A&A 393, 1027–1033 (2002)
DOI: 10.1051/0004-6361:20020883

Astronomy & Astrophysics

The correlation between expansion velocity and morphology in planetary nebulae

J. P. Phillips*

Instituto de Astronomia y Meteorologia, Avenida Vallarta No. 2602, Col. Arcos Vallarta, C.P. 44130 Guadalajara, Jalisco, Mexico

Received 19 March 2002 / Accepted 11 June 2002

Abstract. It is usually accepted that the differing morphological classes of planetary nebulae (PNe) arise from progenitors of differing mass. The primary evidence for this derives from the differing galactic distributions of the sources. This, if true, would be expected to result in other differences as well, including variations in the kinematics of the nebular envelopes. We point out here that there is now sufficient evidence to determine that this is the case. We find that BRET-type sources (i.e. nebulae possessing "bipolar rotating episodic jets") have the lowest velocities of expansion $V_{\rm EXP}$, followed (in order of increasing velocity) by bipolar (BPNe), elliptical and circular nebulae. In addition to this, we find that the distributions $N(V_{\rm EXP})$ of circular, elliptical and bipolar sources are quite distinct, with BPNe being biased towards lower velocities, and circular sources distributed more uniformly. It appears therefore that bipolar outflows contain, within the same shells, evidence for both the highest and lowest velocities of expansion. Whilst the outer wings of these nebulae are expanding at ~175 km s^{-1}, the brighter parts of the shells (probably corresponding to equatorial toroids) have velocities of only ~18 km s^{-1}.

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

1. Introduction

It is well known that planetary nebulae display a broad range of morphologies, although most such sources may be categorised as circular, elliptical or bipolar (e.g. Manchado et al. 1996). These differences in appearance not only imply radical variations in structure, but may also reflect more deep-seated differences between the properties of these outflows. It is well established, for instance, that circular nebulae possess high mean scale heights z_0 above the galactic mid-plane, whilst bipolar sources have the lowest values of z_0 (e.g. Phillips 2001a). This difference in vertical distributions is likely to arise because of the differing masses of the nebular progenitors, with circular nebulae deriving from stars having $1 < M_{\rm PG}/M_\odot < 1.2$, and bipolar nebulae arising where $M_{\rm PG} > 2.3\ M_\odot$ (Phillips 2001b).

This difference in progenitor masses is likely to have consequences for the properties of both nebulae and central stars. Thus, higher mass progenitors lead to central stars having high luminosities and rates of evolution (e.g. Pottasch 1984), and to the ejection of higher mass shells. Lower progenitor masses probably result in a reverse suite of characteristics.

These differences in shell and central star characteristics are likely, in turn, to affect the observed kinematics of the shells. Thus, central star luminosity plays a leading role in determining the velocities and mass-loss rates of interior stellar winds (e.g. Pauldrach et al. 1988). Similarly, the degree to which shocked wind material drives the principal ionised shells is dependent upon the mass and density of the superwind outflow; the material which is ejected near the tip of the AGB. These latter quantities (the mass and density) are functions of the initial/final mass relation (Weidemann 1987; Jeffries 1997), and the velocity and pulsational characteristics of the mass loss process. They also depend, yet again, upon the masses of the progenitor stars.

One therefore anticipates that differing nebular morphologies may be associated with varying shell kinematics.

There have been relatively few studies of this correlation over the past few years, although Corradi & Schwarz (1995) have noted that bipolar sources appear to display higher velocities than other nebular subgroups. They find also that elliptical, irregular, point-symmetric and stelllar PNe have broadly similar velocities of expansion. We shall, in the following, analyse this question in rather more detail, taking full account of the range of morphological classification which has recently become available. We shall find, as a consequence, that there are significant differences between the kinematics of differing morphological groups. We shall also find that whilst the maximum velocities of BPNe are appreciable, the brighter parts of their shells are expanding much more slowly, at speeds which are typically less than those for elliptical and circular sources.

