ARE PROTO-PLANETARY NEBULAE SHAPED BY A BINARY? RESULTS OF A LONG-TERM RADIAL VELOCITY STUDY*

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ABSTRACT

The shaping of the nebula is currently one of the outstanding unsolved problems in planetary nebula (PN) research. Several mechanisms have been proposed, most of which require a binary companion. However, direct evidence for a binary companion is lacking in most PNs. We have addressed this problem by obtaining precise radial velocities of seven bright proto-planetary nebulae (PPNs), objects in transition from the asymptotic giant branch to the PN phases of stellar evolution. These have F–G spectral types and have the advantage over PNs of having more and sharper spectral lines, leading to better precision. Our observations were made in two observing intervals, 1991–1995 and 2007–2010, and we have included in our analysis some additional published and unpublished data. Only one of the PPNs, IRAS 22272+5435, shows a long-term variation that might tentatively be attributed to a binary companion, with $P > 22$ yr, and from this, limiting binary parameters are calculated. Selection effects are also discussed. These results set significant restrictions on the range of possible physical and orbital properties of any binary companions: they have periods greater than 25 yr or masses of brown dwarfs or super-Jupiters. While not ruling out the binary hypothesis, it seems fair to say that these results do not support it.

Key words: binaries: general – binaries: spectroscopic – circumstellar matter – planetary nebulae: general – stars: AGB and post-AGB – stars: mass-loss

1. INTRODUCTION

1.1. Background to the Question

Arguably the most controversial area in planetary nebula (PN) research at present is the determination of the mechanism for shaping the nebula. This has been brought to the fore by the visually stunning, high-resolution Hubble Space Telescope (HST) images. PNs generally possess an elliptical or bipolar structure, often with additional point-symmetric features (ansae, jets; see Balick & Frank 2002). In contrast, their precursors, asymptotic giant branch (AGB) stars, have been considered to be basically spherical (Olofsson 1999; Neri et al. 1998), although some recent resolved molecular-line observations show that a significant fraction show some axial symmetry (Castro-Carrizo et al. 2007). So the question can be posed as to how a mass-losing AGB star, which is basically spherical, can evolve into the variety of PN shapes.

The presently emerging consensus is that the axial and bipolar asymmetry is caused directly or indirectly by the presence of a binary companion to the central star. A binary companion could influence the density structure in at least the following three ways.

1. Most directly, a companion could gravitationally focus the mass loss into the orbital plane, forming an equatorial density enhancement and perhaps a torus. This density enhancement or torus would then collimate the fast wind producing a bipolar outflow (Livio & Soker 1988). A variation on this would be the formation of an accretion disk around the binary companion; this could collimate a fast wind and carve out the lobes and also lead to point-symmetric ejecta (Soker & Rappaport 2000).
2. The mass could be preferentially lost in the equatorial plane of the PN during the AGB phase due to a rotationally induced oblate shape, producing a collimating torus (García-Segura et al. 1999). However, given the low rotational velocity of an intermediate-mass star on the main sequence, it would probably require the presence of a close companion to spin up the resulting AGB star by the transfer of orbital angular momentum. This binary-induced mass loss could occur during a common envelope phase (Nordhaus & Blackman 2006).
3. The central star could possess a magnetic field that collimates the outflow into bipolar lobes (García-Segura et al. 1999, 2005). Recent work indicates that something like a binary interaction would most probably be needed to sustain such a magnetic field through the transfer of angular momentum (Nordhaus et al. 2007).

