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# BIPOLAR NEBULAE AND TYPE I PLANETARY NEBULAE

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RESUMEN

Se sugiere que la naturaleza bipolar de las nebulosas planetarias de Tipo I se debe a que sus estrellas progenitoras ($M_i \geqslant 2.4\ M_\odot$) tienen que perder una fracción apreciable de su masa y momento angular durante la etapa de nebulosa planetaria. En una primera fase de pérdida de masa a baja velocidad se produce un disco y en una segunda fase de pérdida de masa a mayor velocidad la materia es limitada por el disco, dando origen a la estructura bipolar. Se analizan los siguientes objetos en relación con esta sugerencia: NGC 6302, NGC 2346, NGC 2440, CRL 618, Mz-3 y M2-9. Se encuentra que CRL 618 es sobre-abundante en N/O comparado con la Nebulosa de Orión por un factor de 5 a 10.

ABSTRACT

It is suggested that the bipolar nature of PN of Type I can be explained in terms of their relatively massive progenitors ($M_i \geqslant 2.4\ M_\odot$), that had to lose an appreciable fraction of their mass and angular momentum during their planetary nebula stage. The following objects are discussed in relation with this suggestion: NGC 6302, NGC 2346, NGC 2440, CRL 618, Mz-3 and M2-9. It is found that CRL 618 is overabundant in N/O by a factor of 5-10 relative to the Orion Nebula.

*Key words:* **ABUNDANCES – STARS-MASS LOSS – NEBULAE-PLANETARY**

## I. INTRODUCTION

From kinematical properties, galactic distribution, chemical composition and mass of the envelope it follows that PN are a mixed group which includes progenitors in a wide mass range.

Greig (1971) divided PN in several classes: binebulous or filamentary (B), centric (C), and annular (A); B nebulae are found to have very strong lines of [O II], [N II] and [O I]. B nebulae are of Population I while C and A nebulae are of Population II (Greig 1972). Peimbert (1978) divided PN in four types according to chemical composition, He and N rich objects were classified as Type I. These apparently have the most massive stellar precursors (Peimbert and Serrano 1980) and correspond to an extreme subset of Greig's class B. Peimbert and Torres-Peimbert (1983*b*) noticed that a large fraction of Type I PN show a bipolar or hourglass structure. It is the purpose of this paper to explore the relationships between morphology, mass of the precursor and chemical composition.

In §II the properties of PN of Type I are described; in §III the models that have been suggested to explain the bipolar structure are presented; in §IV a possible origin of bipolarity in Type I PN is suggested; in §V a group of PN and protoplanetary nebulae are examined; in particular the N/O abundance ratio of CRL 618 is determined; in §VI a summary is presented.

## II. TYPE I PLANETARY NEBULAE

Type I PN have been defined by Peimbert (1978) as PN with $N(He)/N(H) \geqslant 0.14$ or $\log N/O \geqslant 0$; Peimbert and Torres-Peimbert (1983*a,b*) have relaxed this definition by including those objects with $N(He)/N(H) \geqslant 0.125$ or $\log N/O \geqslant -0.3$. These values are considerably higher than those of Orion Nebula and of the sun which yield $N(He)/N(H) = 0.100$ and $\log N/O = -0.9$ (Peimbert and Torres-Peimbert 1977; Torres-Peimbert, Peimbert and Daltabuit 1980; Lambert 1978). Peimbert and Serrano (1980) give evidence in favor of the idea that Type I PN correspond to objects whose parent stars had masses larger than $2.4\ M_\odot$.

From the theoretical point of view, it is predicted that intermediate mass stars, those of $1 \lesssim M/M_\odot \lesssim 5$, enrich their surface He and N due to three dredge-up episodes, and that the enrichment is larger for larger masses (Iben and Truran 1978; Renzini and Voli 1981).

From the observational point of view several facts support the high mass hypothesis for Type I PN: a) the concentration of Type I PN towards the galactic plane, b) their galactic kinematical properties, c) the relatively high mass of the progenitor ($> 2.4\ M_\odot$) based on the central stars of NGC 3132, NGC 2346 and NGC 2818 (Peimbert and Serrano 1980), d) the mass of the envelope of NGC 2818 (Peimbert 1978), and e) the location on the HR diagram of the central stars (Kaler 1983; Peimbert and Torres-Peimbert 1983*b*).

As more information is gathered on the general nature of Type I PN it has become apparent that in addition to their extreme filamentary structure a substantial fraction of them are bipolar in form; moreover the bipolar nature of some of these nebulae has been strengthened by the measured expansion velocities from the central object (Peimbert and Torres-Peimbert 1983*b*). In this note we will suggest a natural explanation for this apparent correlation and we will indicate some observations to test the proposed hypothesis.

## III. BIPOLAR MODELS

The bipolar phenomenon has now been observed extensively in objects of diverse nature from pre-main sequence to planetary nebulae (Calvet and Cohen 1978); several mechanisms have been proposed in the literature to account for the bipolarity. In what follows we will mention three of them.

### a) *Toroids as Focussing Mechanisms*

Cantó (1980) has advanced a model to explain the morphology of bipolar nebulae consisting on a star surrounded by a thick toroid that acts as a focussing mechanism for the stellar wind. The details of the resulting bipolar morphology depend on the strength of the wind and the density of the surrounding medium.

Barral and Cantó (1981) and Cantó *et al.* (1981) explain the bipolar morphology in pre-main sequence objects as a consequence of events associated with the star formation process. An interstellar disc around the star produced by the original rotating cloud, from which the star itself formed, acts as a focussing mechanism for the wind leaving the star (Torrelles *et al.* 1982).

