BOLETIN DE LOS OBSERVATORIOS DE TONANTZINTLA Y TACUBAYA, Nº 37, 6, 1971.

PLANETARY NEBULAE
IV. PREDICTED CHEMICAL COMPOSITION AND INTERSTELLAR ENRICHMENT

Silvia Torres-Peimbert and Manuel Peimbert

SUMARIO

Se estudia la variación de la composición química de las capas exteriores de las estrellas a partir de modelos evolutivos. Las secuencias analizadas varían de 1 a 1.45 $M_\odot$ y de $Z = 0.023$ a 0.10. Los modelos en la rama de las gigantes rojas alcanzan un punto en que la envolvente convectiva llega a su máxima extensión; esto último acontece un poco antes de la conversión de helio en carbono en el núcleo de estas estrellas. Se discute como la composición química que adquiere la envolvente cuando alcanza su máxima extensión corresponde a la de las nebulosas planetarias.

A partir de una composición química homogénea los valores iniciales de $N(\mathrm{He})/N(\mathrm{H}) = 0.125$ y $N(\mathrm{N})/N(\mathrm{O}) = 0.091$ se alteran a valores comprendidos entre 0.128 y 0.130 y entre 0.16 y 0.32, respectivamente. Para valores mayores de Z el enriquecimiento de nitrógeno es mayor.

Se sugiere que las nebulosas planetarias producen el gradiente de N/O observado a lo largo de los discos de galaxias espirales. Basándose en los resultados de la evolución estelar y en las líneas de emisión observadas en los núcleos de M51 y M81 se encuentra que las abundancias relativas de N/O y O/H son mayores que las de la vecindad solar.

ABSTRACT

Based on stellar evolution models and on observations of planetary nebulae we have studied the change of chemical abundances in the interstellar medium. It is found that the contribution to the N/O abundance gradient present across disks of spiral galaxies by planetary nebulae is considerably more important than that produced by supernovae. We analyze the chemical abundances of the nuclei of M51 and M81 from stellar evolution results and the observed emission lines.

I. Introduction

It is known that envelopes of planetary nebulae feed continuously the interstellar medium. The purpose of this paper is to study to what extent the planetary nebula phenomenon alters the chemical composition of the interstellar gas.

In §II we describe the characteristics of the atmospheric chemical abundances of evolutionary models at the red giant phase. In §III we compare the theoretical results with the observations of Peimbert and Torres-Peimbert (1971; hereinafter referred as Paper III). In §IV we discuss whether planetary nebulae or supernovae are mainly responsible for the N/O abundance gradients present across the disks of spiral galaxies. In §V we discuss the chemical abundances of the nuclei of M51 and M81. The conclusions are presented in §VI.

II. Theoretical Predictions

a) Evolutionary Models

In the present section we will discuss the chemical abundances predicted for planetary nebulae envelopes based on the evolutionary sequences computed by Torres-Peimbert (1969, 1971*b*). The models are in the 1 to 1.45 $M_\odot$ range with Z values in the 0.023 to 0.10 range, and $Y/X = 0.5$.

Although the overall composition of stars varies substantially during their evolutionary history, the chemical abundance of the surface material remains practically unchanged. Nevertheless, small variations occur specially at the red giant phase. In what follows we will discuss extensively the expected changes in composition of the surface layers.

Evolutionary models predict that after a star leaves the main sequence a hydrogen burning shell develops, the helium core contracts causing an expansion of the outer layers and, due to the decrease of the surface temperature, the mass of the convective envelope increases. However, the convective envelope cannot reach the central regions of the star, as its growth is limited by the hydrogen burning shell; and the energy transport mechanism within the shell is radiative because of the steep density gradient present.

During the red giant phase the region of hydrogen burning in a shell proceeds outward *in mass* pushing out the boundary of the convective envelope; this process continues until helium burning sets in, whereby the effective temperature increases and the mass of the convective envelope diminishes drastically.

In the present discussion it is of great interest to note that the mass within the convective envelope reaches a maximum during the red giant phase. Figure 1 shows schematically the evolution of a star of 1.25 $M_{\odot}$, $X = 0.651$, $Z = 0.023$. Indicated in this figure is also the time variation of the mass within the convective envelope.

