Draft version April 8, 2019
Typeset using LaTeX **twocolumn** style in AASTeX62

A Triple Origin for Twin Blue Stragglers in Close Binaries

Simon Portegies Zwart[1] and Nathan W. C. Leigh[2,3,4]

[1] *Leiden Observatory*
Leiden University
PO Box 9513, 2300 RA
Leiden, the Netherlands
[2] *American Museum of Natural History*
Department of Astrophysics
79th Street at Central Park West
New York, NY 10024-5192, USA
[3] *Stony Brook University*
Department of Physics and Astronomy
Stony Brook, NY 11794-3800, USA
[4] *Departamento de Astronomía*
Facultad de Ciencias Físicas y Matemáticas
Universidad de Concepción
Concepción, Chile

(Received January 1, 2018; Revised January 7, 2018; Accepted April 8, 2019)

Submitted to ApJ

ABSTRACT

We propose ~~a formation mechanism for~~ that twin blue stragglers (BSs) in compact binaries ~~that involves~~ evolve through a phase of mass transfer from ~~an evolved~~ a giant outer tertiary companion on to the inner binary~~via a circumbinary disk~~. We apply this scenario to the ~~observed double BS-binary WOCS~~ twin-BS binary WOCS ID 7782 in the old open cluster NGC ~~188, and show that its observed properties can be reproduced within the context of the proposed model. Based on this model, we predict the following properties for twin BSs: (1) For the outer tertiary orbit , the initial orbital period should lie between 220 days $\lesssim P_{\rm out} \lesssim$ 1100 days, assuming initial masses for the inner binary components of $m_1 = 1.1$~~ 188. This binary has two comparable-mass main-sequence stars in an almost circular ($e \lesssim 0.1$) orbit of $\lesssim 10$ days. Our theoretical arguments are supported by simulations of an inner binary that accretes from an outer Roche-lobe overfilling star using the Astrophysical Multipurpose Software Environment. At least 80 % of the mass liberated by the tertiary star goes through a circum-binary disk before it is accreted by in the inner binary, causing the two stars to turn into blue stragglers. In order to acquire a relatively stable phase of mass transfer the donor should be about 1.4 $M_\odot$ and over-fill it's Roche lobe before ascending the asymptotic giant-branch. The outer star eventually turns into a 0.43 to 0.54 $M_\odot$ white dwarf in a relatively wide $\gtrsim 5.8\,yr$ orbit. Although, the scenario is generic, it requires some fine-tuning to achieve parameters comparable to the observed twin WOCS ID 7782. This system is best reproduced when starting with a $m_3 = 1.4$ $M_\odot$ ~~and $m_2 = 0.7$~~ outer star in an 220 to 1100 day orbit around an inner binary composed of an 1.1 $M_\odot$ primary and a $m_2 = 0.7$ to 0.9$M_\odot$ ~~and an outer tertiary mass of $m_3 = 1.4$ $M_\odot$. (2) After Roche-lobe overflow, the outer star turns into a white dwarf (WD) of mass 0.43~~ secondary star in an 8.6 to ~~0.54~~24 ~~$M_\odot$. There is a correlation between the mass of this WD and the outer orbital period: more massive WDs will be on wider orbits. (3) The rotational axes of both BSs will be aligned with each other and the orbital plane of the outer tertiary WD. (4) The BSs will have roughly equal masses, independent of their initial~~

Corresponding author: Nathan W. C. Leigh
nleigh@amnh.org

~~masses (since the lower mass star accretes the most). The dominant accretor should, therefore, be enriched more effectively by the accreted material. As a result, one of the BSs will appear to be more enriched by either He, C and O or by s-process elements, depending on whether the donor started to overflow its Roche lobe on, respectively, the red giant or early asymptotic giant branch. (5) Relative to old dense clusters with high-velocity dispersions, twin BSs in close binaries formed from the proposed mechanism should be more frequent in the Galactic field and younger open clusters with ages $\lesssim$ 4-6 Gyr, since then the donor will have a radiative envelope. (6)~~ day orbit. Based on our simulations and theoretical arguments we predict that twin BSs that formed through mass transfer from a Roche-lobe over-filling outer tertiary are generally comparable in mass and have aligned spins, which are in turn aligned with the orbit of the ~~binary BS will have a small semi-major axis (typically $\lesssim 0.3$ au) and be close to circular ($e \lesssim 0.1$)~~tertiary white-dwarf star. If the two inner stars were initially unequal in mass the less massive star will have accreted more material from the tertiary star, and should therefore be more enhanced in CNO-processed material.

Keywords: stars: blue stragglers – binaries: general – globular clusters: general – scattering

1. INTRODUCTION

Most blue straggler stars are brighter and bluer than the main-sequence (MS) turn-off in a cluster colour-magnitude diagram (e.g. Sandage 1953; Leonard 1989; Simunovic & Puzia 2014). Two primary channels for BS formation have been proposed: mass transfer from an evolved donor on to a MS star in a binary star system (e.g. McCrea 1964; Portegies Zwart et al. 1997a; Knigge et al. 2009; Leigh & Sills 2011; Geller & Mathieu 2011), and direct stellar collisions involving MS stars likely mediated via binaries (e.g. Hills 1975; Portegies Zwart et al. 1997b; Leigh et al. 2007, 2013; Hypki & Giersz 2013; Portegies Zwart 2019). The first mechanism predicts BSs in binaries with WD companions, whereas the second predicts MS companions in a wide and eccentric binary. Other possible, albeit related, formation mechanisms include mergers of close MS-MS binaries (Portegies Zwart 2019), and mergers of the inner binaries of hierarchical triple star systems induced by Lidov-Kozai oscillations coupled with tidal damping (e.g. Perets & Fabrycky 2009). The latter predicts no binary companion, whereas the former predicts a MS companion in a wide binary.