The first mechanism is generally favored to produce the density enhancement or collimating torus, although it can be seen that a binary companion would be important in all three mechanisms. Population synthesis studies suggest that binary interactions can produce the correct number of Galactic PNs (Moe & De Marco 2006). Thus, it is common to hear it stated at PN conferences that elliptical or bipolar PNs are due to the effect of a binary companion, or even that the presence of an axially symmetric or bipolar structure implies a binary. However, this hypothesis has not been adequately supported observationally. An extensive review of the question of what shapes PNs, with a thorough investigation of the evidence for the binary hypothesis,
has recently been presented by De Marco (2009); the need for direct observational tests of this hypothesis is stressed. 5

1.2. Why Search for Binary PPNe?

Proto-planetary nebulae (PPNs) are the objects in transition between the AGB and PN phases in the evolution of intermediate- and low-mass stars. During the AGB phase, such stars are surrounded by an expanding circumstellar envelope (CSE) of mass being lost at an increasing rate. In the PN phase, the high-rate mass loss has ended and the star is surrounded by a detached, expanding envelope (Kwok 1993). PPNs are a subset of the larger class of post-AGB stars, which also includes RV Tau and R CrB variables (Van Winckel 2003). PPNs can be distinguished by having more massive circumstellar nebulae and in many cases showing clear abundance patterns from AGB nucleosynthesis. As such, PPNs appear to be the most likely set of the larger class of post-AGB stars, which also includes PPNs from post-AGB stars in general and compare our results with those found for other post-AGB stars.

PPNs display a basic axial symmetry, often showing bipolar lobes and occasionally point symmetry. This has been particularly seen in high-resolution HST images (Ueta et al. 2000; Su et al. 2001; Sahai et al. 2007; Siodmiak et al. 2008). Some also display an obscured equatorial region. Thus, one sees in PPNs the same basic structures as in PNs, but at an earlier stage in the nebula, a stage closer to the beginning of the shaping process. This commends the study of PPNs to investigate the shaping mechanism(s).

Binarity can manifest itself in several ways: a visible companion, photometric light variations, composite spectrum, and radial velocity variations. A survey of the results of these methods has been presented earlier (Hrivnak 2009a) with null results; no evidence of binary companions to PPNs was found.

In this paper, we discuss the observational evidence of binarity in PPNs based on long-term radial velocity studies of seven bright PPNs. The results of this study and their implications for the binary nature of PPNs are then discussed, and conclusions drawn and discussed on whether or not they provide evidence to support the binary hypothesis.

2. OBSERVATIONAL SAMPLE AND DATA SETS

Our sample consists of the seven brightest PPNs observable from midlatitudes in the northern hemisphere. They range in visual brightness from 7.1 to 10.4 mag and are listed in Table 1. We examine later the question of what biases might result from observing the brightest PPNs. For uniformity, we will refer to all of them by their IRAS identification numbers. All show the double-peaked spectral energy distribution characteristic of PPNs (e.g., Hrivnak et al. 1989), and all have F–G spectral types. All are known to vary in light and all but one have variable star designations. Detailed light-curve studies of all seven of these have been presented elsewhere (Hrivnak et al. 2010; Arkhipova et al. 2010, 2006; Fernie 1983).

The main data sets used in this study are the radial velocity observations we carried out at the Dominion Astrophysical Observatory (DAO), initially from 1991–1995 and then more recently from 2007–2010. The 1991–1995 data were obtained with the radial-velocity spectrometer (RVS; Fletcher et al. 1982), while those from 2007–2010 were derived from CCD spectra by cross-correlation with several IAU standards. However, the velocities of those standards were taken to be those derived at the DAO photographically (Scarfe et al. 1990; Scarfe 2010) and with the RVS. The zero point of the much more numerous RVS observations of standard stars has been adjusted to match that of the photographic data for this purpose, thus ensuring that the CCD and RVS data are on the same system. With F–G spectral types, these objects have numerous sharp absorption lines, which result in an observational precision of $\sim 0.7$ km s$^{-1}$. The individual radial velocity measurements will be published elsewhere in the context of our detailed pulsational studies of the individual objects. We find that they all vary in velocity and light due to pulsation, with periods ranging from 35 to 130 days (Hrivnak 2009b; Hrivnak et al. 2010; see also Arkhipova et al. 2000, 2010). Substantial radial velocity data sets have also been published by other investigators for three of the objects, IRAS 07134+1005 (Lébre et al. 1996; Barthès et al. 2000), 17436+5003 (Burki et al. 1980), and 22272+5435 (Zács et al. 2009), as part of their study of pulsation in these objects. These published data sets and a few individual published and unpublished velocity observations have also been incorporated into this study.

