Binary Interactions and the Shaping of Planetary Nebulae

Philipp Podsiadlowski

Dept. of Astrophysics, University of Oxford, Oxford, OX1 3RH, UK

Summary. Binary interactions affect the shaping of planetary nebulae in numerous ways. Here I review the main types of interactions: common-envelope ejection, binary mergers, stable Roche-lobe overflow and gravitational focusing, and assess their relative importance. Recent observations of Mira AB have shown that even a very distant companion can dramatically affect the mass loss from a Mira variable, significantly increasing the overall importance of the wide-binary channel.

1 Introduction

The majority of all stars are known to be members of binary systems. Since there is a large variety of possible binary interactions, it is only reasonable to suspect that these affect the geometry of the mass loss from the system and hence the shaping of planetary nebulae (PNe). Some of the key questions are in what fraction of PNe are the observed asymmetries caused by binary interactions and by what mechanisms. Here I first discuss the physical causes of PN asymmetries, then review the most important binary interactions and, in particular, the only recently realized, potentially important role of relatively wide binaries and end with a general assessment assessment of the situtation.

2 The Origin of PN Asymmetries

Shaping by the external medium: the interacting wind model
One of the best studied models for the shaping of asymmetric planetary nebulae is the interacting wind model [31, 9]. In this model, the asymmetric nebulae are caused by the interaction of a fast, energetic wind emitted from the young, hot white dwarf and a slow, asymmetric wind emitted in the progenitor's AGB phase. In order to produce non-spherical nebulae, the AGB wind has to be equatorially enhanced to various degrees. This model has been very successful in explaining a large variety of observed PN shapes; however, it does not directly address the cause of the large asymmetries in the AGB winds.
Intrinsic, asymmetric ejection

An alternative to the wind interaction model is that the PN ejection is intrinsically asymmetric. This is expected if the nebula is the result of an ejected common envelope or is associated with a binary merger event.

The role of rotation

While the shapes of PNe can be extremely complicated in detail, the majority of asymmetric PNe still show a basic axi-symmetry. This immediately suggests that rotation may play an important role in their shaping. However, the problem with rotation is that 'true' single stars have to be slowly rotating in their AGB phase. This follows directly from simple considerations of angular-momentum conservation. Indeed, since young white dwarfs are observed to be slow rotators, this also applies to the cores of AGB stars.

The role of magnetic fields

Shaping by magnetic fields has occasionally been suggested as an alternative to rotation (e.g. [22, 3]). The problem, as discussed at this meeting by Nordhaus [21], is that the strong B fields that are necessary for having an effect on a stellar wind require fairly rapid (differential) rotation in the envelope, which in turn almost certainly requires an additional angular-momentum source. Binary interactions, in particular those involving a common-envelope phase or a binary merger, could possibly provide such a source.

Indeed, it seems that binary interactions more generally are the most natural cause to explain the observed asymmetries.

3 Binary Interactions

A large fraction of all stars are not only members of binary systems, but are close enough that the two components interact directly. As a rule of thumb, each decade in $\log P$ (where P is the orbital period) contains 10% of all stars (for P from $10^{-3} - 10^{7}\,\mathrm{yr}$). This implies that $\sim 50\%$ of all stars are in binaries with $P < 100\,\mathrm{yr}$. One important uncertainty in the binary statistics is the mass-ratio distribution. While it is clear that in massive systems the masses are strongly correlated, for lower-mass stars this is more uncertain, even controversial. If the masses are correlated for the progenitors of PNe, one would expect more asymmetric PNe for more massive stars. In the following, we consider the main binary interactions, common-envelope evolution, stable Roche-lobe overflow, binary mergers and wind focusing.

3.1 Common-Envelope Ejection

In the sample of well-studied PNe, at least $10 - 15\%$ of PNe contain close binary cores, proving that the observed nebulae are ejected common envelopes (CE) [1, 6]. Common-envelope evolution is a consequence of unstable Roche-lobe overflow, illustrated in the left panel of Fig. 1. This typically occurs when a giant star transfers matter to a significantly less massive star that cannot accrete all of the transferred mass. This leads to common envelope, formed out of the envelope of the giant, surrounding the core of the giant and the companion star. Due to the friction of this immersed binary with the envelope, the system spirals in, releasing orbital energy in the process. This ultimately leads to the ejection of the envelope, now seen as a PN, leaving a very close binary (e.g., [13]). The orbital periods in most known post-CE

