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A possible observational measure of evolution in bipolar nebulae

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Abstract. Bipolar planetary nebulae (BPNe) possess a broad range of shapes, ranging from narrow-waisted butterfly-like structures, through to those which are more nearly cylindrical. We point out that these morphologies appear to be correlated with radio surface brightness T_b, in the sense that higher values of T_b are associated with envelopes having narrower waists. If one interprets the variation in T_b as arising from shell evolution, as is usually assumed for other planetaries, this would then imply that shell morphology varies with time in a manner which appears not to be consistent with evolutionary models. It also remains possible, however, that different BPNe morphologies arise as a result of differing mechanisms of formation, and that the pre-collimation of high velocity central winds gives rise to narrower waists, and higher surface brightness nuclei. Our results, if this is true, may then imply that central winds possess a broad range of collimations.

Key words. ISM: planetary nebulae: general – ISM: jets and outflows

1. Introduction

It is generally believed that post-main-sequence bipolar nebulae (BPNe) arise through the interaction of stellar winds with collimating disks (e.g. Corradi & Schwarz 1995; Cuesta et al. 1995). The resulting shocked bubbles of high temperature gas then drive the lobal structures to velocities of $\sim$150 km s^{-1} or so (Corradi & Schwarz 1995).

Beyond this, our understanding of the formation and evolution of such sources is extremely restricted, whether regarded in theoretical or observational terms. Modeling of such sources appears to indicate that BPNe morphologies are sensitive to the presence of magnetic fields, wind rotation, density contrasts within the slower AGB wind, the rate of evolution (i.e. the mass) of the central star, the level of pre-collimation of the fast wind (see discussion in Sect. 3), and various other parameters (e.g. Garcia-Segura et al. 1999; Frank et al. 1993; Mellema 1995; Soker & Rappaport 2000). The relative importance of these mechanisms is however uncertain. The time evolution of such sources has been considered by Mellema et al. (1991) and Mellema & Frank (1995), whence it is clear that morphologies are expected to vary considerably during the initial phases of expansion. Mellema (1997) and Mellema & Frank (1995), however, suggest that much of this development may be confined to the earliest stages of expansion. Later expansion of the I-fronts would be expected to reduce density contrasts within the exterior, aspherical AGB wind, and result in an invariant morphology during subsequent phases of evolution.

There is some observational evidence to support this presumption. Thus Corradi et al. (2001) find evidence for "ballistic" expansion in the lobes of He 2-104, a trend that appears also to be present in other BPNe (Corradi & Schwarz 1993a; Corradi & Schwarz 1993b; Redman et al. 2000), and has been noted in more spherically symmetric nebulae as well (e.g. Weedman 1968; Wilson 1958). This is interpreted as arising from self-similar evolution of the lobes (i.e. evolution with constant morphology) subsequent to the phase in which lobes are confined and shaped within the AGB envelopes. This, if true, would conflict with certain earlier models of BPNe evolution, in which it was presumed that the ratio between disk and lobal dimensions decreases with time (Balick 1987).

Much here depends, however, upon a narrow observational data base, and the parameters and codes which are employed for hydrodynamical modeling. It also, in the latter cases, depends upon whether the analyses are fully three dimensional, include the effects of central star evolution, the degree to which radiative transfer is incorporated, and the manner in which non-ionized regions are treated; it is sensitive, in short, to the level of analytical sophistication which is employed. Taking all of this into account, it is probably fair to state that our understanding of such evolution remains in its infancy, and that our ideas may still be open to considerable revision.

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Table 1. Summary of spatial and surface brightness paramaeters for bipolar sources.