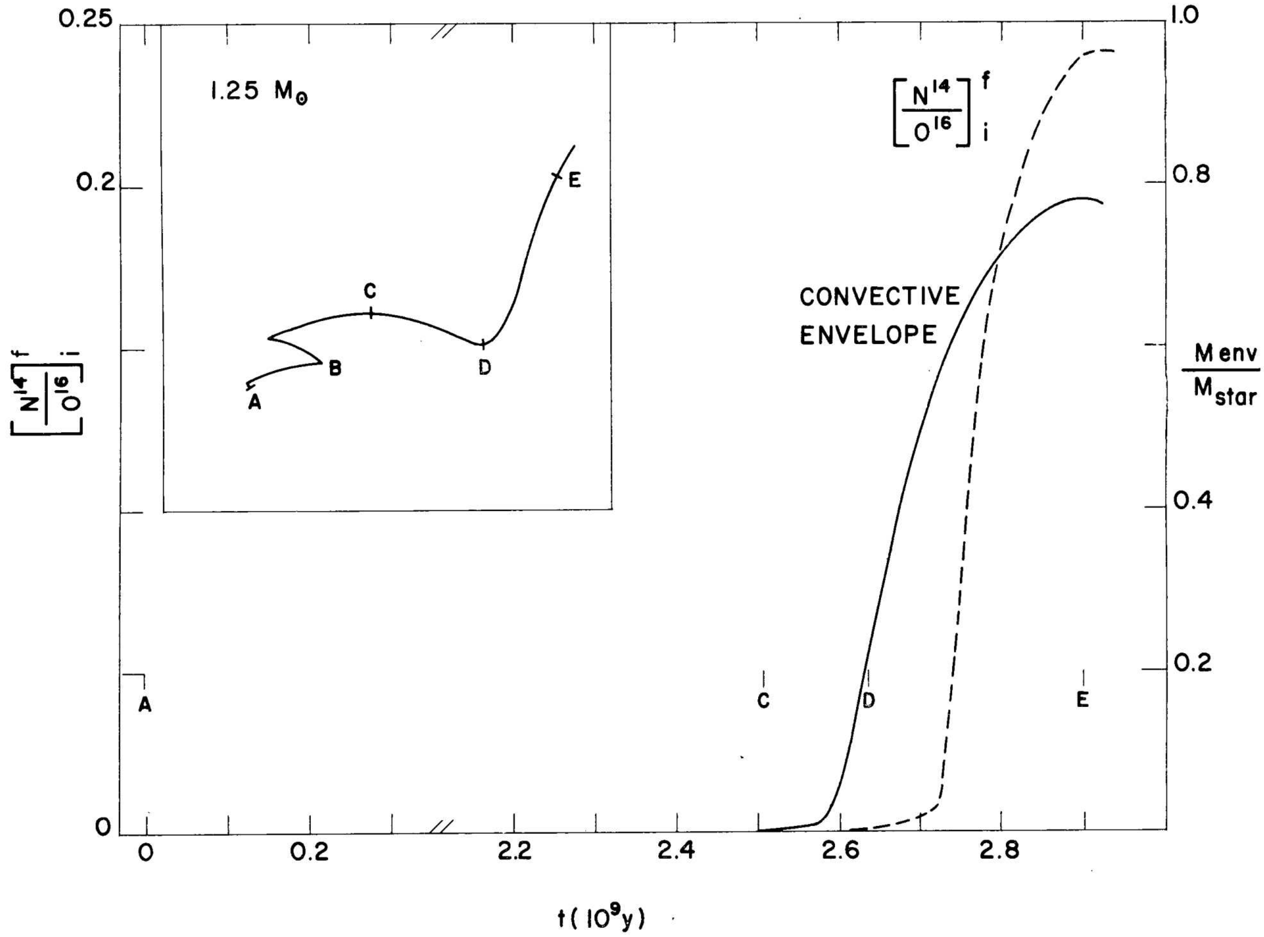

Fig. 1.—*Time dependence of the mass of the convective envelope and the N/O abundance ratio of the envelope material. The computations refer to a 1.25* $M_{\odot}$ *star with* $Z = 0.023$ *and* $X = 0.651$. *The abundance values are the logarithm of the final ratio relative to the initial one. Included are the evolutionary phases in the* (M_{bol}, *log* T_e) *plane.*

The change in composition of the surface material during the red giant phase is due to (*i*) the large extent of the convective envelope since it includes material that has already undergone partial combustion during hydrogen burning in a thick shell; and (*ii*) nuclear reactions still taking place in the inner layers of the convective region. The latter process becomes less important in more advanced phases since the temperature of the layers of the convective envelope decreases monotonically with time (excepting those that become part of the hydrogen burning shell and abandon the envelope).

The maximum variations on the abundance ratios of the surface layers are only of a few per cent so far as hydrogen and helium are concerned. However, less abundant elements show more significant changes. Some of the material that constitutes the envelope has already taken part in the CNO cycle, so that in the innermost regions a large fraction of C^{12} has been transformed into N^{14} and a smaller fraction into C^{13}. The net result is that the surface values of the ratios C^{13}/C^{12}, N^{14}/C^{12}, and N^{14}/O^{16} increase during the red giant phase. Figure 1 shows the time variation of the surface value of $N(\mathrm{N})/N(\mathrm{O})$ relative to the initial ratio.

Table 1 contains the initial chemical composition of the evolutionary models under discussion (Torres-Peimbert 1969, 1971*b*). Table 2 presents the maximum changes in surface chemical composition obtained from the individual stellar models by Torres-Peimbert. For comparison a summary of the available data from the evolutionary computations by Iben (1965, 1966*a*, *b*, 1967*a*, *b*), with $Z = 0.02$ and $X = 0.70$ was prepared and is presented in Table 3.

TABLE 1

*Chemical Abundances**

	Evolutionary Models	*Orion Nebula*†	*Planetary Nebulae*‡	*Solar Values* *G. M. A.*	*Solar Values* *Lambert*
He/H	–0.90	–1.00	–0.98	–	–
C^{13}/C^{12}	–2.0	–	–	–	–
N^{14}/C^{12}	–0.80	–	–	–0.74	–0.57
N^{14}/O^{16}	–1.04	–1.16	–0.52	–0.98	–0.84
C^{12}/O^{16}	–0.24	–	–	–0.24	–0.27

* Given in log $N(X_a)/N(X_b)$.
† Peimbert and Costero 1969.
‡ Peimbert and Torres-Peimbert 1971.

TABLE 2

*Abundances of Pre-Planetary Nebula Objects relative to Initial Values from the Models by Torres-Peimbert**

	1.45 $M_\odot$ $X = 0.60$ $Z = 0.10$	1.25 $M_\odot$ $X = 0.60$ $Z = 0.10$	1.0 $M_\odot$ $X = 0.60$ $Z = 0.10$	1.25 $M_\odot$ $X = 0.651$ $Z = 0.023$
He/H	+0.009	+0.014	$>+0.017$	+0.012
C^{13}/C^{12}	+0.41	+0.82	$>+0.83$	+0.37
N^{14}/C^{12}	+0.72	+0.79	$>+0.52$	+0.30
N^{14}/O^{16}	+0.52	+0.55	$>+0.38$	+0.24
C^{12}/O^{16}	–0.20	–0.24	<-0.13	–0.06
O^{16}/H	+0.003	+0.005	$>+0.007$	+0.004
M_{ce}/M_{star}	0.83	0.81	0.76	0.78

* Given in $[N(X_a)/N(X_b)] \equiv \log N(X_a)/N(X_b)_f - \log N(X_a)/N(X_b)_i$.

TABLE 3

Maximum Abundance Variations in the Convective Envelope of Models by Iben

	1 $M_\odot$	1.25 $M_\odot$	1.5 $M_\odot$	2.25 $M_\odot$	3 $M_\odot$	5 $M_\odot$	9 $M_\odot$
N^{14}/C^{12}	$.18 < r < .36$	$.34 < r < .38$	$.32 < r < .49$	.52	.51	.43	.59
N^{14}/O^{16}	$.12 < r < .24$	$.23 < r < .26$	$.22 < r < .31$	.34	.34	.27	.44
C^{12}/O^{16}	$-.05 > r > -.12$	$-.11 > r > -.12$	$-.10 > r > -.17$	–.18	–.17	–.16	–.15

* Given in $[N(X_a)/N(X_b)] \equiv \log N(X_a)/N(X_b)_f - \log N(X_a)/N(X_b)_i$.

From Table 2 it follows that the predicted increase of $N(\mathrm{He})/N(\mathrm{H})$ is very small, a result difficult to confirm observationally. Alternatively, the C/N relative abundances show a substantial change. For the models considered, the outer envelope has been enriched of N^{14} and C^{13} and has been depleted of C^{12}. In our models although O^{16} is already transformed in the central region, its products do not reach the surface, so that the change in O^{16}/H in Table 2 reflects essentially the change of hydrogen at the surface. Analogously, any production of O^{18} in the central regions does not appear at the surface.

In the mass range considered here the final value of the abundance ratio of $N(\mathrm{N})/N(\mathrm{O})$ is not sensitive to the stellar mass, but depends rather on the overall Z value. The higher the Z value the higher the enrichment.