3. RESULTS OF THE BINARY INVESTIGATION

3.1. Investigating the Sample

In Figures 1(a) and (b) are plotted the radial velocity data for these seven objects. In the left-hand panels are shown our observations from 1991–1995 on a scale that allows one to get a better sense of the velocity variations, and in some cases the clear cyclical nature of the pulsations is indicated by sine-curve fits. In the right-hand panels are shown the data over the entire range of observations, including those by others. The combined

| IRAS ID     | HD      | Var. Star | Other Names | V (mag) | Sp.T. | Morph. Class.|
|-------------|---------|-----------|-------------|---------|------|--------------|
| 07134+1005  | 56126   | CY CMi    | LS V1 +10 15| 8.2     | F5 I | Ec*0.41, h(e)|
| 17436+5003  | 161796  | V841 Her  | ...         | 7.1     | G3 Ib| Ec0.41       |
| 18095+2704  | 10.4    | V887 Her  | ...         | F3 Ib   |      |              |
| 19475+3112  | 331319  |           | LS II +31 9 | 9.4     | F3 I | Mc0.43, ps(m, s), h |
| 19500–1709  | 187885  | V5112 Gsr | ...         | 8.7     | F3 I |              |
| 22223+4327  | ...     | V448 Lac  | DO 41288    | 9.7     | G0 Ia| Ec0.43, h(a) |
| 22272+5435  | 235858  | V354 Lac  | ...         | 9.0     | G5 Ia| Ec0.55, h(a) |

Note. a According to the classification system of Sahai et al. (2007). The main classifications are E—elongated, B—bipolar, M—multipolar, c indicates closed lobes, * that the star is visible, ps the presence of point symmetry, and h the presence of a halo. For more details, see their paper.
Figure 1. (a) Radial velocity curves from our 1991–1995 observations, showing sine-curve fits to the periodic pulsational variations (left). Radial velocity curves showing the long-term velocity variations, including both our observations (filled circles) and those of others (open circles; right). Sample average error bars ($\pm 1\sigma$) are shown for each PPN in the lower right-hand corner of the left panels. (b) Radial velocity curves, with symbols similar to (a). The dashed lines in the right-hand panel for IRAS 22272+5435 represent the average velocities in the two observing intervals.

data sets for each of the objects show a range of velocities of $10$–$14$ km s$^{-1}$.

Comparing our 1991–1995 data with 2007–2010 data for the seven objects (summarized in Table 2), we find only one object, IRAS 22272+5435, for which the average values differ by more than $1.5$ km s$^{-1}$ (or $2\sigma$). For the others, the difference between the two data sets is $\leq 2\sigma$ and it does not appear that the average values differ significantly between the two epochs of observation. Nor is there evidence for systematic change when we include the other data sets. A formal period analysis of all
of the data was carried out for each object using the Period04 (Lenz & Breger 2005) program. Beyond the pulsation mentioned earlier, there is a suggestion of a long-term periodicity only in IRAS 22272+5435, which will be discussed in Section 3.2.

To investigate even longer-term variations, we compared the average radial velocity from these optical, photospheric spectra with the radial velocity determined from the circumstellar CO or OH emission. The CO and OH represent the emission from the CSEs, which have been expanding over several thousand years, since the late stages of the AGB phase. Thus, their velocity centers should be the same as that of the average PPN velocities, which should be that of the optical PPN velocity if there is no binary motion and that of the barycenters if there is binary motion. These results are also listed in Table 2. We see that these molecular-line velocities, when transformed to the heliocentric system, are all, with one exception, close to the velocities based on the visible spectra, differing by 0 to −2 km s\(^{-1}\). The lone exception is IRAS 18095+2704, which differs by +5 km s\(^{-1}\). This is the only target detected in OH (Eder et al. 1988), and inspection of the spectrum shows that the two separate maser components are relatively weak compared to most of the others in the study and that they show structure. Bujarrabal et al. (1992) cite a tentative CO detection at a velocity that would reduce the difference to +2 km s\(^{-1}\). Based on these data, we do not see any evidence from the molecular-line observations to indicate a significant difference between the photospheric and the CSE velocities, although there appears to be some inconsistency with the OH velocity of IRAS 18095+2704.