An explanation for the bipolarity of the Type I PN NGC 6302 in terms of Cantó's (1980) model was first given by Meaburn and Walsh (1980). These authors required the presence of a dense thick disk to produce the observed morphology. Recently neutral hydrogen has been detected associated with the nebulosity (Rodríguez and Moran 1982), with an angular resolution of 10 arc sec at the center of the nebula. In addition, a ring-shaped structure was found in the radio continuum with dimensions $\sim 6'' \times 9''$ at the center (Rodríguez *et al.* 1982). These authors interpret the observed structure as a gaseous toroid around the central star, in which the inner part is ionized and the outer part is neutral and produces the H I absorption; they associate the outer part with a dark lane evident in a photograph taken by Evans (1959). The central toroid is rather extended, since preliminary observations by Rodríguez *et al.* (1982) indicate a larger reddening for the fainter (W) lobe than for the brighter (E) lobe of the nebulosity.

### b) *Stellar Rotation and Gravitational Braking*

Phillips and Reay (1977) have investigated the structural development of nebular shells ejected from rotating stars where the principal mechanism determining shell development is gravitational braking. Assuming different shell ejection modes they have been able to produce a range of nebular types resembling many bipolar and hourglass PN; in particular their model MA8 is very similar to NGC 2474-5.

### c) *Bipolar Ejection*

Pişmiş (1974, 1979) based on the velocity fields of NGC 6164-5, NGC 2359 and M1-67 has proposed that in each case the material forming the H II complex was ejected from the ends of a diameter of the central star, where the agent funnelling the ejecta is presumably a dipolar magnetic field, along the direction of ejection.

## IV. ORIGIN OF BIPOLARITY IN TYPE I PN

Models that can explain bipolar structures, as those by Cantó (1980) and Barral and Cantó (1981), and those by Phillips and Reay (1977), have a basic difference. In the first kind of models a toroid is needed, the axis of rotation of the star coincides with the axis of symmetry of the toroid and with the major axis of the nebula. Furthermore, the toroid has to come from the star itself, since the latter has undergone several rotation periods around the galactic center and conserves no association with the high density regions from which it was formed. In the second case, no toroid is needed and the equatorial plane of the star coincides with the major axis of the nebula. In many cases there is direct or indirect evidence for the presence of an accumulation of material in an axis passing through the star position and perpendicular to the long axis of the bipolar nebulosity (Rodríguez and Moran 1982; Rodríguez *et al.* 1982; Calvet and Cohen 1978; Schmidt and Cohen 1981; cases discussed below). This evidence favors models as those proposed by Cantó (1980) for the production of the bipolar structure, although the problem of forming the toroid still remains.

We suggest that a model with two stages of mass loss is needed to explain bipolarity in PN of Type I, without a sharp discontinuity between both stages. In the first stage, a toroid-like structure is produced, and in the second, the bipolar structure itself arises.

We propose that there is a first stage of mass ejection in which the rotation of the central star is a determining factor in the ejection process. In this stage, a model as those proposed by Phillips and Reay (1977), with an ejection velocity smaller than the escape velocity at the poles, could produce a toroid around the star. The thickness and density of the toroid depends on the values of the ejection velocity, the rotational velocity and other stellar parameters. For the following reasons we think that this type of mechanism may be relevant for the more massive PN. (1) The ejected mass in a PN is an increasing fraction of the mass of the parent star. In Figure 1 we show the core mass, $M_c$, the mass lost in the wind, $M_W$, and the mass of the planetary nebula envelope, $M_{PN}$, from estimates by Renzini and Voli (1981). These quantities are given as a function of the mass of the progenitor, $M_i$. Values A and B denote two extreme cases for the masses of the PN shells according to the computations by Renzini and Voli (1981). (2) Main sequence stars of $M \geqslant 2.4\ M_{\odot}$, which presumably will form PN of Type I, are of spectral types earlier than A5. The rotational velocity of main sequence stars rises sharply from $< v > \sim 2$ km $s^{-1}$ to $< v > \sim 100$ km $s^{-1}$ at spectral type $\sim$ A5; this can be seen in more detail in Figure 2, which shows $< v \sin i >$ for main sequence stars as a function of mass, from data by Sletteback (1970). Thus, progenitors of Type I PN have to get rid

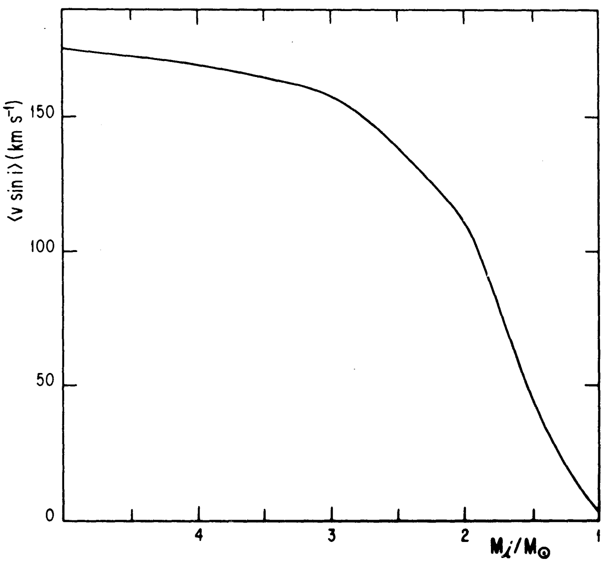


Fig. 2. $< v \sin i >$ for main sequence stars as a function of mass.

