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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 $\dot{M} > 10^{-5}$ M$\odot$ 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 $p \sim$ 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 $M_{\rm MS} > 1.9$–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.

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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 superwind ($\dot{M} > 10^{-5}$ $M_\odot$ yr^{-1}) at the tip of the AGB (Iben & Renzini 1983); otherwise the PN would be too low in surface brightness to be observed. Most mass loss prescriptions require a progenitor mass of M_{MS} = 1.5 – 2.5 $M_\odot$ in order for the subsequent AGB star to achieve a superwind (Wachter et al. 2002). A binary system can also achieve a superwind due to a common envelope (CE) event and/or tidal spin-up of the primary giant above ~15% its Keplerian velocity (Dorfi & Höfner 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 Shatsky & Tokovinin (2002)
- Latest stellar evolutionary models (Bertelli et al. 2008, 2009; Marigo et al. 2007, 2008)
- Tidal capture equations of Zahn (1989) and Tassoul (1987) as described in Soker (1996)
- Onset of synchronization assuming corotating giant with $I_{giant} \sim 0.18 M_{env} R^2$, and Roche lobe overflow (RLOF) occurs as described in Eggleton (1983)
- Metallicity dependent initial to final mass relation (IFMR) (Meng et al. 2008)
- CE curtails central stars (CS) growth by ~0.01 – 0.09 $M_\odot$
- Post-CE separation determined by α_{CE} = 0.2, 0.6, & $0.1q^{-1}$ (De Marco et al., submitted)
- Post-AGB evolution dependent on core mass *and* final binary separation (Vassiliadis & Wood 1994 and Blöcker 1995)

III. Binary evolutionary channels

1) RLOF on the RGB – these do *not* make PN
2) CE on the mid AGB where final separation is determined by α_{CE}
3) CE near AGB tip, i.e R > 0.8 R_{max}, so that primary giant quickly detaches from Roche lobe leaving companion at final periods log P (days) = 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_{MS} < 0.05 undergo CE, spin primary's envelope >15% Keplerian, and merge with core
6) White dwarf + AGB binaries undergo a second phase of synchronization >15% Keplerian and/or CE at the AGB tip

III. Binary evolution (cont.)

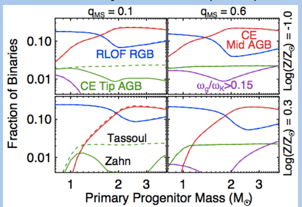


Fig. 1 – Fraction of binaries that enter various evolutionary channels. **Note that the rates are independent of the tidal mechanism for q_{MS} > 0.15.**

IV. PN Numbers & Distributions

Channel	Thin Disk	Galaxy
All Stars	37,000 ± 15,000	61,000 ± 17,000
CE Mid AGB	2,600 ± 1,800	3,300 ± 1,800
CE Tip AGB	490 ± 230	770 ± 240
Synchronized	170 ± 100	370 ± 120
Merger	260 ± 290	340 ± 290
Double Degenerate	140 ± 80	230 ± 80
All Strong Binary	3,700 ± 2,100	**5,100 ± 2,100**

Table I – Predicted number of PN with radii < 0.9 pc, i.e. ages < 35,000 yr.

# PN w/ r < 0.9 pc	Galaxy	Bulge	Globular Clusters
Synthesis-All stars	61,000 ± 17,000	18,700 ± 7,000	43 ± 13
Synthesis-Binary	5,100 ± 2,100	1,000 ± 310	2.9 ± 0.7
Expected Number	10,000 ± 2,000	2100 ± 400	4 ± 2
Binary Fraction	**(51 ± 23)%**	**(48 ± 17)%**	**(72 ± 36)%**

Table II – Comparison with expected number from observations. Assuming the three binary fractions are independent, then **the best estimate of the fraction of PN that derive from strong binary interactions is (52±13)%.**

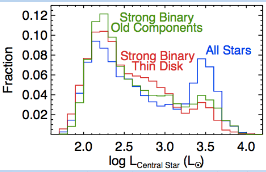


Fig. 2 – Central star luminosity distribution. Note that the ~50% difference between the peak at $\log(L/L_\odot)$~3.0 and dip at $\log(L/L_\odot)$ ~3.2 in **the binary model is more consistent with observations of the PNLF** (Ciardullo 2009) than the factor of ~3 difference predicted for single stars. This is due to **the CE accelerating the post-AGB evolution toward the `knee' in the HRD**. Also note that using **a metallicity dependent IFMR reproduces the observed consistency of the PNLF between older and younger stellar populations.**

IV. PN Distributions (cont.)

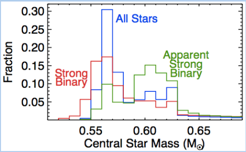


Fig. 3 – Central star (CS) mass distribution. The apparent strong binary distribution is determined by using the PN age and CS temperature on the HRD to estimate the core mass from single star post-AGB evolution models. **Since a CE accelerates the CS to hotter temperatures, the CS masses are overestimated using this method. The strong binary and apparent strong binary CS mass distributions agree better with observations** (Napiwotzki 1999 and Gesicki & Zijlstra 2007, respectively) than the single star model. **Assuming the remaining ~4,900 PN in our galaxy that avoided a strong binary interaction derived from the top ~8% high mass tail (≈ 4,900 / 61,000), then only single stars with M_{core} > 0.67 ± 0.04 $M_\odot$, i.e. M_{MS} > 1.9 – 2.7 $M_\odot$, can create a PN, similar to our mass loss rate argument.**

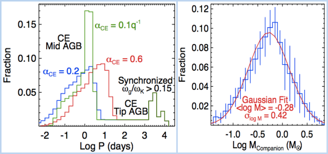
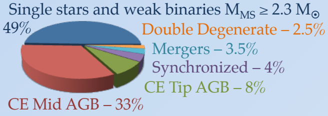


Fig. 4 & 5 – Final period and companion mass distributions. Of all strong binary interactions, only 33% – 60% have periods < 3 days (dependent on α_{CE}). Of these systems, ~70% have companions earlier than M3 (M_{comp} > 0.3 $M_\odot$). **An overall binary fraction of ~50% is consistent with the observed close CSPN binary fraction of ~15%** (Bond 2000), considering 0.5×0.45×0.7 ≈ 16%. **Companions at longer periods remain undetected via the photometric variability technique because the temperature distribution equalizes across the companion's surface in timescales of $\tau \approx$ 1 day** ($\approx R/c_{sound} \approx R[3\mu m_H/5kT]^{1/2}$).

V. Conclusions

Percentage of PN in our Galaxy



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.