Source	G.C.	F(5GHz) mJy	Ref.	Diameter arcsec	Diam. type	Ref.	T_B	Γ
NGC 6445	008.0+03.9	230	4	33	O/R	5,12	23.9	0.35
NGC 6537	010.1+00.7	610	5	4.1	R	3	2489	0.15
M 2-9	010.8+18.0	36	5	46	R	5	1.20	0.45
M 3-28	021.8-00.4	33	5	5	R	5	93.3	0.42
M 1-57	022.1-02.4	70	5	8	R	5	75.1	0.28
M 2-46	024.8-02.7	3	5	4.4	O	12	11.0	0.32
M 4-14	043.0-03.0	8	5	7	R	5	31.7	0.57
M 2-48	062.4-00.2	19	5	3.1	R	5	139.7	0.43
M 1-75	068.8-00.0	28	7	14	O	13	10.1	0.56
NGC 7026	089.0+00.3	310	8	20	O	12	54.8	0.38
SH 1-89	089.8-00.6	42.5	9	38	O	13	2.08	0.53
K 3-91	129.5+04.5	1.5	5	10	O	13	1.06	0.85
NGC 650-1	130.9-10.5	110	8	100	R	5	0.78	0.70
NGC 2346	215.6+03.6	86	1	54.6	O	13	2.04	0.63
NGC 2440	234.8+02.4	370	5	18	R	4	92.1	0.22
NGC 2818	261.9+08.5	33	10	45	O	12,13,14	1.15	1.00
NGC 2899	277.1-03.8	86	10	90	O	12	0.75	0.67
MyCn 18	307.5-04.9	106	6	12.6	O	13	47.2	0.23
He 2-114	318.3-02.0	11	6	36.6	O	13	0.58	1.00
IC 4406	319.6+15.7	110	1	35	O	12	6.35	0.91
Mz 3	331.7-01.0	649	1	25.4	O	13	71.1	0.32
NGC 6072	342.1+10.8	152	10	70	O	12	2.25	0.83
NGC 6302	349.5+01.0	3100	11	10	R	5	2168	0.29
Hb 5	359.3-00.9	550	2,10	20	O	5,15	97.2	0.20

Refs: 1. Milne & Aller (1975); 2. Milne & Aller (1982); 3. Isaacman (1984); 4. Phillips & Mampaso (1988); 5. Zijlstra et al. (1989); 6. Milne (1979); 7. Cahn & Rubin (1974); 8. Kaftan-Kassim (1969); 9. Zhang (1995); 10. Calabretta (1982); 11. Rodriguez et al. (1985); 12. Cahn & Kaler (1971); 14. Chu et al. (1987); 15 Perek & Kohoutek (1967)

With this in mind, we have therefore investigated whether there may be further ways in which the evolution of BPNe may be assessed. In particular, we shall investigate whether trends may be discerned between the relative sizes of collimation disks and lobes.

2. Observational data base

2.1. Evaluation of the structural parameter Γ

We have, for the purposes of this analysis, evaluated a parameter $\Gamma = D/B$ for some 24 BPNe, where B corresponds to the maximum width of the bilobal structures, and D is the diameter of the collimating disks – both of these assessed along directions perpendicular to the primary outflows (see Table 1). This total of sources represents approximately 30% of known BPNe, and corresponds to nebulae for which it was possible to identify and measure central collimating disks (see below).

The parameter Γ has the merit of being relatively independent of bipolar inclination i. By contrast, the use of lobe dimensions L along the principal axes of the outflows (in place of the perpendicular dimensions B) would suffer from two primary disadvantages; that the size of L varies as sin i (where i is usually poorly known), and that the major axis limits of the lobes are often faint, fragmentary, and extremely ill-defined.

Most if not all BPNe contain bright central condensations, out of which the primary outflows appear frequently to be emerging. We take these structures to represent the central collimating disks. There are several indicators to support this presumption. The first is that many of these features appear (where inclinations permit) to possess ring-like morphologies (e.g. Phillips 2001). It is also clear that most (and possibly all) of these structures are elongated perpendicularly to the bipolar outflows, as would be expected for tilted collimating disks.

Finally, it is apparent that several of these regions are associated with bands of extinction (cf. NGC 6302, M 2-48 and Hen 3-401) and toroids of molecular emission (Sahai et al. 1991; Bachiller et al. 1989; Zweigle et al. 1997), implying the presence of collimating disks with high contents of neutral gas.

We have been able to evaluate values of Γ from imaging published by Manchado et al. (1996), Corradi & Schwarz (1995), Schwarz et al. (1992), Perek & Kohoutek (1967), Balick (1987), at the web sites `http://ad.usno.navy.mil/pne/` and `http://astro.uni-tuebingen.de/groups/pn/`, and from individual images published in the scientific literature. These are indicated in Table 1; where it should be noted that we have listed only those sources having measured 5 GHz brightness temperatures T_b (see discussion below).

