Predicting the Evolutionary Descendents of Sequence E Stars

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Abstract. Sequence E variables are close binary red giants that show ellipsoidal light variations. They are likely to terminate their red giant evolution by a common envelope (CE) event when the red giant fills its Roche lobe, and produce close binary Planetary Nebulae (PNe). We made a Monte Carlo simulation to predict the fraction of Planetary Nebulae Nuclei (PNNe) that are post-CE binaries, using the observed frequency of sequence E binaries in the LMC to normalize our calculations. We find that 10-16\% of PNNe should be short period, post-CE binaries.

1. Introduction

Sequence E variables are ellipsoidal binaries which follow a loose period-luminosity relation (Wood et al. 1999; Soszyński et al. 2004). In the LMC, they make up 0.5 to 2\% of luminous red giant stars. Most of the sequence E stars lie on the first giant branch in the case of low mass stars (Wood et al. 1999), and some of them also evolve to the AGB (Soszyński et al. 2004; Soszyński 2007). While all the sequence E stars show ellipsoidal variations, about 7\% of them show eclipses in addition to the ellipsoidal light variations (Soszyński et al. 2004). In the ellipsoidal binary systems, the primary star is a red giant substantially filling its Roche lobe, and the secondary star is an unseen companion orbiting the primary star. Due to the tidal interaction, the primary star is distorted by the companion, causing an ellipsoid or pear-like shape. As the system orbits around, the change in the apparent surface area gives rise to the ellipsoidal light variation.

Sequence E stars are likely the precursors of close binary Planetary Nebulae (PNe). In the ellipsoidal binary systems, the red giant primary star has already substantially filled its Roche lobe. As the star evolves, it will experience a Roche lobe overflow and then faces a common envelope (CE) event. The primary star will terminate its red giant phase by ejecting the CE and it will produce a close binary PN.

At the present time the most favoured theory explaining the nonspherical PNe is the binary hypothesis (Bond & Livio 1990; Yungelson et al. 1993; Soker 1997; Bond 2000; Zijlstra 2007; de Marco 2009). Theoretical considerations suggest that a binary with CE will eject the entire envelope to produce an asymmetrical PN, with elliptical or bipolar shape. In fact, PNe with close binary nuclei have been confirmed by observations (Bond & Grauer 1987; Bond et al. 1992; Bond 1994, 2000; Miszalski et al. 2009). However, about their fraction, little is known. Bond and collaborators found about 10-
15% of PNe with close binary central stars, while Miszalski et al. (2009) found 12-21% of Planetary Nebulae Nuclei (PNNe) are close post-CE binaries.

Sequence E stars are likely to produce close binary PNe, and their fraction is known. In the LMC, Wood et al. (1999) found 0.5% of the red giants on the top 1 magnitude of the RGB in the LMC are sequence E variables. Similarly, Soszyński et al. (2004) and Soszyński (2007) found 1–2% (we use 1.5%) of red giants in the LMC show ellipsoidal variations. Moreover, for these fractions, we found the detectability limit of the full light curve amplitude is $\sim 0.05$ mag for Macho Red band ($M_R$), and $\sim 0.025$ mag for OGLE $I$ band. It is our aim to use the observed fraction of sequence E stars among all the red giants to estimate the fraction of PNe with close binary central stars that will be produced by a CE event.

2. Monte Carlo Simulation

A Monte Carlo simulation is made to predict the fraction of close binary PNe. One million red giant binaries are initially generated by using the observed orbital elements distributions. All the binaries are evolved up to the RGB and AGB and their evolutionary fates are examined to find which stars would produce close binary PNe. The fraction of close binary PNe is estimated by using the observed fraction of sequence E stars on the top 1 magnitude of the RGB.

2.1. Generating the binary systems

The simulation requires as input the orbital elements distributions of the binary systems. However, these are poorly known in the LMC, so we adopt the distributions from binaries in the solar vicinity. Input from LMC sources are used when available.