In spite of these specific predictions for the expected properties of BSs formed from each of the above production mechanisms, many BSs exist with observed properties that defy these simple scenarios. For example, in the old open cluster (OC) M67, there lurks a candidate triple system that is posited to host two BSs (van den Berg et al. 2001; Sandquist et al. 2003); one in the inner binary and one as the outer triple companion (Sandquist et al. 2003; van den Berg et al. 2001). In order to reproduce the total system mass at least five stars are needed (Leigh & Sills 2011), which is strongly indicative of a dynamical origin for the system; a single direct interaction involving a binary and a triple that resulted in two separate collisions is the most probable explanation for its origin (instead of back-to-back direct binary-binary interactions) (Gualandris et al. 2004; Leigh & Sills 2011).

Even more curious, there exists in the old OC NGC 188 a double BS binary, called WOCS 7782 (Geller et al. 2009). The BS population in NGC 188 has a bi-modal period-eccentricity distribution. As discussed in Leigh & Sills (2011), this could be hinting at a triple origin for at least some subset of the total BS population. As for WOCS 7782, Mathieu & Geller (2009) observed a compact and mildly eccentric (i.e., $e \sim 0.1$) binary star system with an orbital period of ~ 10 days hosting two roughly equal-mass BSs. During a given binary-binary interaction, the probability that not one but two direct (MS-MS) collisions will occur is less than 10^{-2} (Leonard 1989; Leigh & Sills 2011; Leigh & Geller 2012). Plus, binaries with collision products typically have relatively long orbital periods (Fujii & Portegies Zwart 2011). Dynamically, it is difficult to form a short-period binary composed of two collision products during a collisional interaction in a star cluster (Leigh & Sills 2011; Fujii & Portegies Zwart 2011), and the timescale for exchanging another BS into a pre-existing BS-MS or BS-WD binary is much longer than the expected BS lifetime (see Leigh & Sills (2011) and the end of Section 2 below). So, how did WOCS 7782 form?

We propose a formation channel for WOCS 7782, and compact double BS binaries in general, which involves mass transfer from an outer tertiary companion on to an inner binary composed of two MS stars. In section 2, we constrain the range of initial (i.e., pre-mass transfer) orbital parameters for a hypothetical outer tertiary companion, using a combination of dynamical and stellar evolution-based constraints. In Section 3 we present the numerical simulations used to study the mass transfer process in this triple system. We adopt orbital parameters that, according to our expectations, are most promising for the progenitors of the twin BS 7782. The calculations are performed using the Astrophysical Multipurpose Software Environment (`AMUSE` for short, see Portegies Zwart et al. 2013b; Portegies Zwart & McMillan 2018) with a combination of stellar evolution, hydrodynamical and gravitational simulations. With these calculations we further constrain the possible range of initial parameters that naturally lead to twin BSs with orbital parameters similar to the 7782 system, without exhaustively covering parameter space. We summarize and discuss the implications of our results for compact double BS binaries and, more generally, mass transfer in stellar triples in Section 5.

2. CONSTRAINTS ON THE PRESENT-DAY ORBITAL PARAMETERS FOR A HYPOTHESIZED TERTIARY COMPANION IN THE COMPACT BS BINARY WOCS 7782

In our scenario, we start with a binary star with component masses m_1 and m_2 that is orbited by a tertiary of mass m_3. The inner and outer binary orbital semi-major axes are denoted $a_{\rm in}$ and $a_{\rm out}$, respectively. For specificty, we assume both orbits, the inner as well as the outer, to be circular and in the same plane, which minimizes chaotic effects during the mass transfer process, facilitates more stable mass transfer and ultimately allows us to simulate our target system for longer while also maximizing the amount of mass transferred. These assumptions are also supported by the population of observed low-mass triples (Tokovinin 2010; Moe & Kratter 2018). This initial configuration for our assumed formation scenario for WOCS 7782, described below, is depicted in figure 1.

According to our scenario $m_3 > m_1 > m_2$ and the outer orbit is sufficiently small that the tertiary star is filling its Roche lobe and transfers mass to the inner binary before it reaches the asymptotic giant branch. We constrain the inner orbit by requiring the triple system to be dynamically stable, for which we adopt eq. 1 in Mardling & Aarseth (1999). While transferring mass, the accretion stream gathers around the inner binary at the circularization radius $a_{\rm c}$, and forms a circumbinary disk (Frank et al. 2002). Using conservation of angular momentum, we equate the specific angular momentum of the accreted mass at the inner Lagrangian point of the (outer) donor star to the final specific angular momentum of the accretion stream at the circularization radius about the inner binary, this results in

$$v_{\rm orb,3}(a_{\rm out} - R_{\rm L}) = v_{\rm orb,c} a_{\rm c}, \quad (1)$$

where $R_{\rm L}$ is the radius of the Roche lobe of the outer tertiary companion, $a_{\rm c}$ is the semi-major axis of the orbit

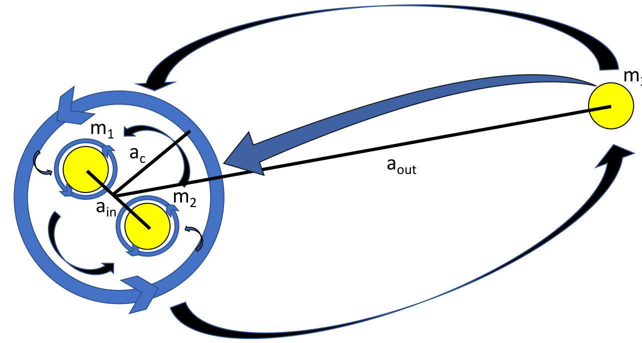

Figure 1. Cartoon depiction of our proposed scenario for the formation of WOCS 7782, specifically mass transfer from an evolved outer tertiary companion on to a compact inner binary via a circumbinary disk. The outer tertiary component has mass m_3, whereas the inner binary components have masses m_1 and m_2. The inner and outer orbital separations are denoted by, respectively, $a_{\rm in}$ and $a_{\rm out}$. The circularization radius of the accretion stream is denoted $a_{\rm c}$, as calculated via Equation 2, and marks the mean separation of the circumbinary disk.

