Morphology and Evolution of the LMC Planetary Nebulae

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The LMC Survey with *HST*

Planetary Nebulae (PNe) have for many years been used as probes of the late stages of stellar evolution. While in many ways such studies have been very successful, and have inspired elaborate theoretical work on stellar evolution, they have been hampered by the great difficulty of determining accurate distances to PNe. As well, extinction within the Galaxy introduces substantial selection effects in the observed samples, making a direct comparison with theory very challenging. These are the single greatest limitations to further advances in the study of post-AGB evolution. These problems can now be addressed using the superior resolution and instrumentation of *Hubble Space Telescope* by studying PNe in the Magellanic Clouds, where the spatial resolution is comparable to that for typical Galactic PNe observed from the ground.

We have obtained images and slit-less spectra in a survey of LMC planetary nebulae (PNe), which is now underway. These data on 27 targets were obtained within the last year with *HST* using the Space Telescope Imaging Spectrograph. The data permit us to determine the nebular dimensions and morphology in the monochromatic light of several emission lines, including those that have traditionally been used for morphological studies in the Galaxy (Hα, [N II] 6583 Å and [O III] 5007 Å), plus others of varying ionization, such as [O I], He I, and [S II]. The broad-band images will allow us to determine the central star magnitudes (for the brighter stars), which will yield the evolutionary state of the central stars. This paper examines the evolution of the nebulae themselves, and the relationship of the PNe morphology and chemistry to the progenitor star. Our LMC sample is ideal for studying the co-evolution of PNe and their central stars, in that the debilitating uncertainties of the Galactic PN distance scale and the selection effects of interstellar dust do not apply, and the nebular dynamical ages can be used with greater confidence.

Morphology and Nebular Evolution

We classified the morphologies in our sample from the [N II] 6548 Å images in the G750M spectra (although we were guided by the Hα and [O III] 5007 Å images), using the classification scheme of Manchado et al. (1996). With this dataset, together with the ~30 LMC PNe for which monochromatic images exist in the *HST* archive (see Stanghellini et al. 1999), we can for the first time explore the question of temporal evolution of the nebular morphology by examining the change in surface brightness of nebulae as a function of nebular size (Fig. 1). Only two nebulae are spatially unresolved (one of those is probably a symbiotic star), and the rest are larger than 0.36 arcsec (~7 pixels) in diameter. This is probably a result of discovery selection, in that the presence of the [O III] lines is often a prerequisite for classification as a PN.

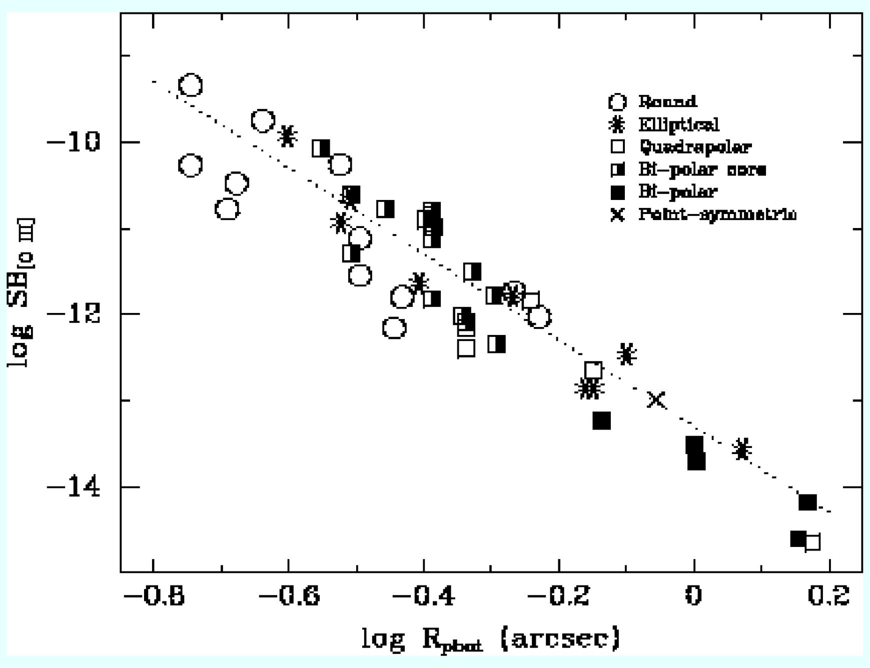

Figure 1: The decline of surface brightness (in the light of [O III] 5007 Å) with nebular radius is consistent with $SB \sim R^{-5}$ (*dotted line*) which corresponds to a geometric dilution of the emitting gas. The segregation of morphological types is likely a result of real evolution of morphological type, although classification ambiguity at small radii cannot be ruled out (see text). Two nebulae in this sample (not shown) are unresolved.