---

* e-mail: `jpp@udgserv.cencar.udg.mx`

2. The morphological and kinematic data base

There have been various attempts to determine the structures of planetary nebulae over the last forty or so years. However, recent advances in CCD imaging have now made it possible to classify a broader range of PNe than was previously conceivable. The accuracy of the classifications has also improved. Thus many of the sources previously identified as having elliptical structures (e.g. the nebulae classified as 2a and 3a by Hromov & Kohoutek 1968) can now be shown to be bipolar. Indeed, the sensitivity of current imaging has revealed that many more sources are bipolar than was previously appreciated.

In drawing up a concatenated list of PNe morphologies, it is therefore important to be aware of the weaknesses and strengths of previous classifications. We have included the type I sources Hromov & Kohoutek (1968), for instance, since they correlate well with round nebulae identified in other surveys. We have excluded, on the other hand, all of the type 2 and 3 classifications of these authors. We have used the listings of bipolar sources provided by Corradi & Schwarz (1995), Schwarz et al. (1992), Manchado et al. (1996) and Stanghellini et al. (1993). These, it is clear, represent the primary class of collimated outflow. However, many nebulae also show evidence for point-reflection symmetry (e.g. Schwarz et al. 1992), and periodic bipolar jets which rotate with angular velocities of $\sim 10^{-12}$ rad s^{-1} (the so-called BRETs; see Lopez 1997). These latter features often reside within what would otherwise be identified as round, elliptical and bipolar sources. Since BRETs and point reflection sources both contain evidence for jets, and have similar morphological characteristics, we have considered them as a separate morphological entity within the present analysis. So close appears the relation, indeed, that several of these nebulae (e.g. He2-186, IC 4634 and J320) have been classified as having both sets of characteristics. Lists of these nebulae are to be found in Lopez (1997), Stanghellini et al. (1993), Schwarz et al. (1992) and Manchado et al. (1996).

Given that most (88%) of these sources are designated as BRETs, we shall briefly categorise them as such in our future discussion. It will be found that they possess velocities of expansion which are distinct from other morphological subgroups.

The round and elliptical nebulae have been classified by Manchado et al. (1996), and also (as noted above) by Hromov & Kohoutek (1968). Stanghellini et al. (1993) have combined these together to form a single class of elliptical + round sources, which they designate E, with various subdivisions to take account of internal structures, halos and so forth. Most of the elliptical sources are likely to possess ellipsoidal structures, although whether they are prolate, oblate, a mixture of the two or neither, is still a matter for continuing debate (Phillips 2000). It is also likely that circular shells consist largely of spherical outflows. However, there is also a considerable leeway for "structural confusion". Thus, prolate shells viewed along their long axes, or oblate shells along their short axes may show a distinctly circular appearance. Similarly, bipolar nebulae may appear elliptical or circular when viewed along their polar axes (Phillips 2001c).

It is therefore probable that whilst the two primary morphological subtypes (circular and elliptical) correspond mostly to spherical and ellipsoidal sources, there may also be a significant cross-contamination of structures.

Finally, it should be emphasised that we have not used classifications which are driven by the need to explain particular models of nebular formation (viz. Soker 1997). All of the morphological schemes described above are based upon the observed structures alone. Similarly, it should be noted that Soker (1997) has defined circular nebulae in a rather more stringent way than other authors, and this would lead to a more restricted population than that employed here.

There are literally hundreds of PNe expansion velocities scattered throughout the literature, and these have been conveniently summarised on several occasions. Prior catalogues of expansion velocity include those of Sabbadin (1984) and Weinberger (1989). We have preferred to use the most comprehensive survey of this kind provided by Acker et al. (1992), in which [OIII] and [NII] expansion velocities are summarised for in excess of 280 nebulae. We have also used a few additional published measures where this proved possible.

We are able, using these results, to identify velocities of expansion for some 153 circular, elliptical, bipolar and BRET outflows. The mean trends in their velocities are the subject of the proceeding discussion.

Finally, it is important to note that the large majority of these expansion velocities correspond to the brightest parts of the nebular shells. The kinematics of fainter extensions and interior features may differ radically from these values, as we shall note later in the following section.