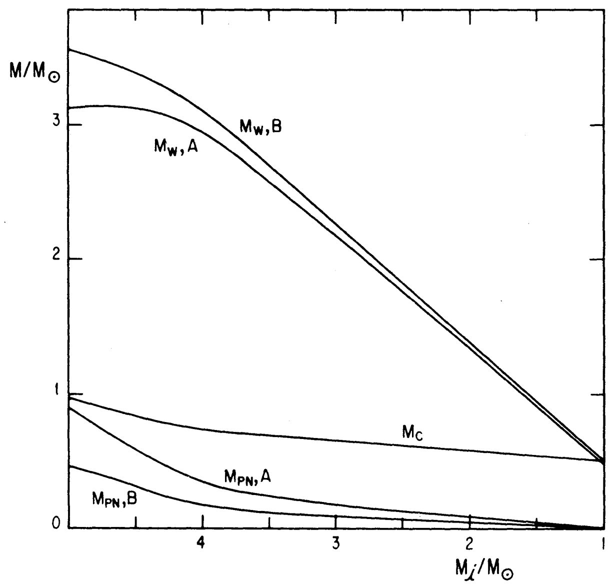


Fig. 1. Core mass, $M_C$, mass lost in the wind, $M_W$, and mass of the planetary envelope, $M_{PN}$, plotted as a function of the mass of the progenitor, $M_i$ (Renzini and Voli 1981; A and B refer to cases A and B from these authors).

both of more mass and more angular momentum than lower mass stars.

The stage in which the star has freed itself of most of its excess mass and angular momentum would be followed in this scenario by another stage, in which the star is losing mass in a more or less isotropic fashion. The presence of the toroid, however, would produce a bipolar morphology for the nebula, with a mechanism like that proposed by Barral and Cantó (1981).

Many issues need to be solved in the model presented here in a qualitative way. On the one hand, the nature of the ejection and the stellar stage of evolution when this ejection occurs have to be known. On the other hand, the model requires a toroid, with the appropiate mass, density and velocity field. Moreover, the timescale for dissipation of the toroid has to be long enough to produce a noticeable focussing effect.

The presence of multiple shells and filaments in PN indicate that the mass loss process did not occur instantaneously at a unique velocity. The filamentary structure is probably due to shocks and instabilities produced by denser, and/or, faster material catching up with material ejected previously. Due to the mass loss process and the reduction of the stellar radius it is likely for the escape velocity, as well as for the ejection velocity, to increase with time. In support of the previous arguments it is interesting to note that the velocity of expansion of the H I material associated with NGC 6302 is of $\sim$ 10 km $s^{-1}$ (Rodríguez and Moran 1982), a value considerably smaller than the velocity of the observed ionized material in NGC 6302 and other PN.

## V. DISCUSSION

### a) *Protoplanetary Nebulae*

So far, classification work on Type I PN has been restricted to those having central stars hotter than T* ∿ 50000 °K, since these stars will provide enough ionizing photons to keep most of the He ionized. Following the previous discussion we propose as a working hypothesis that all bipolar planetary nebulae come from the higher mass stars, and the validity of this hypothesis can be tested observationally by determining their N/O ratio, wich we predict to be enhanced over the solar neighborhood value. We present in Table 1 a list of bipolar nebulae with central star temperatures cooler than ∿ 50000 °K, which we suggest are some of the cooler counterparts of the Type I PN studied so far. We propose that their abundances be determined carefully, particularly their N/O ratio. Within our working hypothesis these objects should have log N/O$\gtrsim$ −0.3.

The bipolar nebulae presented in Table 1 have central stars of T* ∿ 30000 °K, and are isolated from star-forming material. Moreover, the luminosities and temperatures of their central stars place them at the beginning of the sequence of central stars of planetary nebulae. They all show thermal emission by dust grains that may be indicative of the presence of a disk (Calvet and Cohen 1978).

TABLE 1

PROTOPLANETARY NEBULAE

| Object | $T_*$ (°K) | D (kpc) | z (pc) |
|---|---|---|---|
| M1−91[a] | 30200 | 3.1 | 190 |
| M1−92[b] | 21800 | 3.0 | 220 |
| M2−9[c] | 35000 | < 1.0 | < 290 |
| Mz−3[d] | 32400 | 1.8 | 170 |
| CRL 618[a] | 30200 | < 2.5 | < 140 |
| CRL 2789[e] | 36300 | 7.5 | 170 |

a. Calvet and Cohen 1978
b. Cohen and Kuhi 1977
c. This paper
d. Cohen *et al.* 1978
e. Cohen 1977

In what follows we will determine the N/O abundance ratio for CRL 618 and we will discuss the abundance determinations for Mz-3 and M2-9.

#### *(i)* CRL 618

Westbrook *et al.* (1975) present photoelectric photometry of CRL 618 which can be used to derived the N/O

TABLE 2

LINE INTENSITIES[a]

