The Immediate Precursors of Binary Planetary Nebulae

P.R. Wood[1], J.D. Nie[2] and C.P. Nicholls [3]

[1]*Research School of Astronomy and Astrophysics, Australian National University, Cotter Road, Weston Creek, ACT 2611, Australia*
[2]*Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*
[3]*Center for Astrophysics and Space Science, University of California San Diego, La Jolla, CA 92093, USA*

Abstract

By observing the number of red giants almost filling their Roche lobes in binary systems relative to the number of single red giants, we can predict the numbers of planetary nebulae (PNe) produced by binary interaction relative to the numbers of PNe produced by single stars or wide binaries. When we have both radial velocity and light curves, we can derive the masses of these binary PN precursor stars. In this paper we discuss our recent work on the precursors of binary planetary nebulae in the LMC.

1 Introduction

A binary star system in which an evolving red giant star fills its Roche lobe on the AGB or the RGB is thought to produce an Asymmetric Planetary Nebula, probably bipolar in nature. Immediately before the Roche lobe is filled, the red giant becomes distorted by its companion. The change in the observed orientation of the red giant as it orbits its companion leads to light variability known as ellipsoidal variability. Many such variables have now been discovered in the LMC by surveys such as MACHO and OGLE. These variables are known as sequence-E stars since they lie on a period-luminosity sequence that has been designated sequence-E (e.g. Wood et al. 1999, Soszyński et al. 2004, Fraser et al. 2005). We now have reliable estimates (from MACHO and OGLE) of the population of detectable ellipsoidal red giant binary variables in the LMC. We also have reliable estimates of the total population of red giants, single and binary, in the LMC from surveys such as 2MASS and SAGE. This led Nie, Wood and Nicholls (2012) to use the population of ellipsoidal red giant binaries in the LMC, relative to the population of all red giants, to predict the fraction of planetary nebulae (PNe) that are produced by a common envelope event terminating red giant evolution. Such PNe are presumably bipolar in shape. Nie et al. (2012) also estimated the fraction of PN produced from binary systems where the companion is sufficiently close that it is capable of inducing a less extreme non-spherical shape in the PN. In the next section, we briefly describe the results of these calculations (see Nie et al. 2012 for full details).

Because the distance to the LMC is well known, it is possible to derive the complete set of orbital parameters for ellipsoidal red giant binary variables there when both light and velocity curves are available. There are very detailed light curves available for thousands of sequence-E stars in the LMC from the MACHO and OGLE projects. We have recently completed a radial velocity monitoring project for about 80 of these sequence-E stars and in Section 3 we present some preliminary results from this project and compare those results with the predictions in Nie et al. (2012).

2 Modelling the red giant binary population in the LMC

The advantage of using sequence E stars for population modelling is that these stars are the immediate precursors of binary PN. Hence, the modelling uses only those parts of any assumed binary period and separation distributions that are relevant to common envelope events or binary mergers on the RGB and AGB. The full population modelling details are given in Nie et al. (2012). Briefly, the initial binary mass ratio distribution and the initial period distribution came from Duquennoy & Mayor (1991), the Salpeter (1955) initial mass function was used for the primary star mass and the LMC star formation history from Bertelli et al. (1992) was assumed. A Monte Carlo scheme was used to form binary systems over the lifetime of the LMC and the systems were then evolved. The fraction of red giants in binary systems was calibrated by requiring that the predicted number-amplitude distribution of sequence-E ellipsoidal red giant variables matched the observed distribution. The output was the production rate of single and binary PN in the LMC.

The first result from the calibrated population simulations is that the predicted total number of PN in the inner 25 square degrees of the LMC (548 PN) agrees remarkably well with the number observed by Reid and Parker (2006) (541±89 PN). Most importantly, since more than 90% of these PNe come from single or non-interacting binary stars in our model, this means that most such stars produce a PN. This is contrary to the 'binary hypothesis' (Moe & De Marco 2006; De Marco 2009) which suggests that binary interaction is required to produce a PN.