Figure 1 shows that most of the angularly smallest nebulae (0".17 < R < 0".28) are round or elliptical. In this size regime the nebulae are well resolved (>11 pixels diameter), so the lack of asymmetric nebulae here could indicate an evolutionary effect, in the sense that any initial asymmetry in the gas distribution and velocity field may not have had time to manifest itself in the morphology. Note, however, that the onset of asymmetric features appears even in very young nebulae (< 2000 yr), suggesting that the gross features of the nebular morphology are well connected to PN formation. As well, the possibility of ambiguity in our morphological classification, the small number statistics in this ([O III]-selected) sample, and possible selection effects, makes firm conclusions about evolutionary effects in young PNe difficult. What is more clear is the segregation of bi-polar core PNe (between 0".30 < R < 0".60), which have a round or elliptical outer contour, and pure bi-polar nebulae (> 0".60, or ~0.15 pc). This suggests that the bi-polarity may become the dominant morphological feature during the lifetime (after ~5000 yr) of bi-polar core nebulae, perhaps through subsequent shaping by the radiation field and wind from the central star (Balick 1987). Our data also show that the incidence of non-symmetric nebulae (including bi-polar nebulae, which is an indicator of Population I ancestry in the Galaxy) is much higher than that reported for the Galaxy.

Morphology as a Population Discriminant

It is well known from observations and stellar evolution theory that the abundance of several elements, including He, C, N, and O, are altered during the post-main sequence lifetime of stars in the 1—8 M_O range; many others, such as Ne and Ar, are not altered and should therefore reflect the metal abundance of the progenitor star. Published abundances are available for many of these nebulae (mostly from Leisy & Dennifield 1996; and Dopita et al. 1997), from which we find that these indicators of Population type correlate well with the morphological type of the PN that is produced . That is, stars with higher initial metal abundance tend to produce more asymmetric (bi-polar or bi-polar core) nebulae, and progenitors with lower initial metal abundance tend to produce symmtric nebulae (round or elliptical). Figure 3 shows the correlation, and extends to the LMC the relationship found in the Galaxy (e.g., Greig 1972) that the nebular morphology is a good indicator of the Population of the progenitor star (Stanghellini et al. 2000).

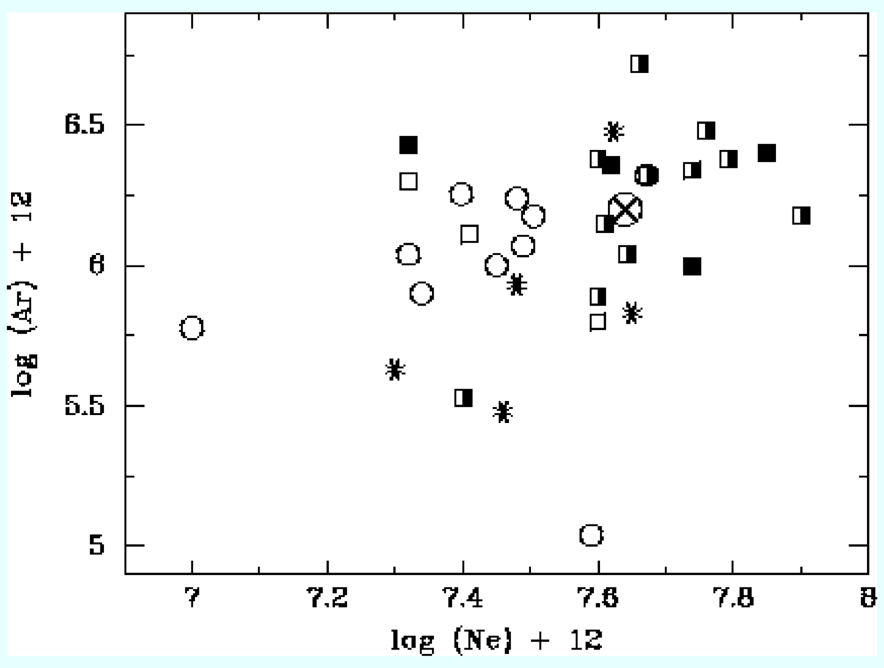

Figure 2: The abundance of both Ne and Ar (for lower-mass stars) should be unchanged throughout the course of evolution for single stars that form PNe. The segregation of nebular morphological type is especially apparent for Ne. Symbols are as in Fig. 1; average of H II regions within the LMC is indicated (circled cross).

