SHAPING POINT- AND MIRROR-SYMMETRIC PROTOPLANETARY NEBULAE BY THE ORBITAL MOTION OF THE CENTRAL BINARY SYSTEM

Sinhué A. R. Haro-Corzo1, Pablo F. Velázquez1, Alejandro C. Raga1, Angéls Riera2,3,4, and Primoz Kajdic5

1 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad Universitaria, Apartado Postal 70-543, CP 04510, México D.F., México; haro@nucleares.unam.mx, pablo@nucleares.unam.mx, raga@nucleares.unam.mx
2 Departament de Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, Comte d’Urgell 187, E-08036 Barcelona, Spain
3 Departament d’Astronomia i Meteorologia, Universitat de Barcelona, Av. Diagonal 647, 08028 Barcelona, Spain
4 Institut d’Estudis Espacials de Catalunya (IEEC), E-08034 Barcelona, Spain
5 Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad Universitaria, México D.F., México

Received 2009 June 1; accepted 2009 August 12; published 2009 August 27

ABSTRACT

We present three-dimensional hydrodynamical simulations of a jet launched from the secondary star of a binary system inside a protoplanetary nebula. The secondary star moves around the primary in a close eccentric orbit. From the gasdynamic simulations we compute synthetic [N II] λ 6583 emission maps. Different jet axis inclinations with respect to the orbital plane, as well as different orientations of the flow with respect to the observer, are considered. For some parameter combinations, we obtain structures that show point- or mirror-symmetric morphologies depending on the orientation of the flow with respect to the observer. Furthermore, our models can explain some of the emission distribution asymmetries that are summarized in the classification given by Soker & Hadar.

Key words: binaries: general – ISM: jets and outflows – methods: numerical – planetary nebulae: general – stars: AGB and post-AGB

1. INTRODUCTION

The shell of ionized gas coming from the ejected envelopes of the very late stage in the death of an intermediate initial mass ($M_\ast \lesssim 8 M_\odot$) star is called planetary nebula (PN). Since the onset of high spatial resolution observational facilities, such as the Hubble Space Telescope, optical images of PNe have revealed a rich variety of morphologies, highly collimated structures and small-scale features. These nebulae have been classified according to their large-scale morphologies such as bipolar, circular, elliptical, or irregular. In particular, bipolar PNe are axially symmetric, having two lobes with an equatorial waist between them.

Soker & Hadar (2002) proposed a classification of PNe depending on their departure from axisymmetry. The departures from axial symmetry can be point-symmetry or mirror-symmetry, with respect to the equatorial plane (which separates the two lobes).

In the last decade, the point-symmetric shape of some PNe and protoplanetary nebulae (PPNe) has been successfully explained in terms of collimated outflows. For example, Lee & Sahai (2003) carried out axisymmetrical simulations for modeling the morphology and emission of the PPN CRL 618. Velázquez et al. (2004; also see Riera et al. 2004), modeled the multiple shocked structures, emission, and kinematics of the PPN Hen 3–1475 in terms of a precessing jet with a periodic velocity variation, using three-dimensional (3D) hydrodynamical simulations. Velázquez et al. (2007) modeled the thermal radio-continuum emission of the PN K3–35 as a continuous, precessing jet. Guerrero et al. (2008) present an observational and numerical study of the PN IC 4634, showing that a variable velocity, precessing jet is the origin of its point-symmetric morphology. Some features observed in PNe (i.e., low excitation knots/clumps moving at supersonic velocities) could be produced by cosmic “bullets” (e.g., Raga et al. 2007; Dennis et al. 2008).

The presence of a companion to the asymptotic giant branch (AGB) star is thought to be required in order to produce jets and point-symmetric morphologies (Balick & Frank 2002). The presence of binary star system progenitors of PNe was initially proposed by Bond et al. (1978), who discovered that UU Sge, the central star of PN Abell 63, is an eclipsing binary. Fabian & Hansen (1979) suggested that the particular shape of the Helix nebula can also be due to the action of a binary system. Livio et al. (1979) suggested that non-spherical PNe host close binaries. Furthermore, the survey of De Marco et al. (2008) shows strong evidence that at least 10%–15% of PNe are composed of binary systems with short orbital periods (<3 days). Even though this fraction is not high enough to be consistent with the large fraction of PNe that apparently have been shaped by binary interactions, this survey is not able to detect large orbital periods and therefore the binary fraction of 10%–15% has been considered a lower limit.

