Common Envelope Evolution through Planetary Nebula Eyes

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Abstract. The common envelope interaction is responsible for evolved close binaries. Among them are a minority of central stars of planetary nebula (PN). Recent observational results, however, point to most PN actually being in binary systems. We therefore ask the question if it is feasible that most, or even all Galactic PN derive from a common envelope interaction. Our recent calculation finds that if all single and binary primary stars with mass between $\sim1-8\ M_\odot$ eject a PN, there would be many more PN in the galaxy than observed. On the other hand, the predicted number of post-common envelope PN is more in agreement with the total number of PN in the Galaxy. This is a new indication that binary interactions play a functional role in the creation of PN and an encouragement to intensify efforts to detect binary companions.

INTRODUCTION

Most planetary nebulae (PN) are not spherical, but have elliptical or bipolar shapes [1]. The explanation of why Asymptotic Giant Branch (AGB) stars would more often than not eject a non spherical PN has been the center of a hot debate in the field. Among the theories of the origin of the asymmetry, are fast rotation of the AGB star, global magnetic fields and binary interactions (see [author?] [2] for a review). However, none of these theories allows the case to rest. AGB stars are large and are not known to rotate at rates that would allow them to eject a sufficiently equatorially-concentrated wind. AGB stars and post-AGB central stars of PN are known to possess magnetic fields, but these are unlikely to have the global structure capable of shaping the AGB wind and induce the observed PN morphologies [3].

The large variety of binary parameters allows interactions scenarios capable of creating any type of morphology. (author?) [1] lists these scenarios, which include binary interactions between the primary star and stellar or sub-stellar companions with a variety of separations: the outcome of the interactions vary between binaries that do not enter CE, to those that do enter a CE phase and emerge from it as a close binary, to those that enter a CE phase and merge. To each scenario corresponds a specific PN morphology.

The problem with these scenarios is that, appealing as they may be, it is difficult to constrain them observationally. Thus far, there is conclusive evidence that only about 10% of all PN harbour close binary central stars [4], with an additional 10% with wide binary central stars [5]. These numbers, however, are biased because the close-binary detection technique of (author?) [4] can only detect binaries with periods shorter than a few days. In an attempt at determining the exact number of close-binary central stars (author?) [6] carried out a radial velocity (RV) survey of central stars of PN in the northern hemisphere and (author?) [7] have done the same with a sample in the southern hemisphere [Bond, these proceedings]. Their results indicate that most of the central stars observed have radial velocity variability. If all the RV-variable stars are binaries, these results imply that PN are by and large a CE phenomenon.

Unfortunately, the sampling of the observations did not allow either study to determine periods (except in the case of IC4593 for which a period of 5.1 days was convincingly detected). With one period and small sample sizes, these results are indicative but not conclusive. RV variability could, for instance, be due to wind variability for at least half of the samples. The RV variable stars are the subject of a new observing campaign, at echelle resolutions, which will determine the impact of wind variability and, hopefully, detect periods (De Marco et al., in prep.).

In addition to the challenge of accounting for binarity in the central star population observationally, there is the additional theoretical challenge of determining what to expect. Theory can guide observations, but thus far our knowledge of the interaction that leads to a PN and a short period binary central star is deficient (for a review see [8]). The CE is thought to be responsible for the production of short period binaries, but the details of the interaction, e.g., the efficiency with which the secondary transfers its orbital gravitational energy and angular momentum to the envelope of the primary, are
murky at best.

In this contribution we carry out a simple calculation of the expected number of galactic PN deriving from CE ejections as well as report on some progress on CE simulations.

POPULATION SYNTHESIS MODEL OF THE GALACTIC PN POPULATION

Detecting binary companions to the bright component of central stars of PN is an extremely hard task. Radial velocity surveys are time-consuming and if unknown periods are to be determined, the correct time sampling is key. This is hard to achieve due to restrictions in telescope scheduling, as well as bad weather or any other unpredictable factors. This is why, after four years of successful telescope allocations, the northern sample of (author?) 2 still stands at 11 objects with only one period determined.