The errors in Γ are difficult to assess precisely, but arise (for the most part) where nebular structures are ill-defined; where shells fade gradually, without sharply defined limits; where the lobal structures are complex and/or filamentary; and where seeing disk sizes are comparable to the sizes of the nebulae, leading to smoothing of the apparent shell structures. None of these factors are likely to be important for the nebulae considered here, although they may all play their part in contributing to overall errors.

All of the nebular images are, for instance, considerably larger than those of nearby field stars, and appear (for the larger part) to be reasonably sharply defined. Similarly, we note that images of the central collimating disks are in all cases reasonably deep (the disks are often much brighter than the bipolar extensions), and reasonably well defined. It is unlikely that deeper exposures would yield significant changes in apparent dimensions. Although certain of the disks are enveloped by more extended emission, this is usually very much fainter, and unlikely to be associated with the primary disk structures.

The values of Γ may also depend upon stratification effects, and upon which ionic transitions are contained within the filter passbands. Thus, low excitation lines (such as [NII], [SII] and so forth) are likely derive from differing regimes of the outflows than those of higher excitation transitions ([OIII], [Ar IV] and etc.). It is at least plausible, therefore, to suppose that differing images may give rise to differing values of Γ. We find little evidence for this in the images used here, but have nevertheless chosen to evaluate Γ using images in HI where at all possible. The effects of this uncertainty (both random and systematic) are likely to be extremely modest, and dwarfed by the intrinsic scatter in Γ between differing sources.

Given the various comments above, we therefore believe that errors in Γ are likely to be small. Comparisons between values of Γ determined from independent images suggests a typical uncertainty of $\sigma(\Gamma)/\Gamma \sim 0.1$.

Finally, we wish to take note of a possible ambiguity in the analysis of M 2-9. We have, for this source, taken the size of the disk to be $D \cong 6$ arcsec, corresponding to the maximum dimension of the central optical condensation (Kohoutek & Surdej 1980). This approach is consistent with the methodology applied for other sources in this study. The use of this value is also supported through measurements at millimetric wavelengths, which indicate the presence of a toroidal structure of precisely this dimension (Zweigle et al. 1997). It seems clear however that the source also possesses much smaller structures close to the central star(s); structures which are detectable at radio and optical wavelengths, and appear (at most) to be a few tenths of an arcsecond in size (Kwok et al. 1985; Balick et al. 1997). If these structures correspond to the true collimating disk, then the value of Γ would require increasing by at least an order of magnitude. This would, in turn, take the nebula well outside of the sequence for BPNe to be discussed in Sect. 3.

2.2. Radio properties and evolutionary sorting

Having established a reasonable corpus of values Γ, it is now of interest to evaluate the evolutionary status of the nebulae. One common way of doing this is to determine the radii R of the nebulae, on the supposition that older nebulae are intrinsically larger. The problem in this case, however, is how to determine reliable values for R. Whilst the angular dimensions of planetaries can be determined

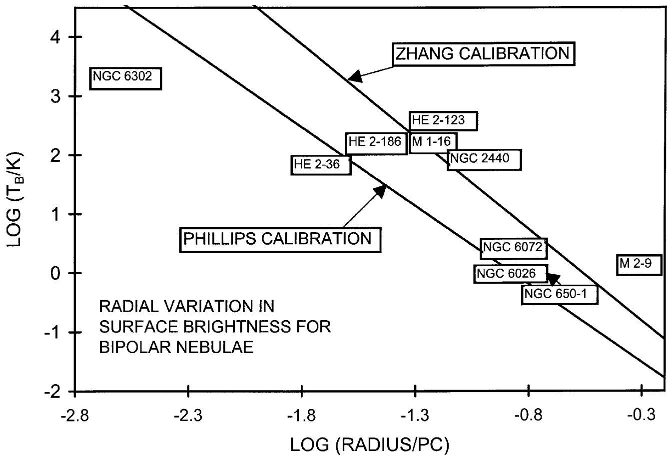

Fig. 1. Variation of brightness temperature with radius for bipolar nebulae at known distances. The two diagonal lines correspond to the calibrations of Zhang (1995) and Phillips (2001), determined using general populations of PNe.

to a tolerable level of accuracy (although bipolar sources are particularly problematic in this regard) their distances cannot. Similarly, whilst statistical distances are available for many of the sources in our list (van de Steene & Zijlstra 1994; Zhang 1995; Cahn et al. 1992; and etc.), none of these estimates can be regarded as secure.