about the inner binary corresponding to the circularization radius and $v_{\rm orb,c}$ is the orbital velocity at $a_{\rm c}$. The distance from the centre of mass corresponding to the tertiary defined by the Roche lobe is given by eq. 2 in Eggleton (1983). Combining eq. 2 in Eggleton (1983) (with mass ratio $q = m_3/(m_1+m_2)$) with eq. 1, we solve for the circularization radius as a function of $a_{\rm out}$ and the assumed stellar masses:

$$a_{\rm c} = a_{\rm out}(1 - R_{\rm L}). \quad (2)$$

In order for a circumbinary disk to form around the inner binary, we require that $a_{\rm in} < a_{\rm c}$.

Figure 2 shows the parameter space in the $P_{\rm out}$-$P_{\rm in}$-plane for WOCS 7782. Here we adopted, for clarity, initial component masses of $m_1 = 1.1$ $M_\odot$ and $m_2 = 0.9$ $M_\odot$ for the inner binary components, and $m_3 = 1.4 M_\odot$ for the outer tertiary. The scenario worked out is general, but we opt for these specific parameters because they appear to naturally result in a system with parameters similar to WOCS 7782. We compare the circularization radius to the semi-major axis of the inner binary, for which we require $a_{\rm c} > a_{\rm in}$, after folding in all constraints from the requirements for dynamical stability (listed in the caption of figure 2), and the assumption of an outer tertiary that is Roche lobe-filling (see de Vries et al. (2014) for more details). Note that the range of plotted orbital periods $P_{\rm in}$ corresponding to a contact state for the inner binary lies outside the range of plotted values for $P_{\rm in}$ (for components with radii of 1 $R_\odot$), since it does not contribute to constraining the outer orbital properties. The thick horizontal solid red line shows the allowed range of outer semi-major axes, after folding in all of the aforementioned criteria. These constraints result in a rather narrow range of initial conditions for the outer orbit, namely 2.2×10^2 days $\leq P_{\rm out} \leq 1.1 \times 10^3$ days, which also directly translates into constraints on the final outer tertiary orbit.

Finally, we compute the timescales for our hypothesized triple to undergo a direct interaction with another single or binary star. Using the same assumptions for the host cluster properties of NGC 188 outlined in Section 3.2 of Leigh & Sills (2011) (right-hand column), we find upon setting the single-triple (3+1) and binary-triple (3+2) timescales equal to the expected duration of the mass transfer phase (i.e., ~ 1 Myr) critical outer orbital periods for triples for $\gg 1$ Myr. These critical outer tertiary orbital periods, which correspond to the times for a specific triple to undergo an interaction, correspond to 3+1 and 3+2 interaction times that are much longer than the maximum predicted outer orbital period of the hypothesized white dwarf tertiary in our scenario. We therefore do not expect the mass transfer process to be interrupted by a dynamical interaction in the cluster center.

Adopting a mass for the tertiary star of $m_3 = 1.4\,{\rm M}_\odot$, we can constrain the initial parameters for the inner binary as well as the orbit of the outer star after mass transfer. We first calculate the stellar radius as a function of core mass. In figure 3 we present this relation calculated using the `SeBa` stellar evolution code (Portegies Zwart & Verbunt 1996) as the dark blue curve. The interruption in this curve, around a core mass of $m_{\rm core} \sim 0.5\,{\rm M}_\odot$ is a result of the evolution along the horizontal branch, where the core of the star continues to grow but the stellar radius actually shrinks. Roche-lobe overflow in this phase is not expected to happen, because it would already have happened in an earlier evolutionary state of the donor star, when it was bigger.

Adopting masses for the inner binary $m_1 = 1.1\,{\rm M}_\odot$ and $m_2 = 0.9\,{\rm M}_\odot$ we can calculate the outer orbital separation at the onset of Roche-lobe overflow $a_{\rm out}$, and subsequently the maximum orbital separation for the inner binary for which the orbit is stable and a circumbinary disk can form. These two limits are presented as the light blue and light green curves in figure 3. The allotted region of parameter space is then above the dashed horizontal line and to the right of the vertical dotted line.

With the adopted parameters, we can also estimate the final orbital period of the left-over core from the tertiary star after mass transfer. The change in orbital separation due to non-conservative mass transfer can be expressed in terms of the mass of the outer star before and after mass transfer, i.e. m_3 and m_3' respectively, the total mass in the inner binary before ($m_{\rm in}$) and after accretion ($m_{\rm in}'$) and the amount of angular momentum lost per unit mass $\eta \simeq 3$. The value of $\eta = 3$ was derived in Pols et al. (1991); Portegies Zwart (1995) by