Successful telescope proposals depend on convincing the time allocation committees that the time devoted to the project will produce results. This is particularly hard when results have been slow coming. In addition, two objections have repeatedly arisen when the high RV-variability results are presented at talks. One of them is why should single post-AGB stars not eject a PN. The other is that the main sequence

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The former objection to the binary PN hypothesis has been investigated by (author?) 2 who argue that the spherical PN produced by single AGB stars could be much less likely to be detected because they are inherently less luminous. Below, we attempt to answer the latter objection by constructing a population synthesis toy model. A more sophisticated version of the calculation below is underway (Moe & De Marco, in prep.).

The number of PN deriving from common envelope interactions

- To start, we assume that only systems that undergo a CE on the AGB will result in a PN. This is because very few central stars of PN have ever been found to be post-Red Giant Branch (RGB) stars (two examples of post-RGB central stars are EGB5 and PHL932; (author?) 10). We therefore exclude systems that undergo a CE on the RGB, i.e., those main sequence binaries with separations smaller than \( \sim 100 \text{ R}_\odot \) 10.

- We do not account for systems that have undergone two AGB CEs, i.e., both the primary and secondary have evolved through the AGB expansion and each time a CE has ensued. These systems are responsible for WD-WD binary central stars. We will deal with these interesting systems in our refined calculation but forecast that they are infrequent and will not add much to the total number of PN with close binary central stars.

- Determination of the total number of binary systems in the Galaxy. First, we summed the matter contributed by stars in the galactic disk, bulge, and halo \( (7.5 \times 10^{10} \text{ M}_\odot) \) (author?) 12, 13). The total number of stars in the galaxy is then calculated by normalizing the luminous matter to the average mass of a star \( (0.54 \text{ M}_\odot) \) calculated using the Initial Mass Function (IMF) 14, 15. This results in \( 1.4 \times 10^{11} \) stars. Applying the incidence of binaries, which is observed to be about 60\% of all systems investigated 16, to the number of stars in the Milky Way, the number of binary stars is determined to be \( 5.2 \times 10^{10} \) (NB this is not just the number of stars times 0.6, since each binary system contributes two stars).

- Determination of the number of primaries with the right mass and calculation of the mean primary's mass of our sample of binaries. Some stars have masses that are too low \( (< 1.05 \text{ M}_\odot) \) to evolve off the main sequence in the average age of the galaxy (assumed to be 8.5 Gyr: (author?) 18, 19). Stars with masses too high \( (> 10 \text{ M}_\odot) \) will never contribute to the PN population, but instead will undergo a supernova explosion. Using the IMF 21, 15, we determined the number of binary systems with primaries between minimum and maximum mass limits \( (8.4\% \text{ of all binary systems in the Galaxy, i.e., } 4.4 \times 10^9 \text{ systems}) \). This population of binaries is then represented by the mean mass of the primaries \( (1.78 \text{ M}_\odot) \) calculated integrating the IMF between our minimum and maximum mass values.

In the future we will not represent the entire population of binaries by the mean mass of the primaries, but we will split the populations of primaries into mass bins, each represented by a mean mass and we will follow the evolution of each group. Also, the stellar lifetimes depend on the metallicity of the star. For further refinements of our calculation, we will consider the Galaxy as continually star-forming and use the star formation history as well as the age-metallicity relation to follow the lives of stellar mass bins.

- Determination of the total number of binaries with the right orbital separation. We assume that all
post-CE binaries, where the CE happened on the RGB, will not produce a PN (a \( < 100 \, R_\odot \)). Therefore, we are only concerned with the binaries that have the orbital separation in a range such that the companion will be engulfed as the primary expands during its ascent of the AGB. This implies separations in the range \( 100 \, R_\odot < a < 500 \, R_\odot \). From the period distribution of binaries \( [16] \), the number of systems within this range was determined (12.1\% of all the binaries previously counted, i.e., \( 5.3 \times 10^8 \) systems). We currently assume that when a primary fills its Roche-Lobe at the bottom of the AGB the mass transfer is always unstable and a CE will always ensue. This is a good assumption since the primary’s envelope will quickly become convective.

- **Binaries with the right mass ratio.** The companion must have sufficient gravitational energy to unbind the envelope of the primary during the CE. Therefore, the companion-to-primary mass ratio has to be large enough. We took \( M_2/M_1 = q > 0.15 \) \( [22] \) (see also below). By investigating the observed distribution of mass ratios \( [16] \), the fraction of binaries that will eject the AGB CE can be determined (80.3\% of all systems previously counted, i.e., \( 4.3 \times 10^8 \) systems).