### 3.2. Evidence for a Possible Binary Companion to IRAS 22272+5435

A comparison of the earlier (1989–1995) and later (2005–2010) observations of IRAS 22272+5435, including the data from Zács et al. (2009), shows a bimodal distribution of velocities. There exists a significant difference of −2.2 km s\(^{-1}\) in the average velocities of the data sets from the two epochs, about four times the sum of the uncertainties in the values. We interpret this velocity difference as most probably due to the motion of the PPN around the barycenter of a binary star system. We note that IRAS 22272+5435 is the coolest and reddest star in the sample and presumably has the lowest surface gravity, as indicated by its spectral type and the results of a model atmosphere analysis (Reddy et al. 2002). Hence it is likely to be the least stable on a timescale of many years. While we have considered this possibility, we still think that the binary hypothesis is more likely to explain the long-term velocity variation.

A formal period study was carried out of all of these data. In addition to the pulsation period of 128.3 ± 0.1 days, no reliable long-term period could be determined. This is not surprising, given the distribution of the velocities in the two observing intervals around two nearly constant average velocities, −37.8 km s\(^{-1}\) for the 1989–1995 observations and −40.0 km s\(^{-1}\) for the 2005–2010 observations, with no transition between them.

This does not mean, however, that we have no idea of the period of the suspected binary. Given the observing intervals, it would not be possible for a binary to go through a complete cycle of variability in a time less than the total observing interval of 22 yr. Thus, we have a minimum value for the period of the suggested binary orbit. Continued monitoring will help to further constrain this by revealing a period or increasing the minimum value.

Thus, on the basis of the change in the radial velocities of IRAS 22272+5435, we make a tentative, but we think probable, identification of a binary companion. If we make the assumption that the long-term velocity difference is due to binary motion, we can then carry out a radial velocity solution and determine limiting binary parameters. For this we use the minimum values of 22 yr and 1.3 km s\(^{-1}\) for the values of the period and observed velocity semi-amplitude, the latter being half of the difference in the average velocity of the two intervals when the 128.4 day period is removed from the data. Assuming a circular orbit, \(M_{\text{PPN}} = 0.62 M_{\odot}\) (which appears to be a typical post-AGB core mass based on models for a star with an initial main-sequence mass of 2–3 \(M_{\odot}\); Blöcker 1995; Vassiliadis & Wood 1994), and a range of inclinations, one finds from the mass function a range of possible masses for the secondary: \(M_2 = 0.10 M_{\odot}\) (\(i = 90^\circ\),

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**Table 2** Summary of Radial Velocity Observations

| IRAS ID     | Number of Observations | \((V_R) (\text{km s}^{-1})\) | \(\Delta V_R^b\) | \(V_{\text{LSR}}(\text{CO,OH})^d\) | \(V_R(\text{CO,OH})^d\) | Comments |
|-------------|------------------------|-----------------------------|-----------------|-----------------------------|-----------------------------|-----------|
|             | 1991–1995\(^e\) | 2007–2010\(^e\) | Total\(^f\) | | | |
| 07134+1005  | 21 | 18 | 141 | 88.0(0.8) | 86.3(0.5) | 87.5(0.3) | 14 | 73 | 88 | ... |
| 17436+5003  | 59 | 45 | 178 | −53.1(0.2) | −52.6(0.4) | −52.6(0.2) | 11 | −35 | −54 | Longer \(P\) |
| 18095+2704  | 47 | 29 | 77 | −29.4(0.3) | −30.5(0.3) | −29.8(0.2) | 13 | 18 | 0 | ... |
| 19475+3112  | 38 | 29 | 71 | 2.1(0.4) | 1.9(0.5) | 1.7(0.3) | 10 | 25 | 13 | ... |
| 19500–1709  | 35 | 13 | 58 | 14.5(0.5) | 13.8(0.7) | 13.9(0.3) | 12 | 25 | 13 | ... |
| 22223+4327  | 34 | 36 | 81 | −40.5(0.4) | −41.9(0.3) | −41.3(0.2) | 11 | −30 | −42 | ... |
| 22272+5435  | 34 | 36 | 155 | −37.6(0.3) | −40.6(0.3) | −39.4(0.2) | 12 | −28 | −40 | Longer \(P\) |

