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MORPHOLOGY AND GALACTIC DISTRIBUTION OF PNe: A NEW SCENARIO

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RESUMEN

Se revisan trabajos recientes sobre la morfología y distribución galáctica de las nebulosas planetarias (NPs), así como los avances recientes en modelaje MHD de las NPs. Llegamos a una explicación tentativa sobre la conexión entre las clases morfológicas y la distribución galáctica.

ABSTRACT

We review recent works on morphology and Galactic distribution of planetary nebulae (PNe), as well as recent advances in MHD modeling of PNe. We arrive at a tentative explanation for the connection between morphological classes and Galactic distribution.

Key Words: **HYDRODYNAMICS — ISM: JETS AND OUTFLOWS — PLANETARY NEBULAE: GENERAL**

1. INTRODUCTION

The advances in morphological studies of PNe and their connections with the Galactic distribution have been notorious during the past decades. The search for systematic segregation among PNe of different shapes started with the analysis by Greig (1972). The main morphological classes were binebulous (50%) and circular (50%). He found that the bi-nebulous class shows higher strength in the forbidden lines [O III], [O II] and [N II]. He also found a hint of a correlation between this class and smaller distances to the Galactic plane on average. From PN classification based on chemistry, Peimbert, Torres-Peimbert and collaborators (Peimbert & Torres-Peimbert 1971; Torres-Peimbert & Peimbert 1977; Peimbert 1978; Torres-Peimbert & Peimbert 1979; Peimbert & Torres-Peimbert 1983; Torres-Peimbert & Peimbert 1983; see Torres-Peimbert & Peimbert 1997 for a review) found four classes, from Type I to Type IV, with decreasing abundances of Helium and heavy elements. It was found that most Type I PNe have bipolar shape. These important results lead to the conclusion that there might be population differences between bipolar and circular PNe in our Galaxy. Quoting the abstract by Calvet & Peimbert (1983):

> "It is suggested that the bipolar nature of PN of Type I can be explained in terms of their relatively massive progenitors ($M \geq 2.4 M_\odot$), that had to lose an appreciable fraction of their mass and angular momentum during their planetary nebula stage. In a first mass-loss stage at low velocity it is produced a disk and in a second mass-loss stage at higher velocity the matter is limited by the disk, giving rise to the bipolar structure."

After those seminal studies, several authors have improved our knowledge. Zukerman & Aller (1986) and Zukerman & Gatley (1988) classified 108 PNe in bipolar, round, disk-like, and annular. They found an anti-correlation between metallicity and Galactic latitude, as well as a segregation of morphological types according with Galactic latitude, in agreement with previous studies.

Balick (1987) made a major contribution to the morphological classification (50 PNe), naming the classes: Round, elliptical and butterfly. At the same time, Chu et al. (1987) published a catalog of 126 PNe with more than one shell (50% of the sample), identifying this new class as multiple-shell PNe.

During the last decade, two important surveys were carried out on both hemispheres: Schwarz, Corradi, & Melnick (1992), Stanghellini, Corradi & Schwarz (1993, 250 PNe), Corradi & Schwarz (1995), Corradi (2000, 400 PNe) for the southern hemisphere (*The ESO Survey*); and Manchado et al. (1996, 243 PNe), Manchado et al. (2000, 255 PNe) for the northern hemisphere (*The IAC Survey*), the latter one being complete in the statistical sense (cf. our discussion in §5).

The first detailed study of the differences between elliptical and bipolar nebulae has been done

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by Stanghellini et al. (1993, *The ESO Survey*, see also Corradi 2000). They found that the bipolar class has a scale height above the Galactic plane smaller than the one for ellipticals (130 pc and 320 pc, respectively). Also, bipolars have the hottest central stars among PNe, and display smaller deviations from pure circular Galactic rotation than other morphological types. In addition, bipolars also display the largest physical dimensions and have expansion velocities of up to one order of magnitude above the typical values of PNe. These properties together with chemistry studies cited above indicate that bipolar PNe are produced by more massive progenitors than the remaining morphological classes. This conclusion is in line with an earlier suggestion by Calvet & Peimbert (1983)

The main results from both surveys are key considerations and the motivation for the present paper, which discusses those results in the light of the new MHD models.