This relationship between morphology and progenitor Population sheds some light on the question of PN formation mechanisms. That is, the mechanism for PN formation must account in a consistent way for the subsequent nebular morphology, and in particular the segregation of morphological type with the progenitor Population type. We believe it would be difficult, for example, to identify common-envelope binary evolution as the only (or even the dominant) mechanism for producing highly asymmetric PNe.

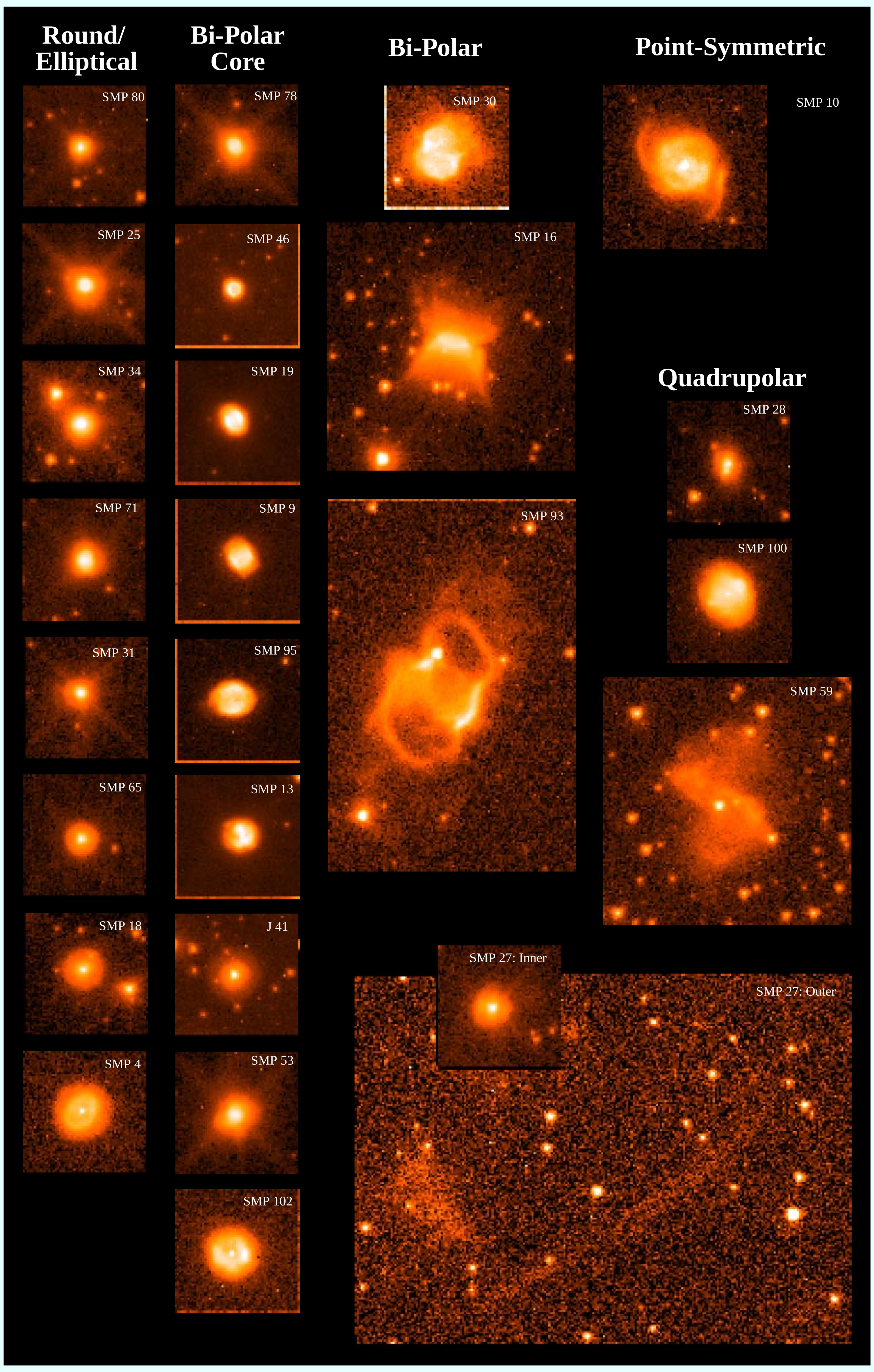

Figure 3: Broad-band, false-color images of each of the observed LMC nebulae in this GO program, arranged by morphological type. All images are on the same spatial scale, with a square-root intensity stretch; the field of view in most images is 3 x 3 arcsec. The physical scale is ~0.245 pc/arcsec.