3. Trends in shell expansion velocities

The mean values of expansion velocity for differing nebular morphologies are summarised in Table 1, where we have included results determined using [OIII] and [NII] forbidden line transitions. The former, in general, correspond to the expansion velocities of the primary shell masses. Both ionisation modelling, and [OIII] mapping confirm that the [OIII] λ 4959+5007 Å transitions arise throughout the larger part of the nebular shells. By contrast, it is clear that [NII] λ 6548+6584 Å derives from the shell peripheries, where lower excitation transitions appear to be preferentially enhanced. This difference in shell locations leads to well-known differences in expansion velocities, and will be remarked upon later this section.

Velocities corresponding to the circular and elliptical sources combined include not only those sources classified separately as round and elliptical, but also the group of round + elliptical sources identified by Stanghellini et al. (1993; see Sect. 2).

By far the largest number of velocities corresponds to [OIII] measures, and mean trends of V_{EXP} ([OIII]) with morphological type are illustrated in Fig. 1. It is clear from this that there is a small but significant trend of $< V_{\mathrm{EXP}} >$ with nebular type. BRET type sources possess the lowest expansion velocities, followed by bipolar, elliptical and round nebulae (which have the highest mean velocities). The difference between the

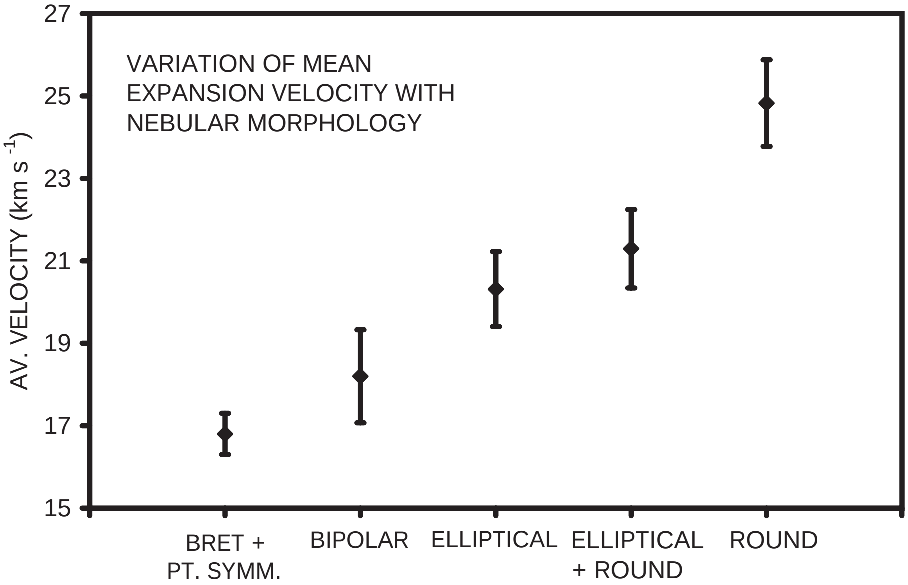

Fig. 1. The variation of mean [OIII] expansion velocities as a function of nebular type. The value corresponding to elliptical + round sources refers to the separate elliptical and round sources combined, together with the E-type nebulae of Stanghellini et al. (1993; a category which includes both species of source).

Table 1. Relation between expansion velocity and morphological type.

Source type	[OIII] expansion vel. (km s^{-1})	No. of sources	[NII] expansion vel. (km s^{-1})	No. of sources
Bret + Point sym.	16.80 ± 0.50	16	21.67 ± 0.58	6
Bipolar	18.20 ± 1.13	25	22.60 ± 1.09	15
Elliptical	20.31 ± 0.91	38	27.83 ± 1.48	15
Circular	24.83 ± 1.05	47	25.60 ± 0.97	15
Ellipt. + Circular	21.29 ± 0.95	112	25.67 ± 1.13	42
Irregular	24.97 ± 0.95	10	28.63 ± 0.63	4

extreme limits of this trend (i.e. between the BRET and circular sources) corresponds to a $\sim 7\sigma$ level of significance, whilst the velocity difference between bipolar and circular sources is of order $\Delta V_{\rm EXP} \sim 4.3\sigma$.

