LARGE MAGELLANIC CLOUD PLANETARY NEBULA MORPHOLOGY: PROBING STELLAR POPULATIONS AND EVOLUTION

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ABSTRACT

Planetary nebulae (PNe) in the Large Magellanic Cloud (LMC) offer the unique opportunity to study both the population and evolution of low- and intermediate-mass stars, by means of the morphological type of the nebula. Using observations from our LMC PN morphological survey, and including images available in the Hubble Space Telescope Data Archive and published chemical abundances, we find that asymmetry in PNe is strongly correlated with a younger stellar population, as indicated by the abundance of elements that are unaltered by stellar evolution (Ne, Ar, and S). While similar results have been obtained for Galactic PNe, this is the first demonstration of the relationship for extragalactic PNe. We also examine the relation between morphology and abundance of the products of stellar evolution. We found that asymmetric PNe have higher nitrogen and lower carbon abundances than symmetric PNe. Our two main results are broadly consistent with the predictions of stellar evolution if the progenitors of asymmetric PNe have on average larger masses than the progenitors of symmetric PNe. The results bear on the question of formation mechanisms for asymmetric PNe—specifically, that the genesis of PNe structure should relate strongly to the population type, and by inference the mass, of the progenitor star and less strongly on whether the central star is a member of a close binary system.

Subject headings: Magellanic Clouds — planetary nebulae: general — stars: AGB and post-AGB — stars: evolution

1. INTRODUCTION

Planetary nebulae (PNe) are produced as stars age. They are fundamental to understanding the evolution of stars whose initial mass lies below the supernova limit. Classically, Galactic PNe have been divided in population classes according to their spatial distribution, kinematics, and chemical content (Greig 1972; Peimbert 1978; Maciel 1999). It appears that there are clearly different PN populations in the Galaxy, from old disk population PNe (Peimbert’s type I) to extreme Population II PNe, located in the Galactic halo or in the bulge (Peimbert’s type IV and V). The PN morphology varies systematically across these classes (Peimbert 1997), and most of the type I PNe are asymmetric in shape.

More recent studies of large Galactic PNe samples have shown that, to first approximation, the morphology of PNe is linked to the spatial distribution within the Galaxy and to the mass of the progenitor star (Stanghellini, Corradi, & Schwarz 1993; A. Manchado, L. Stanghellini, E. Villaver, & M. A. Guerrero 2000, in preparation). The fact that most bipolar and quadrupolar PNe lie on average closer to the Galactic plane than round and elliptical PNe and that highly asymmetric PNe appear to host the most massive central stars suggests that the progenitors of asymmetric PNe are likely to belong to a younger stellar population than the progenitors of symmetric PNe.\(^1\)

An important and long-standing astrophysical issue is the degree to which PNe enrich heavy elements in the interstellar medium (ISM). In the Galaxy, PNe supply almost an order of magnitude more mass per year than supernovae (Osterbrock 1989). Depending on the progenitor’s mass, PNe are expected to enrich the ISM with carbon and nitrogen (Iben & Renzini 1983). PNe stellar progenitors undergo several dredge ups (e.g., Iben & Renzini 1983), some of which enrich the surfaces with C and N. Subsequent winds will carry the enriched gas into the ISM. PNe are known to account for half of the carbon and most of the nitrogen enrichment in the solar environment (Henry, Kwitter, & Buell 1998). Therefore, a study of C and N abundances relative to the elements that are not altered during the evolution of PNe progenitors, such as Ne, Ar, and S, provides a means for gauging the efficacy of C-N enrichment rates by PNe.

Abundance studies as a function of population class and morphological type have been carried out for Galactic PNe. However, since asymmetric PNe lie close to the plane on which foreground extinction is severe and since such nebulae are also formed from the most massive progenitors, Galactic PNe suffer a serious selection bias for understanding enrichment rates by extragalactic PNe.

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PNe of different types. Accordingly, we have begun a comprehensive survey of Magellanic Cloud PNe in order to investigate these and other parameters in a large and well-understood sample. We are using Hubble Space Telescope (HST) and STIS in direct imaging and slitless spectroscopy mode for this survey, and our first observational results are described in R. A. Shaw, L. Stanghellini, J. C. Blades, B. Balick, & M. Mutchler (2000, in preparation, hereafter S2000).

