Planetary Nebulae in our Galaxy and Beyond
Proceedings IAU Symposium No. 234, 2006
M. J. Barlow & R. H. Méndez, eds.

doi:10.1017/S1743921306003097

Macrostructures and microstructures in planetary nebulae

Romano L.M. Corradi[1,2]

[1]Isaac Newton Group of Telescopes, Ap. de Correos 321, 38700 Sta. Cruz de la Palma, Spain
email: rcorradi@ing.iac.es

[2]Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

Abstract. PNe display a variety of large and small-scale structures which have been the object of a large number of observational and theoretical studies in the last two decades. This review contains a brief description of the different observational approaches used to determine the structure of PNe, and some critical discussion about the morphological components whose formation we believe we understand, and those which instead are still poorly understood.

Keywords. planetary nebulae: general. ISM: kinematics and dynamics

---

1. Introduction

One of the richest fields of work concerning PNe is the study of their internal structure. The advent of high sensitivity detectors like the CCDs in the 80's, and later the high spatial resolution provided by the HST, have unveiled an amazing variety of morphological components which have been the object of several hundred articles which appeared in the literature in this period. This makes it a hard job to try to summarise in a few pages all the observational aspects discussed in recent years; in the following, I will focus on the main results from *optical observations* of PNe obtained since the last IAU Symposium in Canberra, as other contributions in this conference have highlighted the basic information that can be gained at other wavelengths, or the importance of studying the transition phase from the AGB to the PN (the so-called post-AGB/proto-PN stage). An excellent review of the subject can be also found in Balick & Frank (2002).

2. Determining the intrinsic structure of PNe

2.1. *What we see in the sky*

As in other branches of science, the first step to understand the structure of PNe was mainly taxonomic. Based on their appearance in the large datasets of optical images which became available in the 90's, several classification schemes dividing PNe into different morphological types were proposed. Table 1 lists the main imaging surveys done so far, which add up to many hundreds of high-quality narrowband images obtained by different groups. In this context, one should also mention the compilation of a large fraction of these images into a jpeg image atlas that B. Balick is producing (see his contribution to this conference). These image catalogues have been the basis for several classification schemes, like those by Chu *et al.* (1987), Balick (1987), Schwarz *et al.* (1993) and Manchado *et al.* (1996). While the principles and details vary from scheme to scheme, most of them are based on a primary classification of the overall nebular shape in terms of an increasing asphericity (from round, to elliptical, up to bipolar objects with narrow waists), adding as a secondary characteristic the presence of multiple shells and small-scale structures (like point-symmetrical features or highly collimated jet-like structures).

Table 1. Collections of narrowband optical images of PNe

Reference	N. of PNe
Chu *et al.* 1987	76
Balick 1987	50
Schwarz *et al.* 1992	255
Manchado *et al.* 1996	243
Górny *et al.* 1999	101
Corradi *et al.* 2003b	50
HST archive	>50
MASH (Parker, this book)	∼1000
IPHAS (Viironen *et al.* & Sabin *et al.*, this book)	a few 10^2?

Nowadays, in the light of modern theories of PN evolution, there is a certain tendency to separate round, elliptical PNe, and mildly bipolar nebulae, whose moderate asphericity can be explained in several ways without requiring a highly peculiar evolution of their progenitors, from strongly asymmetrical PNe (with narrow waist and thin bipolar lobes, often accompanied by point-symmetry and sometimes jets), which seem difficult to produce without invoking additional sources of energy, momentum, or winds probably related to stellar companions and associated accretion discs.

These classification schemes were used to find a number of correlations between morphology, the physico–chemical properties of the nebulae, and the mass of their progenitor stars. The main result is that the class of bipolar PNe is the product of more massive progenitors than the PN types corresponding to more spherical nebulae. This was first found by Greig (1972) and Zuckerman & Gatley (1988) based on small samples of objects, and confirmed by Corradi & Schwarz (1995) by means of an extensive analysis of 400 PNe with CCD images. The result is mainly based on the Galactic distribution (and in particular the scale height) of the different morphological types, but is also supported by a number of other properties (see Corradi & Schwarz 1995). These results were refined by further studies (e.g. Stanghellini *et al.* 2002, and the almost countless number of papers by J.P. Phillips, see for instance Phillips 2005 and references therein). The evidence for an increasing collimation of the outflows with the increasing mass of the progenitors is a basic result that should always be considered when trying to explain the origin of asphericity in PNe. Defining exactly the range of the progenitor masses of each morphological class is however a difficult task, owing to the present limited knowledge of distances of PNe, but also because there is still some controversy about the distribution of main-sequence stars in the Galactic disc.