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Notes.

\(^a\) The values in parentheses represent the uncertainties in the mean values.

\(^b\) Range in radial velocities, based on the total data set.

\(^c\) CO or OH molecular-line velocities in the local standard of rest (LSR) system. References: CO—Likkel et al. (1991); Omont et al. (1993); Bujarrabal et al. (1992); Hrivnak & Bieging (2005); OH—Eder et al. (1988).

\(^d\) \(V(\text{CO,OH})\) transformed from the LSR to the heliocentric system.

\(^e\) Including additional data available from the literature or by private communication as follows: IRAS 07134+1005—Lèbre et al. (1996); Barthès et al. (2000); Vassiliadis & Wood (1994); Eder et al. (1988); Klochkova et al. (2009); Reddy et al. (2002).

\(^f\) Based on our observations only.

\(^g\) IRAS ID Number of Observations
0.12 \ M_\odot (i = 60°), 0.22 \ M_\odot (i = 30°), and 0.51 \ M_\odot (i = 15°). From a mid-infrared imaging and modeling study, Ueta et al. (2001) determined an inclination of the torus of \( i = 25° \pm 3° \). Assuming that the binary orbit is coplanar with the equatorial density enhancement, this leads to a companion mass of \( 0.27 \pm 0.04 \ M_\odot \). This is a very reasonable value for a secondary companion, and the assumption that it is a main-sequence star would place it at a spectral class of \( \sim \text{M4 V} \) (Cox 2000). For a circular orbit, this leads to a separation of \( 8.0 \ \text{AU} \), a value not only well outside the present radius of the PPN of \( R \sim 100 \ R_\odot \), but one that would have been well outside it when the star was at the tip of the AGB, with \( R \ll 500 \ R_\odot \). We emphasize that these are only preliminary, minimum values, based on the hypothesis that this long-term velocity difference is due to binary motion. For example, if this is a binary with a period of 34 yr and the same semi-amplitude as above, the calculated value for the mass would increase to \( 0.32 \ M_\odot \), and if the velocity semi-amplitude were \( 1.8 \ \text{km s}^{-1} \), the mass would increase to \( 0.50 \ M_\odot \). Calculations have shown that a binary with such parameters can form a very narrow waist bipolar PN (Soker & Rappaport 2000), although in this case the visible \( \text{HST} \) image shows the nebula to not be this extreme in shape. These nebulae are all surrounded by a larger halo, representing the earlier AGB mass loss. Huggins et al. (2010) calculate the effects of different parameters \((M_2, i, a)\) on the shaping of an initially spherical AGB wind to produce the observed halo in a PPN. They run a model for a binary with parameters similar to the preliminary values that we found for IRAS 22272+5435, for which they predict an approximately round halo. This is consistent with that observed for this PPN (Sahai et al. 2007, classify the halo as centrosymmetric with arc-like features). (Given an estimated distance of \( 1.9 \ \text{kpc} \) and a luminosity ratio of \( 3 \times 10^5 \) based on the \( \text{M4 V} \) spectral classification, there is presently no hope of observing the companion directly.)