For our purposes, the advantage of LMC PNe is their relatively low foreground extinction (i.e., their low selection bias) as well as their well-determined distances. That is, abundance studies tend to be complete to a limiting nebular luminosity, which is far less of a bias than a brightness-limited survey in the presence of highly variable extinction with Galactic latitude.

In the study presented here, we have selected a subsample of LMC PNe based solely on the availability of morphological information (from HST images) and relative chemical abundances (from ground-based spectroscopy in the literature). The HST data come from S2000, from the HST Data Archive, and from the literature. In § 2 we describe the database and the data analysis and discuss the results; in § 3 we discuss the uncertainties and possible systematic effects.

2. PN MORPHOLOGY, STELLAR POPULATIONS, AND STELLAR EVOLUTION

The morphological data used in this Letter consist of all LMC PNe observed in imaging mode with HST. The sample includes the pre-refurbishment data set of PC1 and FOC images (see Stanghellini et al. 1999), the unpublished WFPC2 images in the Hubble Data Archive (HST Program ID 6407, PI: M. A. Dopita, Cycle 6), and the set of 27 LMC PNe observed to date within our HST/STIS snapshot survey (S2000).

The abundance data set was compiled from papers by Leisy & Dennefeld (1996), Monk, Barlow, & Clegg (1988), Dopita et al. (1997), and Dopita & Meatheringham (1991a, 1991b). We have used abundances of carbon, nitrogen, oxygen, argon, neon, and sulfur where available. However, some of the quoted abundances are model dependent (Dopita & Meatheringham 1991a, 1991b); abundances therein were used only when the model-independent values were not available. A discussion of the effects of the data set inhomogeneity is presented in the next section, along with a critical analysis of the published abundances, including uncertainties and systematic effects that could affect our conclusions.

We classified PN morphologies homogeneously according to their shape in narrowband [O iii] λ5007 images: round, elliptical, bipolar, bipolar core (Stanghellini et al. 1999), quadrupolar, and point-symmetric PNe are included in the sample. While classifying the images, we realized that in a few cases the morphologies are uncertain. These objects are not included in the numerical analysis and discussion or in the figures.

Figures 1 and 2 show the distribution of the morphological types with respect to neon, argon, and sulphur abundances, which have presumably remained unchanged since the birth of the progenitor star. As such, these elements should be good indicators of the population type of the progenitor stars. The crossed large circles in these figures marks the location of the average abundance for LMC H ii regions (Leisy & Dennefeld 1996). These and other young population LMC abundances are given in Table 1 (discussed below).

The segregation of morphological type with respect to S and to Ne (Fig. 1) is striking: Ar does not appear to be as good a discriminant (Fig. 2). Specifically, the overwhelming majority of PNe with log Ne + 12 > 7.6 are asymmetric, and none is round. Furthermore, all PNe with log Ne + 12 < 7.6 are symmetric, with the exception of one quadrupolar PN. Evidently, PN morphology is a good indicator of progenitor population in the LMC. By comparing the Ne abundance in PNe with the average for H ii regions (which gives a good indication of the abundance of the young stellar population), it is evident that most of the asymmetric PNe are enriched with respect to the young population, while the opposite holds for symmetric PNe. Sulfur is related to nebular shape in a similar way. In fact, only one of the 13 symmetric PNe has S larger than the LMC H ii region average, and three asymmetric PNe are underabundant with respect to the H ii regions.

To quantify the importance of the neon, sulphur, and argon overabundance in asymmetric PNe, in Table 1 we list the av-
average abundances for our PN sample, together with the abundances of other significant LMC objects, namely, H II regions and supernova remnants: column (1) lists the atom; in columns (2) and (3) we give the average elemental abundances for the symmetric and asymmetric PNe of our samples, in the usual form $12 + \log (N/X)$, with the sample size in parenthesis; column (4) gives the LMC H II region average from Leisy & Dennefeld (1996), as used in our figures; columns (5) and (6) give the abundance ranges found by Russel & Dopita (1990), respectively, in LMC H II regions and LMC supernova remnants. The ranges are only indicative of the abundance distribution on the LMC, since they include a few observed objects for each diagnostic.

The ratio of the average neon abundance for asymmetric to symmetric PNe in the LMC, 1.7, is similar to that found in the Galaxy, 1.6 (Corradi & Schwarz 1995). Note, however, that the Galactic average is based on a sample that is markedly biased toward the symmetric PNe (see § 1). A similar over-abundance in asymmetric PNe is found for sulfur and argon, although in these cases this includes a few PNe that do not follow the abundance-morphology relation.

