Morphology and Evolution of Galactic and Magellanic Cloud Planetary Nebulae

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Abstract. Planetary nebulae (PNe) exist in a range of different morphologies, from very simple and symmetric round shells, to elliptical, bipolar, and even quadrupolar shapes. They present extremely complex ensembles of filaments, knots, ansae, and shell multiplicity. It is then overwhelmingly complicated to derive reasonable evolutionary paths to justify the observed shapes of PNe. The confrontation between the evolution of the shells and that of the central stars is needed to understand the origin of the morphological variety. We present some background and recent results on the correlations between PN morphology and PN nuclei (PNNi) evolution, including a study on the Magellanic Cloud PNe.

Keywords: Planetary Nebulae: Morphology, Evolution; Central Stars: Evolution; Milky Way; Magellanic Clouds.

1. Introduction

Planetary nebulae originate from stellar ejecta during the Thermal Pulse phase on the Asymptotic Giant Branch (TP-AGB). Stars that do not reach the Chandrasekhar core mass evolve through the AGB phase and beyond, thus setting a stringent limit to the PN progenitor mass, at least if no mass transfer occurs. After the envelope ejection via slow ($\approx 20 \text{ km s}^{-1}$) and very massive ($10^{-5}$ to $10^{-4} \, M_\odot \, \text{yr}^{-1}$) superwind, the star evolves toward higher temperatures at constant luminosity, sustained by stellar wind and nuclear burning in the hydrogen (or, in some cases, helium) shell, and eventually the stellar UV photons ionize the ejecta. After the nuclear burning quenches, the star evolves at nearly constant radius and fades to white dwarf luminosities.

This evolutionary scheme is widely accepted. Nonetheless, there are several nearly unexplored aspects of post-AGB evolution that may create confusion when comparing data and theory. First, the exact path of stellar evolution after the onset of the TP-AGB phase is not totally clear. To date, still questionable is the mass-loss treatment used in evolutionary calculations (e.g., Vassiliadis & Wood 1994, Bloeker 1995); in debate is the mass-luminosity relation, which steepens for very massive progenitors, due to hot-bottom burning (Bloeker & Schönberner 1991), as well as for lower mass stars evolving with overshooting (Hervig
et al. 1998). Second, the transition time lag between the superwind quenching and the PN illumination can not be tracked in evolutionary calculation, since the mass-loss law is not known. Third, the occurrence of hydrogen- versus helium-burning PNNi is not completely understood, although the onset of helium burning in post-AGB stars has been extensively studied (Iben et al. 1983).

The field of AGB and post-AGB modeling is in full bloom, and new evolutionary calculation, together with synthetic evolutionary models (e.g., Marigo et al. 1999, Stanghellini & Renzini 1999 in preparation) are contributing to build a consistent theoretical scenario. On the other hand, hydrodynamical models, pioneered by Franz Kahn (1983), have been updated to compare to observed PNe. The stellar and shell models, in the end, have to reproduce the evolution of stars and nebulae as complex systems, thus PNe and central stars should be studied together.

Planetary nebula morphology carries information on the shell ejection, the central star energetics, and the surrounding medium. Asymmetry in PNe must be ascribed to asymmetries in the formation mechanism, as well as to their evolution. For example, a companion star or planet has proven effective to build up material in the equatorial plane of the system, thus enforcing a bipolar outflow when the envelope ejection occurs. Other types of morphological substructures such as fliers and knots have been observed in many PNs. Such structures can be explained in detail by dynamical evolution (e.g., Dyson, this volume). Multiple shell PNe have been interpreted as multiple ejection or dynamically evolved PNe (Stanghellini & Pasquali 1995). Other phenomena like post-AGB stellar pulsation or magnetic field can be also responsible for other asymmetries.

2. Correlations between PN morphology, stellar astrophysics, nebular evolution, and stellar populations.

In this paper we will limit the analysis to main PN morphologies: round (R), ellipticals (E), bipolar (B), pointsymmetric (P), and quadrupolar (Q) (see Manchado et al. 1996, MGSS). The first correlations that use Galactic PN morphology as an independent variable have been derived a few decades ago, when Greig (1972), found that binebulous PNe were closer to the Galactic plane than other morphological types; Peimbert and collaborators (Peimbert 1978, Peimbert and Torres-Peimbert 1983, Calvet & Peimbert 1983) found a trend between bipolar shape and enhanced helium and N/O abundances; Zuckermann & Aller (1986)
found that the enrichment of CNO elements anti-correlates with the PNe altitude on the Galactic plane.

In 1992 the first large morphological catalog of Galactic PNe was published (Schwarz et al. 1992, SCM). Several studies on morphology versus other parameters, based on the catalog images, followed (e.g. Stanghellini et al. 1993). Most of these studies, together with the older analysis based on smaller samples, are consistent with the following scenario: round PNe originate from the lower mass stars, located randomly within the Galaxy; asymmetric (especially bipolar) PNe have massive progenitors, they are chemically enriched to show dredged-up elements, and they have low Galactic altitude. Elliptical PNe seem to have intermediate properties. Asymmetric PNe have been found to be optically thicker than symmetric PNe.

The above results, if inspiring, have nonetheless two biases. First, the SCM catalog is not complete and homogeneous, it does not include all PNe within the Observatory range. Second, most of the correlations described are based on stellar properties derived by assuming that the statistical distances to Galactic PNe (Cahn et al. 1992) are reliable.

