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Using wide hot subdwarf binaries to constrain Roche-lobe overflow models

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Abstract. Hot subdwarf B (sdB) stars are evolved core helium burning stars that have lost most of their hydrogen envelope due to binary interaction on the red giant branch. As sdB stars in wide binary systems can only be created by stable Roche lobe overflow, they are a great test sample to constrain the theoretical models for stable mass loss on the red giant branch. We present here the findings of a long term monitoring program of wide sdB+MS binaries.

We found two main features in the orbital parameters. The majority of the systems have eccentric orbits with systems on longer orbital period having a higher eccentricity. As these systems have undergone mass loss near the tip of the RGB, tidal circularisation theory predicts them to be circularized. Our observations suggest that efficient eccentricity pumping mechanisms are active during the mass loss phase. Secondly we find a strong correlation between the mass ratio and the orbital period. Using binary evolution models, this relation is used to derive both an upper and lower limit on the initial mass ratio at which RLOF will be stable. These limits depend on the core mass of the sdB progenitor.

Key words: stars: subdwarfs – stars: binaries: spectroscopic – stars: fundamental parameters – stars: evolution

1. Introduction

Hot subdwarf B-type (sdB) stars are core He burning stars with a very tiny hydrogen envelope ($M_{\rm H} < 0.02 M_{\odot}$). The current consensus is that they can only be formed through binary interaction in a binary in which the primary is a red giant near the tip of the red giant branch (RGB). There are three main formation channels for sdB stars. sdBs in short period binaries are formed through a common envelope ejection, while sdBs in wide binaries are formed through stable Roche-lobe overflow (RLOF). Single sdB binaries can be formed by the merger of two white dwarf stars.

The evolution of a typical subdwarf star in the Herzsprung-Russel diagram is shown in the left panel of Fig. 1. The sdB progenitor ascends the red giant branch until it starts the binary interaction phase near the tip of the RGB, and loses its envelope. This model shows an early flasher where He is ignited under degenerate conditions very fast after leaving the RGB. Due to neutrino cooling the He-flashes take place in a shell outside the core and work their way inwards until the star starts central He burning. This is shown in the right panel of Fig. 1. After the core He-burning phase, the subdwarf stars undergoes a phase of stable He-shell burning where it heats up and becomes an sdO star. As the star is too light to burn heavier elements, it then moves on to the white dwarf cooling track.

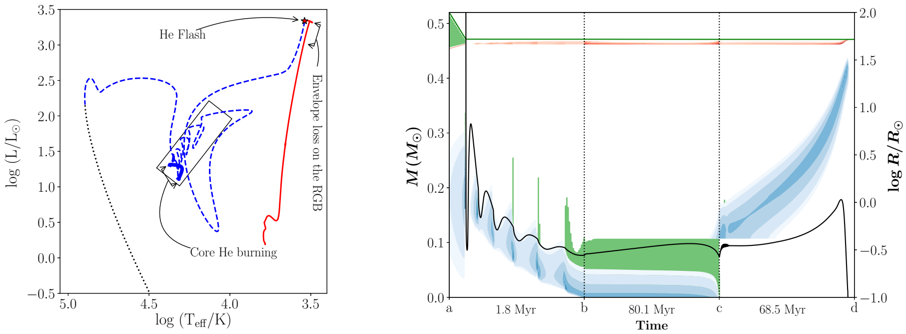

Figure 1. Left: The evolution of a typical hot subdwarf star in the HR diagram. The main sequence and red giant branch are indicated in red full line. The He burning phase is indicated by blue dashed line, of which the core He burning phase is shown in full blue line. The white dwarf cooling track is indicated in black dotted line. Right: The profile from the sdB star during the Helium burning phase. He burning regions are shown in blue color, while H burning regions are shown in red. The convective zones in the star are shown in green. The full black line shows the radius of the sdB star. The figure is split in three stages: He flashes (a-b), stable He core burning (b-c) and stable He shell burning (c-d) with the time the star spends in each of them indicated below the figure. Figures calculated with the MESA stellar/binary evolution code (Vos, 2015)

Because an sdB star can only be formed though binary interaction mechanisms, they are ideal objects to study these mechanisms. When considering low mass stars($M < 2M_\odot$), roughly 15% of the binary stars will interact on the red giant branch (Vos et al., 2017). However, many of the interaction mechanisms are not understood from first principles, e.g. the stability of mass loss, the exact treatment of the CE phase, the mass loss fractions during stable RLOF and many more. With this project we aim to use hot subdwarf stars as a test sample for binary interaction models.

