BINARY CENTRAL STARS OF PLANETARY NEBULAE

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Abstract. This paper reviews our knowledge on binary central stars of planetary nebulae and presents some personal opinions regarding their evolution. Three types of interactions are distinguished: type I, where the binary companion induces the mass loss; type II, where it shapes the mass loss but does not enhance it; type III, where a wide orbit causes the centre of mass to move, leading to a spiral embedded in the wind. Surveys for binary central stars are discussed, and the separations are compared to the distribution for binary post-AGB stars. The effect of close binary evolution on nebular morphology is discussed. Post-common-envelope binaries are surrounded by thin, expanding disks, expelled in the orbital plane. Wider binaries give rise to much thicker expanding torii. Type I binary evolution predicts a wide distribution of masses of central stars, skewed towards low masses. Comparison with observed mass distributions suggests that this is unlikely to be the only channel leading to the formation of a planetary nebula. A new sample of compact Bulge nebulae shows about 40% of nebulae with binary-induced morphologies.

Key words: Stars: AGB and post-AGB – Binaries: close – Stars: mass-loss – planetary nebulae: general

1. INTRODUCTION

The traditional view of stellar evolution on the Asymptotic Giant Branch (AGB) and beyond is that of a single star. An AGB star consists of an inert carbon-oxygen core, surrounded by a nuclear-burning shell. This shell alternates between phases of hydrogen and of helium burning, punctuated by helium shell flashes, the thermal pulses. The nuclear burning region in turn is surrounded by the convective envelope. Radial pulsations increase in amplitude and period whilst the star ascends the AGB. During the Mira phase the pulsation periods are 150–400 days and the bolometric amplitude a magnitude or more. (The visual amplitude can exceed 8 magnitudes, amplified by variable molecular bands.)

The strong pulsations lead to the formation of an extended atmosphere. In the outer regions dust condenses: radiation pressure on the dust now drives a highly efficient stellar mass loss. The mass-loss rate greatly exceeds the nuclear-burning rate, and depletes the envelope. Once the envelope mass is reduced to $M_e \sim 0.02 M_\odot$, the photosphere collapses and the effective temperature increases. The wind reduces or ceases: the star is now surrounded by a detached, expanding envelope. Once the star is hot enough to ionize the ejecta, a planetary nebula (PN) forms.

Although there is strong observational evidence for this scenario (e.g. Habing 1996), doubts have been expressed. The ejecta commonly are non-spherically,
and there is no clear mechanism for a single AGB star to eject a strongly a-
spherical nebula (Soker 1998). The efficiency of the dust-driven wind has also
been questioned (Woitke 2006).

Binary companions can affect the mass loss in several ways. Close companions
will evolve through a common envelope phase, leading to rapid envelope ejection:
this may be called type I. More distant companions interact with and shape the
wind but do not enhance the mass loss rate: type II. Very wide binaries cause
the centre of mass to shift, leading to a spiral embedded in the wind (Mauron &
Huggins 2006), but have no other effect (type III). Thus, type-I is binary-induced
mass loss, type-II binary-shaped mass loss, and type-III orbital shaping of the
mass loss.

2. SURVEYS

Detections of binary companions are done in four different ways. First, di-
rect CCD imaging reveals distant companions. Second, spectroscopy reveals cool
(non-ionizing) components to the stellar spectrum. Third, photometric monitor-
ing shows brightness fluctuations due to rotation of the heated surface of a close
companion, or in a few cases eclipses. Fourth, radial velocity variations trace the
orbital motion. There are some caveats to these methods. Distant companions
may be line-of-sight coincidences. Eclipses can be due to orbiting dust clouds, as
in the case of NGC 2346 (e.g. Roth et al. 1984). Radial velocities can be affected
by wind variations: only strict periodicity can be taken as evidence for a binary
companion, but it has proven difficult to acquire the temporal sampling required
for this.

The main survey for spatially resolved binaries is that of Ciardullo et al. (1999)
using an HST snapshot survey of 113 nearby systems. They find 19 possible com-
panions, of which approximately 6 are expected to be due to confusion. The target
selection criteria for the Ciardullo et al. survey included suspected binarity, so that
converting the detection rate to a binary fraction has some uncertainty. Roughly
10% of PNe are found to have distant \((10^2-10^4\text{ AU})\) companions. The detected
companions are mostly main-sequence stars. This is expected for reasons of sen-
sitivity, as white dwarf companions will be faint and red giant companions short-
lived. More recently, Benetti et al. (2003) detected a companion in NGC 6818
but this requires confirmation. No other surveys have been done. Adaptive optics
using the central star may now be competitive with the HST observations.

More is known on non-resolved binaries. De Marco (2006) presents a list of 25
close-binary central stars. To this may be added Me1-1 (Shen et al. 2004) which
has a K3-4 giant companion but the orbital parameters are not known and it may
be a symbiotic star. On the other hand, the evidence for the claimed companion
of NGC 6302 is unconvincing and this object should be removed for now. Binary
periods range from hours to days. The longest known period is 68 days for Sh 2-71
(Jurcik 1993). The central star of LoTr5 is believed to be a triple; one photometric
period of 5.9 days is believed to be the rotation period (Strassmeier et al. 1997).
A63 is a known triple system, with an 11-hour eclipsing component and a third
star 2.8 arcsec away (Ciardullo et al. 1999). Among the confirmed close binaries,
four objects are eclipsing.