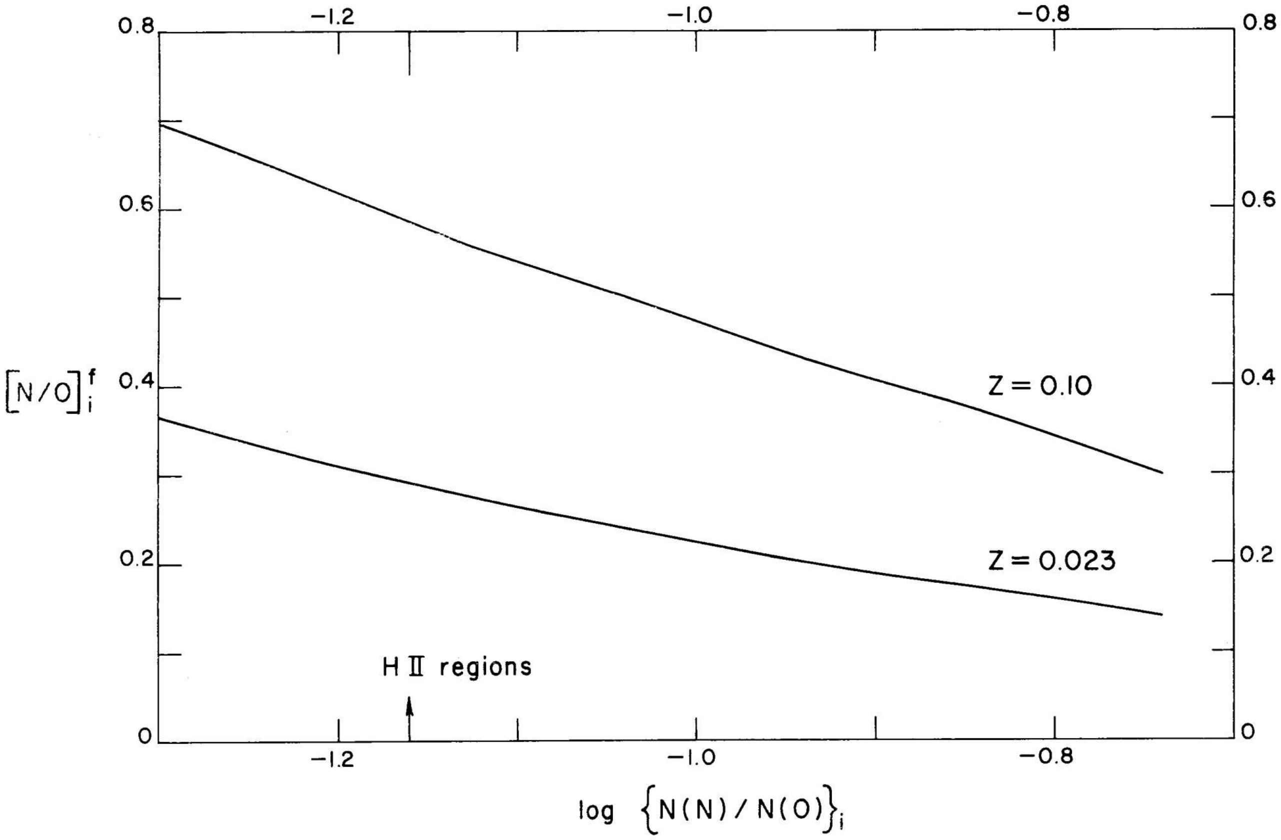

Fig. 2.—*The N/O relative enrichment for stars of different metal abundances. Abscissa is in units of the initial N/O ratio; ordinate is* $[N/O] \equiv \log (N/O)_{final} - \log (N/O)_{initial}$. *The figure has been extrapolated from the models varying N/O but assuming constant C/O.*

In Figure 2 we show the expected increase of (N/O) in units of the initial (N/O) ratio. This diagram has been extrapolated from the evolutionary models. The extrapolation is possible since the opacity, which determines the extent of the convective zone, depends only on the metal abundance and not in great detail on the individual components of Z.

The C^{13}/H abundance ratio increases with decreasing mass and increasing Z for the models considered. The increase of C^{13} is due to the mixing of layers where C^{12} has been converted into C^{13}, however, further mixing may include layers where combustion has been more efficient and include regions depleted of both C^{12} and C^{13} since the latter has proceeded into the $C^{13}(p, \gamma)N^{14}$ reaction.

b) Formation of Planetary Nebulae

A red giant star during the later stages of its evolution becomes unstable and gives origin to a planetary nebula; presumably the gaseous nebula is created from the outer layers of the parent star. If the process giving rise to the planetary nebulae is not explosive (as the observed motions seem to indicate) then the composition of the nebula can be predicted from the evolutionary calculations regardless of the mechanism that releases the gaseous envelope.

It is generally considered that red giants are the immediate precursors of planetary nebulae; the hypothesis was advanced by Shklovsky (1956). Abell and Goldreich (1966) have summarized a series of arguments to support this view. Several mechanisms have been proposed as giving origin to planetary nebulae. Among other possibilities there are: (*i*) instabilities during the helium shell burning stage for models of stars with masses between 0.5 and 5 $M_\odot$; the instability is due to the high temperature sensitivity of the 3α process and the fact that helium burning takes place in a thin shell (Schwarzchild and Härm 1965; Weigert 1965; Rose 1968). (*ii*) Dynamical instabilities of the deep convective envelopes of the red supergiants due to the low value of the adiabatic exponent Γ in the thick cores of partial ionization of hydrogen and helium (Paczyñsky and Ziólkowsky 1968; Lucy 1967; Roxburgh 1967; Paczyñsky 1970); here the energy needed to overcome gravitational binding and the final kinetic energy come from the energy released by the recombination of hydrogen and helium. (*iii*) The radiation pressure gradient may become greater than the weight of the particles; for stars of very high luminosities and low masses, hydrostatic equilibrium no longer holds and a net outward flux of matter is expected (Böhm 1968; Finzi and Wolf 1971).

In the present paper we will assume that the gaseous envelopes of planetary nebulae are formed from the external homogeneous hydrogen rich layers of the star. This assumption implies that no further mixing occurs at later stages than the time of maximum size of the convective envelope, including the formation of the planetary shell, regardless of the mechanisms that might create the phenomenon. That is, we propose that the planetary shells are of the compositions listed in Table 2. The large amount of material in the gaseous envelope, approximately of 0.2 $M_\odot$ (Seaton 1968; Cahn and Kaler 1971), is not inconsistent with our assumption since the maximum extent of the convective envelope of the red giant parent star is massive enough to account for the shell. Table 2 includes data for the maximum mass of the convective envelope of the models considered.