3.3. Selection Effects and Limits on Binarity from the Null Results

For the other six PPNs, no systematic change in velocity has occurred between the 1991–1995 and the 2007–2010 observations, nor is any seen when we include additional published velocities. Period analyses show only the pulsational velocity variation. However, one needs to consider selection effects. Since we observed the brightest PPNs, they are not highly obscured. Thus, if they have a bipolar structure with an enhanced equatorial density region, they are probably biased toward having their equatorial planes close to the plane of the sky, thereby reducing their obscuration. This would reduce the observed orbital velocity, given the reasonable assumption that the binary orbit is in the equatorial plane.

In spite of the uncertainty in the inclination of the equator (which mid-infrared images and spatial–kinematical observations can help solve), these null results still set useful limits on the binary parameter space. These are shown graphically in Figure 2, assuming that \( M_{\text{PPN}} = 0.62 \ M_\odot \), circular orbits, and a conservative detection limit of \( K = 2.0 \ \text{km s}^{-1} \). This shows that to remain undetected, a companion of \( 0.40 \ M_\odot \) must have an orbital period of \( P > 3.5 \ \text{yr} \) if \( i \geq 15° \) and \( P > 24.5 \ \text{yr} \) if \( i \geq 30° \); an undetected companion of \( 0.25 \ M_\odot \) must have an orbital period of \( P > 1.1 \ \text{yr} \) if \( i \geq 15° \), \( P > 8 \ \text{yr} \) if \( i \geq 30° \), and \( P > 23 \ \text{yr} \) if \( i \geq 45° \). Another way to look at it is that \( M_2 > 0.65 \ M_\odot \) is excluded for \( P < 10 \ \text{yr} \) at \( i \geq 15° \) and \( M_2 > 0.30 \ M_\odot \) is excluded for \( P < 13 \ \text{yr} \) at \( i \geq 30° \). Lower-mass or longer-period companions than these would escape detection.

We do know something about the orientation of the bipolar structure in these six PPNs based on \( \text{HST} \) images and on two-dimensional modeling in several cases with resolved mid-infrared images. \( \text{HST} \) images of IRAS 18095+2704 and 19475+3119 suggest that they are viewed at some intermediate angles (Ueta et al. 2000; Sahai et al. 2007). Models based on mid-IR images and, for IRAS 07134+1005, spatially resolved molecular-line spectroscopy, have determined the approximate inclinations of the polar axis with respect to the plane of the sky for two of the objects. For IRAS 07134+1005, \( i \sim 80° \) (Meixner et al. 2004), and for IRAS 17436+5003, \( i \sim 90° \) (Meixner et al. 2002) or \( i \sim 10° \) (Gledhill & Yates 2003), although for the latter of these objects one sees very disparate results. For IRAS 22223+4327, a comparison of mid-infrared and \( \text{HST} \) visible images implies an inclination that is closer to edge-on (90°) than pole-on (Clube & Gledhill 2006). For IRAS 19500+1709, the inclination is more uncertain (Gledhill et al. 2001; K. M. Volk 2008, private communication). Therefore, at least some of these objects appear to be inclined out of the plane of the sky with \( i > 30° \), and there does not appear to be an important bias of the sample to the plane of the sky. In this case, the projection effects are less severe and the constraints on the mass or period of any undetected binary companion are more significant. Thus, it appears that our non-detection of binary in all six of these PPNs cannot be explained away as simply due to a low-binary inclination to the plane of the sky.

4. DISCUSSION AND CONCLUSIONS

This radial velocity study of seven PPNs shows only one has velocity variations, in addition to pulsation, that can tentatively be attributed to a binary companion. The presence of pulsation does complicate the search for a binary companion and makes it more difficult, but it does not invalidate the null result for the other six. As a counterexample, we found for the related post-AGB object 89 Her that we could detect a binary companion \((K = 3.3 \ \text{km s}^{-1}, P = 290 \ \text{days})\) even with a pulsating central star \((K = 1.6 \ \text{km s}^{-1}, P = 66 \ \text{days})\); B. Hrivnak 2011, in preparation). Thus, such binaries could be detected but were not.