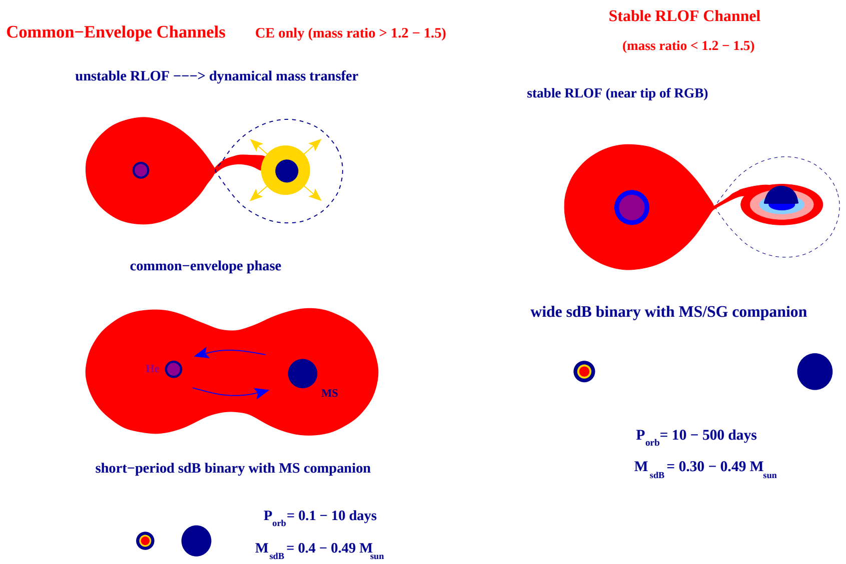

Fig. 1. Main mass-transfer modes. *Left:* Unstable mass transfer leading to a common-envelope phase and the ejection of the envelope in a planetary nebula. *Right:* Stable Roche-lobe overflow, spinning up a giant donor.

binaries have orbital periods $< 3\,\mathrm{d}$; the real number of PNe formed through this channel could be significantly larger, perhaps making up a large fraction of all PNe [7, 28]. Binary population synthesis (BPS) studies [10] suggest that $10-15\%$ of all stars eject their envelopes by CE evolution on the first giant branch, while $\sim 5\%$ do so on the asymptotic-giant branch.

3.2 Stable Roche-Lobe Overflow

Mass transfer tends to be stable if the giant donor is comparable in mass to the companion star. Because of the strong tidal interaction of a Roche-lobe filling object, one expects the envelope of the giant to be tidally locked to the orbit. This by itself will produce a fairly rapidly rotating envelope. It is an elementary exercise to show that the ratio of the rotation velocity to the surface breakup velocity ($v_{\mathrm{rot}}/v_{\mathrm{break}}$) for a tidally locked Roche-lobe filling object just depends on the mass ratio q according to $v_{\mathrm{rot}}/v_{\mathrm{break}} = (1+q)^{1/2}\,(R_1/a)^{3/2}$, where R_1 is the radius of the donor and a is the orbital separation. For a mass ratio $q \simeq 1$, this ratio is $\simeq 0.33$.

In recent years, many post-AGB stars have been found in circular binaries with orbital periods $P > 100\,\mathrm{d}$ [30]. The evolutionary history of these systems is still uncertain (see, e.g., [5]). It may require a somewhat different mode of transfer that may involve a temporary CE phase but without the drastic spiral-in associated with the formation of a close PN binary core [26]. While the mass loss in this phase would be expected to be very non-spherical, it is not entirely clear whether this will produce an observable planetary nebula, since it involves neither dynamical ejection nor an AGB superwind phase.

3.3 Binary Mergers

The most dramatic type of binary interaction involves the complete merger of two stars. This happens when the orbital energy that is released in a CE and spiral-in phase is not sufficient to eject the envelope. BPS simulations [10] estimate that this is the expected fate for $\sim 10\%$ of all stars. The merger of two stars is a particularly efficient way of converting orbital angular momentum into spin-angular momentum and of producing a rapidly rotating single object, at least initially. If the merger occurs early in the star's evolution, one expects subsequent spin-down just as for single stars. In order to still have a sufficiently rapidly rotating envelope to affect the PN, the merger has to occur relatively late in the star's evolution. Indeed, even the merger with a substellar object, a brown dwarf or a massive planet, can in principle provide enough angular momentum to spin up the AGB star's envelope appreciably, possibly enough to produce a moderately asymmetric PN, e.g., an elliptical PN [27].