2.2. *Adding Doppler-shift velocities: spatiokinematical modeling of the nebulae*

Obtaining long-slit (or 2-D) echelle spectroscopy of the nebulae at different positions is a powerful method to recover the intrinsic 3-D geometry of the nebulae and disentangle the contribution of the different morphological components. Such a spatiokinematical modeling has been done by many groups since the pioneering work of Weedman (1967) or the more detailed studies of Sabbadin (e.g. Sabbadin & Hamzaoglu 1981) and Solf (e.g. Solf & Ulrich 1985). Here, I outline different approaches followed by different groups:

(*a*) The most widespread procedure is to fit the observed image and long-slit spectra (or position-velocity plots extracted from the latter) of a nebula with a geometrical description properly tilted in the plane of the sky. Often an analytical shape is used, and axisymmetry is assumed together with purely radial gas motions and a Hubble-like velocity law ($V_{exp} \propto r$, where r is the distance of a gas particle from the central star).

The shape, orientation, and kinematic parameters are then obtained by fitting the data (generally by eye) with the spatiokinematical description. See the contribution of A. Lopez in this book for some examples.

(*b*) A slightly different approach is the "tomographic" method by Sabbadin and collaborators (e.g. Sabbadin *et al.* 2005). In this case, the velocity law (V_{exp} as a function of r) is not assumed, but is instead measured using the information provided by various ions, which are located at different distances from the central star. Thus the method requires obtaining echelle, long-slit spectra of many ions and at different position angles, and takes advantage of the wealth of information contained in such data. Sabbadin and collaborators propose two different ways of determining the velocity law, but the basic idea is to combine 1) the Doppler split of emission lines along the line of sight through the central star, which provides the true expansion velocity for each ion bypassing the uncertainty due to the projection effects, with 2) the analysis, in the spectra, of the spatial profiles of ions emitting at the systemic velocity of the nebula, and hence lying in the plane of the sky (i.e. with no projection effects in their distance from the centre). Once the intrinsic velocity law is recovered (which can be different for each distinct morphological component), and assumed to apply at all radii, then the reconstruction of the 3-D shape of the nebula in each ion and at each position angle is uniquely defined if purely radial motions are also assumed.

(*c*) A more physical approach, but presently limited to nearly spherical PNe, is the direct comparison of the images and kinematical data with state-of-the-art radiative-hydrodynamical simulations, as for instance done by Schönberner *et al.* (2005a). The important information that can be extracted in this way will be outlined in Sect. 3.

It should be noted that in almost all aspherical PNe a Hubble-law seems to be a good description of the variation of the expansion velocity with distance from the central star. In case (a) above, such a law is assumed and then generally found to be fully consistent with the data. In case (b), it is measured directly (but usually within a limited range of distances) using different ions.

2.3. *Two more dimensions in position-velocity space: the expansion in the sky*

The high spatial resolution available nowadays with some instruments (primarily the HST) allows one to add another extremely valuable piece of information, which is the expansion of the nebula in the plane of the sky. This can be obtained by images spaced a few years apart at the HST resolution for relatively nearby nebulae (1 kpc or so). The 'tangential' velocities provide unique information about the dynamical evolution of the nebulae, revealing their growth behaviour which is expected to be different depending on the shaping mechanism (e.g. ballistic vs. winds-heated, winds-blown or magnetically driven). In many (most?) cases, the observed expansion in the plane of the sky would trace the expansion of the *shock fronts* which are believed to drive the nebular evolution; this information is fully complementary with that concerning the expansion of *matter* from Doppler-shift measurements. And, not least, measuring the expansion in the plane of the sky of a nebula provides an estimate of the distance via its expansion parallax.

So far, the potentiality of "movies" from multi-epoch imaging has been demonstrated only in few works (e.g. Balick & Hajian 2004, Santander-Garcia *et al.* in this book), but I expect that along this way a number of important results will be obtained in the future.