Some mechanism invoked to explain the shaping of bipolar PNe involve the action of jets launched by the primary or secondary star (e.g., Morris 1987, 1990; Soker 1992; Livio 1993; Soker & Rappaport 2000). In several models, the jets are supposed to form when a main sequence star (or a white dwarf) accrete material from the AGB (or post-AGB) star, forms an accretion disk and blows two jets (e.g., Frank & Blackman 2004; Frank 2006; Frank et al. 2007). Hydrodynamical simulations have shown that jets (blown by the AGB star or by a companion) can account for some of the observed morphologies. García-Arredondo & Frank (2004) carried out 3D numerical simulations of the interaction of the stellar winds from the components of a binary system. They found that bipolar morphologies as narrow-waisted nebulae can be obtained after the interaction of a slow AGB wind, from the primary star, with a collimated fast stellar wind produced by the secondary.

In this work, we explore the influence of having a binary system in order to reproduce the morphology and brightness distribution of bipolar PPNe. We investigate (3D hydrodynamical simulations) if both point- and mirror-symmetric PPNe could be explained in terms of an interacting jet (source in orbital motion) with an AGB wind. Also, we explore if the observed
morphology of the PPN is affected by the orientation of the flow with respect to the observer. The jet is ejected by the secondary star (a star in the main sequence), which is on orbital motion with respect to the observer. The jet is injected at the center of the computational domain, in a cylindrical volume with radius \( r_j \) and length \( l_j \) with values \( r_j = 1 \times 10^{15} \text{ cm} \) (which are equivalent to 5 pixels in the highest resolution grid). The jet temperature was set to \( 10^3 \text{ K} \). The jet velocity is \( v_j = 1.7 \times 10^7 \text{ cm s}^{-1} \) and a semi-major axis of 3.2 AU (i.e., an orbital period of 5 years).

A detailed exploration of the parameter space (semi-major axis, eccentricity, etc) is carried out by S. Haro-Corzo et al. (2009, in preparation). In this work, we only show the most relevant results, choosing \( M_p + M_s = 1.25 \ M_\odot \) (with \( M_p = 1 \ M_\odot \)) and a semi-major axis of 3.2 AU (i.e., an orbital period of 5 years).

3. INITIAL SETUP FOR THE NUMERICAL SIMULATIONS

The 3D numerical simulations were carried out with the Yguazu-A code (Raga et al. 2000). The Yguazu-A code integrates the gasdynamical equations together with a system of rate equations for the atomic/ionic species: H \(_i\), \( \text{H II} \), \( \text{He I} \), \( \text{He II} \), \( \text{He III} \), \( \text{C II} \), \( \text{C III} \), \( \text{C IV} \), \( \text{N I} \), \( \text{N II} \), \( \text{N III} \), \( \text{O I} \), \( \text{O II} \), \( \text{O III} \), \( \text{O IV} \), \( \text{S II} \) and \( \text{S III} \). With these rate equations, a non-equilibrium cooling function is computed. The reaction and cooling rates are described in detail by Raga et al. (2002). The gasdynamical equations are integrated with a second order accurate technique (in time and space) employing the “flux-vector splitting” algorithm of van Leer (1982).

Our numerical simulations use a five-level, binary, adaptive Cartesian grid, in a computational domain of \( 256 \times 256 \times 512 \) pixels (at the highest grid resolution) along the x-, y-, and z-axes. The size of the computational domain is of \( 2 \times 10^{17} \text{ cm} \) along the x- and y-directions, and \( 4 \times 10^{17} \text{ cm} \) along the z-direction. A jet is injected into a circumstellar medium, which has been swept up previously by a dense and slow wind from the AGB central star. Even though the circumstellar medium in bipolar PNes is aspherical (with higher densities in the equator than along the bipolar axis), for simplicity and in order to only study the influence of the binary orbital motion, we have “turned off” the AGB influence imposing on all computational domain the analytical solution of an isotropic AGB wind. Then, the wind density distribution is given by

\[
\rho_w = \frac{M_w}{4\pi r^2 v_w},
\]

where \( M_w \) is the mass loss rate of the AGB wind, \( v_w \) is the AGB wind terminal velocity, and \( r \) is the distance from the primary star. We assume that the AGB wind is initially neutral, with \( M_w = 2 \times 10^{-6} \ M_\odot \text{ yr}^{-1} \), \( v_w = 1.5 \times 10^6 \text{ cm s}^{-1} \), and a temperature \( T_w = 100 \text{ K} \). A decreasing temperature versus radius dependence (resulting from the adiabatic expansion of the spherically diverging wind) is generated as the time-integration progresses.