3.4 The Triple-Ring Nebula around SN 1987A

The triple-ring nebula surrounding SN 1987A provides a particularly spectacular example to illustrate how a late binary merger may produce a complex nebula (see [24] for a detailed recent review). SN 1987A was in many respect a highly anomalous event. One of its most spectacular features is the complex triple-ring nebula [32, 2], consisting of material that was ejected from the progenitor some 20,000 yr before the explosion in an almost axi-symmetric but in a very non-spherical manner.

Morris & Podsiadlowski [19, 20] recently simulated the mass ejection during the merger and the subsequent evolution of the ejecta, using the 3-d smooth-particle hydrodynamics code GADGET [29], as shown in Fig. 2. They considered the merger of a $15\,M_\odot$ red supergiant with a radius of $1500\,R_\odot$ with a $5\,M_\odot$ companion and modelled first the initial spiral-in phase, where all the initial orbital angular momentum is deposited in the envelope, producing a flat disk-like envelope structure (Fig. 2a). The orbital energy that is subsequently released as a result of the spiral causes the ejection of some of the envelope material, but because of the flat disk-like structure of the envelope, this mass ejection occurs mainly in the polar direction, with a strong density enhancement at about 45° (Figs. 2b,c). After the merger has been completed, the merged object evolves to become a blue supergiant (due to the changes in the core–envelope structure caused by the merger [25]), ejecting the excess angular momentum in an equatorial outflow. The energetic blue-supergiant emitted in this final phase then sweeps up all the structures ejected before, in particular the equatorial outflow and the ring-like enhancements at 45° into the triple-ring structure (Figs. 2d,e), reproducing the HST observations [2].

3.5 Gravitational Focusing

Even in a binary system where the orbit is so large that neither component ever fills its Roche lobe, the presence of a companion star can affect the geometry of the mass loss from the system by gravitational focusing which will generally concentrate