| λ | Identification | CRL 618 F | CRL 618 I | NGC 2440 I | H-H1 (NW) I | H-H32 I | Model O[b] I | Model B[b] I |
|---|---|---|---|---|---|---|---|---|
| 3726 + 3729 | [O II] | < − 1.13 | < − 0.61 | + 0.08 | + 0.36 | + 0.60 | + 0.70 | + 1.19 |
| 4340 | Hγ | − 0.60 | − 0.38 | − 0.32 | − 0.40 | − 0.42 | ... | ... |
| 4861 | Hβ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5007 | [O III] | < − 0.95 | < − 1.00 | + 1.17 | − 0.35 | − 0.07 | + 0.69 | − 0.16 |
| 5198 + 5200 | [N I] | + 0.18 | + 0.05 | − 1.23 | − 0.86 | − 0.89 | − 0.69 | − 1.20 |
| 5755 | [N II] | − 0.68 | − 0.99 | − 1.01 | − 1.40 | − 1.48 | − 1.31 | − 1.09 |
| 6300 | [O I] | + 1.03 | + 0.56 | − 0.94 | + 0.09 | + 0.01 | + 0.29 | − 0.73 |
| 6364 | [O I] | + 0.58 | + 0.08 | − 1.43 | − 0.46 | − 0.58 | − 0.18 | − 1.21 |
| 6563 | Hα | + 0.97 | + 0.42 | + 0.49 | + 0.49 | + 0.39 | + 0.48 | + 0.51 |
| 6583 | [N II] | + 0.46 | − 0.10 | + 0.77 | + 0.11 | + 0.26 | + 0.29 | + 0.34 |
| 6717 + 6731 | [S II] | + 0.77 | + 0.16 | − 0.94 | + 0.05 | + 0.35 | + 0.22 | + 0.17 |
| 7291 | [Ca II] | − 0.23: | − 0.94: | < − 1.60 | − 0.92 | − 0.75 | − 1.45 | − 1.65 |
| 7320 + 7330 | [O II] | − 0.10 | − 0.82 | − 0.99 | − 0.36 | − 0.51 | − 0.44 | − 0.30 |
| C(Hβ) | ... | ... | 1.65 | 0.35 | 0.72 | 1.06 | ... | ... |
| log F(Hβ) | ... | − 13.17 | ... | − 12.28 | − 12.97 | − 13.56 | ... | ... |
| log 5755/7325 | ... | ... | − 0.17 | − 0.02 | − 1.04 | − 0.97 | − 0.87 | − 0.79 |
| log N/O | ... | ... | − 0.10 | + 0.21 | − 0.91 | − 1.01 | − 0.86 | − 0.86 |

a. Given in log F(λ)/F(Hβ) and log I(λ)/I(Hβ). Where F is the observed flux in erg cm$^{-2}$ s$^{-1}$ and I is the instrinsic flux after correcting for reddening. C(Hβ) is the reddening logarithmic correction at Hβ.
b. Raymond (1979).

abundance ratio. In Table 2 we present their observed fluxes, F(λ), and the intrinsic fluxes, I(λ), for an $A_V$ = 3.5 mag using the Whitford (1958) reddening law. We estimated the [Ca II] 7291 flux from the relative intensity scale by Westbrook *et al.* (1975) and subtracted the contribution of [Ca II] 7323 from the observed value of 7320+7323+7330 under the assumption that I(7323) = 0.67 I(7291). The upper limit to [O III] 5007 was estimated from the spectrum by Schmidt and Cohen (1981, SC hereafter). It should be noted that the line intensities in common between Westbrook *et al.* and SC are in excellent agreement; in particular the intensity of the key line 5755 of [N II] (see below).

The nebular lines of [O II] 3726+3729 are not observed. Moreover the [O II] (3726+3729)/Hβ and the [N II] (6583+6548)/Hβ intensity ratios are strongly density dependent for $N_e > 10^5$ $cm^{-3}$, under such conditions it is very difficult to derive reliable abundances based on these lines. On the other hand, collisional de-excitation of the auroral lines of [N II] and [O II] becomes important for $N_e < 10^6$ $cm^{-3}$ and for smaller densities the I(7320+7330)/I(5755) and the I(auroral)/I(Hβ) ratios are weakly dependent on $N_e$. The relevant equations that we will use are:

$$\frac{N(N^+)}{N(O^+)} = \frac{\epsilon(7320+7330)}{\epsilon(5755)} \; \frac{I(5755)}{I(7320+7330)} \;, \qquad (1)$$

$$\frac{N(O^+)}{N(H^+)} = \frac{\epsilon(H\beta)}{\epsilon(7320+7330)} \; \frac{I(7320+7330)}{I(H\beta)} \;, \qquad (2)$$

and

$$\frac{I(6583)}{I(5755)} = \frac{\epsilon(6583)}{\epsilon(5755)} = f(T_e, N_e) \;, \qquad (3)$$

where $\epsilon$ is the emissivity in ergs $cm^{-3}$ $s^{-1}$. Solutions for a considerable range in $T_e$ and $N_e$ are given in Figures 3, 4 and 5, where $x = 10^{-2} N_e T_e^{-1/2}$. The solution were obtained by adopting case B for hydrogen and by solving the equations of statistical equilibrium for the 3 and 5 energy levels of $N^+$ and $O^+$, respectively. The atomic parameters were taken from: Brocklehurst (1971), Saraph and Seaton (1974), Nussbaumer (1971), Pradhan (1976) and Zeippen (1982).

We will assume that $N^+$ and $O^+$ lines originate in the same volume element, which is an excellent assumption for objects of low degree of ionization (e.g. Peimbert and Costero 1969; Peimbert, Rodríguez, and Torres-Peimbert 1974), that is:

$$\frac{N(O)}{N(N)} = \frac{N(O^+)}{N(N^+)} \;. \qquad (4)$$

Westbrook *et al.* (1975) and SC, based on the strength of the forbidden lines from the lobes, conclude that there is evidence for the presence of regions with a large range of electron density, at least from $10^3$ to $10^5$. SC consider a two density model for the lobes, one of $N_e \sim 10^3$ and $T_e \sim 10^4$ °K where the [O I], [N I], [C I], Mg I and Na I lines originate and another of $N_e \sim 5 \times 10^4$ $cm^{-3}$ and $T_e \sim 18000$ °K where the [N II], [S II] and [O II] lines originate. In addition SC from polarization measurements show that about 40% of the permitted line emission observed from the lobes originate is hidden from our direct view and has $N_e \gtrsim 10^6$ $cm^{-3}$ because no such component is detected from the forbidden lines; moreover the self-absorbed spectrum between 5 and 15 GHz also implies that $N_e \gtrsim 10^6$ $cm^{-3}$ for the central region.