2. The wide sdB+MS sample

A long term project to monitor wide sdB+MS binaries was started in 2009 using the HERMES spectrograph at the 1.2m Mercator telescope in La Palma and in later stages extended to the southern hemisphere using CHIRON at the 1.5m SMARTS and FEROS at the 2.2m MPG telescope. In combination with dedicated programs at the smaller telescopes there is also a long running bad weather program using UVES at the 8.2m VLT telescope.

Currently 19 systems have sufficient phase coverage to solve the orbital parameters (Vos et al., 2012, 2013, 2017, 2019). In combination with two sdB binaries solved by Barlow et al. (2013), one by Deca et al. (2018) and one solved from photometry by Otani et al. (2018) the total sample contains 23 systems of which 21 with a known mass ratio. In the following subsections the more interesting results of this survey are summarized.

2.1. Period and eccentricity distribution

The distribution of the orbital periods of the sdB+MS sample is shown in the left panel of Fig. 2. The orbital periods range from around 450 days up to 1400 days with a peak around 1000 days. Original model predictions for the orbital periods of sdB binaries formed by the stable RLOF channel peaked at 100 days (Han et al., 2002, 2003). Based on these observations, Chen et al. (2013) adapted the original models by including a more realistic treatment of angular momentum and the inclusion of atmospheric RLOF. The improved models match very well with the observed period distribution.

The eccentricity of these systems is unexpected. All of the wide sdB+MS binaries have undergone a mass loss phase in their past, at which point the sdB progenitor filled its Roche lobe. Tidal interaction theory clearly shows that all of these systems should have circularised long before the onset of RLOF. To explain the observed eccentricity, an eccentricity pumping process is necessary that is active during or after the mass loss phase. Vos et al. (2015) tested several such processes and found that a combination of two was able to explain the observed eccentricities: a) phase dependent mass loss where more mass is lost near apastron than near periastron leading to an increase in eccentricity of the orbit, and b) the interaction of a stable circumbinary disk formed during the mass loss phase with the binary which can further increase the eccentricity of the orbit.

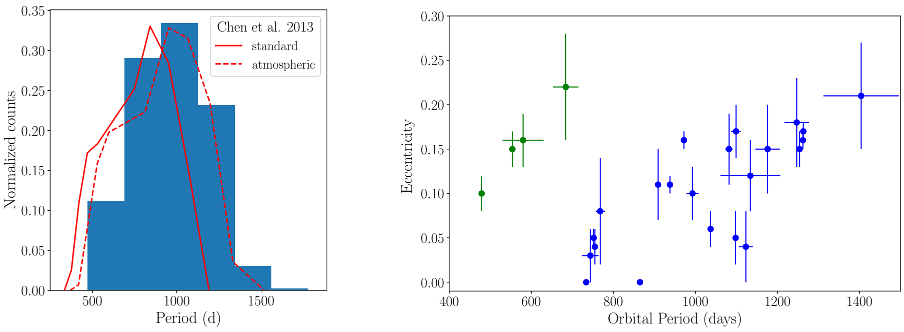

Figure 2. Left: The distribution of orbital periods in blue, and the predicted distribution by Chen et al. (2013) in red line. The dotted red line indicates models which include atmospheric RLOF (Figure taken from Vos et al. (2019)). Right: the eccentricity vs the orbital period for all solved wide sdB+MS binaries. There is an indication for the existence of systems at shorter orbital periods which have higher eccentricity, indicated in green. This second group is selected by eye based on its different location in both the Period - Eccentricity and the Period - Mass ratio distribution (See also Fig. 3).

Orbits with significant non-zero eccentricity are not uncommon in binary systems containing an evolved component. In fact, the majority of the long period post-AGB, S-type and Ba stars in long period binaries have significant eccentric orbits, with eccentricities as high as 0.6 (e.g. Vos et al., 2017; Oomen et al., 2018). The eccentricity pumping mechanisms in Vos et al. (2015) can offer an explanation for these systems as well.