We have therefore chosen to take note of an evolutionary trend in most (non-bipolar) nebulae, and apply this to the case of the BPNe. Specifically, it has been found that where nebular distances are evaluated through more-or-less reliable procedures (i.e. using trigonometric and spectroscopic distances, expansion distances and so forth), then the surface brightnesses of the sources appear to be monotonically related to their radii (e.g. Phillips 2001b; Zhang 1995; van de Steene & Zijlstra 1994). Put at its most simple, the younger sources have high brightness temperatures, and the older sources have low brightness temperatures. The deduced correlation between T_b (5 GHz) and R appears to be reasonably well defined.

It is important, on the other hand, to note that radio surface brightnesses in BPNe are not quite the same as in other planetary nebulae. Thus, whilst the radio and optical diameters of "normal" PNe are broadly comparable, and representative of the overall sizes of the sources, this is not the case with BPNe. On the contrary, much of the radio emission appears to come from the interiors of these sources, and is confined within regions which are very much smaller than the overall nebular dimensions (e.g. Phillips & Mampaso 1988).

It is likely, in brief, that the radio dimensions of most (if not all) of these sources refers to the central higher density, higher emission measure collimating regimes.

Nevertheless, and insofar as it can be assessed, it appears that the trend of T_b with R is similar for both BPNe and other planetary nebulae. This is illustrated in Fig. 1, where we have taken values of "known" (i.e. model independent) BPNe distances from papers by Zhang (1995) and Phillips (2001). It is clear from this that although distances remain uncertain; that the scatter is large; and that the total number of sources is restricted, there is nevertheless a close correspondence between the mean trends for other PNe (represented by the diagonal lines) and that for BPNe. It appears, in short, that the central collimating regimes of BPNe follow a closely similar relation to that noted for the generality of sources. This, in turn, suggests that a similar interpretation is relevant, and that lower surface brightness BPNe are also older.

We shall be assuming this in the proceeding analysis, whilst noting a possible alternative explanation later in Sect. 3.

Values of T_b have been assessed using radio interferometric source dimensions wherever available (i.e. in a little over 40% of the sources considered here; see Isaacman 1984; Phillips & Mampaso 1988; and Zijlstra et al. 1989). We have, otherwise, employed optical diameters based upon the listings of Cahn et al. (1992), Cahn & Kaler (1971) and others (see references in Table 1). Column 6 of Table 1 indicates the type of measurement employed (optical (O) and/or radio (R)). These optical values apply to the brightest central parts of the BPNe; to regions, that is, which are smaller than the overall source sizes, and similar to the areas mapped through radio interferometry. The optical and radio dimensions are therefore expected to be comparable. A comparison between source diameters θ(optical) measured in the visible, and those (θ(radio)) measured in the radio suggests that this is, in fact, broadly the case, although optical diameters are somewhat larger; we determine that $<\theta(\text{optical})>/<\theta(\text{radio})> \sim 1.30$. This may, in turn, imply that values of T_b based upon optical dimensions are typically 0.23 dex too small.

A further important factor to consider is that single dish and radio interferometric estimates of F(5 GHz) appear to differ in the mean, with interferometric measures being $\sim$12% lower where F(5 GHz) $>$ 10 mJy. Fainter sources appear to display even greater anomalies, with interferometric fluxes often being less than half as great as those measured using single dishes. This tendency has already been discussed in the literature, with Zijlstra et al. (1989) mentioning the possibility that single dish measures are affected by extraneous sources. It seems more likely, however, that single beam fluxes are reasonably accurate (Tylenda et al. 1992), and that interferometric results underestimate emission associated with lower spatial frequencies (e.g. emission arising from larger scale nebular structures, halos and etc.).

It transpires, in fact, that the use of single dish or interferometric results makes little difference to our results. However, we have preferred to use interferometric results where at all possible, since these are more closely related to the radio and optical dimensions used here.

It is therefore clear that the values of T_b are open to various uncertainties – use of single dish fluxes may artificially enhance temperatures in the brighter nebular structures, whilst the use of optical dimensions may systematically reduce them. It is possible, therefore, that errors in log(T_b) may be as high as $\sim$0.6 in individual cases, and differ markedly between the various sources. A bar indicating the likely mean error is illustrated in Fig. 2.