Upper limits to the validity of the previous hypothesis can be derived from observations of the He/H value in planetary nebulae shells. In general, the predicted ratio for the planetary nebulae is larger than the initial value by a given fraction δ (given in Table 2), while the observed ratio is different from the initial value by Δ within the mean error $\pm E$. The degree of contamination defined as the ratio of the amount of material from the internal helium rich layers, $M_{\rm int}$, to the external hydrogen rich layers, $M_{\rm ext}$, present in the gaseous envelope of planetary nebulae can be expressed as

$$\frac{M_{\rm int}}{M_{\rm ext}} \leq 4\,\frac{N({\rm He})}{N({\rm H})}\;\frac{\Delta + E - \delta}{1 + 4\,\dfrac{N({\rm He})}{N({\rm H})}}\,. \qquad (1)$$

Where $N({\rm He})/N({\rm H})$ refers to the initial composition.

In §III we will show that a reasonable value for the original He/H ratio is that found in H II regions.

III. Observations of Planetary Nebulae

To be able to compare the theoretical predictions with observations it is necessary to know the initial relative abundances of all the elements in the objects that at present are observed as planetary nebulae.

As discussed in §II the changes predicted are mainly variations of the C^{12}, C^{13} and N^{14} abundances and minor variations of the He^4 abundances. In the following discussion we will assume that oxygen represents the "metallic" abundance since it is a major constituent and does not change appreciably in the outer envelopes of the models considered here.

Average values of the observed abundances in thirteen field planetary nebulae (Paper III) are listed in Table 1, as well as those in the Orion Nebula (Peimbert and Costero 1969). For comparison, the abundance ratios for the solar photosphere are included (Lambert 1968; Goldberg, Müller and Aller 1960). From this table it is clear that the O/H value in field planetary nebulae and in H II regions of the solar neighborhood is essentially the same. This comparison implies that the metal enrichment of the interstellar medium in the solar vicinity since the time of formation of the stellar precursors of planetary nebulae has not been significant.

We will define the *observed nitrogen enrichment* as the value of $N({\rm N})/N({\rm O})_{\rm P.N.}$ determined from planetary nebulae over an assumed initial value, $N({\rm N})/N({\rm O})_{\rm i}$. For the initial composition we will adopt the nitrogen to oxygen abundance ratio found in H II regions instead of the solar value due to two reasons: (*i*) The abundance determinations for H II regions and planetary nebulae are based on the same observational techniques and physical parameters while those for the sun are not; even if the abundances in H II regions and in the sun were the same it is possible that the different methods would yield differences up to a factor of two in the $N({\rm N})/N({\rm O})$ ratio. (*ii*) The value from H II regions is more representative of the solar vicinity than that obtained from the sun itself.

The initial nitrogen to oxygen abundance ratio has to be smaller or equal to the value found in H II regions but since O/H is practically the same in H II regions and in planetary nebulae it follows that $N({\rm N})/N({\rm O})_{\rm i} = N({\rm N})/N({\rm O})_{\rm H\,II}$ is a valid assumption. Under this assumption we observe in planetary nebulae a nitrogen enrichment from three to five while the predicted enrichment varies from 1.7 to 3.5 depending on the Z value (see Table 2). Furthermore, both values would coincide if $N(\mathrm{C})/N(\mathrm{O})_{\mathrm{i}} > N(\mathrm{C})/N(\mathrm{O})_{\odot}$ [in this paper we have assumed $N(\mathrm{C})/N(\mathrm{O})_{\mathrm{i}} = N(\mathrm{C})/N(\mathrm{O})_{\odot}$ because the carbon abundance in H II regions is not well known (Peimbert and Costero 1969)]. It is of course possible that $N(\mathrm{N})/N(\mathrm{O})_{\mathrm{i}} < N(\mathrm{N})/N(\mathrm{O})_{\mathrm{H\,II}}$ in which case the predicted enrichment as well as the observed enrichment would be even higher.

There is a small range in the observed O/H values of planetary nebulae of the solar vicinity and if indeed the effect predicted in §II is present, namely, that for a higher O/H there corresponds a higher nitrogen enrichment, we should expect a positive correlation between $N(\mathrm{N})/N(\mathrm{O})_{\mathrm{f}}$ and $N(\mathrm{O})/N(\mathrm{H})_{\mathrm{f}}$. However, at present the abundance determinations are not of sufficiently high accuracy nor from a sufficiently large number of objects to make such a test meaningful. The three best N/O determinations, those of NGC 6572, IC 418 and NGC 6803, show the expected trend, but, if we consider the rest of the objects the correlation disappears. Incidentally, it should be mentioned that any errors in the temperature determination of the planetary nebulae envelopes would tend to destroy such a correlation.

The observed average value of $N(\mathrm{He})/N(\mathrm{H})$ in H II regions is 0.100 ± 0.010 and in planetary nebulae is 0.105 ± 0.015 (Paper III). For similar reasons as in the case of O/N we postulate that the He/H found in H II regions is the initial value, therefore the *observed helium enrcihment* is

$$[N(\mathrm{He})/N(\mathrm{H})]^{\mathrm{P.N.}}_{\mathrm{i}} = 0.02 \pm 0.06,$$

where

$$[N(\mathrm{X_a})/N(\mathrm{X_b})]^{\mathrm{P.N.}}_{\mathrm{i}} \equiv \log N(\mathrm{X_a})/N(\mathrm{X_b})_{\mathrm{P.N.}} - \log N(\mathrm{X_a})/N(\mathrm{X_b})_{\mathrm{i}} \; .$$

This observational value of the helium enrichment can be introduced in equation (1) to obtain an upper limit for the contamination of the shell due to the internal helium rich material. It is thus found that $M_{\mathrm{int}}/M_{\mathrm{ext}} \leq 4\%$ which is in excellent agreement with the hypothesis that no substantial mixing occurs between the helium rich material and the envelope during the evolution of the pre-planetary and planetary nebula phases. This observational result sets a limitation for any model of planetary nebula formation.

IV. Normal H II Regions

Evidence in favor of the presence of a chemical abundance gradient in several galaxies has been discussed in the literature; the gradient is such that the metallic abundances increase towards the center. The evidence is based on observations of: (*i*) Cepheids in our galaxy, M31 and the Magellanic Clouds; (*ii*) bright blue stars and red supergiants in M33; (*iii*) Wolf-Rayet stars in our galaxy; (*iv*) absorption line variations in the central regions of M31, M32, and NGC 4472; and, (*v*) H II regions in several galaxies (van den Bergh 1968; Fernie 1968; Smith 1968; McClure and van den Bergh 1968; Spinrad, Gunn, Taylor, McClure, and Young 1971; Peimbert and Spinrad 1970; Searle 1971). In particular, the work by Searle contains quantitative determinations across the disks of spiral galaxies of the N/H and O/H gradients, where the former is steeper than the latter, i. e., the N/O ratio also decreases radially.