2. BIPOLARS: ROTATION AND ANGULAR MOMENTUM

If bipolarity comes from the effects of stellar rotation and loss of angular momentum in massive PN progenitors, let us first take a look to the very massive stars and their associated nebulae. In the Hertzsprung-Russell diagram, LBV stars like η Car lie close to the upper borderline of temperature and luminosity beyond which no normal stars are observed (Humphreys-Davidson Limit), near the location of the Eddington limit.

A massive star expanding at constant luminosity L would—*in the non-rotating case*—reach the Eddington limit due to an opacity increase in its surface layers. The Eddington limit is reached when $\Gamma = L/L_{\rm Edd} = 1$, where the Eddington luminosity $L_{\rm Edd} = 4\pi cGM/\kappa$, with c the speed of light, M and L the mass and luminosity of the star, and κ the opacity at the stellar surface. Note that when $\Gamma \rightarrow 1$, the escape velocity $v_{\rm esc} = [(1-\Gamma)2GM/R]^{1/2} \rightarrow 0$. This implies a very slow wind velocity ($\simeq 0$) at the Eddington limit. Thus, when a star passes through a close approach to the Eddington limit, its stellar wind will follow a *fast-slow-fast* sequence. The critical rotational velocity, where the combination of radiation pressure and centrifugal force exceeds surface gravity at the equator, given by $v_{\rm crit} = [(1-\Gamma)GM/R]^{1/2}$, has the same behavior as $v_{\rm esc}$, i.e., when $\Gamma \rightarrow 1$, $v_{\rm crit} \rightarrow 0$. However, the rotational velocity $v_{\rm rot}$ is always finite. That is, critical rotation occurs *before* the Eddington limit is reached. This is the so called Ω *limit* (Langer 1997). Winds with mass loss rates large enough to halt and reverse the stellar expansion are thought to occur when $\Omega = v_{\rm rot}/v_{\rm crit}$ approaches unity (Friend & Abbott 1986). Thus, outflows will always occur before the star reaches its Eddington limit, acting to prevent further expansion.

Using this idea, Langer et al. (1999a) simulated the LBV outburst phenomenon by allowing the star to pass through three successive stages—pre-outburst, outburst and post-outburst—with correspondingly different stellar winds. To include the effects of stellar rotation on the winds, they used the analytic model of Bjorkman & Cassinelli (1993), with stellar parameters appropriate to η Car. The models were not intended to exactly fit all properties of the Homunculus nebula. It is striking how well these models, without much fine tuning, not only reproduce the large-scale, bipolar morphology, but also the small scale turbulent structure seen in high-resolution observations of the Homunculus. This empirical result, together with the observational facts that all LBV nebulae are bipolar (Nota & Clampin 1997), made us to think that we were on the right track.

What about Bipolar PNe? In order to evaluate whether AGB rotation rates can produce similar situations as the one discussed above, we have to compare them with the rate of critical rotation. Direct determinations of rotation rates for AGB stars are rare and mostly provide upper limits, of the order of a few km s^{-1} (except for V Hydrae with $v \sin i \simeq 13\,{\rm km\ s}^{-1}$). According to observations, main sequence stars in the initial mass range related to PN formation (from $\sim 0.8 M_\odot$ to about $5 M_\odot$) can be divided into two groups. Stars with masses below $\sim 1.3 M_\odot$ spin down during main sequence evolution due to flares or magnetic winds which are tied-up to their convective envelopes. When they expand to AGB dimensions, the resulting rotation velocities are below 0.01 km s^{-1}. Thus, these observations indicate that the expected rotation speeds of evolved low-mass stars (i.e., below $\sim 1.3 M_\odot$) should be very small.