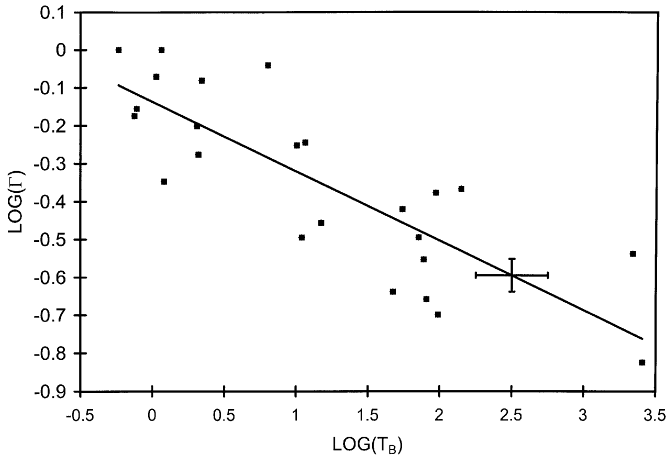

Fig. 2. Variation of the outflow aspect ratio Γ (see text for details) with 5 GHz surface brightness. The representative error bars indicate the mean levels of uncertainty that are likely to be associated with Γ and T_b.

3. The evolution of Γ

If one accepts that the radio surface brightnesses of BPNe vary with shell lifetime (see Sect. 2.2), then the variation of Γ with T_b may be interpreted as indicating the evolution of morphology with time. Such a variation is illustrated in Fig. 2 for the sources listed in Table 1.

However one interprets T_b (and alternative reasons for these trends will be discussed below), it is clear that there is a correlation between Γ and T_b, in the sense that Γ increases as T_b decreases. The least squares relation between these parameters is given through

$$\log\Gamma = -(0.183 \pm 0.032)\log T_b - (0.137 \pm 0.045). \quad (1)$$

The scatter about this trend is appreciable, with much of this arising from uncertainties in Γ and T_b (note the representative error bars in Fig. 2). It is very probable, therefore, that the intrinsic distribution would display an even higher correlation. Even given this, however, it is clear that the deduced least-squares trend appears to be highly significant, with gradients $b = \text{dlog}(\Gamma)/\text{dlog}(T_b)$ of order $\sim 6\sigma_b$. The correlation coefficient $r \cong 0.82$.

Where this trend is interpreted in evolutionary terms, then it would appear that bipolar sources become more "circularized" or "cylindrasized" with advancing age. The belt of material responsible for flow collimation swells in size relative to the lobal extremities – leading first to cylindrical structures such as IC 4406 and He 2-114, and then (possibly) more circular morphologies such as JnEr 1, where an essentially circular (low surface-brightness) shell contains two interior and much brighter condensations (e.g. Manchado et al. 1996). Such a scenario is somewhat different from that postulated by Balick (1987), in which it is presumed that the lobes increase in size relative to the central collimating disks. It would also be inconsistent with the ballistic models discussed in Sect. 1, whereby BPNe are assumed to expand self-similarly.

Much here depends, of course, upon how one interprets the variation in T_b, and upon whether the evolution in this parameter is as assumed in other PNe (see Sect. 2). Presuming however that this is the case, then the present results may be open to a variety of interpretations. It is perhaps relevant, for instance, to note that mass densities within the disks appear to be appreciable, and sufficient to retain molecular material in the face of fierce central star UV fluxes (e.g. Sahai et al. 1991; Bachiller et al. 1989; although the formation and maintenance of such molecules may also be aided through occasional high levels of nuclear dust extinction (e.g. Phillips 1984)). Such higher mass densities may moderate the level of disk acceleration, and result in lower initial velocities of expansion than are found in the lobes. Only later, with full ionization (and further expansion) of the disks, together with increasing central star ionizing fluxes, would velocities of expansion increase and lead to increasing values of Γ. Whilst the kinematics of disks are handled in extant modeling of bipolar evolution, much depends upon the density contrasts which are assumed; the nature of the assumed asphericities in the AGB envelopes; the presence or otherwise of neutral gas, dust, and gas clumping; the relative velocities of the exterior and interior winds, and so forth. In brief, the structures and properties of the exterior disks are essentially unknown, and may have a strong bearing upon nebular evolution, and the timescale over which this occurs.