Carsenty and Solf (1982) have shown that the radial velocity of the 7320+7330 line emission from the lobes agrees with that of the other forbidden lines. Furthermore, they find that there are two velocity components for the permitted lines of H and He: one coincides with the velocity of the forbidden lines, while the other is due

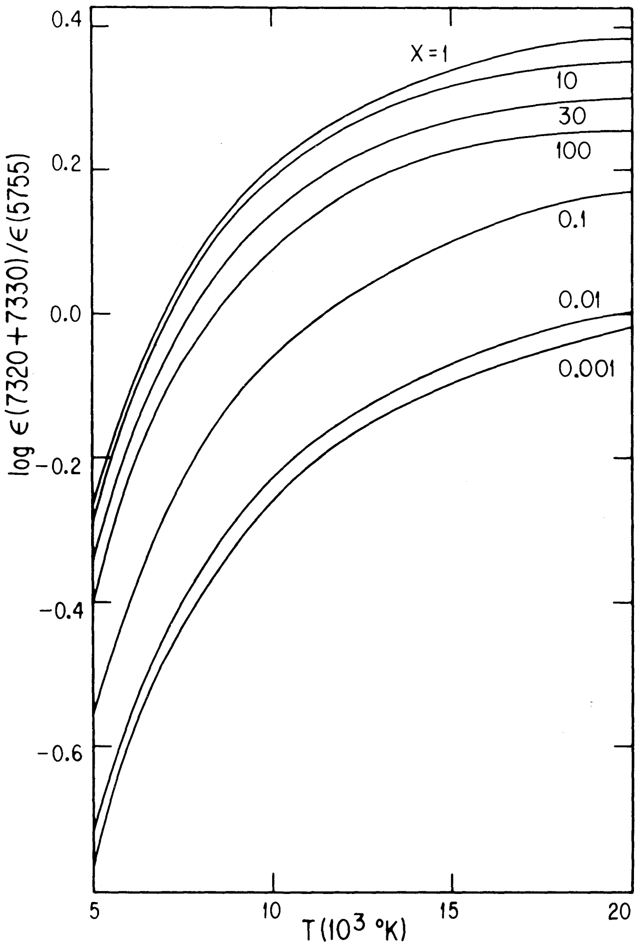


Fig. 3. Ratio of emissivity of auroral lines of oxygen and nitrogen, $\epsilon(7320+7330)/\epsilon(5755)$ as a function of $T_e$ and x.

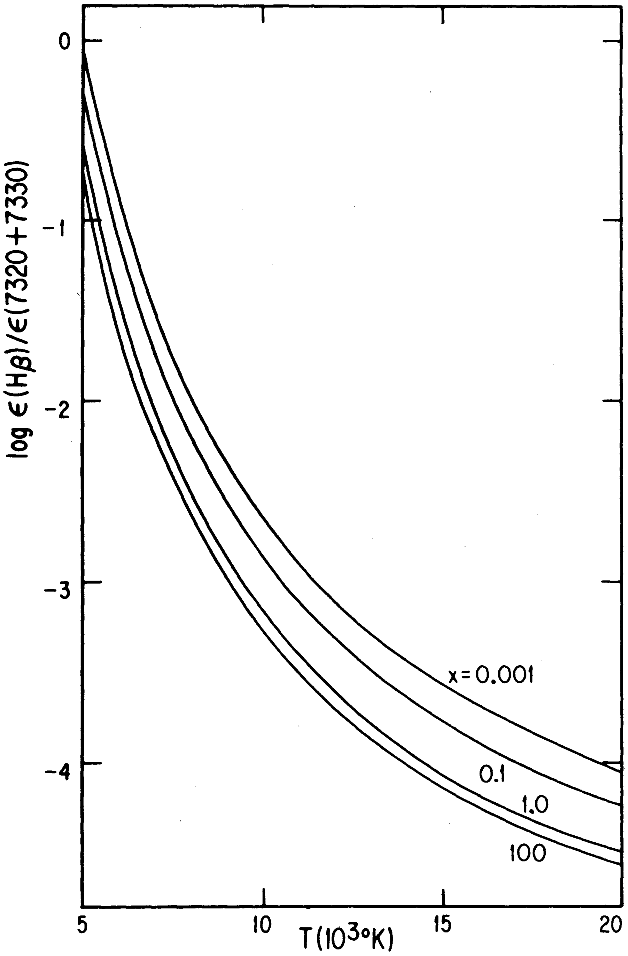


Fig. 4. $\epsilon(H\beta)/\epsilon(7320+7330)$ as a function of $T_e$ and x.

probably to dust scattered light originating in the central high density region, in agreement with SC.

Based on the observations by SC and Carsenty and Solf (1982) we will assume that 60% of the Hβ intensity and all the [N II] and [O II] emission originate in the lobes. Under these assumptions and the observed intensities for CRL 618 presented in Table 2 we have derived physical conditions presented in Table 3.

TABLE 3

PHYSICAL CONDITIONS IN CRL 618

| x | log $N_e$ ($cm^{-3}$) | $T_e$ (°K) | log $O^+/H^+$ | log N/O |
|---|---|---|---|---|
| 60 | 5.72 | 7500 | – 3.06 | – 0.21 |
| 30 | 5.46 | 9200 | – 3.62 | – 0.08 |
| 10 | 5.07 | 13500 | – 4.40 | + 0.14 |

We think that $T_e$ = 7500 °K corresponds to the minimum possible temperature, because at lower temperatures log $N(O^+)/N(H^+) > -3.06$; a value already larger than the total oxygen to hydrogen ratio for the sun (–3.08, Lambert 1978) and for the Orion Nebula (–3.4, Torres-Peimbert *et al.* 1980). On the other hand, $T_e$ = 13500 °K probably corresponds to an upper limit because the $O^+/H^+$ value becomes underabundant with respect to solar neighborhood values by at least an order of magnitude. Due to the possible presence of some $O^{++}$ and of temperature variations along the line of sight, a value of $T_e \sim$ 9000 °K seems indicated.