Stars above $\sim 1.3 M_\odot$ do not have convective envelopes during core hydrogen burning, and they appear to remain as rapid rotators throughout their main sequence evolution. When they develop surface convection on their way to the red giant branch, they create a hydrogen burning shell which separates the helium core from the envelope. The helium core evolves decoupled from the envelope and retains its angular momentum, i.e., the entropy barrier of a nuclear burning shell prevents that angular momentum can leak out of the core. Also in this case, however,

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the angular momentum of the hydrogen envelope will be lost, either due to magnetic braking or to mass loss and re-expansion of the convective envelope on the AGB (cf. Langer et al. 1999b). When the stars move to the thermally pulsing AGB phase, the H and He burning shells periodically switch on and off. Thus the presumable barriers vanish periodically and core-envelope angular momentum exchange can occur during this stage. Such an exchange is very likely, since mixing of matter through the core boundary is known to occur in this phase, which is necessary to activate the $^{13}\mathrm{C}(\alpha, n)$ reaction, which is the neutron source to operate the s-process. To estimate the resulting rotational velocity of the envelope at the end of the AGB (of about $0.1 M_\odot$) we may approximate the specific angular momentum of the core by its main sequence value, which is transferred to the envelope. For a core of $\sim 0.5 M_\odot$ and a main sequence radius of about $0.1 R_\odot$ we get $j \simeq 10^{17}$–$10^{18}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$. Adopting an average radius of the envelope matter of $100 R_\odot$ on the AGB, we obtain a rotation velocity of $v_\mathrm{rot} \simeq 10^{17.5}\,\mathrm{cm}^2\,\mathrm{s}^{-1} \times 0.5 M_\odot / 100 R_\odot / 0.1 M_\odot \simeq 2\,\mathrm{km\ s}^{-1}$. Independent of this estimate, stars at the tip of the RGB or AGB may be subject of a significant spin-up of their surface layers (Heger & Langer 1998). Therefore, we propose here that values of $\Omega = v_\mathrm{rot}/v_\mathrm{crit}$ very close to 1 may be appropriate for AGB single stars above $\sim 1.3 M_\odot$ during the phase of PN ejection. We parametrize the "superwind" in the same way as the giant LBV outbursts (Eddington parameter $\Gamma = L/L_\mathrm{edd}$ close to 1; see García-Segura et al. 1999 for further details).

Furthermore, the possibility exists that stars which are not able to reach the Ω limit on their own might be able to do so in the presence of a companion. For example, main sequence wide binary systems, which become close binaries (either detached or attached) at the AGB phase, can be subject to a very effective spin-up by there companion. Depending on the binary separation and masses, the spin-up can be produced by tidal forces (slow process) or by spiral-in (relatively fast process). In either cases, the orbital angular momentum is transferred to the star.

Soker (1995) has studied the tidal spin-up applied to the formation of elliptical PNe, but the theory can be applied also for the formation of bipolars (Soker & Rappaport 2000). Extreme cases of the same scenario is the common envelope evolution scenario (see for example Livio & Pringle 1996 and references there in, also Reyes-Ruiz & López 1998).

Thus, a binary system of such a class can form a bipolar nebula, however, the nebula will show point-symmetric features, as we will discuss later on sections 4 and 5. Also, these nebulae do not have to show an enrichment by heavy elements, and so, they do not necessary fit into the Peimbert Type I category. Finally, since their primary stars may be below $\sim 1.3 M_\odot$, their scale height over the plane can be much larger than the one for classical Peimbert Type I nebulae (see §5).

3. ELLIPTICALS: A MHD PHENOMENON

Axisymmetric flows can be produced by a magnetized wind with or without the existence of an equatorial density enhancement (EDE) (For examples see Różyczka & Franco 1996; García-Segura 1997; García-Segura et al. 1999; and García-Segura & López 2000). An EDE can be formed with a small amount of rotation at the AGB phase for example (Ignace et al. 1998), by a dipolar magnetic field (Matt et al. 2000), or a combination of both. The magnetic field at the surface of a post-AGB star can be transported out by its wind, similar but not equal to the solar case. Because of stellar rotation, the magnetic field in the wind is dominated by a toroidal component. The resulting toroidal field has a magnetic tension associated with it. Thus, the general effect of the magnetic tension is the elongation of the nebula in the polar direction. The mechanism responsible for the elongation is described by Różyczka & Franco (1996) and Franco et al. (2002, this conference) in detail, and successful examples of the formation of jets and ansae (FLIERS) can be seen in all above articles at the beginning of this section.

