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Orbital properties of binary post-AGB stars

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Abstract. We present the results of a decade-long radial velocity monitoring campaign of post-AGB binaries. We derived the orbital elements of 33 post-AGB binaries. We find a companion mass distribution centred around 1.09 $M_\odot$ with a very large spread. All the post-AGB binaries in our sample are expected to have filled their Roche lobes while at giant dimensions. Current binary evolution models are unable to explain the observed distribution of orbits.

Keywords. stars: AGB and post-AGB, binaries: general

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1. Introduction

During the end-stages in the evolution of low- and intermediate-mass stars the envelope of the star is removed, either via a stellar wind or via binary interactions. As the mass in the envelope of the star becomes very small ($\sim 0.02\ M_\odot$), the radius of the star starts to decrease as a result of mass loss and the star evolves towards higher temperatures. The phase in which the star stops to drive a dust-driven wind but is not yet hot enough to ionise its surroundings to emerge as a planetary nebula is known as the post-asymptotic giant branch (post-AGB) phase (Van Winckel 2003).

The evolution of low- and intermediate-mass stars during the AGB phase is still plagued by many uncertainties. Especially the interaction of evolved stars with a companion is still poorly understood (see reviews by De Marco & Izzard 2017, Jones & Boffin 2017).

There are a number of binary interactions that can impact the evolution of a binary system. Tides play a large role once the radius of the RGB or AGB star increases to the extent that the AGB star fills a significant fraction of its Roche lobe (Zahn 1977). This effect will lead to a synchronisation of the rotational spin of the RGB/AGB star to the orbit and a circularisation of the orbit on a relatively short time scale (Hurley *et al.* 2002). Additionally, the AGB star can interact with its companion via a stellar wind. This can either happen isotropically via the Bondi-Hoyle-Littleton mechanism (Edgar 2004) if the wind velocity is much larger than the orbital velocity, or via a so-called wind-Roche lobe overflow (wind-RLOF, Mohamed & Podsiadlowski 2007). In the latter case, the wind fills the Roche lobe of the AGB star and gets funnelled onto the companion, leading to high accretion rates. The binary can also undergo regular RLOF, but this is usually unstable for AGB stars with deep convective envelopes (Hjellming & Webbink 1987, but see also Pavlovskii & Ivanova 2015). In the unstable case, the binary can enter a common envelope (Izzard *et al.* 2012), leading to spiralling-in of the binary and possibly a merger.

Canonical population synthesis models tend to predict a bimodal period distribution after the interaction (Izzard *et al.* 2010, Nie *et al.* 2012), with on one hand short-period systems that have undergone a common-envelope evolution, and on the other hand wider systems that did not interact much, but where mass loss via a stellar wind led to an increase in the orbital period. However, this is in stark contrast to the observed orbits of binaries that have undergone an interaction involving an evolved star, such as post-AGB binaries (Van Winckel 2003), carbon-enhanced metal-poor (CEMP) stars (Hansen *et al.* 2016, Jorissen *et al.* 2016), Barium stars (Van der Swaelmen *et al.* 2017), and others.

Since the post-AGB phase occurs immediately after the AGB, binary post-AGB stars in intermediate-period orbits (100–3000 days) can be regarded as the immediate products of a binary interaction on the AGB. Consequently, by investigating the orbital properties, chemical properties, and circumstellar environments of these binaries, we aim to learn more about the strong binary interaction on the AGB. In these proceedings, we will focus on the analysis of the orbital properties of post-AGB binaries. For a more in-depth discussion on all the properties of post-AGB binaries, we refer to Oomen *et al.* (2018).

2. Data

In order to investigate the orbital properties of binary post-AGB stars, we have at our disposal the results of a long-term and systematic radial velocity monitoring campaign with the HERMES spectrograph (Raskin *et al.* 2011) mounted on the Mercator telescope in La Palma, Spain (Van Winckel 2015). This high-resolution spectrograph ($R \approx 80000$) is operational since 2009 and has provided us with a large number of radial velocity measurements for many galactic post-AGB stars, selected based on the properties of their spectral energy distribution (SED) (de Ruyter *et al.* 2006, Gezer *et al.* 2015).

Additionally, we have complemented our HERMES data with older data collected from literature taken with several European southern observatory (ESO) telescopes. This allows us to include targets from both the northern and southern hemispheres.

The result from this huge effort is that we managed to fit the orbits for 33 post-AGB binaries. Because we have a large sample of homogeneously derived orbital elements available, we can apply statistical methods to our sample in order to learn more about the general properties of post-AGB binaries.

3. Results

We have derived the distribution of companion masses by making use of the mass functions that are available from the orbital elements. The mass functions are related to the masses of the individual components of the binary according to

$$f(m) = \frac{M_2^3}{(M_1 + M_2)^2} \sin i, \tag{3.1}$$

where M_1 is the mass of the post-AGB star, M_2 is the mass of the companion, and i is the inclination angle.

We can now derive the distribution of companion masses by first assuming a distribution for the post-AGB masses (M_1). This distribution can be estimated since post-AGB stars are stars that have lost their entire envelope, hence we assume that their mass distribution is similar to the observed white-dwarf mass distribution. For that reason, we have used a Gaussian distribution centred around 0.6 $M_\odot$ with standard deviation of 0.05 according to Kilic *et al.* (2018).