1. We consider the Initial Mass Function (IMF) as well as the star formation history to get the initial mass distribution of the primary star. The IMF is assumed to follow Salpeter (1955)’s power law. The LMC star formation history is adopted from Bertelli et al. (1992): a star burst begins $\sim 4$ Gyrs ago and ceases $\sim 0.5$ Gyrs ago, with the ratio of burst to quiescent star formation rate being 10. According to the evolutionary tracks of Girardi et al. (2000), a 4 Gyrs old star has a mass of 1.3 $M_{\odot}$, and a 0.5 Gyrs old star has a mass of 3.0 $M_{\odot}$. The mass range is set from 0.9 $M_{\odot}$ to 1.85 $M_{\odot}$ for RGB stars, where 0.9 $M_{\odot}$ is the mass for red giants born in the early universe of age 13.7 Gyrs (Spergel et al. 2003), and 1.85 $M_{\odot}$ is the upper limiting mass for red giants with electron degenerate helium cores on the first giant branch. For AGB stars, a full mass range from 0.9 to 3.0 $M_{\odot}$ is allowed.

2. The mass ratio of the binary systems is drawn from the distribution of Duquennoy & Mayor (1991), which follows a Gaussian-type relation, with its peak at 0.23.

3. The orbital period of the binary systems is drawn from the distribution of Duquennoy & Mayor (1991), which follows a Gaussian-type relation, with its peak at 173 years.

4. We assume the eccentricity is zero.

5. The orbital separation is calculated by using the equation of the orbital motion.

6. The orbital inclination is obtained assuming a random orientation of the orbital pole.
2.2. The properties of the binary systems

2.2.1. Mass loss

We consider mass loss from the RGB stars via a stellar wind. We use the empirical formulation by Reimers (1975) to calculate the mass loss rate, but with the rate multiplied by a parameter $\eta$ which is set equal to 0.33 (Iben & Renzini 1983; Lebzelter & Wood 2005). In order to know the amount of mass lost per magnitude of evolution up the red giant branch, we need to calculate the evolution rate. According to the evolutionary track of Girardi et al. (2000), the evolution rate for RGB stars is set to $dM_{\text{bol}}/dt \approx 0.15$ mag/Myr. Due to the mass loss from the primary red giant, the binary system loses its orbital angular momentum. The orbital evolution of the system is calculated with equation (20) in Hurley et al. (2002).

AGB mass loss driven by the superwind is not considered explicitly. At the AGB tip, stars will lose their mass by a superwind, causing the termination of the AGB evolution by ejecting the envelope, just as happens for single stars, producing single PNe or wide binary PNe. We treat the AGB superwind simply as terminating AGB evolution at a specific luminosity.

2.2.2. Stellar radius

For an ellipsoidal binary system containing a red giant, the requirement for the detection of the ellipsoidal variability is the minimum fractional filling of the Roche lobe. In order to know the minimum filling factor of the Roche lobe, we use the light curve generator Nightfall\footnote{http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html} to model the observed ellipsoidal light variations of partial-Roche lobe filling systems as a function of binary parameters. The input binary parameters are typical of sequence E stars. We find the relation between the light curve amplitude ($\Delta M_R$) and Roche lobe filling factor $f$ is:

$$\Delta M_R = (0.221 f^4 + 0.005) \times (1.44956 q^{0.25} - 0.44956) \times \sin^2 i ,$$  \hspace{1cm} (1)

for $0.5 < f < 0.9$, $0.1 < q < 1.5$, $0 < i < \frac{\pi}{2}$. We also find the relation between $\Delta M_R$ and $\Delta I$ is well approximated by:

$$\Delta I = 0.87 \times \Delta M_R ,$$  \hspace{1cm} (2)

where $\Delta I$ is the full light curve amplitude in the $I$ band.