Unfortunately, there is no information about stellar magnetic fields at the surfaces of post-AGB stars in one of the most interesting regions of the HR diagram, between the AGB phase and the white dwarf phase. Reid et al. (1979) found strong circular polarization in the OH masers from U Ori and IRC +10420. The OH masers indicate fields of about 10 milligauss emanating from regions of about 10^{15} cm from the star. They suggest that the field strengths at the stellar surfaces are on the order of 10 and 100 gauss respectively. White dwarfs are known to have fields of up to 10^7–10^8 gauss (Schmidt 1989). Therefore, stellar field intensities between the solar value ($B_\mathrm{s} = 2$ gauss, in average) and 10^8 gauss are acceptable for modeling. Note that observations for the detection of magnetic fields in the swept-up shells of PNe (e.g., Terzian 1989) have been tried, however, they give us very little information about the field intensity of the nucleus, since that diluted field (if detected) will correspond to the already expanded and compressed AGB gas.

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4. THE POINT-SYMMETRIC SUBCLASS: SIGNATURES OF BINARIES

A particularly intriguing case in PN morphologies are those that display point-symmetric structures. At first view, the point-symmetric morphological class does not look very important. But, a careful inspection in the statistically, complete sample of the IAC morphological catalog (Manchado et al. 1996) reveals 40 objects with some degree of point-symmetric features, which represent 19% of the total list (215) with a well defined morphology. Note that many of these nebulae are not classified as point-symmetric. In fact, they have been well classified inside the categories of bipolars and ellipticals, such as the case of the Dumbbell nebula. This fact points in the direction that point-symmetry is a common feature related to any morphological class, instead of a separate group (Manchado et al. 2000; see also Guerrero, Vázquez & López 1998). Such a large fraction of the sample (19%) suggest that the reason which produces point-symmetry should be very common indeed.

The most convincing solutions up to now, for the formation of point-symmetric nebulae require the existence of a binary system, and a magnetohydrodynamical collimation of the wind, either for accretion disk winds (Livio & Pringle 1996; Mastrodemos & Morris 1998; Reyes-Ruiz & López 1998; Blackman et al. 2001) or for stellar winds (García-Segura 1997; García-Segura & López 2000).

Since the toroidal magnetic field carried out by the wind, either stellar or coming from a disk (for the last one see Contopoulos 1995), is always perpendicular to the rotation axis of the central star/disk (see Fig. 3 in García-Segura et al. 2000), any kind of misalignment from the axis (wobbling instability, precession, steady tilt respect to the equatorial density enhancement) will produce "naturally" a point-symmetric nebula. In either case, it is easy to imagine the topology of the magnetic field lines in such scenarios, i.e., multiple rings centered and aligned along the "time-dependent" spin axis of the star/disk.

Close binaries are a necessary condition in Livio & Pringle (1996), while wide binaries are a sufficient one in García-Segura (1997) and García-Segura & López (2000). As described in §2, close binaries, either attached or detached, will be in favor of forming bipolars with point-symmetric features, while wide binaries will be in favor of ellipticals with point-symmetric features.

TABLE 1

VERTICAL SCALE HEIGHTS

Morphological Class	$\langle z \rangle$ (pc)
B	110
BPS	248
E	308
EPS	310
R	753

5. DISCUSSION

The average scale height over the plane ($\langle z \rangle$), for different PN morphological classes, allows a comparison with population studies. From those studies, we know that massive stars are much closer to the Galactic plane than those of much lower initial mass. The first data given by the ESO and IAC surveys were quite similar, since the statistic was based on similar criteria: For the bipolar (B) class $\langle z \rangle$ = 130 pc (ESO) vs. 179 pc (IAC); for the elliptical (E) class $\langle z \rangle$ = 320 pc (ESO) vs. 308 pc (IAC); and for the round (R) class $\langle z \rangle$ = 753 pc (IAC).