However, the mass ratio distribution \( [16] \) is for main sequence binaries only; \( q > 0.15 \) however, applies to ratios of the companion to the mass of the primary on the AGB, which is smaller than it was on the main sequence. Thus, in future calculations, we will have to account for the mass-loss rates up through to the AGB phase \( [23] \), and derive the mass ratio at the time of CE from that of main sequence stars. It is also fundamental that the ejection of the envelope occurs when the central core is luminous enough to sufficiently photo-ionize the ejected material and produce a visible PN. If the initial binary separation is too small and the CE ejection happens when the primary is at the very bottom of the AGB, the post-CE primary will have too low luminosity and will never have enough hard photons to ionize the surrounding matter sufficiently for a PN to be detected. We will account for this effect in our refined calculation.

Combining the previous steps yields the absolute number of galactic PN formed via a CE ejection which harbor close binary central stars. If we assume an average PN lifetime of \( 2.0 \times 10^4 \) years and an average stellar lifetime of \( 1.3 \times 10^9 \) years calculated from the average primary mass (1.78 M\(_\odot\)), then the total number of post-CE PN currently in our galaxy is 6600 within a factor of 3 uncertainty.

This number should be compared to the actual number of galactic PN. The number of observed PN in the Galaxy is \( \sim 3000 \) \( [24] \), but this is a lower limit because of the large extinction on the galactic plane. Rather than trying to estimate the total number of galactic PN extrapolating their numbers by accounting for extinction, a better estimate of the total number of galactic PN can be derived by counting PN in external galaxies with similar morphology and mass. This number is \( 7200 \pm 1800 \) \( [25] \), not dissimilar to the predicted number of PN from CE ejections.

Using the calculation above we can also predict the number of PN in the galaxy if both single and binary stars make a PN after ascending the AGB. This is 113,000 within a factor of 2, hence much larger than the observationally-deduced number, even allowing for the considerable uncertainty. This means that only 5.6\% of stars (single or in binaries) capable of ascending the AGB produce a PN via a CE ejection.

This fraction can be compared with the results of \( \text{(author?)} \) \( [26] \). \( \text{(author?)} \) \( [26] \) determined that 13\% of all binaries result in a CE ejection from the primary expansion on the RGB and AGB (where the secondary is a main sequence stars). Only 0.3-0.5 of these binaries are post-CE on the AGB, according to their models. We must further multiply this fraction by 60\%, the total binary fraction on the main sequence. The fraction of suitable stars that produce a PN via a CE interaction on the AGB is therefore 2.5-4\%, not dissimilar from our estimate. A detailed comparison between our calculation and the population synthesis model of \( \text{(author?)} \) \( [26] \) will be presented in Moe & De Marco (in prep.).

### COMMON ENVELOPE SIMULATIONS

\( \text{(author?)} \) \( [22] \) carried out a series of 3-dimensional hydrodynamic simulations using the code and method of \( \text{(author?)} \) \( [27] \). Two of these simulations (Fig. 1) were repeated at higher resolution and with a larger box size. These simulate the effect of a 0.1- M\(_\odot\) companion entering CE with a 1.25- M\(_\odot\) primary at the bottom of the AGB or a 1.04- M\(_\odot\) primary at the top of the AGB (both these stellar models descend from a 1.5- M\(_\odot\) main sequence primary).

The most important result to come from these simulations is the extreme sensitivity of the outcome of the CE interaction to the stellar and system parameters: at the bottom of the AGB the more massive envelope with a smaller radius is practically impervious to the penetration of the companion and no envelope ejection occurs. The same small companion does eject the envelope at the top of the AGB since by then the primary envelope is less massive and more extended. The result is a short period binary with a period of about one month. The primary-to-secondary mass ratio to eject the envelope is therefore
a sensitive function of when the secondary penetrates the primary. Our choice of a value of 0.15 therefore leads to a lower limit to the number of post CE binary central stars since if CE is entered at the top of the AGB it appears that a ratio as low as 0.1 will suffice to eject the envelope.