This tendency is interesting, in that it seems to follow a similar sequence to that noted for progenitor masses (see Sect. 1 and Phillips 2001b). Whilst we do not have much idea concerning the progenitor masses of BRET-type outflows, their present placing might suggest that they have the highest progenitor masses of all.

Such a trend is somewhat counter-intuitive, since it is well known that bipolar and BRET type sources are associated with high velocities of outflow. However, it is important to be aware that such envelopes consist of more that one component. Whilst it is true that we can detect high velocity jets and FLIERS in certain nebulae (see Balick et al. 1994 for a description of these latter features), and that the outer wings of BPNe possess velocities $V_{\rm EXP} \sim 175$ km s^{-1} (Corradi & Schwarz 1995), these do not correspond to the brightest portions of the shells, nor (in all probability) to the primary shell masses. It is the brightest sectors of the shells which are the subject of the present investigation. In the case of BPNe, therefore, it is likely that present expansion velocities refer to the interior equatorial portions of the superwind outflows, located in the higher surface brightness nuclei, whilst the velocities summarised by Corradi & Schwarz (1995) correspond to lower mass fragments at larger distances from the central stars (i.e. the exterior "claws" or "wings" of these outflows).

It therefore appears that BPNe are associated with an unusual suite of properties; they possess, within the same envelopes, what are among the lowest and highest of observed outflow velocities. On the other hand, whilst the toroids of these sources have among the lowest observed velocities, the total range $\Delta < V_{\rm EXP} >$ between the morphological classes is clearly quite modest ($\sim$8 km s^{-1}).

Finally, we have also included in Table 1 the mean velocities for the irregular sources of Stanghellini et al. (1993). There are not many of these, and the statistics are the least secure of all of these groups, but it appears that values $< V_{\rm EXP}([{\rm OIII}]) >$ are comparable to those for circular sources.

These small (but significant) differences in $< V_{\rm EXP}([{\rm OIII}]) >$ mask what are really quite appreciable differences in the distributions of these sources. We have illustrated these distributions in Fig. 2 for the cases of circular, elliptical, and bipolar