Figure 3 shows the oxygen distribution among different population PNe. Oxygen yield should be invariant with respect to progenitor mass or other parameters, at least in the LMC (van den Hoek & Groenewegen 1997). Data shown in Figure 3 are consistent with the expectation that the oxygen abundances are within the same range in symmetric and asymmetric PNe. These results from our limited sample suggest that progenitors of asymmetric PNe were formed in an enriched environment that is typical of a very young stellar population, while precursors of symmetric PNe formed in a medium that was underabundant with respect to the LMC H II region average. PNe split into two distinct population groups according to the oxygen abundance in Figure 4. It is clear that symmetric PNe are well confined in such a plot, and all symmetric PNe are carbon enriched with respect to the H II region average. The situation for asymmetric PNe is rather different: they are all nitrogen enriched, yet three of them are also carbon enriched with respect to the H II region average. The figure could be interpreted as follows: low-mass stars ($< 4 M_\odot$ on main sequence) go through the carbon-star phase and do not produce asymmetric PNe. The high-mass stars do not go through the carbon-star phase; they suffer hot-bottom burning on the AGB, and they produce asymmetric PNe. Some of the low-mass stars producing carbon stars also end up as asymmetric PNe, perhaps through the common envelope phase.

A discussion of the formation mechanisms for asymmetric PNe is in order in light of our findings. If asymmetry in PNe

| ATOM | PLANETARY NEBULAE | H II REGIONS | SUPERNova REMNANTS |
|------|------------------|--------------|--------------------|
|      | Symmetric (2)    | Asymmetric (3)| Leisy & Dennefeld 1996 | Russel & Dopita 1990 |                |
| He   | 11.0 (19)        | 11.0 (18)    | 10.9               | 10.91–11.03          |                |
| C    | 8.76 (11)        | 8.23 (7)     | 7.87               | 6.85–7.27            | 7.26–7.45      |
| N    | 7.83 (19)        | 8.26 (18)    | 6.97               | 8.18–8.60            | 8.10–8.54      |
| O    | 8.30 (20)        | 8.41 (18)    | 8.38               | 7.56–7.78            | 7.11–7.95      |
| Ne   | 7.49 (19)        | 7.73 (18)    | 7.64               | 6.68–7.0             | 6.4–7.0        |
| S    | 7.04 (15)        | 7.15 (13)    | 6.67               | 5.8–6.37             | 6.51–6.65      |
| Ar   | 6.08 (17)        | 6.32 (15)    | 6.20               |                      |                |

**Note.** Abundances are given as $12 + \log (N/X)$. Numbers in parenthesis in cols. (2) and (3) indicate the available PN sample for a given statistic. Abundance ranges for supernova remnants in col. (6) are from Russel & Dopita 1990.
were due uniquely to common envelope evolution, or binary evolution in general, we would not expect to find any of the separations among morphological classes that we show in Figures 1–3. That is, we do not expect the incidence of close binaries to vary as a function of the mass of the PN progenitor. Although this is a qualitative statement, it is substantiated by other observations (i.e., the existence of bipolar PNe that do not show an equatorial ring, such as the Galactic PN Hubble 5) and studies of the initial mass function. On the other hand, there may be a small fraction of asymmetric PNe that are developed as a consequence of close binary evolution, and this is also supported by observations. It may be that we are very far from understanding how the morphology of PNe is created, since there are a large number of variables in this game. What we can conclude with some certainty is that asymmetry in PNe is related to the population type and by inference the mass of the progenitor star. Any model for the formation of PNe that predicts the morphology must be consistent with this relationship.

3. ABUNDANCE UNCERTAINTIES AND SYSTEMATIC EFFECTS

If the results of the previous sections are borne out by additional observations and analysis, the effect on subsequent interpretations of PN formation and evolution could be substantial. In this section, we take a critical look at the derivation of the chemical abundances that are the underpinning of the conclusions presented here.