The jet is injected at the center of the computational domain within a cylindrical volume with radius \( r_j \) and length \( l_j \) with values \( r_j = 1 \times 10^{15} \text{ cm} \) (which are equivalent to 5 pixels in the highest resolution grid). The jet temperature was set to \( 10^3 \text{ K} \). The jet velocity is \( v_j = 1.7 \times 10^7 \text{ cm s}^{-1} \) and the mean atom + ion number density is constant with \( n_j = 5 \times 10^4 \text{ cm}^{-3} \). These values correspond to a \( M_j = 1.5 \times 10^{-6} \ M_\odot \text{ yr}^{-1} \) mass injection, which could seem high. Due to the limited
numerical resolution we are forced to impose the jet on a region larger than its true size. However, the total injected mass after 400 yr is $1.2 \times 10^{-3} M_\odot$, which looks reasonable (Velázquez et al. 2007). With the parameters listed above, the jet is in the domain of “strong jet” according to the description of Soker & Rappaport (2000) and García-Arredondo & Frank (2004), with a parameter $\chi = M_w v_w / M_j v_j = 0.2$. A similar dynamical behavior could be achieved taking into account a less dense jet but with higher velocity, keeping constant the jet ram pressure $\rho_j v_j^2$ and the parameter $\chi$. However, we prefer to employ a dense jet with a low velocity, the last one being comparable with the maximum orbital speed, in order to favor the contribution of orbital motion to the global morphology of the object. Based on these initial conditions, we consider six runs labeled as $Ra_i$ and $Rb_i$, where $i = 1$ corresponds to the case in which the jet axis is perpendicular to the orbital plane, $i = 2$ to a tilt of $20^\circ$ between the jet axis and the orbital axis, on the $x$-$z$ plane, and $i = 3$ to a tilt of $20^\circ$ on the $y$-$z$ plane (the orbital axis is parallel to the $z$-axis, and the $x$-axis contains the foci of the elliptical orbit; see Section 2). Runs $Ra_i$ have an eccentricity $e = 0.73$, and runs $Rb_i$ have $e = 0.94$. The parameters of the runs are summarized in Table 1.

Finally, from the temperature and atomic/ionic/electronic number density distributions computed from the numerical time-integration, we calculate the emission line coefficients of a set of permitted and forbidden emission lines. The forbidden line $\lambda 6583$ was computed by solving five-level atom problems, using the parameters of Mendoza (1983).

4. RESULTS

We find that many of our jet/AGB wind interaction models have morphologies that depend on the projection, and that both point- and mirror-symmetric PNe can be obtained from the same model (depending on the position of the observer). This is illustrated in Figure 2, where we plot the resulting synthetic [N\textsc{ii}] $\lambda 6583$ emission maps at an integration time of 400 yr. The group of six panels correspond to the runs $Ra_i$. The $yz$- and $xz$-projections of run $Ra_1$ show mirror-symmetric morphology. On the other hand, while the $yz$-projection of run $Ra_2$ has a mirror-symmetric morphology, the $xz$-projection of this model has a point-symmetric morphology. A similar switch between point- and mirror-symmetric morphologies is seen in run $Ra_3$. Also, we analyze the asymmetries of the synthetic [N\textsc{ii}] $\lambda 6583$ emission maps for runs $Ra_i$ produced by the inclination ($40^\circ$) of the orbital plane ($x$-$z$ plane) with respect to the plane of the sky. The intensity maps preserve the mirror- and point-symmetric morphologies discussed above (for the case in which the $z$-axis lies on the plane of the sky). Furthermore, we find that the morphologies of the maps obtained from runs $Rb_i$ are similar to the maps from $Ra_i$, although, in general, we note the presence of small-scale internal structures which are brighter for runs $Rb_i$ than runs $Ra_i$. Those are because of the larger eccentricity of the $Rb_i$ runs. The velocity variability of the jet (resulting from the orbital motion) produces these internal substructures in both lobes of the $Ra_i$ and $Rb_i$ maps. In order to see the influence of the increasing eccentricity, in Figure 3 we display the subtraction of the synthetic [N\textsc{ii}] $\lambda 6583$ emission maps corresponding to $Rb_i - Ra_i$ runs.