It is of great interest to analyze whether or not the metal enrichment of the interstellar medium is mainly produced by planetary nebulae. From the discussion in §III it is clear that the O/H ratio is associated with the abundance of metals and that its value in the interstellar medium is not increased by planetary nebulae. Consequently, these objects are not responsible for the overall metal enrichment, but they may be responsible for the observed N/O variations in the interstellar matter.

From the theoretical results given in §II and the results by Arnett (1971), planetary nebulae, as well as supernovae might be responsible for the N/O gradient observed by Searle (1971) since for both types of objects it is predicted that a higher metal abundance, O/H, produces a higher N/O enrichment.

Observations indicate that the N/O ratio is larger than normal in planetary nebulae (Paper III); however, the situation is not so clear in the case of supernovae.

Cas A is the most useful remnant for the study of the enrichment produced by supernovae because it has hardly been contaminated by interstellar matter. In the moving knots associated with the supernova explosion, N/O is deficient by at least a factor of thirty relative to H II regions in the solar neighborhood. Alternatively, the stationary knots which probably represent material lost by the object before the supernova explosion are nitrogen-rich (Peimbert and van den Bergh 1971; Peimbert 1971*a*).

A more profitable way to decide whether planetary nebulae or supernovae are responsible for the nitrogen enrichment is to estimate the amount of mass deposited yearly by each type of object into the interstellar medium. For planetary nebulae it has been estimated that the ejected shell has $\sim 0.2\ M_\odot$ (Seaton 1968; Cahn and Kaler 1971) and that their frequency is of approximately forty events per year (Cahn and Kaler), which yields a rate of contamination of 8 $M_\odot$/year. Alternatively, the supernovae frequency has been estimated at 1 event per 25 years (Tammann 1970). Thus the planetary nebulae frequency is about one thousand times higher than that of supernovae of Types I and II taken together.

The frequency of supernovae of Type II is of the order of one per fifty years. Mass loss estimates per event range from 0.01 $M_\odot$ to 10 $M_\odot$; as in the case of Cas A the relevant quantity is not merely the mass ejected at the time of explosion but also any mass loss prior to the supernova event. Even if we consider the extreme value of 4 $M_\odot$ per object, it would represent a mass loss rate of about 0.08 $M_\odot$/year which is one hundred times smaller than the rate of contamination produced by planetary nebulae. It is conceivable that in the past the frequency of supernovae of Type II was higher; however, at present most of the nitrogen enrichment is being produced by planetary nebulae.

An observational test that might be useful to decide the fractional enrichment produced by planetary nebulae and that by supernovae would be to determine the C^{13}/C^{12}, C^{13}/O^{18}, O^{18}/O^{16} and N^{14}/O^{16} ratios in the interstellar medium since the theoretical predictions for supernovae might be different from those presented in §II for planetary nebulae. Also in the near future, it will be possible to determine these ratios in our galaxy from radio observations of OH, CO, H_2CO, HCN and CS molecules of different isotopes (Rogers and Barrett 1966; Penzias, Jefferts and Wilson 1971; Zuckerman, Palmer, Snyder, and Buhl 1969; Gardner, Ribes, and Cooper 1971; Snyder and Buhl 1971; Penzias, Solomon, Wilson, and Jefferts 1971). In particular, Gardner *et al.* found that C^{13}/O^{18} is higher by a factor of two in Sgr B2 than the terrestrial ratio; according to the results given in Table 2 this enrichment could have been caused by planetary nebulae originating from stars of $M = 1.25\ M_\odot$ and $Z = 0.023$.

V. Nuclear H II Regions

The observations of the gaseous material of the nuclei of M51 and M81 according to Peimbert (1968) imply that the abundances in the nuclei of these galaxies are not solar and that most likely nitrogen is overabundant by factors ranging from two to six. The reported [OI]/Hα line intensity ratios in these objects (Peimbert 1968; Alloin 1970) are larger than those in H II regions; and several authors (Silk 1970; Bergeron and Souffrin 1971; Osterbrock 1971) have considered the possibilities that the ionization might be due to X-rays, cosmic rays or shock waves.

Peimbert (1971*b*) has reported that in several gaseous nebulae, particularly in the nuclei of M51 and M81 it is likely that both the [OI] and [S II] lines originate in the same volumes. If this is the case it follows that these regions have a $T_e \sim 10000°K$ and are partially ionized (for example: H II-H I boundaries, regions ionized by X-rays or cosmic rays, and clouds moving away from the ionizing radiation where this radiation could be from a shock front or a stellar source).

In what follows it will be assumed that the hydrogen lines are produced under case B even though the energy input might be due to cloud collisions, stellar ultraviolet radiation, X-rays or cosmic rays. This hypothesis is based on the observations of the Hα/Hβ intensity ratio in the nucleus of M81 and the theoretical predictions for some of the ionizing mechanisms.

In this section we will make the abundance analysis of the nuclei of M51 and M81 relative to the abundances of H II regions derived by Peimbert and Costero (1969). The analysis by Peimbert (1968) is relative to the sun, and as mentioned in §III it is more significant to refer the abundances to those of H II regions of the solar neighborhood.

The observed ratios of oxygen, nitrogen and hydrogen are given by

$$N(O)/N(H)_f = N(O^+ + O^{++})/N(H^+) = f\ [I(3727),\ I(5007),\ I(H\alpha),\ T_e,\ x], \quad (2)$$

and

$$N(N)/N(O)_f = N(N^+)/N(O^+) = g\ [I(6584),\ I(3727),\ T_e,\ x], \quad (3)$$

where $x = 10^{-2} N_e T_e^{-1/2}$ can be obtained from the $I(3726)/I(3729)$ ratio, the intensities are those by Peimbert (1968) and the explicit expressions are as given in Paper III. The solution to the problem is not unique since there are three unknowns, O/H_f, N/O_f and T_e, to be determined. From the observed line intensities we have plotted in Figures 3 and 4 the temperature dependence of the abundance ratios $N(O)/N(H)_f$ and $N(N)/N(O)_f$ for M51 and M81. For no value of the temperature is it possible to obtain abundances similar to those of H II regions of the solar neighborhood.