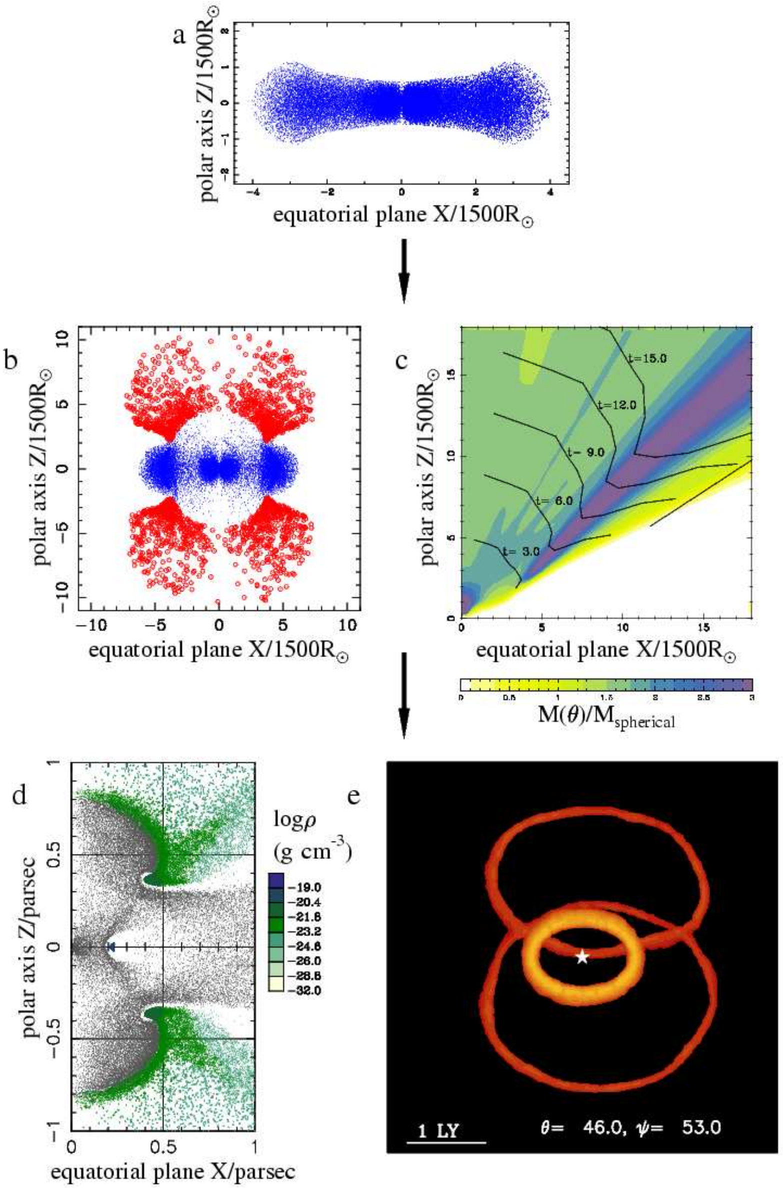

Fig. 2. Three-dimensional hydrodynamical simulations to model the late merger of two massive stars to explain the triple-ring nebula around SN 1987A [19, 20]. *Panel A:* cross section of the rapidly rotating red-supergiant envelope. *Panel B:* ejection phase (particles indicated as circles are ejected). *Panel C:* ejecta asymmetries as a function of time. *Panel D:* the final particle distribution after 20,000 yr after the blue-supergiant wind has swept up the ejecta ejected in the merger. *Panel E:* Simulated emission measure in Hα at ~ 2000 d after the supernova.

Table 1. Summary of binary channels for asymmetric PNe.

Channel	BPS [28]	new	comments
CE ejection	15 – 20%		
Binary mergers	∼ 10%	−5%	early mergers
		+10%	planet mergers
Roche-lobe overflow	?		
Gravitational focusing	∼ 10 – 15%	+20%	Mira!
Total	35 – 45%	+25%	

the wind towards the orbital plane [8, 16, 23, 17], producing a disk-like outflow. To estimate the importance of gravitational focusing, Morris [18] has defined a gravitational focusing fraction (i.e., the fraction of the total mass of the outflow that is focused by the companion) as

$$\alpha_{\rm focus} \equiv \frac{\dot{M}_{\rm focus}}{\dot{M}{\rm outflow}} = \frac{0.8}{V_{\rm W}} \left[\frac{M_2}{a}\right]^2 \left[V_{\rm W}^2 + 0.9\,\frac{M_1+M_2}{a}\right]^{-3/2},$$

where the primary and secondary masses, M_1 and M_2 are in solar units, the binary separation a is in units of 10 AU and the wind velocity $V_{\rm W}$ is in units of $10\,{\rm km\,s^{-1}}$. This formula implies, that for gravitational focusing to be important, the companion star has to be quite close. In their BPS simulations Han et al. [10] estimate that strong focusing (with $\alpha_{\rm focus} > 0.5$) would only affect 3% of all systems, while mild focusing (with $\alpha_{\rm focus} > 0.1$) could be important in ∼ 10% of systems. However, recent observations of Mira AB have shown that these estimates are probably far too conservative.

3.6 The Case of Mira AB

The binary Mira (o Ceti) is one of the best studied and the only spatially and spectrally resolved, D-type symbiotic binary. The system consists of a cool, but very luminous pulsating AGB star, Mira A, and a hot companion, Mira B, which is generally assumed to be a white dwarf (WD) with a separation of > 100AU. HST and Chandra observations in the last decade [11, 12] have indicated that, despite the large separation, the stars are strongly interacting and that Mira A's wind is essentially filling Mira A's Roche lobe and is transferring mass to the companion (see [15] for more details and models). This suggests a new mode of mass transfer, *wind Roche-lobe overflow*, where the slow wind fills the Roche lobe rather than the star. The important implication of this is that the mass-accretion rate can be much higher than in the case of normal Bondi-Hoyle-type wind accretion (by as much as a factor of 100).

Our recent simulations of the mass transfer in Mira, using a reasonably realistic model for the dust acceleration in the wind from Mira A [15] (also see [14]), show that indeed mass loss from the system is strongly enhanced towards the orbital plane, producing essentially an equatorial outflow. In the context of asymmetric PNe, this may provide the necessary equatorial density enhancement to produce a very asymmetric PN in the interacting wind model (see § 2). Since one may also expect a bipolar outflow from the accreting component, Mira AB may in the future evolve into a bipolar proto-planetary nebula such as OH231.8+4.2. In general, the equatorial density enhancement depends on how the wind velocity from the evolved star compares to the orbital velocity of the system. One may therefore expect that, as the evolved star evolves up the AGB and ultimately becomes a Mira variable, the wind velocity decreases steadily, causing a transition from a spherical wind to an increasingly equatorially enhanced wind.

The important lesson to be drawn from these recent observations is that the Mira AB system provides observational proof that gravitational focusing is important for much wider binary systems than had been assumed previously, making this a much more important channel for the shaping of PNe.