Finally, we have obtained the [N\textsc{ii}] $\lambda 6583$ luminosities for the top and bottom lobes for all of the computed maps. Table 2 gives the [N\textsc{ii}] $\lambda 6583$ luminosities for both lobes and all runs. In general, we note that runs $Rb_i$ have larger [N\textsc{ii}] $\lambda 6583$ luminosities than runs $Ra_i$ (of the order of 10%), as a result of the more eccentric orbital motion of runs $Rb_i$. The exception is run $Rb_3$ because the total luminosity measured on the top

| Run   | Ecc | Angle(°) | Plane |
|-------|-----|----------|-------|
| Ra1   | 0.73| 0        | ···    |
| Ra2   | 0.73| 20       | $x$-$z$|
| Ra3   | 0.73| 20       | $y$-$z$|
| Rb1   | 0.94| 0        | ···    |
| Rb2   | 0.94| 20       | $x$-$z$|
| Rb3   | 0.94| 20       | $y$-$z$|

Table 1: Run Parameters

Figure 2. Synthetic [N\textsc{ii}] $\lambda 6583$ emission (erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$) at 400 yr for runs $Ra_1$, $Ra_2$ and $Ra_3$. The emission is on log gray scale. Axes are in units of $10^{17}$ cm.

Figure 3. Synthetic [N\textsc{ii}] $\lambda 6583$ emission at 400 yr for the subtraction $Rb_i - Ra_i$. The same scale as Figure 2.
lobe is the same as that of run \(Ra_3\), while the bottom lobe has less total luminosity. This is due to the fact that the gas material of the top lobe has larger velocities than the bottom lobe gas. In the top lobe, the orbital motion speed is added to the jet velocity, while the opposite occurs for the bottom lobe. For the cases where the resulting shape has mirror-symmetry, the luminosities from the right and left sides of the lobes have also been computed. Comparison of total luminosities between both (top and bottom) lobes show a similar value for runs \(Ra_1\), \(Ra_2\), \(Rb_1\), and \(Rb_2\). However, analyzing the \(xz\)- and \(yz\)-projection cases, an asymmetry in the brightness distribution is observed for the \(yz\)-projection, in general, with the right side being a more luminous, consequence of the orbital motion. In runs \(Ra_3\) and \(Rb_3\) we obtain appreciable \([N\,\text{ii}]\,\lambda\,6583\) luminosity asymmetries between the top and bottom lobes (see Figure 3).

Point- and mirror-symmetric morphologies are simultaneously obtained if the jet axis has a certain inclination with respect to the orbital plane. Interestingly, the classification of a PN belonging to one or other group seems to depend on the point of view of the observer or on the projection. There are significant differences in the total luminosities of both lobes between runs \(Ra_2\) and \(Ra_3\) and similar behavior is observed for runs \(Rb_2\) and \(Rb_3\). Run \(Rb_2\) produces top and bottom lobes with similar total luminosities, while run \(Rb_3\) generates a luminosity difference of at least 36% between the top and bottom lobes. This is due to the fact that the jet axis is tilted 20° on the \(yz\)-plane in the case of run \(Ra_3\). In this case, the jet inclination contributes to the elliptical motion, its being effect larger for the top lobe when the secondary star passes by the periastron, where the orbital motion velocity is maximum. The total jet velocity (the intrinsic constant jet velocity \(\sim 1.7 \times 10^7\,\text{cm s}^{-1}\) plus the eccentric orbital motion velocity) is also maximum at the periastron, producing strong shocks and increasing the emission for the top lobe (the opposite occurs for the bottom lobe).

5. DISCUSSION AND CONCLUSIONS

In this work, we carried out 3D hydrodynamical simulations with the \(yguaz\)–A code in order to explore the binary mechanism for shaping bipolar, point- and mirror-symmetric PNe. We consider a collimated outflow (jet) launched by the secondary star of a binary system, located at the center of a PN. The primary star is the source of the AGB wind, in which the jet is embedded. The two stars have a close, very eccentric orbit, resulting in a maximum orbital velocity of the order of the jet velocity. Because of this, the orbital velocity has a strong effect on the jet dynamics, and strongly modifies the emission line maps predicted from the computed flows.

We have generated \([N\,\text{ii}]\,\lambda\,6583\) emission maps considering different inclinations of the jet axis with respect to the orbital plane and also different tilts between the orbital axis and the line of sight. We find that the predicted maps of some runs exhibit (see Figure 2) either point- or mirror-symmetric substructures depending on the orientation of the flow with respect to the observer. Also, the maps exhibit substructures with different luminosities for the two lobes and with side-to-side asymmetries within the same lobe.