3. Some discussion on round/elliptical PNe

Modern radiative-hydrodynamical simulations of PNe (e.g. Perinotto *et al.* 2004a, Schönberner *et al.* 2005a) can be compared in detail with real nebulae with relatively

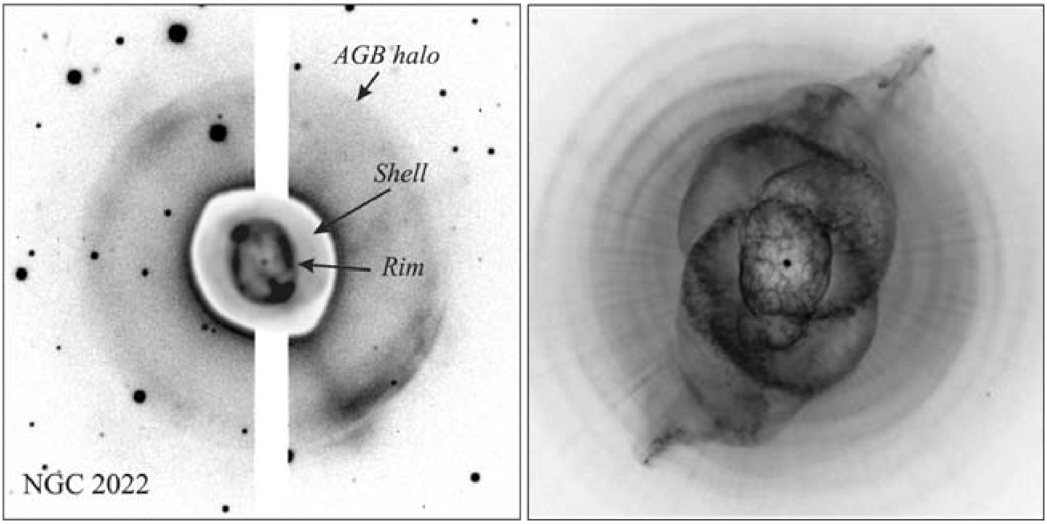

Figure 1. LEFT: [O III] image of NGC 2022 (Corradi *et al.* 2003b). The picture is a combination of a short image (inner inset) and a deep one (full picture). The vertical band corresponds to the gap between the two-CCD mosaic of the imager. RIGHT: [O II]+[N II] ACS image of NGC 6543 (STScI-PRC2004-27). Note the system of rings and the radial strikes.

simple morphologies, like round and elliptical PNe. In fact, we are now probably in the situation that, for the first time in this field, observations are behind theory, in the sense that models have reached such a degree of sophistication that better observational data, specifically tailored to test the models' predictions, are needed. In general, the predictions of the models show a remarkable agreement with the observations, and we can say that we are not far from a good understanding of the basic large-scale structures found in round/elliptical PNe. In the following, I will outline the main conclusions, while further details and a more complete list of references can be found in the contributions by Steffen and Schönberner in this volume.

3.1. *What we think we understand: rims, shells and haloes*

Fig. 1, left, shows the image of NGC 2022, which can be used as an example of how a "well-behaved" PN would appear at intermediate stages of its evolution (i.e. not too young, not too old). The abovementioned models explain quite convincingly the nature of the three main components observed in such a nebula, which are:

- a bright **rim**. This is the result of the compression by the inner hot bubble, which in turn is created by the action of the fast post-AGB wind on the older AGB wind. Rims are generally thin, and their expansion is mainly driven by the balance between the thermal pressure of the shocked fast stellar wind and the ambient matter;
- a thick **shell**, which is the result of the density redistribution caused by the shock created by the ionization front. The expansion of this shock is controlled by the sound speed and the density gradient of the AGB wind;
- an **AGB halo**. These extended shells have a surface brightness 10^{-3}–10^{-4} that of the rims. They are composed of ionized AGB matter, and their limb brightened edge is believed to be the signature of the last thermal pulse suffered by the progenitor star on the AGB. An extensive observational study of haloes has been done by Corradi *et al.* (2003), who showed that they are common in PNe, having been found in 60% of the nebulae for which proper deep imaging was obtained.

Note that some of the observed haloes are not genuine AGB haloes (and should not be confused with them), but instead *recombination haloes*, i.e. limb-brightened shells set up by recombination when the luminosity of the central star drops in its post-AGB evolution (Tylenda 1986, Corradi *et al.* 2000).
In addition, a number of AGB haloes have distorted shapes which can be accounted by interaction with the ISM medium. This phenomenon is covered by the contribution by E. Villaver in this book.