Sensitivity to companions at distances of 1–10 AU is poor: only radial velocity
surveys are sensitive to such companions. For A35, a resolved companion at 18 AU
Binary central stars

was found by Gatti et al. (1998). Kinematic evidence for Hu2-1 suggests a binary with separation of 9–27 AU (Miranda et al. 2001) but the evidence is indirect.

Selection effects need to be considered. Detection of distant companions is easiest for faint central stars and large, faded nebulae. On the other hand, detection of close binaries requires a relatively bright star with a faint nebula. This is found in systems where the star evolves much slower than the nebula, i.e. the nebula has had time to expand but the star is still relatively cool. This favours low-mass central stars. The requirement for a bright central star may also directly select binaries if the visual brightness of the companion is similar to or exceeds that of the central star.

\[ \text{Fig. 1. Observed binary separations as fraction of the population, for planetary nebulae and post-AGB stars. Based on data kindly provided by van Winckel.} \]

Surveys for post-AGB stars have uncovered a number of stars located on the HR diagram between the AGB and the PNe. These include optically bright stars with circumstellar dust. Surveys have shown that these are invariably binaries, with periods of typically 300–1200 days (van Winckel 2003). Fig. 1 shows the orbital separations (assuming a total mass of $1.4 \, M_\odot$) and periods, compared to those of the binary PNe. All are converted to a population fraction, where for PNe I assume that all known binaries come from the $\sim 100$ PNe which have stars bright enough to be easily observable. The lack of overlap is remarkable.

On the short-period side, the PNe systems must have gone through a common-envelope phase. The post-AGB stars have avoided this, as indicated by the ellipticity of the orbits. Thus, these are distinct populations. Very wide binaries are unobservable among post-AGB stars because the stars are too bright. However, one can expect that if a large fraction of PNe central stars were binaries with orbital separations similar to the post-AGB stars, this would have been discovered. It seems probable that the binary post-AGB stars do not evolve into 'typical' PNe.

3. MORPHOLOGIES

The standard morphologies of planetary nebulae are: round, elliptical, bipolar
(or butterfly), and irregular (Balick & Frank 2002). Binary interactions are the main proposed origin of the non-spherical structures, although different precise mechanisms have been suggested. The binary companion acts as a source of angular momentum, either to the stellar ejecta or, in the case of a common envelope, directly to the star.

The most pronounced morphology is that of the butterfly shape. One might predict that PNe around close binary stars would show this shape as they experience the most efficient transfer of angular momentum to the ejecta. However, observations do not fully confirm this. Of the three systems with possible CV nuclei (HFG1, A65, K1-2) none are bipolar (Walsh & Walton 1996). Only one butterfly nebula has a confirmed binary nucleus (NGC 2346): it has a period of 16 days, among the longer periods known.

Planetary nebulae around closer binaries do show deviations from spherical symmetry (Bond & Livio 1991): about half appear bipolar or elliptical, and one shows a jet-like structure. One is perfectly round, but Bond & Livio argue this object (Sp1) is likely seen pole-on. This was confirmed by Mitchell (priv. comm.) from kinematics of the nebula. These objects lack the characteristic double shell morphology of normal PNe. The last point suggests that they evolve differently from other, ‘normal’ PNe.

Overall, rather irregular structures appear to be the norm for the closest binaries, as for example shown in Fig. 2 (from Pollacco & Bell 1997). An interesting case is A63, which shows an expanding, edge-on torus (shown in Fig. 3) and two polar blobs several arcminutes from the star. They trace a tightly collimated flow. Mitchell et al. (2006) show that the polar ejection is almost in the plane of the sky. The central star is known to be eclipsing. This is strong evidence that the torus is expelled in the orbital plane and that the collimated outflow is perpendicular to the orbital plane. This implies that the nebula was expelled by type-I binary interaction.

![Fig. 2. The non-eclipsing PN Ds1 (0.45 days).](image)
An interesting suggestion is that PNe with the closest (hours to days) binary stars show thin, expanding rings, while somewhat longer periods (tens of days) give thick expanding torii and lead to butterfly nebulae. The thin rings (seen in objects such as SuWt1, A 61 and WeBo1: e.g. Bond 2000) contain less mass but are dynamically cold and may contain more angular momentum. The torii are more massive but contain limited angular momentum. These two categories may trace different types of interaction. The thin ring may contain material lost through the outer Langrangian point.

It appears that known post-common-envelope systems have identifiable morphologies which are not particularly common among planetary nebulae. Whether this holds for all such systems remains to be seen.