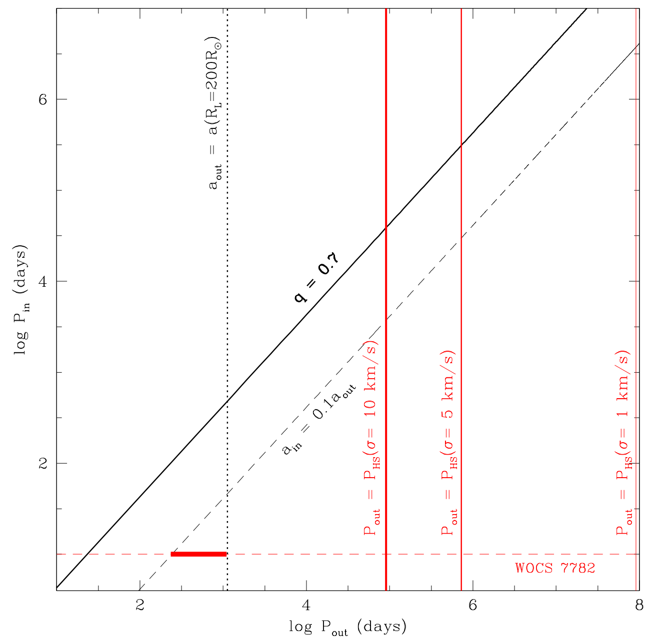

Figure 2. Parameter space in the $P_{\rm out}$-$P_{\rm in}$-plane allowed for the hypothetical outer tertiary orbit of WOCS 7782 before Roche-lobe overflow. The solid diagonal black line shows the period corresponding to the circularization radius a_c for the mass transfer stream coming from the outer star (i.e., at the onset of mass transfer). We assume initial component masses of $m_1 = 1.1$ M$_\odot$ and $m_2 = 0.9$ M$_\odot$ for the inner binary components, and m_3 is computed for the outer tertiary according to our assumed mass ratio (with our fiducial case corresponding to q = 0.7). We assume completely conservative mass transfer for this exercise, and a final mass for the outer tertiary of 0.6 M$_\odot$ once it has become a WD. The dashed diagonal black line shows a rough criterion for dynamical stability in the triple, approximately following Mardling & Aarseth (1999) (i.e., $a_{\rm in} < 0.1a_{\rm out}$ is required for long-term dynamical stability in equal-mass co-planar triples). The vertical solid red lines show the outer orbital periods corresponding to the hard-soft boundary assuming central velocity dispersions of $\sigma = 1$, 5 and 10 km s^{-1}. The vertical dashed black line show the maximum outer orbital period $P_{\rm out}$ for which the outer tertiary companion is Roche lobe-filling, assuming a stellar radius of $R_3 = 200$ R$_\odot$ (which corresponds to the maximum stellar radius reached on the AGB for the range of tertiary masses of interest to us; see figure 3). The horizontal dashed red line shows the observed orbital period for WOCS 7782, using its observed orbital period and our assumed final inner companion masses (i.e., $m_1 = m_2 = 1.4$ M$_\odot$). Finally, the thick solid horizontal red line shows the parameter space for $P_{\rm out}$ allowed after considering all of the aforementioned criteria.

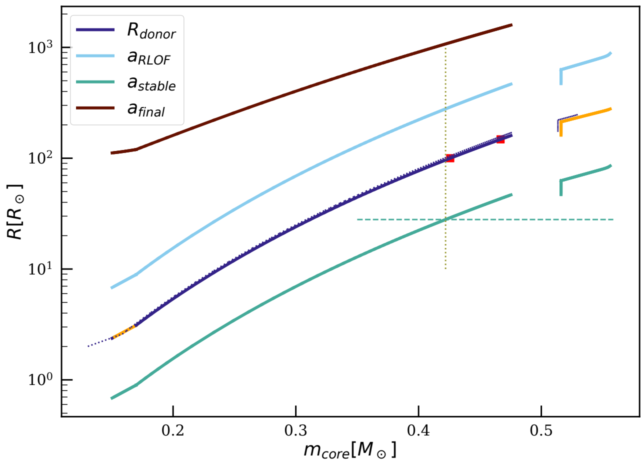

Figure 3. Giant radius as a function of the mass of the core of the Roche-lobe filling outer star (dark blue curve). The first and last parts of this curve are orange to indicate that the star at these masses and radii is on the Hertzsprung-gap (to the left) or after core helium burning stage (to the right). ~~Only when~~ When the donor is on the giant branch (dark blue) Roche-lobe overflow will lead to a binary blue straggler. Here we adopt a donor mass of $1.4\,M_\odot$, but for an $1.2\,M_\odot$ the donor the curve is quite similar (see dotted dark-blue curve). The red squares in the curve show the parameters for which we performed more detailed gravitational-hydrodynamical simulations (see § 3). The horizontal dashed line shows the orbital separation of the observed twin BS 7782. The initial triple in which it possibly formed must at least have been dynamically stable. The minimal orbital separation for the inner binary for which the triple is stable is given by the lower green coloured curve. Donors which are smaller than about $100\,R_\odot$ (light-green curve indicated with a_{stable}) result in a dynamically unstable triple. The minimal core mass associated with a stable triple is then indicated by the left-most vertical dotted line. The orbital separation at which the donor star overfills its Roche lobe is indicated with the light-blue curve. The top curve (brown) shows an estimate of the final orbital separation of the outer star, and therefore of the final orbit of the WD around the inner twin BSs. For core masses $\gtrsim 0.5\,M_\odot$ the final orbital separation, after mass transfer, is smaller than the initial orbit. Here we adopted an initial inner binary mass of $(1.0{+}0.9)\,M_\odot$ and a final twin BS mass of $(1.4{+}1.4)\,M_\odot$.

matching the orbital evolution and birthrate of Be-type x-ray binaries that experience non-considervative mass transfer. This value of consistent with the analysis for non-conservative evolution of type B mass transfer in Krtička et al. (2011) and further constrained in Pols (2007) to understand the mass transfer in the 100-day orbital period binary V379 Cep. Adopting the relation between the orbital separation before mass transfer (a) and after mass transfer (a') from Portegies Zwart (1995)

$$\frac{a'}{a} = \left(\frac{m_3 m_{\rm in}}{m_3' m_{\rm in}'}\right)^{-2} \left(\frac{m_3 + m_{\rm in}}{m_3' + m_{\rm in}'}\right)^{2\eta+1}, \qquad (3)$$

we arrive at the top red curve in figure 3. This curve provides a prediction for the current orbital separation of the WD around the twin BS 7782.

Having limited parameter space for the formation of the twin BS 7782, we continue by performing a series of simulations to investigate the accretion and changes to the inner orbits of triple systems in this range of parameters.