Comparison with Evolution Theory

With morphological type as an indicator of the progenitor Population type, it is possible to examine the predictions from stellar evolution theory (e.g., Iben & Renzini 1983; van den Hoek & Groenewegen 1997) for changes in the abundance of processed elements, such as C, N, and O, with new insight. Figure 4 shows the substantial decline of C/O with increasing Ne abundance (which is used here as a Population indicator), and the decline of C/O with increasing N/O. This is wholly consistent with predictions from stellar evolution theory, where C is converted to N in PN progenitors with the highest mass. Again, the nebular morphologies segregate according to Population type, and suggest that nebular morphology may also correlate with central star mass, in the sense that central stars produced by the younger Population progenitors will on average have higher mass. These relationships have been offered and debated for samples of Galactic PNe, but the relationship to nebular morphology (and the implications for nebular formation) are now much clearer. More detailed comparisons will be possible once the luminosities and temperatures of the central stars are determined, and the evolutionary state can be compared to that of the surrounding nebula.

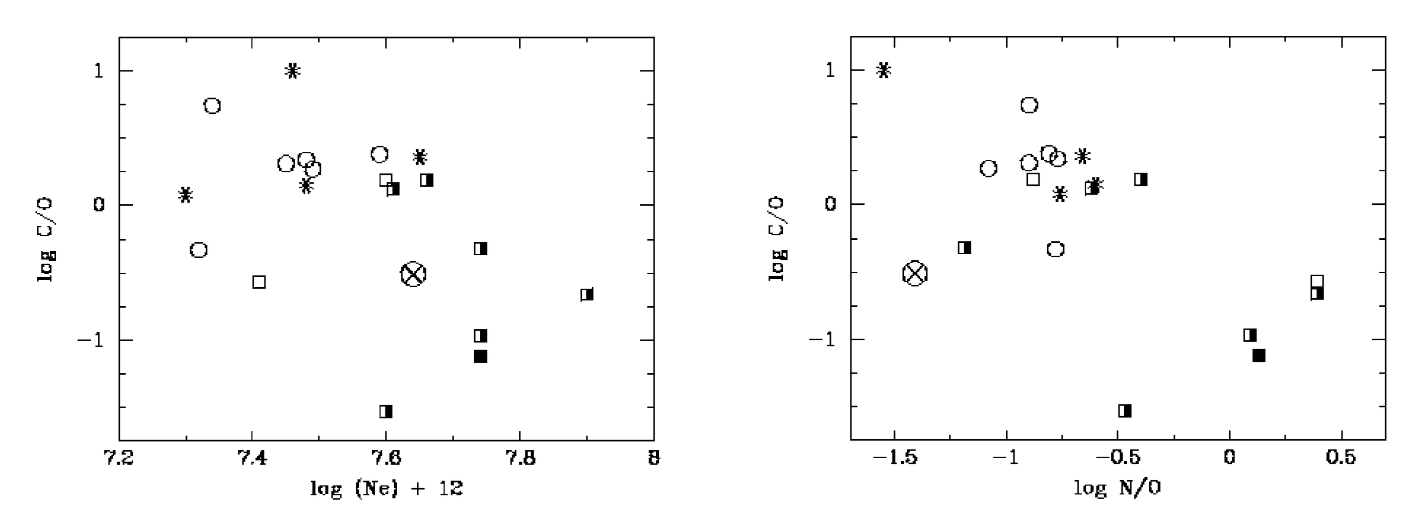

Figure 4: Changes in abundance of processed elements: C/O vs. Ne (*left*) and C/O vs, N/O (*right*) with nebular morphological type. Symbols are as in Fig. 1.

Conclusions

This study of LMC PNe, which is still underway, has given us significant insight into the formation and evolution of the nebulae and their central stars. For the first time we can study a relatively unbiased sample of PNe to examine the formation and evolution of the nebulae. Specifically, there is good evidence for at least some evolution in the morphological type as PNe age. As well, this morphological study places some constraints on the mechanism for PN formation. Finally, this study will permit a much more detailed examination of predictions from stellar evolution theory, particularly when the analysis of the central stars is complete.

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