I would like to stress here the importance of the study of shells and haloes, as it is there (and not in the rims) where the basic information about the mass loss history and evolution of their central stars is contained. For instance, the sizes of the shells and their expansion velocities provide a much better measure than rims of the post-AGB age of the central stars and of the distance via the expansion parallax method (Schönberner *et al.* 2005b). As the expansion speed of the shells is related to the density slope of the AGB halo, which in turn depends on the evolution of the AGB mass loss rate, a combined study of the shell velocity and the surface brightness profile of the halo can allow determination of the evolution of mass loss at the end of the AGB. In addition, the kinematic ages of the halo tell us how long ago the last AGB thermal pulse has occurred.

3.2. *Something we do not understand: rings in the haloes*

Originally not predicted by theory, the existence of concentric rings and arcs in the inner regions of PN haloes was first reported in four PNe by Terzian & Hajian (2000). See Fig. 1, right, for an example. Corradi *et al.* (2004) have shown that these structures are rather common, the detection rate being $> 35\%$. This indicates that a large fraction of PN progenitors experience mass loss modulation with timescales of 10^2–10^3 yrs during the last $1–2 \times 10^4$ yrs of their AGB evolution. While several models have been proposed to explain these structures (see discussion in Corradi *et al.* 2004), we do not have a satisfactory comprehension of the phenomenon which, given its frequency, is likely to be relevant for a better understanding of the physics of mass loss at the very end of the AGB.

4. Highly collimated nebulae: bipolar and point-symmetric PNe

Highly collimated PNe have probably contributed a lot to making this field of work "fashionable" in the last 20 years, mainly because of their extreme, striking departure from the isotropic mode which has characterized all the evolution of their (putative) progenitor stars. Their relevance for understanding similar phenomena in other astrophysical objects (like massive stars, SN, young stars, novae, AGN nuclei) has also contributed to the effort which has been dedicated to study these nebulae. In spite of that, we are still far from proving, both observationally and theoretically, which are the most relevant processes at work to produce the collimation of the outflows.

The class of bipolar PNe contains some 15% of the known Galactic PNe. On the top of the bi-lobal overall structure of these objects, in the last years it has become more and more evident that point-symmetrical structures, along the walls of the lobes or in isolated small-scale structures, are often also present. This observational evidence and the existing models (see the contributions by G. Garcia-Segura and A. Frank in this book) points to the combined action of magnetic fields, (precessing? warped?) accretion disc winds, and possibly rotation, to produce the articulated geometry and dynamics observed. It seems that only a combination of these processes can account for the presence of multiple outflows with different axes and degrees of collimation found in certain objects like for instance Mz 3 (Santander-García *et al.* 2004, Guerrero *et al.* 2004).

One property common to most bipolar PNe (with few notable exceptions) is that they show rather simple velocity fields that can be described by a "Hubble law" ($V_{exp} \propto r$, see also Sect. 2.2). This self-similar expansion with apparently 'ballistic' motions suggests that the nebulae have already reached an asymptotic shape (as predicted under certain conditions by the hydrodynamical theories), or in other words that they are produced by some kind of explosive event that quickly shapes the nebulae with, afterwards, the gas continuing outward under its own inertia. More discussion on this basic dynamical property can be found in Corradi *et al.* (2004).

Another important point to keep in mind is the possible *misclassification* of bipolar nebulae. How many objects classified as bipolar PNe are not genuine PNe? Some well-studied objects like M 2-9, Mz 3, OH231.8+04.2, He 2-25, and M 1-91, have for instance been suggested to host a symbiotic system at their centre, and thus they would not be genuine PNe. Interacting binaries, in general, can at some point of their evolution create outflows which might be misclassified as PNe on a pure morphological basis. Only a thorough study of their central stars (often difficult to do), or indirect evidences like a very low mass of the ejecta, can help to minimise misclassification. An extensive discussion can be found in the proceedings book by Corradi *et al.* (2003a).

Finally, in spite of some increasing observational evidence for multiple bipolar outflows in well developed PNe, still there is a severe discrepancy with what is observed in proto-PNe and young-PNe, where multiple collimated outflows are much more common (if not the rule), and where round and elliptical nebulae are rarely found. A strong effort should be made in order to understand the origin of this discrepancy between the relative frequency of morphological types in proto-PNe compared to what is observed in more evolved PNe.

5. Microstructures

5.1. *Generalised clumpiness*

The most striking case of a clumpy structure that is probably extended to the whole body of the nebula is NGC 7293 (the Helix). Its case and a convincing explanation of the formation of its widespread system of cometary globules is presented in the contribution by P. Huggins in this book.