The second result is that the *birth rate* of PN arising from close binary interactions (common envelope events) is 7-9% of the total PN birth rate. Observations usually give a somewhat larger fraction for the observed *numbers* of binary planetary nuclei (PNNe) compared to non-binary PNNe e.g. Miszalski et al. (2009) find 12-21%. However, the observed number fraction will not be the same as the ratio of the birth rates unless the same evolution rate applies for both single and binary PNNe. However, this may not be the case since re-accretion of hydrogen-rich material stored in a circumbinary disk left by the common envelope event could slow the evolution rate for binary PNNe. This would then increase the observed numbers of binary PNNe relative to non-binary PNNe for a given birth rate ratio. One would then expect the number ratio to be higher than the birth rate ratio, as found above.

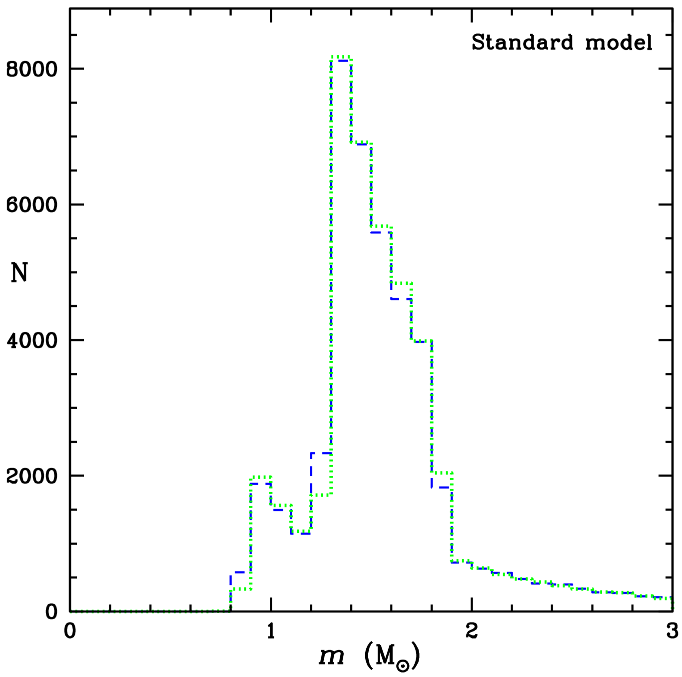

Figure 1. The predicted distribution of the masses of red giants in detectable ellipsoidal variables. These stars are the immediate precursors of PNe. The green curve is normalized using MACHO observations and the blue curve is normalized using OGLE observations. From Nie et al. (2012).

Two other (of many) predictions of the modelling are the mass distribution of red giants in the LMC (Figure 1) and the mass distribution of PNNe (Figure 2). From Figure 1, it is obvious that the most common masses predicted for red giants are 1.3-1.8 $M_\odot$. This is because of the burst of star formation in the LMC from about 4×10^9 years ago until about 0.5×10^9 years ago.

From Figure 2, it can be seen that the most common mass for PNNe is ~0.6 $M_\odot$, in good agreement with the observed distributions (Stasińska & Tylenda 1990, Zhang & Kwok 1993). The mass distribution for binary PNNe extends to lower values because the luminosity (and hence AGB core mass, which is the PNN mass) at which AGB evolution is terminated in this case depends only on the size of the Roche lobe of the red giant and it is not necessary to get to the higher luminosities at which a superwind is capable of driving off all the envelope mass.

3 New radial velocity observations of ellipsoidal variables in the LMC

In order to get statistical estimates of the properties of red giant binaries in the LMC, we have undertaken a 1.5 year radial velocity monitoring program for about 80 red giant ellipsoidal variables on sequence-E in the