Given the minimum amplitude for detectable light variations (0.05 mag in the $M_R$ band or 0.025 in the $I$ band), the minimum radius filling factor $f_{\text{min}}$ of a red giant in a binary system with detectable ellipsoidal light variations can be determined from equations (1) and (2). With minimum Roche lobe filling factor $f_{\text{min}}$, the just-detectable stellar radius is express as:

$$R_{\text{min}} = R_L \times f_{\text{min}} ,$$  \hspace{1cm} (3)

where $R_L$ is the equivalent radius of the Roche lobe (Eggleton 1983). When the Roche lobe is filled, the maximum stellar radius is:

$$R_{\text{max}} = R_L .$$  \hspace{1cm} (4)
2.2.3. Effective temperature and luminosity

The effective temperature and luminosity of the primary red giants are calculated separately for O-rich and C-rich stars. To obtain these, we use the intermediate age LMC globular cluster NGC 1978 as a template for LMC red giant properties.

For O-rich stars, the giant branch slope is obtained by using the data of Kamath et al. (2010). With the evolutionary tracks of Girardi et al. (2000), we make a mass correction for the effective temperature. The zero point of the effective temperature $T_{\text{eff}}(M_{\text{bol}}, m)$ is estimated by fitting the observed HR diagram of sequence E stars. For C-rich stars, we use the giant branch slope obtained from Kamath et al. (2010). The zero point of the $T_{\text{eff}}(M_{\text{bol}}, m)$ relation for C-rich stars is obtained by equating the temperatures of the O-rich and C-rich stars at the transition luminosity from the O-rich to C-rich stars. The transition luminosity is calculated by using the data of Frogel et al. (1990) and Vassiliadis & Wood (1994), with the distant modulus of the LMC equal to 18.54 (Keller & Wood 2006).

With $L = 4\pi\sigma R^2 T_{\text{eff}}^4$, log $L/L_\odot = -0.4(M_{\text{bol}} - 4.75)$ and the $T_{\text{eff}}(M_{\text{bol}}, m)$ from above, we derive the bolometric magnitude for O-rich and C-rich stars as a function of $m$ and $R$. If we substitute $R$ with $R_{\text{min}}$ or $R_{\text{max}}$, then we get the minimum or maximum bolometric magnitude of the red giants with just-detectable light variations or with Roche lobes that are just full, respectively.

2.3. Scenario for finding close binary PNe

An ellipsoidal variable almost filling its Roche lobe will experience a Roche lobe overflow as the star evolves. As a result of the Roche lobe overflow, the binary system will suffer a CE event, leading to the ejection of the entire envelope. A close binary PN will be produced if the primary star is on the AGB, or a post-RGB binary system will be formed if the primary star is on the RGB. For RGB binaries, since the evolution is too slow after envelope ejection, the system will be unable to evolve to high effective temperature quickly enough to ionize the ejected envelope before it disperses. On the other hand, post-RGB stars will evolve slowly through the instability strip where they will be seen as Population II Cepheids or RV Tauris. We note that some Population II Cepheids and RV Tauris do have luminosities below the RGB tip luminosity (Alcock et al. 1998).

3. Results

With the model described in Sect. 2, we calculated the fraction of PNe that are close binaries. The fraction of sequence E stars in the LMC was used to normalize the calculation. In order to get the observed fraction of sequence E stars, we added single stars until the measured fraction is equal to the observed.

The predicted fraction of close binary PNe is $\sim 10$ or 16%, depending on whether we use Wood’s (0.5%) or Soszyński’s (1.5%) frequency. It indicates that short-period post-CE binaries are a small fraction of PNe central stars.

To test the simulation, we predicted the distributions of the period and velocity amplitude of sequence E stars and compared them with the observations. Fig. 1 (left panel) is the period distribution from the model and observation (OGLE II). It shows

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2 We did not consider the coalescence of the two companions.
that the simulation reproduces the observation well. The period ranges from $\sim 30$ to 1000 days, with the peak located at $\sim 250$ days. We also predicted the full velocity amplitude distribution (right panel in Fig. 1). The distribution from the model shows a good consistency with the observational results of Nicholls et al. (2010) although the observed numbers are small.

An updated and improved version of the results presented here is currently being prepared for publication (Nie et al. 2011, in preparation).

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