![Figure 2](image_url)
We used these null results to set limits on the properties of any undetected companions. The one tentative binary has a long period (>22 yr) and probably a normal stellar mass companion ($M > \approx 0.27 M_\odot$).

One might initially be surprised by this low binary fraction in light of the discovery of a large number of post-AGB binaries by Van Winckel and collaborators (Van Winckel et al. 2003; 2007; Van Winckel et al. 2006). They find thus far that 27 out of a sample of 51 post-AGB stars are spectroscopic binaries. However, these 51 post-AGB are not an unbiased sample but were chosen because they possess several of the observed characteristics of previously known post-AGB binaries (De Ruyter et al. 2006). These post-AGB binaries are a distinctly different set of objects than the PPNs. They show a broad infrared excess (broad SED), indicating both hot and cool dust, and have abundance anomalies thought to be due to chemical fractionation of refractory elements onto dust, with re-accretion of non-refractory elements by the star (Van Winckel 2003). These properties are attributed to the presence of a circumbinary disk. Most, and perhaps all, of these objects are binaries, with $P \approx 100$–2600 days and $e = 0.0$–0.6. We would have detected such binaries but did not. In these post-AGB binaries, it is the binary that is thought to be responsible for forming and stabilizing the disk (Van Winckel et al. 2006). The orbital periods of the shorter of these are such that the systems would not accommodate a large AGB star within them. Thus, it appears that it is their binary nature that leads to their special properties (Waelkens & Waters 2004) and brings them to our attention due to their infrared excesses. PPNs do not share these properties, but rather display a clearly double-peaked SED with a much larger infrared excess, indicating a detached shell and much larger mass loss. The PPNs, at least the carbon-rich ones, have abundance anomalies seen in the post-AGB binaries. Also, the PPNs show a visible nebula which most of the post-AGB binaries do not (the Red Rectangle is an exception). Thus, in contrast to De Marco (2009), we conclude that the binary post-AGB objects in general represent a class of objects that are unlikely to evolve into PNs and therefore do not bear directly on the question of the shaping of the nebulae. PPNs, on the other hand, give every indication of being the immediate precursors of PNs.

We can make the comparison instead to the binary central stars of PNs. Photometric searches indicate that 10%–20% of all PNs have a close ($P < 8$ days) companion (Miszalski et al. 2009a; De Marco 2009). With their short periods, it seems likely that the binary PNs formed through common envelope evolution in which the two stars did not merge. Might the PPNs be binaries, but presently in the common envelope stage? Since the common envelope stage is calculated to be very short, on the order of the pre-common envelope orbital period (Ricker & Tamm 2008), this cannot be the case, for it would be far too improbable to find six of our seven in this very short lived phase. We cannot make a comparison with the fraction of PNs with a period in the range of 0.1–30 yr, since this is observationally unknown. Radial velocity studies of PNs with a resolution of 3 km s$^{-1}$ have been initiated (De Marco 2006). However, these are complicated by the broad lines in the central stars and their variable winds, and no definitive results have been obtained.

What do we know about the shapes of the binary PNs and how do they compare with the shapes of these PPNs? Based on a sample of 30 of these binary PNs with good images, it has been determined that $\sim 30\%$ have nebulae with clear bipolar morphologies, and it is suggested that this number might be as high as $\sim 60\%$ if inclination effects and other factors are included (Miszalski et al. 2009b). This result is highly suggestive that a common envelope evolution without merger will commonly produce a bipolar nebula. However, this does not imply the inverse, that bipolar nebulae have a binary central star. All of our seven PPNs have a bright central star and would be classified as SOLE in the classification scheme of Ueta et al. (2000) and Siodmiak et al. (2008). In the more detailed classification scheme of Sahai et al. (2007), six of the seven are classified: four as elongated, one as bipolar, and one as multipolar (see Table 1). This suggests they each have an axis of symmetry that might arise from an equatorial density enhancement, and in several of the cases this enhancement is seen in the mid-infrared images.