How frequent such a generalised clumpiness is in PNe is not known, but certainly there is direct evidence for clumpiness in a number of other PNe. O' Dell *et al.* (2002) studied at high spatial resolution 5 nearby PNe and suggested a progression with age of knots, evolving from dark lanes/knots in younger nebulae to well-defined knots with photoionized cusps facing the central star in more evolved ones. Together with the location of these features, this suggests that knots form at a relatively early stage during the expansion of the ionization front, and then they are left behind where they are subjected to sculpting by the radiation field and winds from the central star.

Evidence for clumpiness is also provided by the radial strikes observed in the shells or haloes of many PNe, like NGC 6543, IC 2165, NGC 40, NGC 2438, NGC 2867, NGC 3918, NGC 6337, NGC 7009, NGC 7662 (see Fig. 1, right, and the images of these nebulae in Corradi *et al.* 2003b and Corradi *et al.* 2004). These strikes (which surprisingly are rarely mentioned in the literature) can be explained as being ionization shadows behind dense clumps, i.e. behind regions opaque to stellar photons, which are ionized by soft, diffuse UV recombination emission from ambient gas (see also G. Garcia-Segura, this book).

5.2. *"Isolated" microstructures (LISs)*

The wide variety of Low-Ionization small-scale Structures (LISs) observed in PNe is illustrated and discussed by Gonçalves *et al.* (2001), who estimated that some 10% of

Galactic PNe of any morphological type have LISs. Some LISs are found inside the main bodies of the nebulae, some outside, some show a definite symmetry, some are more isolated, some expand at a considerably higher velocity than the ambient gas (FLIERs), while other ones seem to share the expansion pattern of the large-scale structure in which they are immersed. This makes it difficult to think of a single scenario to explain the origin of all LISs; it is more likely that different processes are involved. The observational works in the last 5 years have added the following new results to the puzzle:

- the main excitation mechanism of most LISs is photoionization, although, even if shocks are there, the post-shock layer would not be resolved even at the HST resolution (Perinotto *et al.* 2004b). One exception is K 4-47, whose high-velocity knots have been reproduced satisfactorily using shock models (Gonçalves *et al.* 2004a);
- standard optical line ratios indicate that LISs generally display only a moderate increase of electron density with respect to the ambient medium, and their electron temperature is basically the same (Gonçalves *et al.* 2004b, Perinotto *et al.* 2004b). However, high density regions might be "hidden" by collisional quenching of the bright forbidden lines commonly used for density and temperature diagnostics (Perinotto *et al.* 2004b);
- the former suggestion that some LISs (especially FLIERs) might be significantly nitrogen enriched compared to the main bodies of the nebulae (e.g. Balick *et al.* 1994), seems to be strongly weakened and maybe even ruled out by new detailed 3-D photoionization modeling, as shown for NGC 7009 by Gonçalves *et al.* (2006). The bottom line here is that for such small and isolated structures it is extremely important to model correctly the shape of the local radiation field and to take into account processes like charge-exchange reactions (see also Perinotto *et al.* 2004b); for these kind of features, the standard analysis using the *ionization correction factor* method is not applicable.

6. Summary, questions and perspectives

Summarising, it appears that we globally understand the origin of the multiple shells in round/elliptical PNe as the result of complex density waves created by radiation and winds interaction. Detailed modeling coupled to high-quality observations can provide important insights into the mass loss history in the latest AGB evolution. A further theoretical effort is needed to explain rings and arcs in the inner regions of PN haloes, a common feature indicating that rapid mass loss modulation occurs in the last 10^4 years of the AGB. Clumpiness may also play an important role in many PNe.

Bipolar PNe seem to be produced in eruptive events, leading quickly to Hubble-like flows. Because of their dense and bright nebular cores, large dust extinction, and relatively faint central stars (coming from massive progenitors, they evolve quickly to low luminosities in their post-AGB journey), it is very difficult to observe the central engines in order to determine the collimation mechanisms. For the same reasons, the search for binaries in bipolar PNe – the most popular model to explain them – is a tremendous challenge. In this respect, we also need to understand which kind of binaries would produce bipolar PNe: close (= post common-envelope) or wide (=symbiotic-like) systems? One should also be very careful with possible misclassification with other classes of stellar outflows.

Another important point is that we are still far from understanding the evolution of shapes from the proto-PN stage to evolved PNe. Statistical studies of the Galactic distribution, number, and chemical abundances of proto-PNe might help to understand their evolutionary path toward a more mature PN phase.

