, finally, if the yield were constant at all values of O/H no galaxies should be observed with high O/H at all. In these models a given galaxy has the same age across its disk; O/H gradients can exist under small differences in the local gas fractions; and much smaller N/O gradients are explained by gradients in the ratio of infall rate to the star formation rate. Under these assumptions, the stars that produce nitrogen have masses of about 1.3 $M_\odot$ and larger.

If the explanation of the observed N/O vs. O/H relation is correct, most of the nitrogen of the interstellar medium is of secondary origin and has been produced by intermediate mass stars, progenitors of planetary nebulae. This is contrary to the suggestion that novae inject most of the nitrogen present in the interstellar medium,(84) because the nitrogen produced by novae is of primary origin and, as explained, would result in a different behavior of N/O/H.

6. SUMMARY

Planetary nebulae present us with one of the best opportunities of determining element abundances in our own galaxy and in nearby galaxies. These possibilities have been greatly enhanced with the advent of ultraviolet observations. The physical processes occurring in PN are relatively well understood and the relevant atomic data can often be calculated to high accuracy.

In general the changes in surface composition of the stars that become PN appear well understood. Many of the composition differences among PN can be explained in terms of different main sequence masses of their progenitor stars.

Planetary nebulae have contributed to the evolution of the chemical composition of the interstellar material by enriching it with helium, carbon and nitrogen. In the case of the variation of helium and nitrogen, intermediate mass stars, progenitors of planetary nebulae, appear to be the main contributors.

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