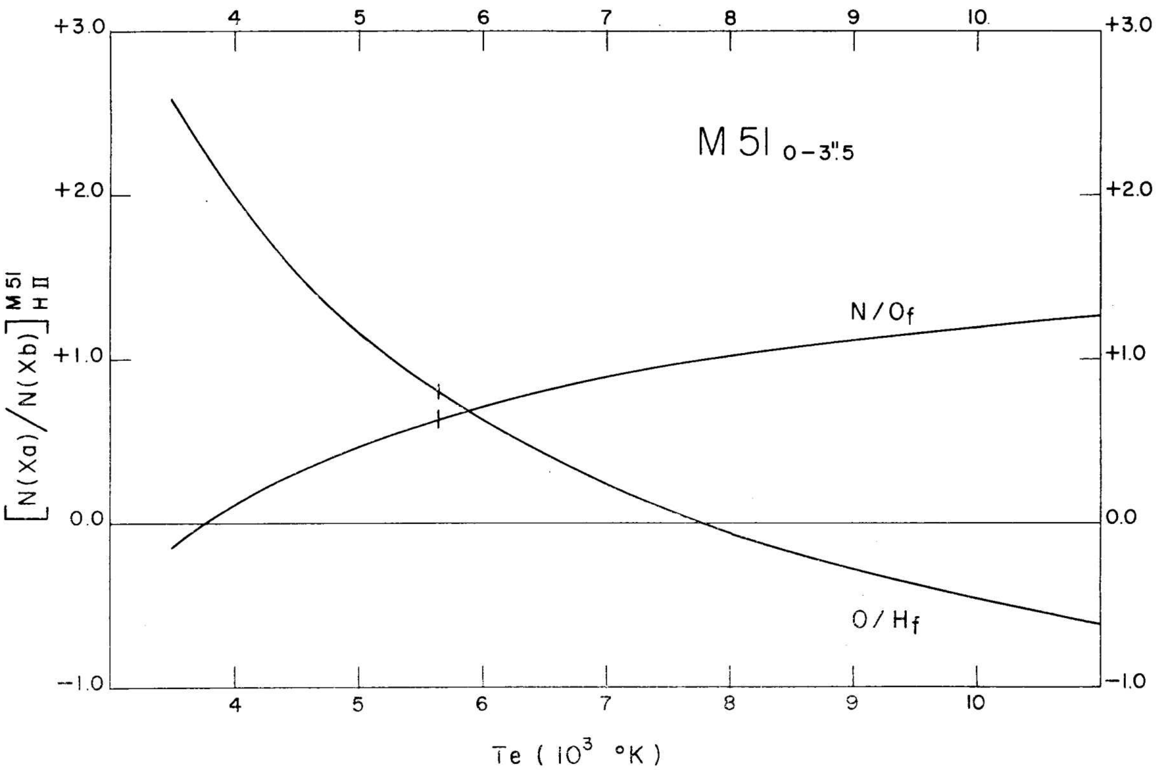

Fig. 3.—*Observed chemical abundances for the nucleus of M51* (r $\leq 3.5''$) *as a function of the electron temperature. The ordinate refers to the abundance ratios given relative to the Orion Nebula (Peimbert and Costero 1969). The dashed line corresponds to* $N(N)/N(O)_{H\,II}$.

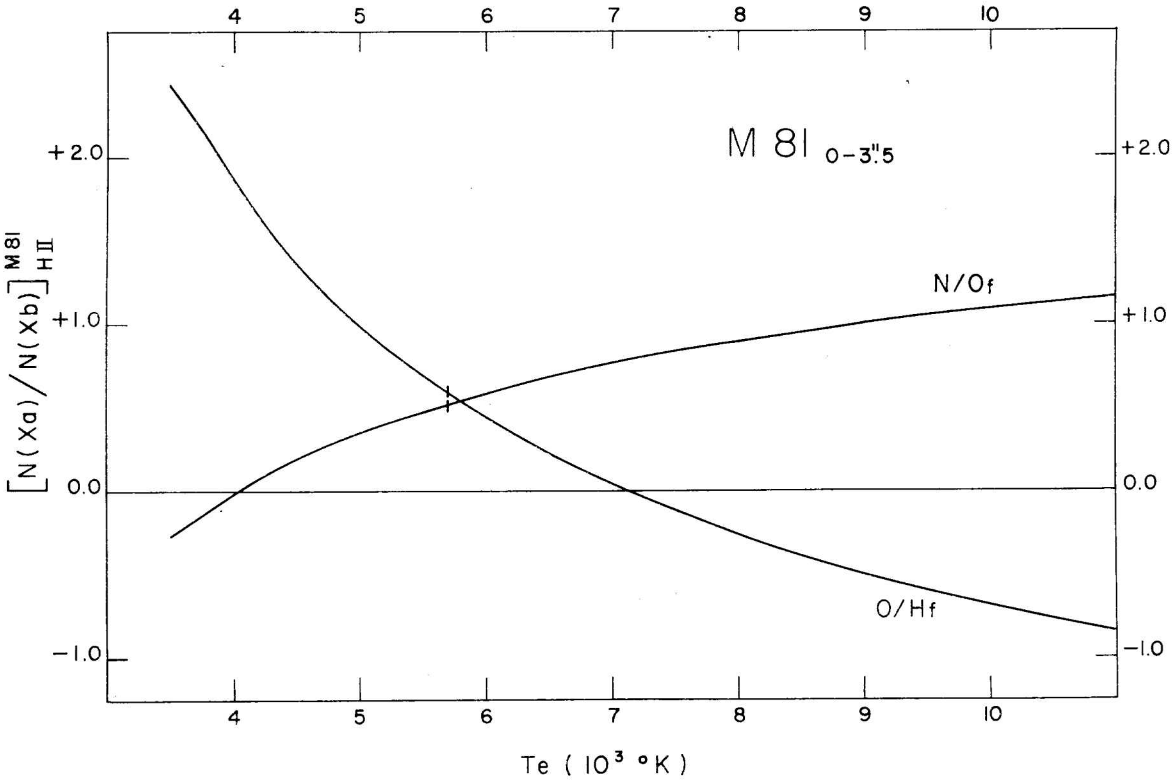

Fig. 4.—*Observed chemical abundances for the nucleus of M81* (r $\leq$ *3.5″*) *as a function of the electron temperature. The ordinate refers to the abundance ratios given relative to the Orion Nebula (Peimbert and Costero 1969). The dashed line corresponds to* $N(N)/N(O)_i = N(N)/N(O)_{H\,II}$.

For the nuclei of M51 and M81 Peimbert (1968) has found that the mass of ionized interstellar material is negligible relative to the mass in stars. Thus, assuming that the mass of the neutral interstellar gas is also negligible relative to that of the stellar content it follows that the interstellar material has been ejected from the stars relatively recently and that the composition of the stellar atmospheres and the interstellar matter is the same.