3. NUMERICAL SIMULATIONS

We perform simulations of a triple star system for which the outer star overfills its Roche lobe while the inner binary remains detached. The calculations start by evolving the three stars to the same age, which is selected such that the outer-most star fills its Roche lobe. First order constraints for the initial conditions are derived in the previous §. In the following two sections we describe how we set up these simulations and then discuss the results. The calculations are performed using the Astrophysical Multipurpose Software Environment using a combination of stellar evolution, gravitational dynamics and hydrodynamics.

3.1. *Setting-up the simulations*

We adopt initial masses of $m_1 = 1.1$ $M_\odot$ and $m_2 = 0.7$ $M_\odot$ or $0.9\,M_\odot$ for the inner binary components, and between $m_3 = 1.2$ and $m_3 = 1.4$ $M_\odot$ for the tertiary star. We evolve the tertiary star using the MESA stellar-evolution code Paxton et al. (2011) to a radius of about $100\,R_\odot$ and $150\,R_\odot$, at which point we assume it to overfill it's Roche lobe (see red squares in figure 3). We perform calculations for an inner orbital separation of $a_{\rm in} = 0.10$ au, $a_{\rm in} = 0.15$ au and $a_{\rm in} = 0.20$ au. In total we performed 12 calculations at a resolution of 40k SPH particles and 12 at 80k.

The stellar-evolution model, including the structure, temperature and composition profiles are turned into a smoothed-particles representation using the module `StellarModelInSPH` in AMUSE (see chapter 4 in Portegies Zwart & McMillan (2018)). We follow the same procedure as described in de Vries et al. (2014) for simulating the future of the triple system χ Tau (HD 97131) in which the outer-most star overfills its Roche lobe and transfers mass to an inner binary. After generating the hydrodynamical representation of the donor star we replace the stellar core by a point mass to prevent the majority of the resolution to be confined in the star's central regions. In a following step we relax the star using the hydrodynamics solver. This relaxation process is realized in 100 steps during which we reduce the velocity dispersion of individual SPH particles to a glasses structure (see, for example, § 3.3 on page 40 in White

(1995)). During this procedure, the gaseous envelope of the star tends to expand by about 20%. To determine the radius of the evolving star we calculate Lagrangian radii and use the distance to the stellar center which contains 90% of its mass. From this 90% mass-radius relation we obtain the stellar radius and match it with the Roche-lobe of the outer orbit.

With these parameters the orbital separation of the outer binary becomes $\sim 250\ \mathrm{R}_\odot$ for the $100\ \mathrm{R}_\odot$ donor star and about $430\,\mathrm{R}_\odot$ for the more evolved donor star. We adopt the outer orbit to be circular and in the plane of the inner binary.

Roche-lobe overflow in triples is modelled using a coupled integrator to follow the complex hydrodynamics of mass transfer from the Roche-lobe filling outer star to the inner binary, while keeping track of the gravitational dynamics of the stars. The equations of motion of the inner binary are solved using the symplectic direct N-body integrator `Huayno` (Pelupessy et al. 2012). The hydrodynamics are performed with the smoothed-particles hydrodynamics code `Gadget2` (Springel 2000), using an adiabatic equation of state. The two inner binary stars are treated as point masses, but we allow them to accrete mass and angular momentum from the gas liberated by the outer star. This is realized using spherical sink-particles that co-move with the mass points in the gravity code. While the inner two stars accrete mass, they also accrete the corresponding amount of angular momentum from the gas (see chapter 5 in Portegies Zwart & McMillan (2018)). The N-body integrator correctly accounts for this. For the radius of the sink particles, we adopt $2R_\odot$ for both stars.

The N-body code, as well as the hydrodynamics solver, operate using their own internal time-steps. The coupling between the two codes is realized using the `Bridge` method in the AMUSE framework (see Sect.4.3.1 in Portegies Zwart et al. 2013a). This coupled integrator is based on the splitting of the Hamiltonian, much in the same way as is done with two different gravity solvers by Fujii et al. (2007). With the adopted scheme, the hydrodynamical solver is affected by the gravitational potential of its own particles, as well as the gravitational potential of the inner binary. The hydrodynamics affects the orbits of the two inner stars and the accretion onto the two stars affects the hydrodynamics. With `Bridge` we realize a second order coupling between the gravitational dynamics and the hydrodynamics. The interval at which the gravity and hydrodynamics interact via `Bridge` depends on the parameters of the system we study, but typically we achieve converged solutions when this time step is about 1/100 that of the inner binary orbital period.

4. RESULTS OF THE HYDRODYNAMICAL SIMULATIONS

To test the hypothesis that the secondary in the inner binary accretes more effectively than the primary star and to measure the change to the inner orbit due to the Roche-lobe overflow of the outer star, we perform a series of calculations in which we take the self gravity and the hydrodynamical effects of the triple into account. The results of one of these simulations (1091 days after the onset of mass transfer) is presented in figure 5.

It is apparent that the mass transfer in the adopted triples leads to a rather untidy evolution, since much of the donor mass is lost through the second Lagrangian point to the right side of the donor star in figure 4. A considerable amount of mass is also lost through the third Lagrangian point (to the left of the inner binary), although it is hard to actually quantify the amount of material lost, becuase an appreciable fraction may to rain back onto the triple system. One remaining question is how much mass is eventually ejected altogether from the triple system and is therefore not accreted to any of the two inner stars. ~~This value is hard to estimate from the simulations , but an accretion efficiency of $\gtrsim 0.8$ is necessary to make the scenario feasible. Over the~~ In our simulations the accretion efficiency on the inner binary has to exceeds $\sim 80\,\%$ for the two blue straggers to reach masses comparable to those observed in WOCS ID 7782. Over the relatively short time scale for which we performed the calculations ~~,~~ this efficiency is ~~reached~~achieved, but it is not clear how the system responds at later stages.

