Population synthesis of galactic PN from strong binary interactions

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We present a population synthesis of Galactic PN that derive from strong binary interactions on the AGB. These binary interactions not only shape the morphology of the subsequent PN, but also induce via tidal spin-up and/or a CE event a significant increase in the mass-loss rate on the AGB, i.e. a superwind with $M > 10^{-5} \text{M}_\odot \text{yr}^{-1}$, which we claim is a prerequisite for PN formation. To infer the rate of strong binary interactions, we use the observed binary frequency, mass ratio, and period distributions, the most up-to-date stellar evolutionary tracks to determine the radial evolution of the giant primaries, a careful treatment of the star-formation history and metallicity evolution of our Galaxy derived by Moe & De Marco (2006), and a detailed analysis of the binary equations governing tidal capture, synchronization, mass loss, Roche-lobe overflow, and CE evolution.

We find that 5,100 ± 2,100 Galactic PN with radii $r < 0.9$ pc (ages < 35,000 yr) derive from strong binary interactions on the AGB, which comprise 30%–70% of the expected total number of PN in our Galaxy with the same radius/age constraint. We report that ∼65% of these PN from strong binary interactions form from a traditional CE with a main-sequence companion in which the companion survives the CE resulting in binaries with final periods 30 min < $p$ < 10 days, ∼15% derive from a CE near the tip of the AGB so that the giant quickly detaches from its Roche lobe and leaves the companion at final periods of 5 days < $p$ < 3,000 days, ∼8% have companions that avoided CE altogether and remain at periods $p$ ∼ 5,000 days but tidally spun up the primary giants above 15% of their Keplerian velocity, ∼7% come from a traditional CE with a brown dwarf companion that did not survive the CE and merged with the core of the primary but still imparted sufficient angular momentum to the AGB’s envelope so that it would spin above 15% of Keplerian at the end of its evolution, and ∼5% are double-degenerate systems with two carbon-oxygen white dwarfs.

We also find that the central star mass and luminosity distributions of the PN that derive from strong binary interactions are in better agreement with observations than the predicted distributions from single stars, mainly due to the fact that a CE will quickly reduce the radius of the post-AGB object, thereby effectively accelerating the post-AGB evolution to hotter temperatures. Furthermore, we explain how current observations of a CSPN close binary fraction of ∼15% is consistent with our population synthesis, considering that only half of our PN from binary interactions have predicted periods < 3 days such that systems at longer periods currently remain undetected via photometric variability (either due to the fact that the observational techniques are insensitive to these companions and/or heat diffusion across the surfaces of these companions equalizes the temperature in timescales ∼3 days). Also, ∼30% of these strong binary interaction systems have companions less massive than 0.3 M$_\odot$ and therefore escape detection due to their faintness. We finally offer a self-consistent paradigm for PN formation where half of PN derive from strong binary interactions on the AGB and the other half come from the most massive stars $M_{MS} > 1.9$–2.7 M$_\odot$ (i.e. the ∼10% high mass tail of the IMF) that do not undergo a strong binary interaction but are luminous enough at the end of their AGB evolution to produce the required superwind to form a PN.
Population synthesis of galactic PN from strong binary interactions
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I. Introduction
We propose that in addition to shaping a PN, a binary companion is also the dominant catalyst in PN formation itself. PN formation requires a supervoid ($M > 10^5 M_\odot$ yr$^{-1}$) at the tip of the AGB (Bonn & Benzini 1983); otherwise the PN would be too low in surface brightness to be observed. Most mass loss prescriptions require a progenitor mass of $M_{\text{env}} = 1.5 - 2.5 M_\odot$ in order for the subsequent AGB star to achieve a supervoid (Wachter et al. 2002). A binary system can also achieve a supervoid due to a common envelope (CE) event and/or tidal spin-up of the primary giant above ~15% its Keplerian velocity (Dorfl & Hoffner 1996). We conducted a population synthesis to determine the expected number of PN in our galaxy that derive from these strong binary interactions on the AGB.

II. Parameters of population synthesis
- Star formation history and metallicity evolution in our galaxy derived in Moe & De Marco (2006)
- Binary fraction, period, and mass ratio ($q$) distributions from Duquennoy &Mayor (1991) and Shakby & Tokovinin (2002)
- Latest stellar evolutionary models (Bertelli et al. 2008, 2009; Marigo et al. 2007, 2008)
- Tidal capture equations of Zahn (1989) and Tassoul (1998) as described in Eggleton (1983)
- Onset of synchronization assuming corotating giant with $L_{\text{Kep}} = 0.15 M_\odot R_\odot$ and Roche lobe overflow (RLOF) occurs as described in Sokor (1996)
- Metallicity dependent initial to final mass relation (IFMR) (Moe et al. 2008)
- CE curtails central stars (CS) growth by $< 0.01 - 0.09 M_\odot$
- CE synchronization determined by $q_{\text{sync}} = 0.2, 0.6, & 0.1q^2$ (De Marco et al., submitted)
- Post-AGB evolution dependent on core mass and final binary separation (Yassiladis & Wood 1994 and Böker 1995)

III. Binary evolutionary channels
1) RLOF on the RGB – those do not make PN
2) CE on the AGB where final separation is determined by $q_{\text{syn}}$
3) CE near AGB tip, i.e. $R > 0.8 R_\odot$ so that the primary giant quickly detaches from Roche lobe leaving companion at final periods log $P$ (days) $\approx 0.5 - 3.5$
4) Companion avoids CE altogether but synchronizes and spins primary giant $> 15\%$ its Keplerian velocity
5) Companions with $0.01 < q_{\text{min}} < 0.05$ undergo CE, spin primary’s envelope $> 15\%$ Keplerian, and merge with core
6) While dwarf $+ AGB$ binaries undergo a second phase of synchronization $> 15\%$ Keplerian and (or CE at the AGB tip

IV. PN Numbers & Distributions

Table I – Predicted number of PN with w $= 0.9$ pc

<table>
<thead>
<tr>
<th>Channel</th>
<th>Thin Disk</th>
<th>Galaxy</th>
<th>CE Mid-AGB</th>
<th>CE Tip-AGB</th>
<th>Synchronized</th>
<th>Mergers</th>
<th>Double Degenerate</th>
<th>All Strong Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td># PN</td>
<td>10,000</td>
<td>16,700</td>
<td>6,200</td>
<td>2,000</td>
<td>3,700 ± 2,100</td>
<td>5,100 ± 2,100</td>
<td>5,100 ± 2,100</td>
<td>7,000</td>
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<td>Synchro.</td>
<td>5,100 ± 2,100</td>
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<td>Mergers</td>
<td>10,000 ± 2,000</td>
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</tr>
<tr>
<td>Binaries</td>
<td>2,000 ± 1,600</td>
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Table II – Comparison with expected number of PN with w $= 0.9$ pc, i.e. ages $> 35,000$ yr.

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V. Conclusions
About 50% of PN in our galaxy derive from strong binary interactions on the AGB, which is consistent with a close CSPN binary fraction of ~15%. The CSPN mass and luminosity distributions are better described by binary progenitors.