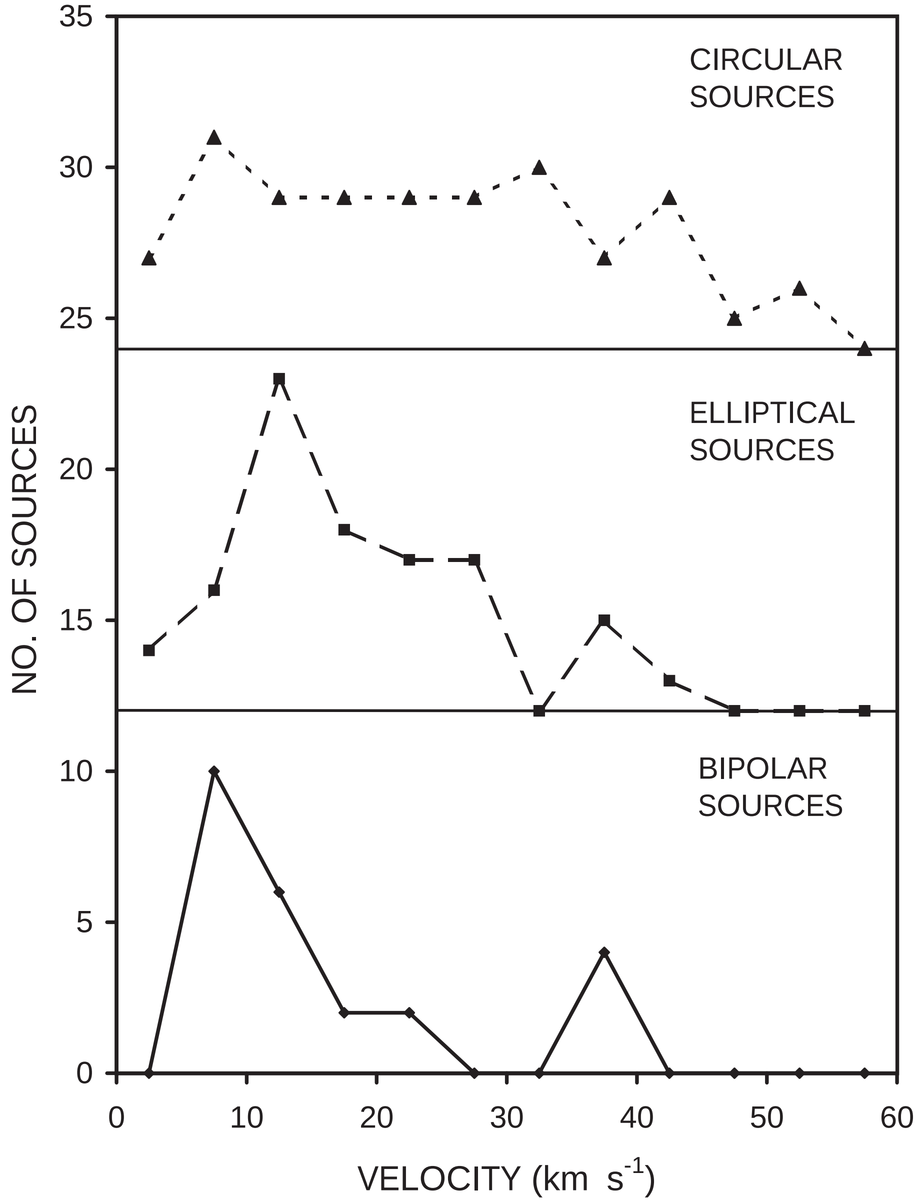

Fig. 2. The distribution of sources with respect to [OIII] expansion velocity for three types of nebular shell. Note the peaking of bipolar sources towards lower velocities, and the relatively uniform distribution of circular sources. Elliptical nebulae appear to possess an intermediate distribution.

nebulae. It is clear from these that BPNe are strongly peaked towards lower values of $V_{\rm EXP}$, whereas circular sources are more uniformly distributed between 8 and 42 km s^{-1}. The apparent deficit of nebulae having $V_{\rm EXP} < 5$ km s^{-1} reflects the difficulties of measuring velocities in this regime.

Elliptical sources appear to display a trend which is somewhat intermediate between those for circular PNe and the bipolar outflows.

There is therefore a strong difference in the biases demonstrated by differing morphological classes, confirming the differences one would expect as a result of differing progenitor masses.

It should be emphasised however that certain of these trends may be affected by morphological cross-contamination (see Sect. 2). Where velocity is proportional to radius, as appears to be the case for many of these sources (see discussion later this section), then circular nebulae may contain a proportion of high and/or low velocity ellipsoidal structures, depending upon whether the outflows are prolate and/or oblate. By contrast, the under-representation of these latter sources among those having elliptical morphologies may lead to a bias towards high and/or low velocities of expansion in these nebulae as well.

Bipolar nebulae may also be confused with circular or elliptical PNe, as noted in Sect. 2. Where one supposes the toroids of BPNe to be expanding most rapidly in a direction perpendicular to their axes of symmetry, then this would lead to a reduction in the proportion of low velocity BPNe. It would also imply some increase in the proportions of elliptical and circular sources having low velocities of expansion.