Alternatively, or in addition, we note that the bubble driven lobes will likely decelerate as a result of cooling of the cavity gas; through disruption of the walls of the lobes, leading to escape of cavity material near the radial limits of the outflow; and from a species of snow-plow effect, whereby the lobes shovel-up increasing amounts of superwind material as they increase in size. These factors, too, might contribute to secularly increasing values of Γ. Some, if not all of these effects have been considered in extant evolutionary modeling – although here again, the precise degree to which they are important depends upon the (as yet uncertain) properties of bipolar winds. An example of this is cited below, where it is noted that prior collimation of the interior winds is at least plausible, if not yet confirmed.

It appears therefore that various mechanisms might, in principle, explain the evolutionary trends noted above, although whether they are in fact relevant depends strongly upon the wind properties of the BPNe. It would, in particular, be interesting to determine whether winds can be made to continue forming and shaping BPNe towards later phases of their evolution.

It would also be of interest to attempt to correlate Γ with the evolutionary time-scale t_exp, although such an analysis is open to considerable uncertainty. As a first approximation, however, and assuming a mean expansion velocity of $\sim$25 $\mathrm{km\,s^{-1}}$, we note that non-bipolar sources are expected to follow a trend

$$\log(t_\mathrm{exp}/\mathrm{yrs}) = -0.376 \log T_\mathrm{b} + 3.720 \quad (2)$$

where we have employed the variation between nebular radius R and T_b deduced by Phillips (2001b). It is likely that the relation for BPNe will be somewhat similar, apart from scaling factors of order a few. Given that this is so, then one anticipates that

$$\log \Gamma \cong 0.49 \log(t_\mathrm{exp}/\mathrm{yrs}) + 0.49 \log \chi - 1.95 \quad (3)$$

where χ is the fraction by which bipolar expansion velocities exceed those of non-BPNe. Inspection of the values summarized by Corradi & Schwarz (1995) suggests that $\chi \sim 6$.

Finally, we note that such trends between Γ and T_b may also arise through other means. Soker & Rappaport (2000), for instance, have suggested that narrow waisted BPNe (i.e. those with small values of Γ) result from the prior collimation of high velocity interior winds – those winds which are interacting with the aspherical AGB envelope, and are responsible for creating the observed bipolar lobes. It is suggested, in brief, that separate and smaller accretion disks may be funneling winds very close to the central emitting sources. Other (broader-waisted) BPNe are, on the other hand, capable of being formed with more spherically symmetric interior winds. The trend in Fig. 2 may therefore reflect the presence of differing formation mechanisms, with sources deriving from prior collimation of the interior winds appearing to be characterized by higher values of T_b.

Having said this, however, it is apparent that the trend of Γ with T_b appears to be reasonably continuous – there is no specific value of T_b at which discontinuities in Γ arise. This might, in turn, then require that central winds display a range of collimations, from very high levels where T_b is large, through to more modest levels where T_b is small.

4. Conclusions

We have pointed out that although the evolution in the morphologies of bipolar nebulae is extremely uncertain, and the province of educated guesses, one may nevertheless assess the possible evolution of such shells in a straightforward manner. Specifically, we note that the ratio Γ between the dimensions of the disks and lobes of BPNe appears to increase with decreasing 5 GHz brightness temperature T_b. Whilst the scatter between Γ and T_b is far from negligible, the statistical significance of the trend appears to be high. We therefore conclude that if older nebulae possess low values of T_b, then the collimating disks increase in size relative to the lobal extremities – perhaps leading, eventually, to almost spherical structures such as JnEr 1. This result appears to conflict with certain models of bipolar expansion, from which it would be expected that $\mathrm{d}\Gamma/\mathrm{d}T_\mathrm{b}$ would be constant, or may even be negative. Various reasons are provided as to why this may arise.

It is also noted that such trends may arise through alternative means. It is possible, for instance, that smaller values of Γ derive from pre- collimation of the interior winds – that the winds are collimated prior to their subsequent interaction with the AGB envelope. If this is true, then our results may suggest a broad continuum of central wind collimations, rather than there being two specific classes of nebulae, with and without collimation.

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