The first step is to give some information on the abundance uncertainties as derived from the original papers. None of the references that we have used for abundance cite individual errors. Dopita et al. (1997) do not discuss errors, but from the error bars in their Figure 7 it is possible to infer that the N, O, and C abundances are good to 0.1 dex, while the errors on the $\alpha$-elements are about 0.08 dex. We should infer similar uncertainties for Dopita & Meatheringham (1991a, 1991b), since the three papers use the same abundance determination method. Monk, Barlow, & Clegg (1988) evaluate that their oxygen and neon abundances are good to 0.1 or 0.15 dex, while neon and argon abundances are more uncertain, up to 0.2 dex. Finally, Leisy & Dennefeld (1996) determine that most elemental abundances are good to 0.1 dex, with the exception of nitrogen, whose uncertainty is up to 0.2 dex or more.

The potential for systematic errors from using different sources of abundance in the literature is worrisome enough to warrant some scrutiny. We compared the abundances from different bibliographic sources and found that the values from Dopita & Meatheringham (1991a, 1991b) and Monk, Barlow, & Clegg (1988) agree, within the quoted errors, with the abundances by Leisy & Dennefeld (1996). Plotting the results of pairs of references shows only a scatter in the final results for most elements with no systematic differences. The only element that is worrisome is nitrogen. Leisy & Dennefeld (1996) give a nitrogen abundance that is systematically about 0.3 dex higher than other authors. However, omitting the work of any one paper does not change the qualitative results of Figure 4. In particular, any discrepancies do not correlate with the ionization states of the nebulae.

Most abundances are derived from observations using some form of the ionization correction method to convert from measured ionic abundances to total abundances. An ionization correction “factor” (ICF) for unseen ionization states is required in this conversion. Alexander & Balick (1997) found that the ICFs are very large in the case of low-ionization nebulae, giving, for example, artificially high neon or sulphur abundances that in principle could alter the effects seen in Figures 1–3. We explored the original intensity lines used for abundance calculation by Leisy & Dennefeld (1996) and Dopita & Meatheringham (1991a, 1991b), and we related the ionization level from the $[N \, ii]$ to $H[zeta]$ line ratio to the morphological type. The question becomes whether those classes of PNe with segregated abundances have systematically low or high ionization. We found no correlation between ionization level and morphology in our combined sample. Most of the nebulae show high ionization, and the few low-ionization objects are equally distributed among symmetric and asymmetric PNe. The only exception to this rule concerns extremely bipolar PNe (indicated with a square in the figures). Among four of such PNe, three are low ionization. Eliminating these extreme binaries from the plots would not change the conclusions of this Letter. It is worth mentioning that Alexander & Balick (1997) compared ICF abundances to those of model computation, and they find that Ne/H is the most reliable measure of the abundance of primordial elements since the O$^+$ and Ne$^+$ volumes are very similar and the corrections for unseen ionization states are relatively small.

In general, LMC PNe are point sources when observed from the ground, and the line intensities quoted in the literature typically refer to the global volume of the nebulae; thus, the ICF problem here is minimal (Alexander & Balick 1997). In fact, often Magellanic Cloud PNe are discovered via $[O \, iii]$ imaging (or $[O \, ii]$ must have been present in an objective prism spectrum), so fewer PNe in our sample have low ionization.

One last concern comes from the possibility that the line intensities used for abundances calculation suffer from alteration due to the presence of a shock front. This is particularly worrisome for the sulphur abundances. In fact, artificially high sulphur abundances may derive from excessively high intensities of the low-ionization states of sulphur. We have checked the line intensities for all PNe with $12 + \log (S/H) > 7$ to obtain diagnostic ratios for shocks, as explained by Veilleux & O-
terbrock (1987). In our sample, only two PNe have O\(\text{I}\) \(\log \frac{\lambda6300}{H\alpha}\) and [S\(\text{II}\)] \(\lambda\lambda6716+6731/H\alpha\) close to the limit for shock fronts (see the dash-dotted lines in Figs. 4–6 of Veilleux & Osterbrock 1987). We conclude that only a negligible fraction of the asymmetric PNe in Figure 1 may have high sulphur abundance due to the presence of a shock front. The overall scientific results that we describe in the previous chapter hold even if this was the case.

In conclusion, we feel that the results shown in this Letter are quite sound, in spite of the inhomogeneous abundances. This work will be extended to the SMC in which the metal abundances are considerably lower than in the LMC. In addition, we are extending the ground-based spectroscopy to a far larger sample of LMC and SMC PNe. Both the numbers of targets and the accuracy of the data will be greatly improved as a consequence.

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