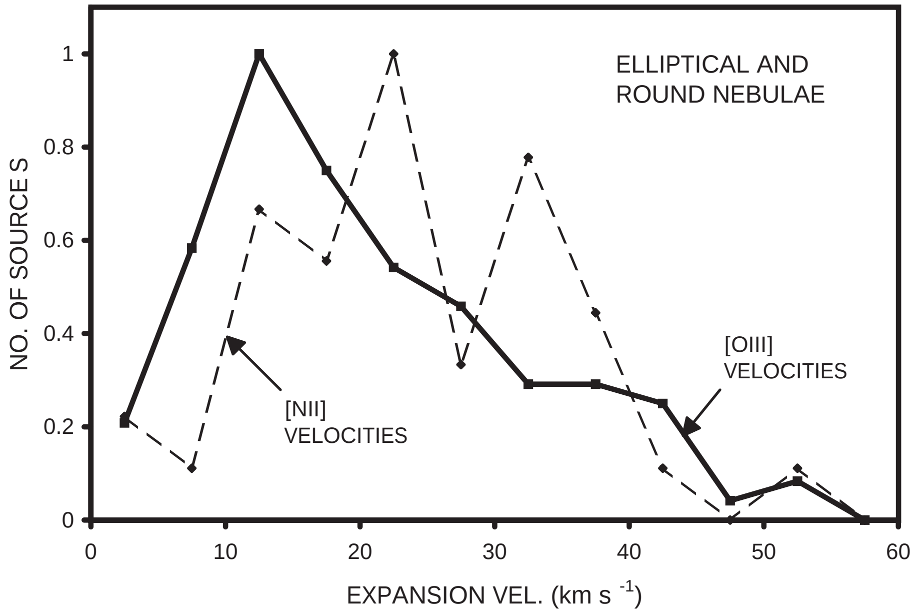

Fig. 3. Comparison between the [NII] and [OIII] velocity distributions of round + elliptical sources. It may be noted that the trend for [NII] is based on fewer sources, and is consequently much more noisy. The curves are normalised along the vertical axis.

None of these trends are likely to be crucial in determining the trends noted in Fig. 2, however. Thus prolate or oblate structures need to be rather precisely aligned before they give rise to circular morphologies, and the number of such cases is probably small. Similarly, although the degree of contamination may be greater in the case of BPNe, it is likely that they represent only ~13% of all circular and elliptical sources (e.g. Phillips 2001b,c).

Finally, we note that the [NII] velocities in Table 1 are larger than those evaluated for [OIII]. The total number of sources is also much smaller, which leads less secure overall statistics. It is nevertheless clear that there remains a significant disparity in $V_{\rm EXP}$ ([NII]) between BRET and bipolar flows on the one hand, and circular and elliptical sources on the other.

This increase in velocities ($V_{\rm EXP}$ ([NII]) over $V_{\rm EXP}$ ([OIII])) inevitably affects distribution curves such as those illustrated in Fig. 2, although it is impossible to undertake a detailed analysis of such changes given the restricted nature of the data to hand. Some idea of the changes involved may however be noted from Fig. 3, where we compare [OIII] and [NII] distributions for the elliptical and circular sources combined. Although the [NII] trend is extremely noisy, the bodily shift to higher values of $V_{\rm EXP}$ is clearly apparent.

We have already noted (see Sect. 2) that [NII] and [OIII] expansion velocities refer to differing sectors of the shells. The larger values of $V_{\rm EXP}$ ([NII]) (arising at the shell peripheries) can therefore be seen as implying an increase in velocity with radius; a trend which been previously noted for circular and elliptical envelopes (Weedman 1968; Wilson 1958), and also for the case of BPNe (Corradi et al. 2001; Corradi & Schwarz 1993a; Corradi & Schwarz 1993b; Redman et al. 2000).

It is clear, in summary, that the range of data currently available enables us to determine that there are significant differences in velocity between the various nebular morphologies. This is another datum to add to the evidence of differing galactic distributions, shell structures, differences in shell abundances (e.g. Torres-Peimbert & Peimbert 1997) and so forth, all of which point to the fact that individual morphologies represent quite distinct types of source. Such results also act as a further challenge to theoretical modelling of the outflows, in that it is necessary to explain why bipolar toroids are biased towards the lower end of the velocity range, whilst the velocity distribution of circular sources is much more uniform.

Finally, we note that some of the wide range in velocities $V_{\rm EXP}$ noted in Fig. 2 probably arises as a result of kinematic evolution. It is not our brief to investigate the time evolution of $V_{\rm EXP}$, and this for various reasons. In the first place, such analyses have already been undertaken in several previous publications, with varying results and conclusions (see e.g. Bohuski & Smith 1974; Robertson et al. 1982; Sabbadin et al. 1984; Weinberger 1989; Bianchini 1992). Secondly, reliable distances are known to only a few of the nebulae considered here. Nevertheless, and insofar as statistical distances can be trusted, it is possible to determine whether there is any likelihood of such evolution.