The evolution of the inner orbit presented for several simulations in figure 5 is complicated. This is caused by the complex transport of mass, energy and angular momentum through the accretion stream and throughout the system. It is therefore hard to quantify distinct trends in the evolution of the triple system. In simulations of the response of an inner binary on accretion from a circumbinary disk, Mösta et al. (2018) conclude that the complexity of angular momentum transport between the outer star and the accretion stream onto the individual inner stars, is complicated and without clear trends. For most of our calculations we agree with this statement, but in figure 5 we nevertheless present the results of 6 of our calculations, three for a $1.2\,\mathrm{M}_\odot$ donor star and three for a $1.4\,\mathrm{M}_\odot$ donor. The various coloured curves give the resulting evolution of the inner orbit as a function of the total mass in the inner binary. As the inner two stars accrete, the orbit shrinks for a $1.2\,\mathrm{M}_\odot$ donor. These systems are expected to result in a contact binary, that eventually may merge to form a single BS with a mass more than twice the turn off in orbit around

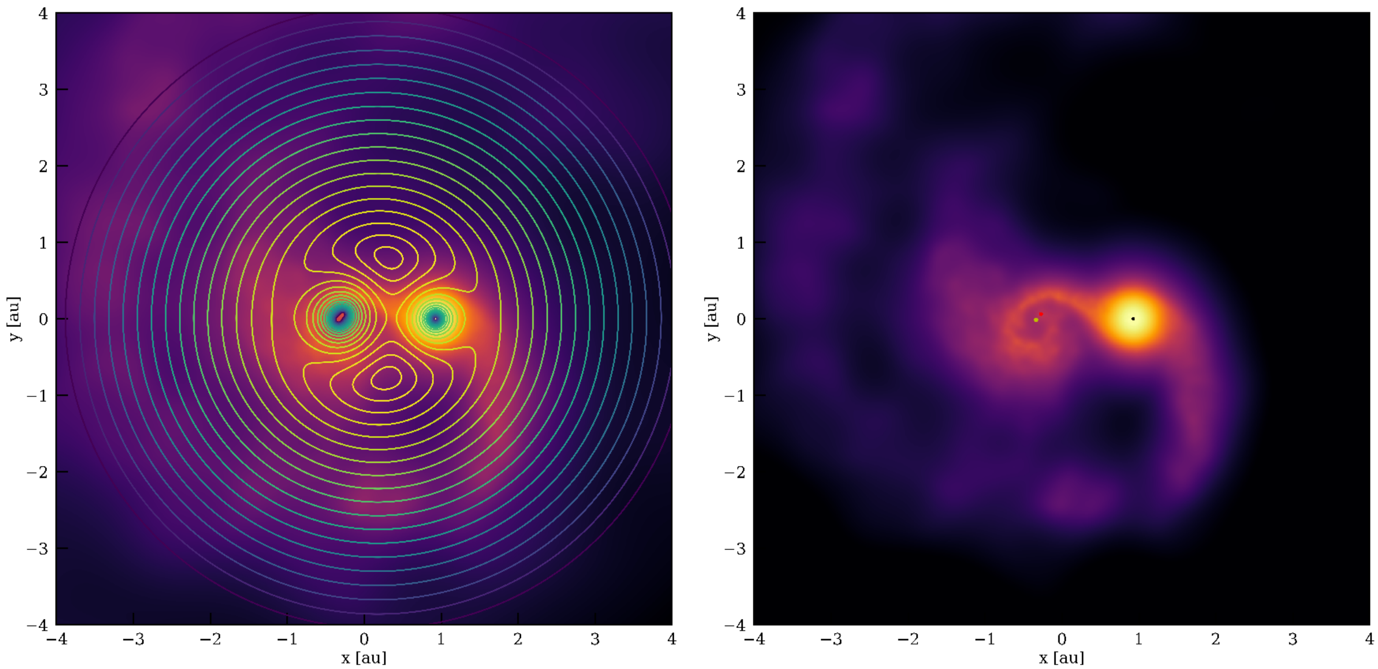

Figure 4. Top view of one of the simulated triple systems at an age of $t \simeq 1091\,days$ after the start of the simulation when the $100\,\mathrm{R}_\odot$ outer star of $1.4\,\mathrm{M}_\odot$ over-fills its Roche-lobe. The star is represented by 80000 SPH particles and a core particle of $\sim 0.4\,\mathrm{M}_\odot$(black bullet in the middle of the right-most yellow blob). The inner binary (to the left) is represented by the yellow and red bullets for, respectively, the $1.1\,\mathrm{M}_\odot$ primary and $0.9\,\mathrm{M}_\odot$ secondary stars in a circular orbit of 0.1 au. The $1.4\,\mathrm{M}_\odot$ giant star is presented to the right in a circular orbit with semi-major axis $\sim 250\,\mathrm{R}_\odot$ in the plane of the inner binary. Left panel shows the equipotential surfaces of the triple overplotted with the gas distribution, the right panel shows just the gas and the stars as bullets.

a low-mass white dwarf. The required evolution in order to explain the observed twin BS 7782 is indicated by the three black curves; the simulated path clearly deviates from these. We, therefore, argue that a $1.2\,\mathrm{M}_\odot$ donor has difficulty explaining the observed orbital separation of ~ 0.13 au in BSS 7782.

In the right-hand panel in figure 5 we present the evolution of the orbit for the $1.4\,\mathrm{M}_\odot$ donor for several initial orbits of the inner binary. A more massive donor appears to be more effective in producing a twin BS with parameters consistent with the observed system 7782. There is more mass available in the envelope of the donor star, and the orbital evolution of the inner binary matches better with the anticipated evolution needed to reproduce the observed parameters of WOCS 7782. A more massive donor may therefore have a lower accretion efficiency while still accomodating the observed constraints. The longer thermal time scale of the stellar envelope of the higher-mass donor at the same stellar radius eventually leads to a higher mass-transfer rate, and therefore to a lower accretion efficiency. However, the larger mass budget in the envelope appears to compensate.