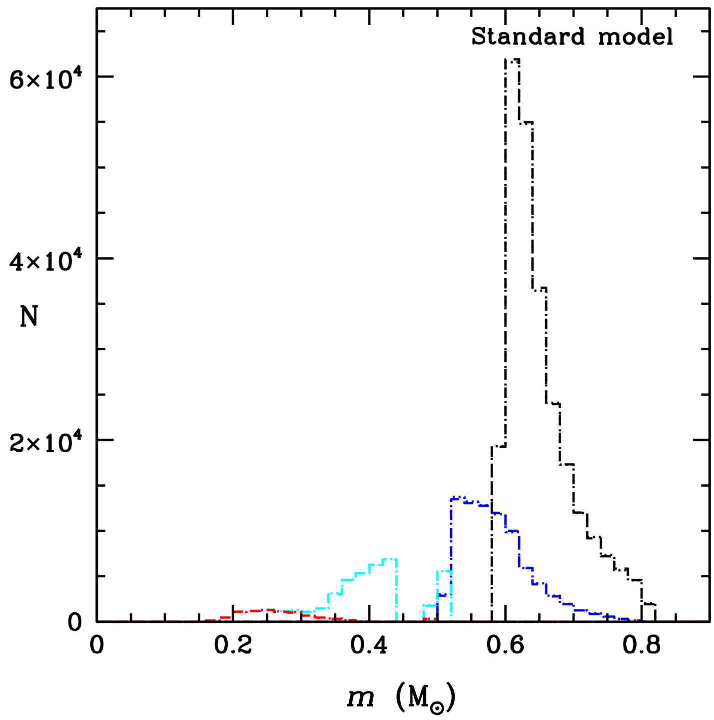

Figure 2. Mass distributions of PNNe evolved from non-interacting binaries (black) and close binaries (blue). PNNe from single stars have the same distribution as the PNNe from non-interacting binaries. The mass distributions for post-RGB and post-EAGB stars (cyan) and double degenerate secondaries (red) formed by common envelope interactions are also shown. Note that the cyan curves include the double degenerate component. From Nie et al. (2012).

LMC. When combined with existing radial velocity observations for other LMC red giants, we will be able to derive the binary properties (orbital period *P*, binary masses *m1* and *m2*, inclination *i* of the orbital plane, eccentricity *e*, semi-major axis *a*) for about 100 sequence-E stars in the LMC, enough for a statistical analysis of properties as a function of evolutionary state. Here we present some preliminary results for 67 LMC red giant ellipsoidal variables. In passing, we note that not one of the ~100 ellipsoidal red giant variables that we have observed shows emission lines i.e. there are no symbiotic stars. Thus the birth rate of double degenerates should be less than a few percent of the birth rate of post-common envelope PN. This is not surprising as Figure 2 shows that close double degenerates are mostly formed by common envelope interactions low on the giant branch or at an even earlier evolutionary stage.

The top panel of Figure 3 shows the mass distribution found for the red giant primary stars in the 67 observed ellipsoidal variables compared to the model distribution of Nie et al. (2012). The observed distribution shows a peak around M ~ 1.6 $M_{\odot}$. This is at the same place as the peak seen in the model distribution due to the burst in star formation assumed from 4-0.5×10^9 years ago. However, the observed distribution is broader and not as peaked as the model distribution, suggesting that the burst intensity was not as high as in the model and that the burst ceased later than 0.5×10^9 years ago. Note that the considerable number of observed stars with masses more than 3$M_{\odot}$ were deliberately added to our target list so they do not represent a statistically unbiassed sample.

The lower panel of Figure 3 shows the mass ratio *q=m2/m1* in the observed sequence E variables and in the models of Nie et al. (2012). There is good agreement between these two distributions giving us confidence in the assumptions used by Nie et al. (2012).

4 Summary

Sequence-E ellipsoidal binary variables are the immediate precursors of binary PN. Comparison of the number of PN in the LMC with the number of luminous red giants shows that most PN arise from single star mass loss. Population modelling of the numbers of observed sequence-E stars in the LMC predicts that the birth rate of PN arising from close binary interaction (common envelope events) is 7-9% of the total PN birth