We have determined the variation of $V_{\rm EXP}$ ([OIII]) with nebular radius R using the statistical distances of Phillips (2002a), and angular sizes taken from Acker et al. (1992). The results are illustrated in Fig. 4 for circular and elliptical PNe. Because the differing statistical scales are linearly related (Phillips 2002b), one expects very closely similar trends to arise for the distances of Zhang (1995), van de Steene & Zijlstra (1994), Cahn et al. (1992) and Daub (1982). The solid curve corresponds to a second order least squares polynomial fit.

It is clear from this that $V_{\rm EXP}$([OIII]) is probably variable. It appears that velocities increase by ~0.3 dex for a change of ~1.3 orders of magnitude in R. Whilst some of the observed range in $V_{\rm EXP}$ may therefore be due to intrinsic differences between nebulae at similar stages of evolution, a certain element of this may arise through evolution in $V_{\rm EXP}$, and the fact that

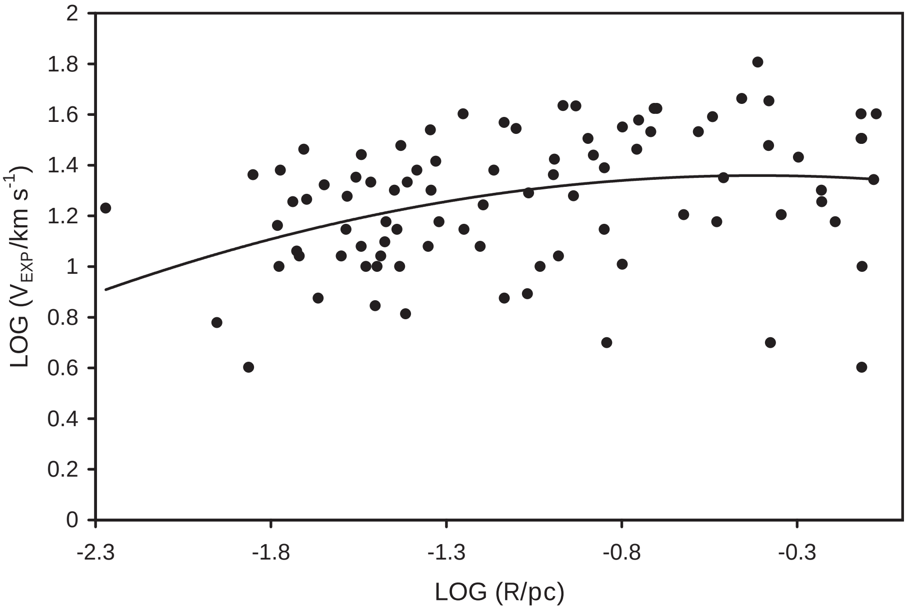

Fig. 4. The variation of [OIII] velocity with nebular radius for sources having circular and elliptical morphologies. There appears to be a trend for increasing velocities towards larger radii. The solid curve represents a second order polynomial least-squares fit.

mean shell velocities are higher in larger (more evolved) nebulae than in the case of younger outflows.

It cannot be emphasised too strongly, however, that whilst the trends in Fig. 4 are probably real, they are only indicative. The random and systematic errors in distance may be appreciable, and sufficient to wash out the finer details of any variation.

4. Conclusions

It is usually accepted that the various morphological classes of PNe arise from progenitors having differing masses. This, if true, might be expected to result in differing velocities of shell outflow. There have heretofore, however, been relatively few attempts to determine whether this is the case.

We have, in the present case, drawn together a wide range of estimated morphological types, and correlated these with expansion velocities determined using [NII] and [OIII] forbidden line transitions.

The results show that there is a modest but significant difference in the mean expansion velocities of differing nebular shells. Mean [OIII] velocities, in particular, appear to take their lowest values for BRET type sources, followed (in sequence of increasing $< V_{EXP}([OIII]) >$) by bipolar, elliptical and circular outflows. In addition to this, the distributions $N(V_{EXP})$ of sources with respect to velocity are also quite distinct for the differing structures. Bipolar sources are strongly peaked towards lower velocities, whilst the distribution of circular sources is uniform between $V_{EXP} \sim 8$ and 42 km s^{-1}. Elliptical sources appear to have a somewhat intermediate distribution. Although these trends may be somewhat affected by nebular orientation, and the confusion this causes between ellipsoidal, spherical and bipolar outflows, we believe that such influences are likely to be minor.