The orbit of the inner binary expands in these cases as a result of accretion onto the inner two stars. In all three cases for the $1.4\,\mathrm{M}_\odot$ donor presented in figure 5 the inner orbit expands at about the same rate. Consequently, the inner binaries that start with $a = 0.15$ au and $a = 0.20$ au eventually become dynamically unstable. The binary with an initial separation of 0.10 au expands to reach a separation of about 0.126–0.145 au for final masses for the inner two stars of $1.4\,\mathrm{M}_\odot$, which is consistent with the observed twin BS WOCS 7782. In our simulations the eccentricity of the inner binary grows to about $e \simeq 0.0028$.

With the accretion of mass, both stars in the inner binary also accrete angular momentum. By the end of the simulation the spins of the two BSs are aligned along the orbital angular momentum axis with an angle of 90.0° for the primary star and 93.4° for the secondary star with respect to the argument of pericenter of the inner orbit. This supports our naive prediction that the spin angular momenta of the two stars in the inner binary should be more or less aligned post-mass transfer, due to the non-negligible amount of mass accreted. By the end of the simulations the spin of the primary is about 50.5 rotations per day, and 41.5 rotations per day for the secondary star. Such high spin rates immediately post-mass transfer are supported by other work (see, for example, de Vries et al. (2014)), ~~which could then~~

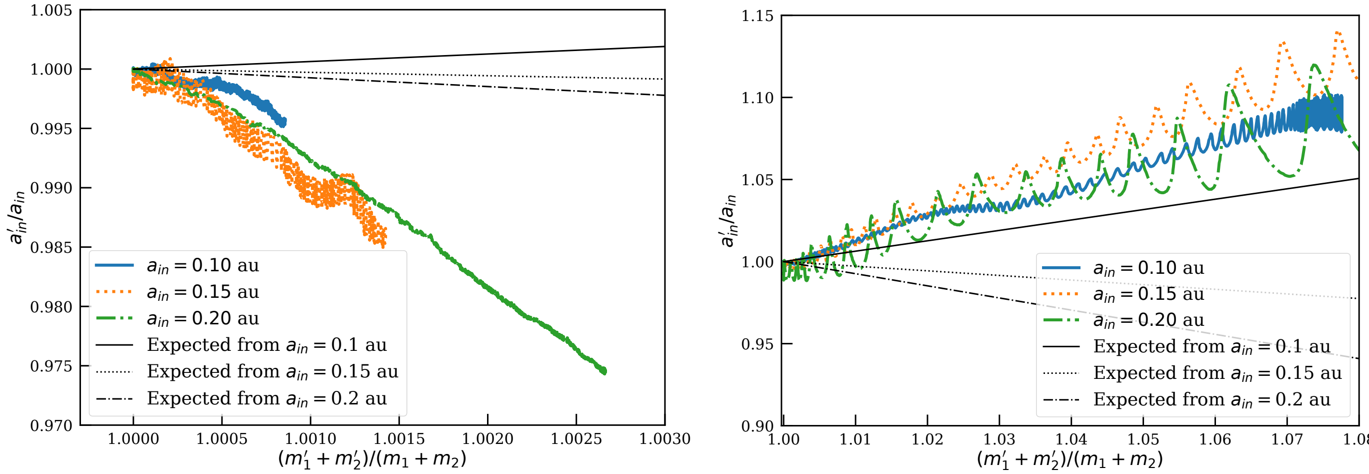

Figure 5. Evolution of the orbital separation as a function of the total mass of the inner binary for six calculations with somewhat different initial conditions (see the legend). The left panel shows the result for a 1.2 $M_\odot$ donor star and the right panel for a 1.4 $M_\odot$ donor. The initial binary shown by the blue curve of the right-hand panel is presented in fig. 4 we present the final conditions of this system. The black curves give the expected evolution of the orbital separation of the inner binary assuming that the binary evolved towards the observed orbital separation of 0.13 au at a total binary mass of 2.8 $M_\odot$.

~~subsequently spin down~~ but the twin blue stragglers in WOCS ID 7782 are not observed to be spinning that fast Leiner et al. (2018b). Rapidly spinning stars may slow due to, for example, magnetic braking, bringing them closer to the actually observed spin rates ~~.~~ Leiner et al. (2018a).

5. DISCUSSION

In this paper, we propose a formation scenario for twin equal-mass blue stragglers in tight binaries, as observed for WOCS 7782 in the old OC NGC 188. The proposed scenario involves mass transfer from an evolved outer tertiary companion. Part of this mass is accreted by the inner binary via a circumbinary disk, while the rest escapes through the second and third Lagrangian points in the potential of the triple system. Our scenario makes several predictions for the observed properties of a hypothetical outer triple companion, now a WD. These are:

1. For the predicted outer tertiary orbit, the initial orbital period should lie between 220 days $\lesssim$ P$_{\rm out}$ $\lesssim$ 1100 days, assuming initial masses for the inner binary components of $m_1 = 1.1$ $M_\odot$ and $m_2 = 0.9$ $M_\odot$ and an initial outer tertiary mass of $m_3 = 1.4 M_\odot$. The final orbital period of the white dwarf around the binary blue straggler should ~~exceeds the initiall~~ exceed the initial orbit, but be smaller than ~ 4100 days.

2. Larger final WD masses, and hence larger core masses for the donor at the time of mass transfer should correspond to larger final outer orbital periods for the tertiary. This is because the Roche radius is larger for larger outer orbital periods, such that the donor must evolve to larger radii, and hence core masses, before the onset of mass transfer. We expect the orbital separation to range from $\gtrsim 6.4$ yr for a ~ 0.42 $M_\odot$ white dwarf to $\gtrsim 11.2$ yr for a ~ 0.48 $M_\odot$ white dwarf.