In the recent analysis of the IAC Survey (Manchado et al. 2000), the bipolar (BPS) and elliptical (EPS) objects with point-symmetric features were separated from those which do not present such kind of symmetries, i.e., from the B and E classes respectively. The new results from the IAC Survey are given in the Table 1.

Comparing the results of the IAC Survey with those of theoretical studies, 110 pc correspond to ZAMS masses up to $1.9 M_\odot$ according to Miller & Scalo (1979). This is in line with the pioneering studies by Calvet & Peimbert (1983) and the refinement to those by García-Segura et al. (1999).

To summarize, from the new MHD studies (sections 2, 3 and 4) we can conclude that:

Bipolarity ⇔ Omega Limit ⇔ Angular Momentum (either orbital or stellar).

Ellipticity ⇔ MHD effects ⇔ Symmetric Microstructures (FLIERS, jets, etc.).

Point-Symmetry ⇔ Binaries ⇔ Precession, Wobbling, ...

Finally, the relation between morphology and Galactic distribution could be explained as (see Fig. 1):

- Peimbert Type I Bipolars = (B):

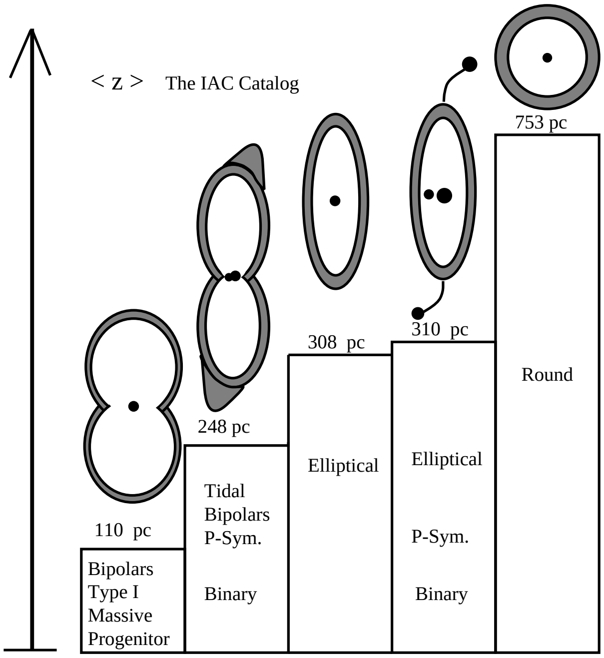

Fig. 1. Proposed classification scheme.

Small $\langle z \rangle$ (110 pc) $\Longleftrightarrow$ Massive Progenitor $\Longleftrightarrow$ Stellar Rotation $\Longleftrightarrow$ Ω Limit $\Longleftrightarrow$ Classical Bipolarity.

- Tidal Bipolars = (BPS):

  Moderate $\langle z \rangle$ (248 pc) $\Longleftrightarrow$ Non-Massive Progenitor in Close Binary System $\Longleftrightarrow$ Tidal Spin-Up $\Longleftrightarrow$ Shaping by Ω Limit + MHD Effects + Precession/Wobbling $\Longleftrightarrow$ Bipolarity with Point-Symmetry (Lobes, FLIERS, Jets).

- Ellipticals = (E):

  Medium $\langle z \rangle$ (308 pc) $\Longleftrightarrow$ Non-Massive Progenitor $\Longleftrightarrow$ Shaping by MHD Effects $\Longleftrightarrow$ FLIERS & Jets with Axisymmetry.

- Ellipticals with Point-Symmetry = (EPS):

  Medium $\langle z \rangle$ (310 pc) $\Longleftrightarrow$ Non-Massive Progenitor in Wide Binary System $\Longleftrightarrow$ Shaping by MHD Effects + Precession $\Longleftrightarrow$ FLIERS & Jets with Point-Symmetry.

- Round = (R):

  Large $\langle z \rangle$ (753 pc) $\Longleftrightarrow$ Low-mass Progenitor $\Longleftrightarrow$ Neither Rotation nor MHD effects.

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