It is possible that case B might not apply to this object and that shock waves might be responsible for a substantial fraction of the ionization. In that case, equation (3) is no longer valid, but equation (4) still holds in general, and equations (1) and (2) hold for each volume element; when integrating along the line of sight, a weighted mean of the electron temperature needs to be used. It should be noted that the [Ca II] lines are very strong in shock wave models and Herbig-Haro objects while they are very faint or not present in planetary nebulae with $T^* > 50000$ °K or in H II regions, a similar statement can be made for the Na I lines. In Table 2 we present observations of H-H1 and H-H32 by Brugel, Bohm, and Mannery (1981) and shock wave models O and B by Raymond (1979) where solar abundances were adopted. It is important to notice that for nebulae ionized by shock waves

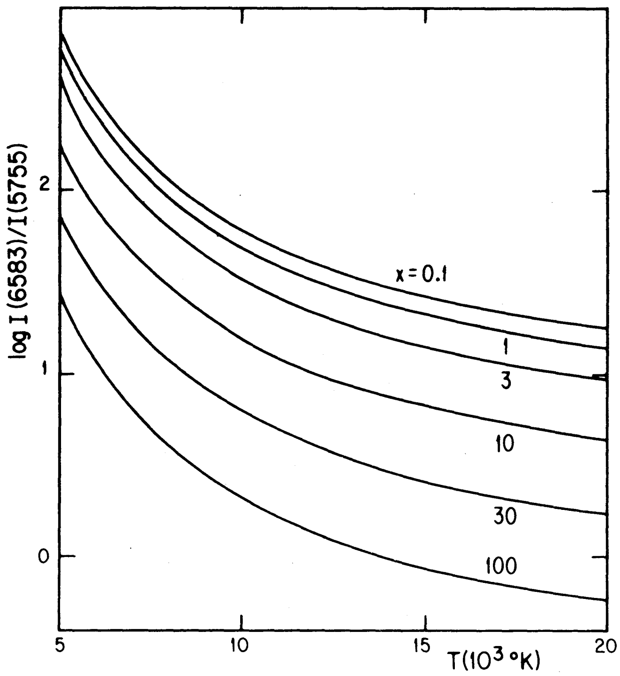


Fig. 5. Ratio of nitrogen nebular to auroral lines I(6583)/I(5755), as a function of $T_e$ and x.

$$\log I(5755)/I(7320+7330) \approx \log N(N)/N(O). \quad (5)$$

This equation reflects the fact that I(5755) and I(7320+7330) originate in the same regions and that their temperature and density dependence is similar.

Also in Table 2 we present observations for the central regions of the PN of Type I NGC 2440 (Peimbert and Torres-Peimbert 1983*a*) where most of the ionization is radiative. From the previous discussion of equations (1)-(5) we conclude that in CRL 618 log N(N)/N(O) = –0.1 ± 0.1.

*(ii)* Mz-3

Mz-3 was studied by Cohen *et al.* (1978) and from observations of eight different regions they determine N(He)/N(H) = 0.18 and log N(N)/N(O) = –0.4 with $N_e = 1.8 \times 10^4$ cm$^{-3}$ and $T_e$ = 17000 °K as typical values. The dispersion in the N(He)/N(H) and in the $T_e$ values for the different points probably indicate that the photometry is not very accurate, unfortunately most of the line intensities were not published and it is not possible to assess their accuracy.

An average intensity of log I(5200)/I(6300) = –0.12 was determined by Cohen *et al.* (1978) for Mz-3. It is not possible to determine an accurate N/O abundance ratio without having a precise value of the electron density because for $N_e \gtrsim 2 \times 10^3$ cm$^{-3}$ collisional de-excitation of the [N I] 5198+5200 A lines becomes very important. Nevertheless, the predicted maximum value in the low density limit is log I(5200)/I(6300) = –0.41 (e.g., model N by Raymond 1979), which combined with the Mz-3 value implies an overabundance in N/O of at least 0.3 dex. Furthermore, a value of log N(N)/N(O) = +0.1 ± 0.3 is derived for Mz-3 which is a factor of ten higher than for the Orion nebula and the sun by assuming that the collisional de-excitation effect for I(5200) is the same for Mz-3, H-H32 and CRL 618, (a conservative assumption since the [S II] 6717/6731 ratios yield $N_e$ values of 18000, 3500 and 7000 cm$^{-3}$ respectively).

From this discussion we conclude that Mz-3 is N and He rich and meets the Type I PN main classification criterion. Nevertheless, we suggest that the I(7320+7330)/I(5755) line intensity ratio should be measured to obtain a more accurate N/O abundance ratio.

*(iii)* M2-9

It is a bipolar nebula with a central star located at the beginning of the theoretical sequence for nuclei of planetary nebulae (Calvet and Cohen 1978). These authors estimate a B1 spectral type for the central star. However, from the degree of ionization present in the nebulosity (Barker 1978*a,b*) we estimate a T* ∿ 35000 °K. Schmidt and Cohen (1981) based on spectrophotometry and spectropolarimetry at several points in the nebula have developed a model with a flattened central toroid and nebular lobes along its axis. In particular, they find that a large amount of the Balmer emission arises near the central star and escapes freely into the polar lobes, but is absorbed in our direction by what they interpret as a dusty toroid. In agreement with this hypothesis, the reddening towards the center is ∿ $2^m\!.7$ larger than towards the lobes (Calvet and Cohen 1978).