Similarly, we can assume a distribution for the inclination angles if we assume that all the orbits are randomly inclined in 3-dimensional space. This is described by

$$i = \arccos(z), \tag{3.2}$$

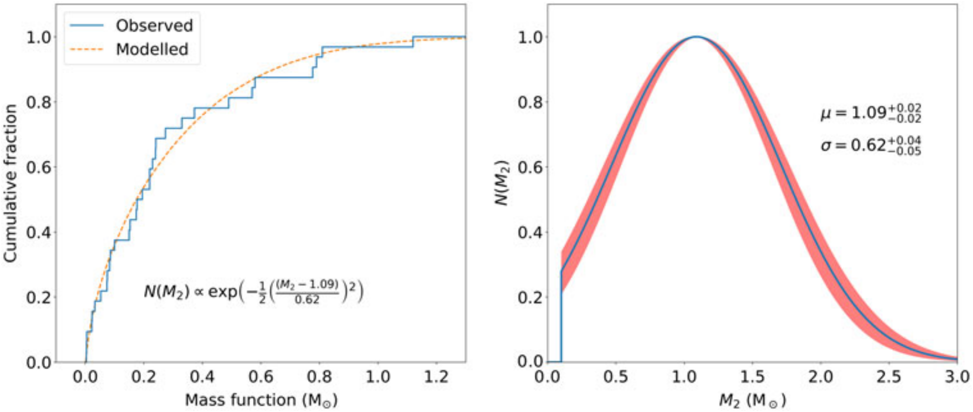

Figure 1. Left: observed vs modelled cumulative mass-function distributions for our sample of post-AGB binaries. Observed mass functions are showed as a blue line, while the simulated distribution is shown as a dashed orange line. Right: distribution of companion masses. The blue curve is described by a Gaussian profile around 1.09 $M_\odot$ with standard deviation of 0.62. The red-shaded region shows the uncertainty. Figures are taken from Oomen *et al.* (2018).

where z is the length of the projection of the unit normal vector along the line-of-sight to the observer, which is uniformly distributed in $[-1, 1]$.

Finally, we can derive the distribution of companion masses, such that the three distributions together result in a mass function distribution according to Eq. 3.1 that best fits the observed cumulative mass function distribution. In this process, we account for observational bias by removing combinations that result in a low velocity semi-amplitude, since we would not have detected those binaries. Moreover, we limit the inclination angle to 75°, since edge-on systems would be obscured by the circumbinary disc, hence would not be observed.

The result of this procedure is that a Gaussian distribution centred around $1.09^{+0.02}_{-0.02}$ $M_\odot$ with standard deviation of $0.62^{+0.04}_{-0.05}$ $M_\odot$ best fits the observed cumulative mass function distribution, which is shown in Fig. 1.

The shape of the companion mass distribution is given on the right panel of Fig. 1. The most remarkable feature of this distribution is the large spread in masses that is observed. The companion masses range from 0.1 $M_\odot$ to about 3 $M_\odot$. This shows the very large diversity in post-AGB binary systems that is observed. Moreover, the large spread in masses leads to a large spread in mass ratios of the binaries, which has strong implications for binary evolution models. Most binary interaction mechanisms, such as the stability of mass transfer, or the orbital evolution of the system in general, depend critically on the mass ratio.

Now that we have derived a distribution of companion masses, we can use the orbital periods of the binaries and Kepler's third law to find a distribution of orbital separations, and finally Roche-lobe radii. If we assume that the separation and masses of the binary did not change much since the end of the interaction on the AGB, then the current distribution of Roche-lobe radii should remain the same.

The distribution of derived Roche-lobe radii is shown in Fig. 2. The Roche lobes range from 0.2 AU to about 1.5 AU, with the majority of Roche lobes being smaller than 1 AU. Since the typical maximum size of an AGB star is 1–2 AU, we expect almost all our post-AGB stars to have filled their Roche lobe at some point in their evolution. This means that all the post-AGB stars in our sample are the result of a strong interaction during the AGB phase.

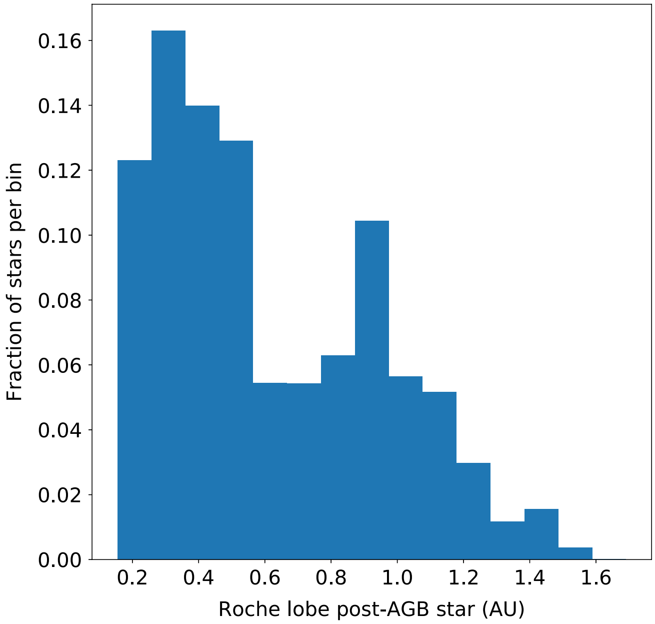

Figure 2. Histogram of the distribution of Roche lobes for our sample of post-AGB binaries. Figure is taken from Oomen *et al.* (2018).

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Discussion

SAHAI: You find that many companions have large masses, $\gtrsim 1\ M_\odot$, so that means the primary must have been more massive at the main-sequence; so where is the mass that the primary must have ejected? Why is it not visible?

Oomen: We expect only a very small fraction of the mass to go to the formation of the circumbinary disc. It is possible that quite some mass gets transferred onto the companion, making it more massive than it initially was. It can also be that the AGB star interacts with the companion at a later stage in the evolution, such that already a large amount of mass is lost via a stellar wind long before the AGB star filled its Roche lobe. However, the short answer is: we do not know.