2.2. Mass ratio - period relation

One of the most interesting results from this project up till now is the discovery of a strong correlation between the mass ratio and the orbital period in the wide sdB+MS sample shown in the left panel of Fig 3. Taking into account that the sdB mass is well constrained to $M_{\rm sdB} = 0.47 \pm 0.05 M_{\odot}$, this means that sdB stars with low mass companions have short orbital periods and those with high mass companions have long orbital periods.

This P-q relation can be used to derive a stability criterion for RLOF. Using the current mass of the sdB, which is related to the orbital period (Chen et al., 2013), and the mass ratio, the mass of the companion can be determined. By assuming a likely progenitor mass between 1 and 2 $M_{\odot}$ for the sdB, the initial mass ratio at the start of mass loss can be derived. As the current sdB mass is the same as the core mass of the sdB progenitor (which is a red giant at the start of RLOF), a relation between the initial mass ratio at the start of mass loss and the core mass of the sdB progenitor is found. This clearly shows an upper limit depending on the core mass, leading to a stability criterion of:

$$q_c = M_{\mathrm{sdB}}^{-2} - 0.25 M_{\mathrm{sdB}} - 2.55 \quad (1)$$

This stability criterion together with the relation between the initial mass ratio and the core mass at the start of RLOF is shown in the right panel of Fig. 3. The initial mass ratio is shown for sdB progenitors with 2 different initial masses: 1.2 and 1.6 $M_{\odot}$. The exact initial mass can not be determined from the current evolution models, thus a range between 1 and 2 $M_{\odot}$ was used in the derivation of the stability criterion.

The 3 systems plotted in green squares in the left plot of Fig. 3 are not included in the derivation of the stability criterion. Due to their separate location in both the period - eccentricity and period - mass ratio distribution it is likely that they are formed by a different channel. The shorter orbital period indicates that they likely descend from higher mass sdB progenitors ($M > 2M_{\odot}$) that ignited He under non-degenerate conditions. This also explains why there are only few of them found. For an extended discussion see Vos et al. (2019).

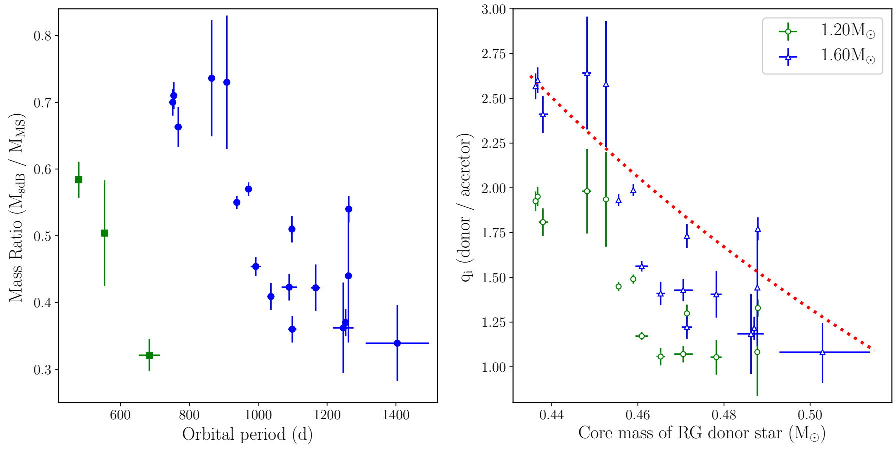

Figure 3. Left: The orbital period vs the mass ratio of all solved wide sdB+MS binaries. There is a strong correlation between the period and mass ratio, and there are again a second group visible (green squares, same systems as in Fig. 2). Right: The initial mass ratio in function of the core mass of the sdB progenitor at the start of the RLOF phase. The initial mass ratio is shown for 2 different sdB progenitor masses: 1.2 and 1.6 $M_{\odot}$. A clear upper limit is visible determined by the stability of RLOF. The derived stability criterion is shown in red dashed line. Figures adapted from Vos et al. (2019).

3. Conclusions

Hot subdwarf binaries are useful systems to study binary interactions mechanisms. Due to the reasonable brightness and the need for observations spread over a long time, small and medium sized telescopes are ideal for this survey project. Currently two main results from this survey are the discovery that the majority of the systems are eccentric, which indicates that eccentricity pumping mechanisms are at play during or after the mass loss phase. The second result is the discovery of a strong correlation between orbital period and mass ratio, which is linked directly to the stability of RLOF. Based on this correlation the first observational stability criterion for mass loss on the red giant branch was derived.

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