It is noted that bipolar envelopes are exceptional in showing evidence for both the lowest and highest velocities of expansion.

Finally, it is suggested that the broad range of velocities noted in PNe may, in part, arise from the evolution of V_{EXP} with time.

References

Acker, A., Ochsenbein, F., Stenholm, B., et al. 1992, Strasbourg-ESO Catalogue of Planetary nebulae (ESO: Garching)
Balick, B., Rugers, M., Terzian, Y., & Chengalur, J. 1994, ApJ, 411, 778
Bianchini, L. 1992, A&A, 260, 314
Bohuski, T. J., & Smith, M.G. 1974, ApJ, 193, 197
Cahn, J. H., Kaler, J. B., & Stanghellini, L. 1992, A&AS, 94, 399
Corradi, R. L. M., Livio, M., Balick, B., Munari, U., & Schwarz, H. E. 2001, ApJ, 553, 211
Corradi, R. L. M., & Schwarz, H. E. 1993a, A&A, 269, 462
Corradi, R. L. M., & Schwarz, H. E. 1993b, A&A, 273, 247
Corradi, R. L. M., & Schwarz, H. E. 1995, A&A, 293, 871
Daub, C. T. 1982, ApJ, 260, 612
Hromov, G. S., & Kohoutek, L. 1968, BAC, 19, 1
Jeffries, R. D. 1997, MNRAS, 288, 583
Lopez, J. A. 1997, in Proc. of Symp. 180 of the IAU, Planetary Nebulae, ed. H. J. Habing, & H. J. G. L. M. Lamers (Kluwer: Dordercht), 197
Manchado, A., Guerrero, M. A., Stanghellini, L., & Serra-Ricart, M. 1996, The IAC Morphological Catalog of Northern Planetary nebulae (IAC, Spain)
Pauldrach, A., Puls, J., Kudritzki, R. P., Mendez, R. H., & Heap, S. R. 1988, A&A, 207, 123
Phillips, J. P. 2000, A&A, 358, 1049
Phillips, J. P. 2001a, PASP, 113, 846
Phillips, J. P. 2001b, MNRAS, 326, 1041
Phillips, J. P. 2001c, PASP, 113, 846
Phillips, J. P. 2002a, ApJS 139, 199

Phillips, J. P. 2002b, Astron. Nacht., in press
Pottasch, S. R. 1984, Planetary Nebulae (Dordrecht: Reidel)
Redman, M. P., O'Connor, J. A., Holloway, A. J., Bryce, M., & Meaburn, J. 2000, MNRAS, 312, L23
Robertson, G. J., Reay, N. K., & Atherton, P. D. 1982, MNRAS, 199, 649
Sabbadin, F., 1984, A&AS, 58, 273
Sabbadin, F., Gratton, R. G., Bianchini, A., & Ortolani, S. 1984, A&A, 136, 181
Schwarz, H. E., Corradi, R. L. M., & Melnick, J. 1992, A&AS 96, 23
Soker, N. 1997, ApJS, 112, 487
Stanghellini, L., Corradi, R. L. M., & Schwarz, H. E. 1993, A&A, 279, 521
Torres-Peimbert, S., & Peimbert, M. 1997, in Planetary Nebulae, ed. H. J. Habing, & H. J. G. L. M. Lamers (Kluwer: Dordercht), Proc. of Symp. 180 of the IAU, 175
van de Steene, G. C., & Zijlstra, A. A. 1994, A&A, 293, 541
Weedman, D. W. 1968, ApJ, 153, 49
Weidemann, V. 1987, A&A, 188, 74
Weinberger, R. 1989, A&AS, 78, 301
Wilson, O. C. 1958, Rev. Mod. Phys., 30, 1025
Zhang, C. Y. 1995, ApJS, 98, 659