To alleviate the first bias, a new set of observations has been recently undertaken (MGSS), providing a homogeneous and complete database. Several studies are underway based on this catalog, a preview of whose is presented in §2.1.

Circumventing the distance bias is difficult, since only a dozen or so Galactic PNe have measured reddening, or cluster membership, distances. A way to check some of the earlier results without the distance bias is to study Magellanic Cloud PNs (MCPNe), whose morphology can be seen almost exclusively with the use of HST. In §2.2 we show some of the MCPNe morphological correlations.

2.1. Galactic PNe

We introduce in this paper a sample of the correlations found with the MGSS morphological database. In most cases we group B and Q PNe together, given their morphological similarities. Figure 1 shows the correlations between H I and He II Zanstra PNN temperatures. The closer the two temperatures, the thicker is the PN to the ionizing UV flux. We see that, on average, more B (and Q) PNe are closer to the 1:1 line, thus they are optically thicker than R and E PNe. Nonetheless, the correlation is weaker than in Stanghellini et al. (1993). We conclude that the result is still uncertain.

From the location of central stars on the HR diagram, we were able to make a rough estimate of the PNNi masses, whose histograms are plotted in Figure 2. The histogram bins are built accordingly to the
evolutionary tracks by Vassiliadis and Wood (1994; M/M⊙ = .55, .57, .68, .9). This Figure confirms that most of the high mass PNNi are hosted by asymmetric PNe.

In Figure 3 we examine the Galactic distribution of PNe according to their altitude on the Galactic plane, plotted against nebular radius. The result is that bipolar PNe are located, on average, at lower altitudes than other morphological classes, hinting to a different stellar population.

The results of Figures 1 through 3 are in agreement with the older finding that bipolar PNe have massive progenitors and belong to a different stellar population than elliptical or round PNe. Before confirming this scenario, we must also examine whether there is a fundamental bias in the observation of bipolar versus other PNe. By analyzing the extinction to different types of PNe, we find that bipolar and quadrupolar PNe are heavily extincted, while round PNe have, in general, lower extinction. If the observed extinction of all morphological types were mostly external, then we are sampling different volumes in the Galaxy for each morphological type. In order to solve this question, we plan to study the internal to external extinction ratios for a sample of bipolar and round/elliptical PNe in the Milky Way.
Figure 2. Central star’s mass distribution of round (dashed line), elliptical (thin line), and bipolar/quadrupolar (shaded histogram) PNe.

Figure 3. Distance of PNe from the Galactic plane, versus nebular radius. Symbols as in Fig. 2.
Figure 4. Third dredge-up enrichment in MCPNe. Round PNe: open circles; Elliptical PNe: filled circles; bipolar PNe: filled squares. The line divides type I (top half of the plot) and non-type I PNe (from SBOBL).

2.2. Magellanic Cloud PNe

MCPNe can be resolved at the optical wavelengths via space astronomy, and offer a way to study PNe and their evolution in a distance-bias free environment. HST images of MCPNe have been acquired and studied by Blades et al. (1992), Dopita et al. (1996), Vassiliadis et al. (1998), and Stanghellini et al. (1999, SBOBL). To date, only 27 MCPNe have published resolved images from space, thus we lack a statistically significant sample to extend and explore the results obtained for Galactic PNe. Nonetheless, it has been noted that (1) MCPN morphological classes are the same as in Galactic PNe; (2) all bipolar PNe are type I (high N/O, an indication of third dredge-up occurrence) and all round PNe are non-type I; (3) the fading time of round PNe is longer than for other morphologies, indicating lower mass progenitors.

The correlation of chemical enrichment with morphology is shown in Figure 4. The observed N/O ratio is plotted against the dynamical time of the PNe for each main morphological group. We find a striking confirmation of the segregation of bipolar PN as type I. In addition we find that all round PNe of this sample are non-type I. Elliptical PNe belong to both groups. We do not detect any evolutionary enhancement
of N/O. This result is an important link between progenitor mass, chemical enrichment, and morphology of PNe. It states that since all bipolar PNe have enhanced N/O, they have gone through the third dredge-up during the AGB. It is classically assumed that the third dredge-up is related to the massive stars, although recent work implies that the third dredge-up phenomenon may involve a larger mass range (Hervig et al. 1998).

In Figure 5 we show the decline of the [O III] surface brightness with dynamical time for MCPNe of various morphological types. This Figure suggests that round PNe of this sample have low nuclear mass. In fact, the post-AGB evolution of the surface brightness depend on the central star fading time, which is directly correlated with the mass of the star.

3. Summary and Future Projects

Recent analysis of Galactic and Magellanic Cloud PNe have generally confirmed that PN morphology is a tracer of stellar population and progenitor mass. On the other hand, the new, homogeneous Galactic database (MGSS) has posed the problem of space distribution of the
different PN morphologies, which need to be solved before we can ultimately confirm our findings.

The spatially-resolved MCPNe, on the other hand, are still too few to have a sound confirmation of the Galactic results. We are planning an extended study of PNe in the Large Magellanic Cloud via (Cycle 8) STIS/HST slitless spectroscopy. We will obtain stellar and nebular high-resolution information on a sample of at least 50 PNe, with the goal of attach statistical significance to the correlations described in this paper.

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