In this sense, Soker & Hadar (2002) built a classification of PNe based on their departure from axisymmetry considering both morphological and brightness distribution criteria. From Figure 2 and Table 2, we note that runs \(Ra_3\) and \(Rb_3\) would correspond to class 2 (i.e., unequal intensity of both sides) of Soker & Hadar (2002), because top lobes are brighter than bottom ones. Into this class could be also included maps of runs \(Ra_1\) and \(Ra_2\), for example, because their \(yz\)-projection displays an asymmetry in the right and left brightness distribution. The \(yz\)-projections of \(Ra_1\) and \(Rb_1\) could be also included in class 4 (i.e., the jets are bent to the same side, therefore there is a mirror-symmetry) because the small-scale structure is observed on the right side of both lobes.

From our study we conclude that a jet ejected from a companion to the AGB star (which gives rise to a PN) in a highly eccentric orbit leads to morphologies with either point- or mirror-symmetries (in some cases both, depending on the inclination to the observer). Also, the bipolar nebular structure resulting from the jet/AGB stellar wind interaction has brightness asymmetries with contrasts similar to the asymmetries observed in some PNe (Soker & Hadar 2002). We must note that, except for the eccentricity, the orbital parameters we used are commonly found in the last evolution state of low mass and small post-AGB stars, which can be close binaries without a common envelope (Van Winckel 2003; Frankowski 2004; Van Winckel et al. 2009; de Marco 2009; Miszalski et al. 2009). The eccentricities we used are uncommon for post-AGB stars; however, there are reports of highly eccentric orbits in other binary systems, such as Ba stars (Van Winckel 2003; Jorissen et al. 1998), de Marco (2009) argued that for post-AGB stars that have been monitored spectroscopically, low eccentricities have been found for systems with intermediate periods (between 100–1500 days), but for periods > 1 yr the eccentricities can be close to unity). A larger sample of post-AGB in binary systems is needed to assess the feasibility of our model.

It is interesting that we can generate models which produce either point- or mirror-symmetric emission line maps, depending only on the orientation of the flow with respect to the observer. For other choices of flow parameters, however, it is easy to obtain models which produce point-symmetric structures regardless of the orientation of the flow with respect to the observer (e.g., by having a precessing jet from a source with low orbital velocity; Masciadri & Raga 2002). Therefore, while a large range of parameters will produce point-symmetric nebulae, we find that

| Run | Bottom | \(xz\) | \(yz\) | \(Top\) | \(xz\) | \(yz\) |
|-----|--------|-------|-------|-------|-------|-------|
| \(Ra_1\) | 3.4 | 1.7 | 1.7 | 1.3 | 2.1 | 3.4 | 1.7 | 1.7 | 1.3 | 2.1 |
| \(Ra_2\) | 6.9 | ... | ... | 3.2 | 3.7 | 6.9 | ... | ... | 3.2 | 3.7 |
| \(Ra_3\) | 5.6 | 2.9 | 2.7 | ... | ... | 6.9 | 3.6 | 3.3 | ... | ... |
| \(Rb_1\) | 3.8 | 1.9 | 1.9 | 1.5 | 2.3 | 3.7 | 1.8 | 1.9 | 1.5 | 2.2 |
| \(Rb_2\) | 7.6 | ... | ... | 3.4 | 4.2 | 7.4 | ... | ... | 3.3 | 4.1 |
| \(Rb_3\) | 5.0 | 2.6 | 2.4 | ... | ... | 6.8 | 3.6 | 3.2 | ... | ... |

Notes. Each lobe has been parted as left and right side. We ignore the central emission (20 pixels from each lobe).
it is necessary to have both an appropriate parameter combination and an appropriate orientation of the flow (with respect to the observer) in order to produce mirror-symmetric structures. This result might be consistent with the fact that many more bipolar PNe are observed to have point-symmetric structures (as opposed to mirror-symmetric structures). In order to decide whether this is indeed the case, a more detailed study limiting the parameter space relevant for nebulae resulting from jet/AGB wind interactions will have to be made, as well as a study of the statistics of the resulting flow morphologies observed at random orientations.