From the work by Barker (1978*b*) it follows that for M2-9, log N(N)/N(O) = –0.8; a value which is very similar to those of the Orion nebula and the sun. Moreover, Barker presents two results that indicate a Population II nature for this object: a) an O/H abundance ratio from 0.4 to 0.5 dex smaller than in the Orion nebula and the sun, and b) a 5.3 kpc distance that places this object 1.6 kpc above the galactic plane. In what follows we will discuss why we consider these two results to be incorrect.

From the results of SC it follows that about 60% of the Balmer line emission is due to dust scattered light that does not originate in the lobes; this fact increases the O/H abundance ratio by 0.4 dex to log N(O)/N(H) = –3.2, a value typical of Population I objects. Moreover, about 10% of the emission in the forbidden line intensities is due to dust scattered light that originates in the central region where the auroral to nebular line ratios of [O III] and [N II] are very large; it can be shown that this effect increases fictitiously the derived $T_e$ and consequently produces O/H abundances lower than the real ones.

There are several estimates to the distance of M2-9. Some of these are based on the assumption that M2-9 is a typical PN, optically thin to Lyman continuum emission from the central star; based on this assumption distances of 3.45, 3.25 and 5.3 kpc have been obtained (Cahn and Kaler 1971; Cahn 1976; Barker 1978*b*). However, the presence of high density toroid, as well as the very large intensity of the [O I] and [N I] lines, indicate that this object is optically thick to Lyman continuum emission and consequently these distances should be considered as upper limits. Calvet and Cohen (1978) estimated d ∿ 1 kpc under the assumption that the central star has the luminosity that corresponds to the theoretical track at the beginning of the evolution of PN nuclei. Kohoutek and Surdej (1980) based on the assumption that the detection of apparent motions of some gaseous blobs in the lobes is due to rotation, suggest a distance of 50 pc for this object. We notice that at this distance the central star would be underluminous by a factor of 400 with respect to the beginning of PN nuclei tracks in the HR diagram.

A different estimate of the distance can be made based on the mass of dust present in the nebula; following Méndez and Niemela (1981; MN hereafter) the visual absorption is given by

$$A_V = 1.086\, Q_V\, \pi a^2\, N_d \quad . \quad (6)$$

and the mass in dust by

$$m_d = (4/3)\,\pi\, a^3\, \rho\, N_d\, S \ , \qquad (7)$$

where $\rho$ is the density of grain material, $Q_V$ is the extinction efficiency factor, $N_d$ the column density ($cm^{-2}$) $a$ the grain size and S the area of the column base given by $\pi r^2 d^2$ where d is the distance and r is the angular radius in radians. We will adopt $a = 10^{-5}$ cm, which for graphite grains yields $\rho = 3$ g $cm^{-3}$ and $Q_V = 2.1$ (Wickramasinghe 1973). From the extinctions determined towards the lobes, $A_V \sim 2.7$ mag and towards the center $A_V \sim 5.4$ mag(Calvet and Cohen 1978), and adopting sizes of $\sim 17''$ and $\sim 5''$ respectively, we can estimate the dust mass; and finally by assuming a 1% dust to gas ratio we obtain for the nebular gaseous mass a value of

$$M_g \sim 0.5\ (d/kpc)^2\ M_\odot \qquad (8)$$

The z distance above the plane for $d \sim 1$ kpc is 290 pc. If the object were farther out than 1 kpc, then it would belong to Population II. However, if this were the case, the mass in the nebulosity obtained from equation (8) would be excessive for a low mass Population II object. We conclude thus that the distance is of the order of 1 kpc or somewhat smaller and that it is not a Population II object.

### b) *Planetary Nebulae*

In what follows we will discuss two bipolar PN. We give evidence that they conform within our working hypothesis, namely, that they have Type I PN abundances, and possess a toroid around the central star which would cause the bipolar structure. The cases presented should be considered as part of a much larger list of bipolar PN that must be studied in order to test the model presented in this paper.

#### *(i)* NGC 2346

Peimbert and Torres-Peimbert (1983*a*) have determined values of N(He)/N(H) = 0.125 and log N(N)/N(O) = –0.46, which marginally meet the main criterion for a PN of Type I; on the other hand, this object amply satisfies the secondary criteria: namely, filamentary structure, very hot central star, emission lines of very low to very high degree of ionization, and bipolar structure.

This nebula has an A-type star projected in its center which is too cool to account for the nebular ionization degree. Kohoutek and Senkbeil (1973) first suggested that the central star could have a subluminous hot companion responsible for the ionization of the nebula. Calvet and Cohen (1978) found that the presence of a companion with $T \sim 10^5$ °K and $L \sim 90\ L_\odot$ would not be noticed over the flux of the A star in the optical region. The issue was proven by MN who have found that the central star of NGC 2346 is a single-lined spectroscopic binary, and moreover that the $\gamma$-velocity of the binary system agrees with the nebular velocity. They find a mass function of $f(M) = 0.0073 \pm 0.0015\ M_\odot$ for the system.

MN, using the $A_V$ determined for the A star argue that the extinction is lower towards the rest of the nebula. They use this fact to prefer the model of Phillips and Reay (1977) for the formation of the bipolar nebula. As mentioned before, this model predicts that the regions of higher density, and hence of higher extinction, would be located in the minor axis but *away* from the central star.