For the nucleus of M81 the main sequence turnoff point is at F8-G0 (Spinrad and Taylor 1971) which corresponds to $\sim 1.2\ M_\odot$ for $Z \sim 0.06$ (Torres-Peimbert 1971*a*). Mass loss occurs relatively shortly after the stars leave the main sequence mainly due to the planetary nebulae phenomenon. Therefore it is expected that a large fraction of the interstellar matter in the nucleus of M81 has been ejected from stars slightly more massive than $1.2\ M_\odot$ and that the results presented in §II apply to these stars.

The main sequence of M51 extends up to the late B stars (Spinrad 1971); however, the early main sequence is not very rich in stars and it is expected that a large fraction of the mass loss has come from objects in the 1-2 $M_\odot$ range. It should be mentioned again that for the expected range of stellar masses the nitrogen to oxygen enrichment depends almost exclusively on the metal content (see Tables 2 and 3).

From the previous discussion it follows that for the nuclei of M51 and M81 it is possible to combine the observed abundances of the interstellar gas and the stellar evolution results given in §II. Therefore, in addition to equations (2) and (3) we have the conditions that the oxygen to hydrogen abundance ratio remains constant

$$N(\mathrm{O})/N(\mathrm{H})_{\mathrm{i}} = N(\mathrm{O})/N(\mathrm{H})_{\mathrm{f}}\ ; \qquad (4)$$

and that the nitrogen enrichment depends on the initial N/O ratio and the metal abundance (see Figure 2), or

$$N(\mathrm{N})/N(\mathrm{O})_{\mathrm{f}} = h\ [N(\mathrm{N})/N(\mathrm{O})_{\mathrm{i}}, N(\mathrm{O})/N(\mathrm{H})_{\mathrm{i}}]\,. \qquad (5)$$

Consequently, there are four relations and five unknowns, $\mathrm{O/H_f}$, $\mathrm{N/O_f}$, $\mathrm{O/H_i}$, $\mathrm{N/O_i}$ and T_e. Implicit in relation (4) is the assumption that in the solar neighborhood, as well as in the nuclei of these galaxies, most of the metal enrichment took place before a significant fraction of the present stars was formed. This enrichment could have been produced by supernovae of Type II.

If any one of the abundance ratios $N(\mathrm{O})/N(\mathrm{H})_{\mathrm{f}}$, $N(\mathrm{O})/N(\mathrm{N})_{\mathrm{f}}$, $Z/N(\mathrm{H})_{\mathrm{f}}$ or $Z/N(\mathrm{N})_{\mathrm{f}}$ [since Z is proportional to $N(\mathrm{O})$] were available from observations of the stellar content of the nuclei of galaxies, then from equations (2) to (5) the electron temperature of the gas, the present abundance ratios $\mathrm{O/H_f}$ and $\mathrm{N/H_f}$ and the initial value $\mathrm{N/O_i}$ would be derived.

In Table 4 we present various solutions for the interpretation of the observations of the nuclei of M51 and M81. For this table equations (2) to (5) have been used (see Figures 2, 3 and 4) and the abundances are given relative to those of the Orion Nebula. Most of the difference between the results given in Table 4 and those given by Peimbert (1968; Table 7) is due to the lower N/H ratio in the Orion Nebula compared to the sun.

TABLE 4

*Electron Temperatures and Chemical Abundances**

Object	T_e (°K)	$N(\mathrm{N})/N(\mathrm{O})_{\mathrm{f}}$	$N(\mathrm{O})/N(\mathrm{H})_{\mathrm{f}}$	$N(\mathrm{N})/N(\mathrm{H})_{\mathrm{f}}$	$N(\mathrm{N})/N(\mathrm{O})_{\mathrm{i}}$
$\mathrm{M}\ 51_{0\text{-}3.5''}$	3700	1	180	180	—
	5600	4.3	6.3	27	1
	6300	5.6	3.3	19	3.3
	7800	10	1	10	8
	36000	52	1/52	1	—
$\mathrm{M}\ 81_{0\text{-}3.5''}$	4100	1	63	63	—
	5700	3.8	3.2	12	1
	6200	4.3	2.2	9.5	2.2
	7100	6	1	6	4.4
	17000	24	1/24	1	—

* All abundance ratios are given relative to the Orion Nebula (Peimbert and Costero 1969).

As mentioned earlier there is no solution where both N/O_f and O/H_f are in agreement with the ratios of H II regions of the solar neighborhood, furthermore for no value of the temperature are the ratios N/O_i, N/O_f and O/H_f simultaneously smaller than those of the solar vicinity. However, in M51 for $5600 < T_e < 7800°K$, N/O_i, N/O_f and O/H_f are all higher than those of nearby H II regions. Under the assumption that these abundance ratios are related to each other, that is, they increase or decrease together, it follows that the solution to the problem corresponds to $5600 < T_e < 7800°K$. Similarly for M81 likely solutions lie in the $5700 < T_e < 7100°K$ range which also implies that not only the nitrogen to hydrogen abundance ratio is increased relative to the value of the solar neighborhood but also the oxygen to hydrogen abundance ratio, *i. e.* Z/X, is higher than solar. If and overall metal enrichment took place before the nitrogen enrichment then the solutions with higher Z are more likely, which would correspond to the temperatures of 5600 and 5700 for M51 and M81, respectively.

Spinrad and Taylor (1971) found that the stars in the nucleus of M81 are super-metal-rich, similar to those of NGC 188 ($Z \sim 0.06$; see Torres-Peimbert 1971*a*); this conclusion agrees with the results of the previous discussion. In the case of M51 it is difficult to decide whether the stellar content is SMR or not since the early type component delivers a considerable fraction of the light masking the line indexes which enable us to determine the chemical abundances; therefore, it is not possible to make a distinction between normal and SMR objects.

VI. Conclusions

1) The theoretical prediction of the *relative* increase of $N(\mathrm{He})/N(\mathrm{H})$ for planetary nebulae envelopes is very small, ranging from 0.002 to 0.006. Due to the observational errors this prediction is neither confirmed nor discarded; however, the measurements imply that for the observed objects less than 4% of material from the stellar interior rich in helium is mixed with the ejected envelope.

2) An increase over the initial value of the ratio N/O is predicted for planetary nebulae. The observed value is somewhat larger than the prediction, however, assuming that the initial carbon abundance in the stars that originate the planetary nebulae is slightly higher than that in the sun an excellent agreement can be obtained.

3) The predicted increase in the nitrogen to oxygen abundance depends on the original metal abundance; the higher the metal abundance the higher the increase. It is predicted that the nitrogen enrichment is not very sensitive to the mass of the object.

4) The ratio C^{13}/C^{12} increases significantly relative to the initial values. The variation is more extreme for lower masses or higher metal abundances.

5) The oxygen to hydrogen and the metal to hydrogen abundance ratios of the ejected envelopes of planetary nebulae are very similar to the original abundances from which the stars were formed. This applies to both O^{16} and O^{18}.