The authors acknowledge the anonymous referee for her/his very useful comments and suggestions. We thank Martín Guerrero and Luis F. Miranda for many clarifying and useful comments. The authors acknowledge support from grants CONACyT 46828-F and 79744, and DGAPA IN119709. The work of A.R. was supported by the MICINN grant AYA2008-06189-C03 and AYA2008-04211-C02-01 (co-funded with FEDER funds). We also thank Enrique Palacios, Antonio Ramírez, and Martín Cruz for the assistance provided, and Alejandro Esquivel for reading this manuscript.

REFERENCES

Balick, B., & Frank, A. 2002, ARA&A, 40, 439
Bond, H. E., Liller, W., & Mannery, E. J. 1978, ApJ, 223, 252
de Marco, O. 2009, PASP, 121, 316
De Marco, O., Hillwig, T. C., & Smith, A. J. 2008, AJ, 136, 323
Dennis, T. J., Cunningham, A. J., Frank, A., Balick, B., Blackman, E. G., & Mitran, S. 2008, ApJ, 679, 1327
Fabian, A. C., & Hansen, C. J. 1979, MNRAS, 187, 283
Frank, A. 2006, in IAU Symp. 234, Planetary Nebulae in our Galaxy and Beyond, ed. M. J. Barlow & R. H. Méndez (Dordrecht: Kluwer), 293
Frank, A., & Blackman, E. G. 2004, ApJ, 614, 737
Frank, A., De Marco, O., Blackman, E., & Balick, B. 2007, arXiv:0712.2004
Frankowski, A. 2004, in ASP Conf. Ser. 313, Asymmetrical Planetary Nebulae III: Winds, Structure and the Thunderbird, ed. M. Meixner et al. (San Francisco, CA: ASP), 511
García-Arredondo, F., & Frank, A. 2004, ApJ, 600, 992
Guerrero, M. A., et al. 2008, ApJ, 683, 272
Jorissen, A., Van Eck, S., Mayor, M., & Udry, S. 1998, A&A, 332, 877
Lee, C.-F., & Sahai, R. 2003, ApJ, 586, 319
Livio, M. 1993, in IAU Symp. 155, Planetary Nebulae, ed. R. Weinberger & A. Acker (Dordrecht: Kluwer), 279
Livio, M., Salzman, J., & Shaviv, G. 1979, MNRAS, 188, 1
Masciadri, E., & Raga, A. C. 2002, ApJ, 568, 733
Mendoza, C. 1983, in IAU Symp. 103, Planetary Nebulae, ed. D. R Flower (Dordrecht: Reidel), 143
Miszalski, B., Acker, A., Moffat, A. F. J., Parker, Q. A., & Udalski, A. 2009, A&A, 496, 813
Morris, M. 1987, PASP, 99, 1115
Morris, M. 1990, in From Miras to Planetary Nebulae: Which Path for Stellar Evolution?, ed. M. O. Mennessier & A. Omont (Paris: Editions Frontières), 520
Raga, A. C., de Gouveia Dal Pino, E. M., Noriega-Crespo, A., Mininni, P. D., & Velázquez, P. F. 2002, A&A, 392, 267
Raga, A. C., Esquivel, A., Riera, A., & Velázquez, P. F. 2007, ApJ, 668, 310
Raga, A. C., Navarro-González, R., & Villagrán-Muniz, M. 2000, RevMexAA, 36, 67
Riera, A., Velázquez, P. F., & Raga, A. C. 2004, in ASP Conf. Ser. 313, Asymmetrical Planetary Nebulae III: Winds, Structure and the Thunderbird, ed. M. Meixner et al. (San Francisco, CA: ASP), 487
Soker, N. 1992, ApJ, 389, 628
Soker, N., & Hadar, R. 2002, MNRAS, 331, 731
Soker, N., & Rappaport, S. 2000, ApJ, 538, 241
Soker, N., & Rappaport, S. 2001, ApJ, 557, 256
Soker, N., Rappaport, S., & Harpaz, A. 1998, ApJ, 496, 842
van Leer, B. 1982, in Lecture Notes in Physics, Vol. 170, Numerical Methods in Fluid Dynamics, ed. E. Krause (Berlin: Springer), 507
van Winckel, H. 2003, ARA&A, 41, 391
van Winckel, H., et al. 2009, arXiv:0906.4482
Velázquez, P. F., Gómez, Y., Esquivel, A., & Raga, A. C. 2007, MNRAS, 382, 1965
Velázquez, P. F., Riera, A., & Raga, A. C. 2004, A&A, 419, 991
Zijlstra, A. A. 2007, Balt. Astron., 16, 79