Finally, low-ionization microstructures are relatively common and found in any morphological class. They show extremely varied shapes, locations, and kinematical properties, but contrary to previous claims it seems now that they do not have peculiar chemical abundances. Their origin is still very poorly understood.

Acknowledgements

I am grateful to D. Gonçalves for helping in the preparation of the section on microstructures, A. Mampaso for his comments on the manuscript, and B. Balick, D. Schönberner and M. Steffen for a continuous fruitful exchange of ideas. My participation to the symposium was supported by Spanish grant AYA02-0883, the ING, and I would also like to thank the IAU and the conference organizers for the additional financial help received.

References

Balick, B. 1987, AJ 94, 671

Balick, B. & Frank, A. 2002, ARAA 40, 439

Balick, B. & Hajian, A. 2004, AJ 127, 2269

Balick, B., Perinotto, M., Maccioni, A., *et al.* 1994, ApJ 424, 800

Chu, Y.-H., Jacoby, G.H. & Arendt, R. 1987, ApJS 64, 529

Corradi, R.L.M., Mikolajewska, J., & Mahoney, T.J. 2003a, ASP Conference Series, Vol. 303

Corradi, R.L.M. Sánchez-Blázquez, P., Mellema, G., Giammanco, C., & Schwarz, H.E. 2004, A&A 417, 637

Corradi, R.L.M., Schönberner, D., Steffen, M., & Perinotto, M. 2000, A&A 354, 1071

Corradi, R.L.M., Schönberner, D., Steffen, M., & Perinotto, M. 2003b, MNRAS 340, 417

Corradi, R.L.M. & Schwarz, H.E. 1995, A&A 293, 871

Gonçalves, D.R., Corradi, R.L.M., & Mampaso, A. 2001, ApJ 547, 302

Gonçalves, D.R., Mampaso, A., Corradi, R.L.M., Perinotto, M., Riera, A., & López-Martin, L. 2004a, MNRAS 355, 37

Gonçalves, D.R., Mampaso, A., Corradi, R.L.M., & Perinotto, M. 2004b, ASP Conference Proceedings, Vol. 313, p.198

Gonçalves, D.R., Ercolano, B., Carnero, A., Mampaso, A., & Corradi, R.L.M. 2006, MNRAS 365, 1039

Guerrero, M.A., Chu, Y.-H., & Miranda, L.F. 2004, AJ 128, 1694

Górny, S.K., Schwarz, H.E., Corradi, R.L.M., & van Winckel, H. 1999, A&AS 136, 145

Greig, W.E. 1972, A&A 18, 70

Manchado, A., Guerrero, M.A., Stanghellini, L., & Serra-Ricart, M. 1996, 'The IAC Morphological Catalog of Northern Galactic PNe', IAC Publ.

O' Dell, C.R., Balick, B., Hajian, A.R., Henney, W.J., & Henney, W.J. 2002, AJ 123, 3329

Perinotto, M., Schönberner, D., Steffen, M., & Calonaci, C. 2004a A&A 414, 993

Perinotto, M., Patriarchi, P., Balick, B., & Corradi, R.L.M. 2004b, A&A 422, 963

Phillips, J.P. 2005, MNRAS 362, 847

Sabbadin, F. & Hamzaoglu, E. 1981, MNRAS 197, 363

Sabbadin, F., Benetti, S., Cappellaro, E., Ragazzoni, R., & Turatto, M. 2005, A&A 436, 549

Santander-García, M., Balick, B., Corradi, R.L.M., & Mampaso, A. 2004, A&A 426, 185

Schönberner, D., Jacob, R., Steffen, M., Perinotto, M., Corradi, R.L.M., & Acker, A. 2005a, A&A 431, 963

Schönberner, D., Jacob, R., & Steffen, M. 2005b, A&A 441, 573

Schwarz, H.E., Corradi, R.L.M., & Melnick, J. 1992, A&AS 96, 23

Schwarz, H.E., Corradi, R.L.M., & Stanghellini, L. 1993, in Planetary Nebulae, IAU Symp. N.155, eds. Weinberger & Acker, p.214

Solf, J. & Ulrich, H. 1985, A&A 148, 274

Stanghellini, L., Villaver, E., Manchado, A., Guerrero, M.A. 2002, ApJ 576, 285

Terzian, Y. & Hajian, A.R. 2000, ASP Conf.Ser. 199, 34

Tylenda R. 1986, A&A 156, 217

Weedman, D.W. 1967, AJ 72, 836

Zuckerman, B. & Gatley, I. 1988, ApJ 324, 501