6) The N/O abundance gradient observed across disks of spiral galaxies and the overabundance of nitrogen in the nuclei of some galaxies can be explained as an enrichment of the interstellar matter through planetary nebulae.

7) It is found that at present the mass contributed by supernovae of Type II to the interstellar matter in our galaxy is one hundred times smaller than that by planetary nebulae. For the supernova rate we have considered mass loss both during the outburst *and* that previous to it. From this result is follows that the contribution of planetary nebulae to the nitrogen enrichment of the interstellar matter is considerably more important than that from supernovae.

8) From the predictions presented in §II and similar ones for supernovae it might be possible to evaluate the relative contribution from both types of objects by means of radio observations of CO, H_2CO, OH, HCN and CS molecules of different isotopes from different objects in our galaxy.

9) Since the amount of interstellar matter in the nuclei of elliptical galaxies and of some spiral galaxies is apparently small it is suggested that this material has been recently ejected from stars. Furthermore, this material reflects the chemical composition found in the atmospheres of red giants which are the objects that radiate a significant fraction of the observed spectra of the nuclei of these objects.

10) It is argued that the metal abundances in the nuclei of M51 and M81 are higher than the solar one by factors of 6 and 3 respectively, and that the ratio N/O is higher than that of H II regions of the solar vicinity by a factor of 4.

11) The electron temperatures of the H II regions in the nuclei of M51 and M81 are in the range of 6000-7000°K.

It is a pleasure to acknowledge several fruitful discussions with Drs. Leonard Searle, Hyron Spinrad and Paris Pishmish.

REFERENCES

Abell, G., and Goldreich, P. 1966, *Pub. A. S. P.*, **78**. 232.
Alloin, D. 1970, *Astr. and Ap.*, **9**, 45.
Arnett, W. D. 1971, *Ap. J.*, **166**, 153.
Bergeron, J. E., and Souffrin, S. 1971, *Astr. and Ap.*, **14**, 167.
Bergh, S. van den 1968, *Journal of the Royal Astronomical Society of Canada*, **62**, No. 4.
Bohm, K. H. 1968, *I. A. U. Symp. No. 34, Planetary Nebulae*, ed. D. E. Osterbrock and C. R. O'Dell (Dordrecht: D Reidel Publishing Co.), p. 390.
Cahn, J. H., and Kaler, J. B. 1971, *Ap. J. Suppl.*, **22**, 319.
Fernie, J. D. 1968, *A. J.*, **73**, 995.
Finzi, A., and Wolf, R. A. 1971, *Astr. and Ap.*, **11**, 418.
Gardner, F. F., Ribes, J. C., and Cooper, B. F. C. 1971, *I. A. U., Circular*, No. 2354.
Goldberg, L., Müller, E. A., and Aller, L. H. 1960, *Ap. J. Suppl.*, **5**, 1.
Iben, I., Jr. 1965, *Ap. J.*, **142**, 1447.
———. 1966*a*, *ibid.*, **143**, 483.
———. 1966*b*, *ibid.*, **143**, 505.
———. 1967*a*, *ibid.*, **147**, 624.
———. 1967*b*, *ibid.*, **147**, 650.
Lambert, D. L. 1968, *M. N. R. A. S.*, **138**, 143.
Lucy, L. B. 1967, *A. J.*, **72**, 813.
McClure. R. D., Bergh, S. van den 1968, *A. J.*, **73**, 313.
Osterbrock, D. E. 1971, (paper presented in the Vatican Conference on Active Nuclei of Galaxies and Quasi-Stellar Objects).
Paczyñsky, B. 1970, *Acta Astr.*, **20**, 47.
Paczyñski, B. and Ziólkowsky, J. 1968, *I. A. U. Symposium No.* **34**, *Planetary Nebulae*, ed. D. E. Osterbrock and C. R. O'Dell (Dordrecht: D. Reidel Publishing Co.), p. 396.
Peimbert, M. 1968, *Ap. J.*, **154**, 33.
———. 1971*a*, *ibid.*, (in press).
———. 1971*b*, *Bol. Obs. Tonantzintla y Tacubaya*, **6**, 97.
Peimbert, M. and Bergh, S. van den 1971, *Ap. J.*, **167**, 223.
Peimbert, M. and Costero, R. 1969, *Bol. Obs. Tonantzintla y Tacubaya*, **5**, 3.
Peimbert, M. and Spinrad, H. 1970, *Astr. and Ap.*, **7**, 311.
Peimbert, M. and Torres-Peimbert, S. 1971, *Ap. J.*, **168**, 413.
Penzias, A. A., Jefferts, K. B., and Wilson, R. W. 1971, *Ap. J.* **165**, 229.
Penzias, A. A., Solomon, P. M., Wilson, R. W., and Jefferts, K. B. 1971, *Ap. J. (Letters)*, **168**, L53.
Rogers, A. E. E. and Barrett, A. H. 1966, *A. J.*, **71**, 868.
Rose, N. K. 1968, *I. A. U. Symposium No. 34, Planetary Nebulae*, ed. D. E. Osterbrock and C. R. O'Dell (Dordrecht: D. Reidel Publishing Co.), p. 390.
Roxburgh, I. W. 1967, *Nature*, **215**, 838.
Schwarzschild, M. and Härm, R. 1965, *Ap. J.*, **142**, 855.
Searle, L. 1971, *Ap. J.*, **168**, 327.
Seaton, M. J. 1968, *Ap. Letters*, **1**, 55.
Shklovsky, I. S. 1956, *Astr. Zhurnal U. S. S. R.*, **33**, 315.
Silk, J. 1970, *Ap. J. (Letters)*, **161**, L37.
Smith, L. F. 1968, *M. N. R. A. S.*, **141**, 317.
Snyder, L. E., and Buhl, D. 1971, *Ap. J. (Letters)*, **163**, L47.
Spinrad, H. 1971, (private communication).
Spinrad, H., Gunn, J. E., Taylor, B. J., McClure, R. D., and Young, J. W. 1971, *Ap. J.*, **164**, 11.
Spinrad, H., and Taylor, B. J. 1971, *Ap. J. Suppl.*, **22**, 445.
Tammann, G. A. 1970, *Astr. and Ap.*, **8**, 458.
Torres-Peimbert, S. 1969, doctoral dissertation, Univ. of California, Berkeley.
———. 1971*a*, *Bol. Obs. Tonantzintla y Tacubaya*, **6**, 3.
———. 1971*b*, *ibid.*, **6**, 113.
Weigert, A. 1965, *Mitt. Astr. Ges.*, 53.
Zuckerman, B., Palmer, P., Snyder, L. E. and Buhl, D. 1969, *Ap. J. (Letters)*, **157**, L167.