One is still left with the question of why only one of our seven PPNs shows evidence of being a binary, given that the binary fraction of stars is so much higher. The careful study of a sample of 164 solar-type ($F7$–$G9$ IV–V, V, VI) stars by Duquennoy & Mayor (1991) finds $\sim 50\%$ to be binaries. But this included visual binaries and common proper motion pairs, and resulted in a mean period of 180 yr. If we restrict our comparison to the spectroscopic binaries, the fraction drops to $\sim 25\%$ (with orbits) or $\sim 33\%$ (including those detected to vary in velocity as binaries but without determined orbits). These results are based on high-precision velocities ($\sigma < 0.3$ km s$^{-1}$) over an observing range of up to 13 yr (average 8.6 yr) and are a better comparison with our radial velocity sample. Given their higher precision and the absence of the pulsational variations which complicate the study of our stars, our tentative detection of one in seven (14%) to be binaries does not appear to be anomalously low.

Might these PPNs be binaries but with periods longer than 25 yr? These might not be detected in this radial velocity study, but they could still affect the shaping of the nebula, although their effect would be reduced with increasing orbital period and separation. Might they be binaries but with low-mass ($<0.25 M_\odot$) companions? Our above limits on binarity do not exclude such companions. If the companion is a brown dwarf or a super-Jupiter planet, then it would escape detection in our program. While these can have a significant effect on the mass loss in certain cases and produce elliptical nebulae, it is estimated that planets will significantly affect mass loss in only 4%–10% of AGB stars (Livio & Soker 2002).

The results of this present radial velocity study provide the first direct test of the binary hypothesis in shaping PPNs, the direct precursors of PNs. While they do not rule it out, it seems fair to say that they do not support the binary hypothesis. Although this study has not answered the question of whether the shaping of PPNs and PNs is ultimately due to a binary companion, it has set significant constraints on the properties of a binary companion during the PPN phase. The lack of detection of a companion in six of the cases probably implies that any such companion either has a period that is very long (>25 yr) or a mass that is very low (<0.25 $M_\odot$). The effects of these on the mass loss and its shaping are obviously less than in the case of a higher-mass, shorter-period companion. These constraints can help guide future attempts to model the formation of the circumstellar density asymmetries with a binary companion. And of course they might not be binaries, and the asymmetric mass loss would then be due to something else. We know that they were pulsating during the previous AGB phase, and perhaps pulsation coupled with some other mechanism such as cool star spots (Soker 2000) is the mechanism responsible for the shaping. These results also do not appear to support the hypothesis that
the intensive mass loss at the end of the AGB (the “superwind”) is driven by a binary companion (De Marco 2009). Since in these seven PPNs it is apparent that the envelopes are detached and the shaping of the nebula has started, these results might suggest two ways to form the shapes seen in PNs: (1) through a common envelope evolution, as evidenced by the close binary nuclei of some PNs, or (2) through a non-common envelope process, which is occurring in these PPNs. This latter process might involve a distant and/or low-mass companion or be due to a single, pulsating central star.

This radial velocity study is continuing so that we can extend the temporal baseline in the search for evidence of even longer period binaries and seek to confirm the one tentative case. We have also begun a radial velocity study of several edge-on bipolar PPNs in which we make the reasonable assumption that the binary orbit would be in the plane of the equatorial density enhancement. In such a case, we would see the full orbital velocity variations without suffering from an inclination effect. While in these cases the star is completely obscured from view in visible light, it is seen in the near-infrared and thus amenable to near-infrared spectroscopy. These PPNs have bipolar lobes and an obscuring dust lane, implying very strong shaping of the outflow. Rotation will also be investigated by comparing these edge-on cases with ones that are more nearly pole-on; since the pole-on ones are expected to appear as slow rotators, this comparison can give evidence in the edge-on cases of possible rotational spin-up or merger by a companion.

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