SUMMARY

- There is a strong indication that the central star of PN close binary fraction might be much higher than the 10% believed thus far and possibly as high as 90-100%. If confirmed this would establish that PN are fundamentally a binary interaction byproduct.
- Based on a population synthesis toy model it is not inconceivable that all of the PN present in the Galaxy today derive from CE interactions that lead to the ejection of the envelope and leave behind a short-period binary.
- If all of the single and binary post-AGB stars within a certain mass range produced PN we should observe about 5-10 times more PN in the galaxy today.
- To determine the CE parameters which are key in any population synthesis calculation we need more theoretical knowledge of the interaction. From our calculation we can already say that CE interactions can lead to a binary for secondary-to-primary mass ratios as small as 0.1.

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REFERENCES

1. N. Soker, ApJS 112, 487+ (1997).
2. B. Balick, and A. Frank, ARAA 40, 439–486 (2002).
3. N. Soker, ArXiv Astrophysics e-prints (2005).
4. H. E. Bond, “Binarity of Central Stars of Planetary Nebulae,” in ASP Conf. Ser. 199: Asymmetrical Planetary Nebulae II: From Origins to Microstructures, 2000, pp. 115+.
5. R. Ciardullo, H. E. Bond, M. S. Sipior, L. K. Fullton, C.-Y. Zhang, and K. G. Schaefer, AJ 118, 488–508 (1999).
6. O. De Marco, H. E. Bond, D. Harmer, and A. J. Fleming, ApJL 602, L93–L96 (2004).
7. H. E. Bond, and M. Afsar, American Astronomical Society Meeting Abstracts 205, + (2004).
8. I. J. Iben, and M. Livio, PASP 105, 1373–1406 (1993).
9. N. Soker, and E. Subag, ArXiv Astrophysics e-prints (2005).
10. R. H. Mendez, R. P. Kudritzki, H. G. Groth, D. Husfeld, and A. Herrero, AAP 197, L25–L28 (1988).
11. B. Dormann, R. T. Rood, and R. W. O’Connell, ApJ 419, 596+ (1993).
12. W. Dehnen, and J. Binney, MNRAS 294, 429+ (1998).
13. D. Mera, G. Chabrier, and R. Schaeffer, AA 330, 937–952 (1998).
14. P. Kroupa, C. A. Tout, and G. Gilmore, MNRAS 262, 545–587 (1993).
15. G. Chabrier, PASP 115, 763–795 (2003).
16. A. Duquennoy, and M. Mayor, AA 248, 485–524 (1991).
17. L. Portinari, C. Chiosi, and A. Bressan, AA 334, 505–539 (1998).
18. W. M. Liu, and B. Chaboyer, ApJ 544, 818–829 (2000).
19. M. Zoccali, A. Renzini, S. Ortolani, L. Greggio, I. Saviane, S. Cassisi, M. Rejkuba, B. Barbay, R. M. Rich, and E. Bica, AA 399, 931–956 (2003).
20. I. J. Iben, Phys. Rev. 250, 2–94 (1995).
21. P. Kroupa, MNRAS 322, 231–246 (2001).
22. O. De Marco, E. L. Sandquist, M.-M. Mac Low, F. Herwig, and R. E. Taam, “Wolf-Rayet Central Stars and the Binary Evolution Channel,” in Revista Mexicana de Astronomia y Astrofisica Conference Series, 2003, pp. 24–30.
23. J. R. Hurley, O. R. Pols, and C. A. Tout, MNRAS 315, 543–569 (2000).
24. Q. A. Parker, M. Hartley, D. Russeil, A. Acker, D. H. Morgan, S. Beaulieu, R. Morris, S. Philipps, and M. Cohen, “A Rich New Vein of Planetary Nebulce From the AAO/UKST Hot Survey (invited review),” in IAU Symposium, 2003, pp. 25–++.
25. M. Peimbert, Revista Mexicana de Astronomia y Astrofisica, 20, 119+ (1990).
26. Z. Han, P. Podsiadlowski, and P. P. Eggleton, MNRAS 272, 800–820 (1995).
27. E. L. Sandquist, R. E. Taam, X. Chen, P. Bodenheimer, and A. Burkert, *ApJ* **500**, 909–+ (1998).