4. POPULATION STUDIES

Corradi et al. (1995) find that 15 per cent of Galactic PNe are bipolar. The bipolars have a smaller scale height in the Galaxy than other types, indicating on average a higher progenitor mass. If the link between bipolarity and binaries holds, this indicates that 15 per cent of PNe progenitors have companions close enough to affect the mass loss. An unpublished survey of compact Bulge PNe carried out with HST shows 27 per cent to be bipolar; an additional 13 per cent show morphologies which may be post common envelope systems: multi-polar, spiral (one object), or thing ring structures. Adding the bipolar/butterfly systems would give a maximum fraction of type-I interaction of order of 40 per cent. New nearby bipolar nebulae are still being discovered (Frew et al. 2006) and the percentage among Galactic disk PNe could increase.

Detailed population studies are presented by de Marco & Moe (2006). About half of stellar systems are known to be multiple. Of the multiple systems, about 25 per cent have wide separations in the range traced by Ciardullo et al., and a similar number are so close that interaction is expected during the post-main sequence evolution. Of the latter, about a third will form a common envelope on the first giant branch, and will never reach the AGB, unless a merger occurs first. They are unlikely to form PNe. The remaining fraction is not inconsistent with the fraction of post-common envelope systems found in the Bulge, and the fraction of detected binary systems shown in Fig. 1.

However, de Marco & Moe (2006) arrive at a different conclusion, and argue
that only close binary interactions lead to PN, i.e. the fractions above become 100 per cent. This requires that single-star mass loss is insufficient to create a dense PN. Soker & Subag (2005) predict that single stars give rise to fainter PNe, which are under-represented in existing samples.

The easiest way to distinguish between type-I binary evolution models and all other models is to test the predicted final masses of the stars. To obtain observed mass distributions, Gesicki & Zijlstra (2000) use diagrams of dynamical age versus stellar temperature to infer the rate of temperature increase of the star, which is a strong function of mass of the (pre-white-dwarf) central star. These diagrams measure the stellar masses, much more accurately than can be done with photometric or spectroscopic methods. They find a narrow distribution, between 0.57 and 0.65 $M_\odot$ (Fig. 4, left panel). (Note that the method used is restricted to regular PNe and that therefore the sample excludes bipolar nebulae.) The observed distribution is consistent with expectations: for lower masses, stars evolve so slowly that the nebula disperses before the onset of ionization. At higher masses the evolution is so fast that there is little chance of catching an object in this phase.

![Fig. 4. Left: Mass distribution of central stars of PNe (from Gesicki et al. 2006). Right: predictions from type-I binary models (from de Marco & Moe 2006).](image)

The narrow mass range fits in well with our knowledge of AGB evolution: the mass loss is linked to stellar parameters such as the core mass, and the AGB evolution is terminated at a fixed point where the mass-loss rate exceeds the nuclear burning rate. But common envelope evolution does not predict such a narrow range. The end point of evolution depends on the mass and orbital parameters, and a wider range of resulting masses may be expected, biased towards lower final masses than obtained from single-star AGB evolution. The right panel of Fig. 4 shows the binary-model predictions from Marco & Moe (2006) (their Fig. 11). As expected, it is strongly peaked towards lower masses, and differs significantly from observed distributions.

5. EVOLUTION

The stellar mass distribution of Fig. 4 indicates that common envelope evolution is not the dominant evolutionary branch on the AGB. However, it can account for a larger fraction of the lower-mass PNe central stars.

The observations now suggest several distinct routes to the post-AGB region of the HR diagram. Single-star evolution leads to normal PNe. Type II interactions
also evolve on this track. Type I evolution early on the AGB leads to a low mass remnant, which evolves too slowly to become a PN. These may be the binary post-AGB stars discussed above. Finally, type-I evolution during the thermal-pulsing AGB leads to a remnant which evolves sufficiently fast to become a PN, leading to the ‘thin ring’ or ‘thick torus’ nebulae.

6. CONCLUSIONS

The established models for AGB/post-AGB/PNe stellar evolution are in terms of single-star evolution. But the nebular morphologies suggest that binary interactions do have an important role to play. The work by de Marco & Moe (2006) has invigorated the field. Whether binary interactions are as dominant as argued by them remains to be proven, but there is a strong case that the binary channel is a significant one for post-AGB evolution.

Observationally, we can distinguish three types of interactions: binary-induced mass loss (type I), binary-shaped mass loss (type II) and shaping by orbital motion (type III). From present samples, it appears that type-I interactions lead to identifiable morphologies, characterized by expanding rings and collimated outflows for the closest binaries, and thick expanding torii tracing somewhat wider binaries. The physical parameters determining the final result are not known, but bipolar nebulae tend to have higher mass progenitors. Type-II interactions are probably very common, as shown by the companion to Mira itself and the possible shaping of its wind (e.g. Josselin et al. 2000). These are therefore a leading contender for the main shaping mechanism for planetary nebulae.

Surveys for binary companions have not yet been completed. To spatially resolve systems, ground-based adaptive optics may proof to be competitive with HST. Binaries of separations of order 1 AU are missing among the PN samples: velocity monitoring should be attempted to find this missing link.

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