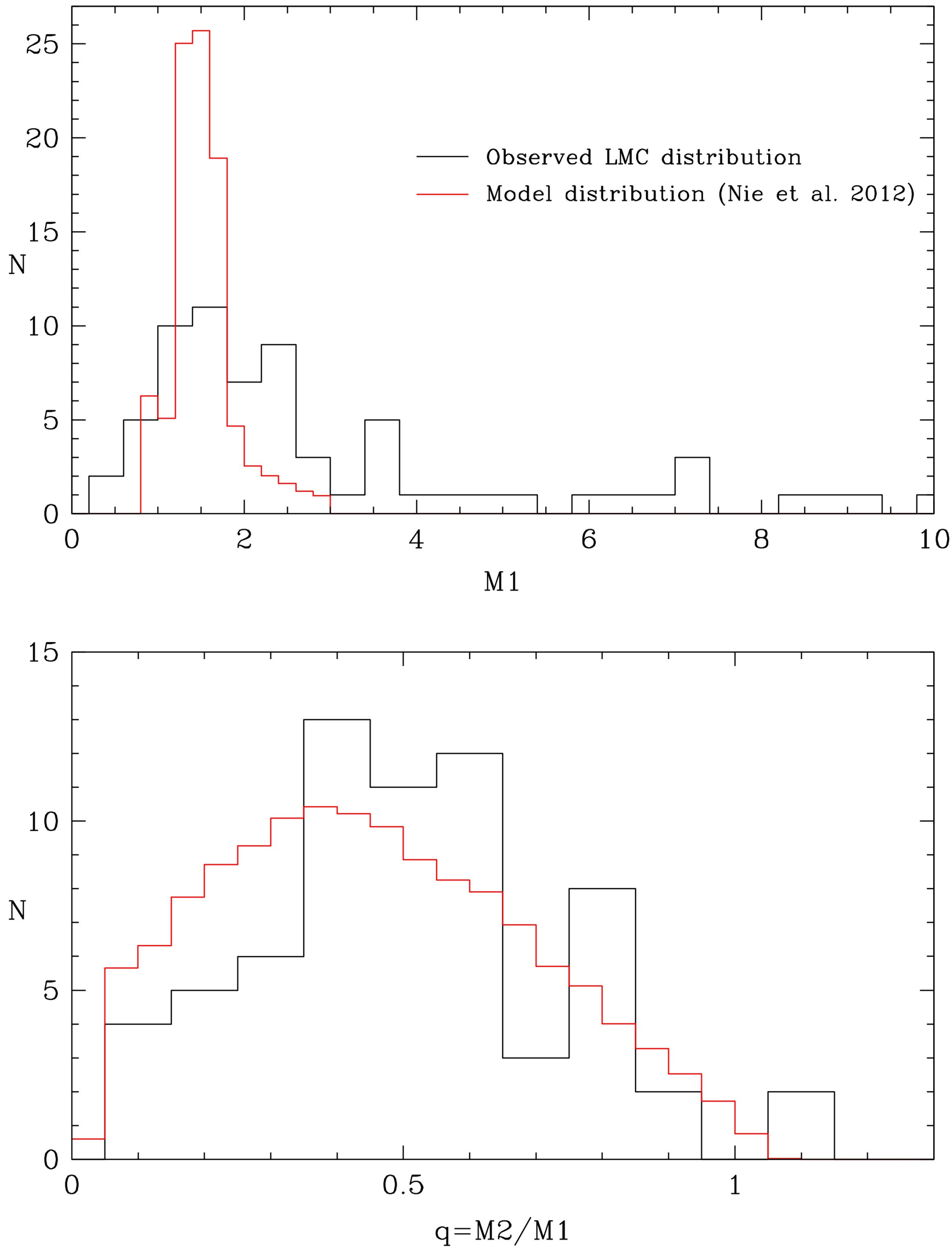

Figure 3. Top panel: The distribution of the masses of the red giant primary stars in the sequence-E binaries in the LMC. The black line shows the distribution for 67 observed stars and the red line shows the distribution in the standard model of Nie et al. (2012). The observed and model histograms are normalized to the same number of points with M < 3M$_\odot$. Bottom panel: The observed and model mass ratio distributions. Line types are as in the top panel. The two histograms are normalized to the same number of points.

rate. This is somewhat less than current estimates of the fraction of PN that have central stars in close binary systems. The difference between the birth rate ratio and the observed number ratio may be due to re-accretion of H-rich material slowing the evolution of binary PNNe. Masses and mass ratios derived for LMC red giant ellipsoidal binaries agree well with the population model. In particular, the burst of star formation beginning about 4×10^9 years ago in the LMC is apparent in the mass distribution of red giants.

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