4 The Importance of Binary Interaction

Table 1 summarizes the various binary channels discussed in this contribution, where the second column lists the estimates from the BPS simulations of [10], i.e., it lists the fraction of stellar systems in which binary interactions can be expected to affect the shaping of the final PNe. The third column lists an adjustment to these estimates based on our present re-assessment, as indicated in the 'comments' column, which are particularly affected by the recent observations of Mira AB. These estimates show that binary interactions are likely to be the dominant cause for asymmetric PNe. Probably all bipolar/butterfly PNe, which make up $\sim 10 - 20\,\%$ of all PNe [4] and which require very large asymmetries, need a strong binary interaction. In contrast, for the elliptical PNe, which require a much more moderate asymmetry in the mass loss, a much weaker interaction may suffice, such as the merger with a planet/brown dwarf or an early merger, or gravitational focusing by a relatively distant companion; even single stars need not produce perfectly spherical PNe. One question that has been raised at this meeting [7] is whether perhaps all PNe require binary evolution. While it is clear from the above estimates that the majority of PNe should be affected by binary interactions, explaining why most of them are non-spherical, the necessity of binarity has, in my personal view, not yet been proven, and it is unclear to me why single stars should not be able to produce PNe. On the other hand, proving that a 'truly' single star can actually produce an observable PN may be an even tougher observational challenge than discovering the origin of the most asymmetric bipolar PNe.

References

1. Bond, H.E., Livio, M.: **ApJ**, 355, 568 (1990)
2. Burrows, C., et al.: ApJ, **452**, 680 (1995)
3. Chevalier, R.A., Luo, D.: ApJ, **421**, 225 (1994)
4. Corradi R.L.M., Schwarz H.E.: A&A, **293**, 871 (1995)
5. Frankowski, A., Jorissen, A.: Balt. Astron., **16**, 104
6. De Marco, O., Bond, H.E., Harmer, D., Fleming, A.J.: ApJ, **602**, 93 (2004)
7. De Marco, O.: these proceedings (2008)
8. Fabian, A.C., Hansen, C.J.: MNRAS, **187**, 283 (1979)

9. Frank, A., Balick, B., Icke, V., Mellema, G.: ApJ, **404**, L25 (1993)
10. Han, Z., Podsiadlowski, Ph., Eggleton, P.P.: MNRAS, **272**, 800 (1995)
11. Karovska M., et al.: RevMexAA, **20**, 92 (2004)
12. Karovska M., et al.: ApJ, **623**, L137 (2005)
13. Livio, M., Soker, N.: ApJ, **329**, 764 (1988)
14. Mastrodemos, N., Morris, M.: ApJ, **523**, 357 (1999)
15. Mohamed, S., Podsiadlowski, Ph.: these proceedings (2008)
16. Morris, M.: ApJ, **249**, 572 (1981)
17. Morris, M.: PASP, **99**, 1115 (1987)
18. Morris, M. 1990: In *From Miras to Planetary Nebulae: Which Path for Stellar Evolution*, ed. M.O. Mennessier & A. Omont (Gif-sur-Yvette, editions Frontières), 520
19. Morris, T., Podsiadlowski, Ph.: MNRAS, **365**, 2 (2006)
20. Morris, T., Podsiadlowski, Ph.: Science, **315**, 1103 (2007)
21. Nordhaus, J.: these proceedings (2008)
22. Pascoli, G.: A&A, **180**, 191 (1987)
23. Pilyuin, L.S.: SvA, **31**, 282 (1987)
24. Podsiadlowski Ph.: In Aspen Conference on SN 1987A, in press (2007)
25. Podsiadlowski, Ph., Joss, P.C., Rappaport, S.: A&A, **227**, L9 (1990)
26. Podsiadlowski, Ph., Joss, P.C., Hsu, J.J.L.: ApJ, **391**, 245 (1992)
27. Livio, M., Soker, N.: ApJ, **571**, L161 (2002)
28. Sorensen, P., Pollacco, D.: ASP Conf. Proc., **313**, 515 (2004)
29. Springel, V., Yoshida, N., White, S.: NewA, **6**, 51 (2001)
30. Van Winckel, H.: Balt. Astron., **16**, 112
31. Volk, K.M., Kwok, S.: A&A, **153**, 79 (1985)
32. Wampler, E.J., et al.: ApJ, **362**, L13 (1990)