We propose an alternative view in which the bright region appearing in short exposure plates (see Minkowski's plates in Cohen and Barlow 1975) corresponds to ionized material forming the innermost parts of a torus which surrounds the star. The extinction towards the central star could be lower either because we see the central cavity of the toroid by projection effects, or because the toroid is in a state of disruption. This last alternative is supported by the non-uniform brightness and the condensations apparent in the optical plates (Minkowski 1964). Note that this toroid would be perpendicular to the disk running NS proposed by MN. The model presented here can interpret the observations in the following way. The observations of Calvet and Cohen (1978) refer to the densest part of the toroid. The extinction towards this condensation is higher than towards the star but is also higher than towards the lobes of the nebulosity (Peimbert and Torres-Peimbert 1983*a*). Measurements of the infrared energy distribution of the central star of NGC 2346 (that do not include the bright condensation) are interpreted by Cohen and Barlow (1975) as thermal emission by circumstellar dust grains. The source for this infrared excess would be that part of the toroid located behind the central system, against which the central star is seen in projection. MN compare the amount of dust required to produce the infrared excess at the central position and that needed to produce an extinction of $A_V$ = 1.1 mag; they find that the mass in dust producing the infrared excess is far too small to account for that extinction. This could be interpreted as evidence against the toroid hypothesis. However, this evidence is not conclusive since an $A_V \sim 1.5$ mag corresponds to the brightest and densest condensation in the partially fragmented toroid (Calvet and Cohen 1978).

MN determine an upper limit of $0.45\ M_\odot$ for the mass of the companion, assuming a projection angle of 50° which would be lower than expected for a high mass progenitor. This determination is highly dependent on the mass of the companion, which in turn depends on its adopted luminosity class. Kohoutek and Senkbeil (1973) and Calvet and Cohen (1978) classify the primary star as A0 III. MN compare the observed fluxes of the A star with theoretical models by Kurucz (1979), from which they deduce that log g = 4. However, an inspection of Kurucz's (1979) models indicates that the largest difference between models with log g equal to 3 and 4 at $T_{eff}$ = 8000 °K is of 0.05 mag, a value which is within the intrinsic scattering of the observational points by MN. We consider that the luminosity class is underdetermined. If the A star were above the main sequence, it would have a larger mass than that assumed by MN. The mass of the companion would be correspondingly higher for the same mass function and inclination. Alternatively, a smaller inclination, which cannot be ruled out would produce the same result. For instance, if the mass of the companion were 2.5 $M_{\odot}$ and the inclination 40° (instead of 1.8 $M_{\odot}$ and 50°), the mass of the ionizing star would be 0.65 $M_{\odot}$ (instead of 0.45 $M_{\odot}$).

There is additional evidence for the central star having a higher mass than that estimated by MN. Calvet and Cohen (1978) have estimated a Zanstra temperature of $10^5$ °K; the uncertainty in distance implies that $15 < L/L_{\odot} < 90$. The T* and L* values are in agreement with a theoretical track of an 0.65 $M_{\odot}$ star (e.g., Paczyński 1971).

*(ii)* NGC 2440

This object meets the main criterion for a PN of Type I since N(He)/N(H) = 0.112 and log N(N)/N(O)= +0.18 (Peimbert and Torres-Peimbert 1983*a*); it also satisfies the secondary criteria: filamentary structure, very hot central star, emission lines from very low to very high degree of ionization, and bipolar structure.

A series of pictures and drawings showing increasingly fainter regions of NGC 2440 are available in the literature (e.g., Curtis 1918; Aller 1956; Minkowski 1964; Phillips, Reay, and Worswick 1980; Condal 1982). The brighter regions near the center might correspond to a partially disrupted toroid at a position angle of 129° (the position angle of the ansae is 39°), while the faint spherical envelope probably was ejected before the toroid was formed. In the drawings by Curtis the two brightest regions about 7″ apart and at position angle 153° are clearly visible. There are two pieces of evidence that support the idea of a toroid: a) Campbell and Moore (1918) obtained a spectrogram with the slit at 153° joining the two brightest regions and found that " the N1 line is broad and hazy, and appears somewhat curved with the concavity toward the violet", according to us this observation implies that in the relatively faint region between the two bright regions we are only looking at the velocity component in our direction while the back part is obscured by dust that belongs to the partially disrupted toroid; b) Peimbert and Torres-Peimbert (1983*a*) observed the central region between the two bright regions, as well as the northern region and determined values for the logarithmic extinction at Hβ, C(Hβ), of 0.35 and 0.05, respectively. The excess of reddening in the central region is also present in the observations by Condal (1982, see Figure 5). The central parts of NGC 2440 should be corrected for reddening before attempting to fit a particular model.

## VI. SUMMARY


We have suggested that intermediate mass stars with $M_i \geqslant 2.4\ M_{\odot}$ in their PN phase produce bipolar structures with a toroid as a focussing mechanism.

The previous prediction implies that bipolar PN should be He and N rich since according to stellar evolution theory the surface composition of stars with $M \geqslant 2.4\ M_{\odot}$ is appreciably enriched in these elements.

Planetary nebulae ionized by stars with T* < 50000 °K present large amounts of neutral helium within the H II zone, therefore it is very difficult to determine whether or not they are helium rich. By contrast, their N and O are mostly singly ionized and it is possible to determine accurate N/O ratios for them. We suggest to use the auroral lines of N and O 5755/7325 to determine the N/O ratio since this line ratio depends weakly on $T_e$ and $N_e$.

We have found that CRL 618 is N rich, and that probably Mz-3 is N and He rich. Alternatively M2-9 shows a solar N/O ratio, nevertheless arguments were given indicating that this object is of Population I.

Finally arguments supporting our hyphotesis based on the planetary nebulae of Type I NGC 6302, NGC 2346 and NGC 2440 are discussed.


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*Note added in proof.* In a recent paper, López and Meaburn (1983, *M.N.R.A.S.*, in press) find that $N_e \gtrsim 10^5$ cm$^{-3}$ in the core of Mz-3. This result supports our conclusion that this object is overabundant in N.

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