3. For the inner binary, the rotational axes of both the BSs should be aligned with each other and the orbital plane of the outer tertiary WD. This is because accretion onto the BS progenitors proceeds via an accretion disk, that forms at the circularization radius and that has an orbital plane aligned with that of the outer tertiary.

4. The BSs in the inner binary should have roughly equal masses, independent of their initial masses. This is because it is the lowest mass object that typically accretes the fastest, since its orbital velocity and distance relative to the circumbinary disk is typically the lowest (e.g. Bate 2000; Shi et al. 2012; Miranda et al. 2017). The mass ratio of the inner binary, therefore grows to unity.

We further validated this statement by performing an additional series of calculations in which we vary the mass of the tertiary star in the initial triple from 0.5 $M_\odot$ to 0.7 $M_\odot$ and 0.9 $M_\odot$. In fig. 6 we present the evolution of the normalized mass ratio in these binaries. ~~with~~ With these calculations we demonstrate that a low-mass ratio initially tends to evolve towards an equal mass ratio.

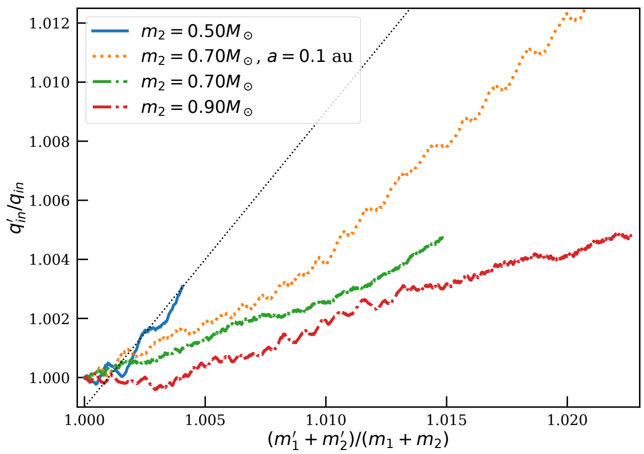

Figure 6. Evolution of the mass ratio for initial triples with an inner orbital separation of 0.1 au (orange dotted curve) and 0.2 au (all other curves). The initial primary mass was $1.4\,M_\odot$ overfilling it's Roche lobe at a radius of $100\,R_\odot$. ~~the~~ The companion masses are $m_2 = 0.9\,M_\odot$ and the mass of the tertiary ~~is~~ are indicated in the legend. The dotted black line indicates the required mass-ratio evolution in order to eventually reach an equal mass-ratio ~~blue-straggler~~ blue straggler binary.

5. ~~As a consequence of the above, the initially lower mass MS star should accrete the most, and therefore be more enriched by accreted material. This could be observable in the surface layers of a radiative star. If the donor is an RGB star, the accretors will be enriched in mostly carbon, oxygen and helium, but if the donor is an AGB star the enrichment will be mostly in s-process elements. Note that part of the mass liberated from the triple system through the second and third Lagrangian points may eventually be accreted back onto the system. This could also have interesting consequences for the enrichment of the low-mass white dwarf. Such a debris disk was recently found around the white dwarf SDSS J122859.93+104032.9 (Manser 2019).~~

6. ~~We expect twin BSs in compact binaries formed from the mechanism proposed here to be more frequent in younger clusters with ages $\lesssim$ 4-6 Gyr. This is because stars in clusters with a MS turn-off mass $\lesssim 1.2\,M_\odot$ have convective envelopes (e.g. Iben 1991; Maeder 2009), and a radiative envelope for the donor in a mass transferring binary ensures stable accretion on to the accretor.~~

Finally, we emphasize that the choice for the initial mass of the outer tertiary may be rather critical. Mass transfer in our proposed scenario proceeds from the most massive tertiary to a binary of lower ~~total~~ mass. This may result in an unstable phase of mass transfer, in particular if the donor has a convective envelope (e.g. Maeder 2009). A radiative envelope of the donor ensures that the mass transfer will be maximally conservative, such that the accretion stream will be maximally stable, accreting at a stable and roughly constant rate (e.g. Iben 1991). This stability regime may also be of interest for explaining very massive twins, of $\gtrsim 20\,M_\odot$ which could be promising sources for gravitational wave detectors once both twins evolve to a binary black hole (de Mink & Mandel 2016).

6. SUMMARY

In this paper, we consider the formation of twin BSs in tight binaries. These systems may form through mass transfer from an outer Roche-lobe filling tertiary star. Once this star ascends the giant branch, part of its envelope is transferred to the inner binary, and accreted by the two inner stars which are still on the MS.

As illustrated via SPH simulations, the mass transfer stream forms a circumbinary disk, from which the inner binary stars accrete, driving the inner binary toward a mass ratio close to unity. Our simulations indicate that the inner binary orbital separation can decrease or expand depending on the details of the transfer of mass and angular momentum. More work is certainly needed in order to fully understand mass transfer in triples.

We summarize the results of these simulations as follows: for a $1.2\,M_\odot$ tertiary donor mass, we expect the inner two stars to eventually merge and form a single BS. This reduces the system to a binary with a primary BS and an outer WD in a relatively wide orbit. Such a BS will distinguish itself from other BSs by potentially being more than twice the turn-off mass in a star cluster. An example could be the $2.9 \pm 0.2\,M_\odot$ BS S1237 in the Galactic cluster M67 (Leiner et al. 2016). It is the primary of a ~ 698 day binary with an eccentric orbit of ~ 0.10.

With an original outer star of mass $\sim 1.4\,M_\odot$, the inner orbit tends to expand. This eventually leads to a dynamically unstable system resulting either in a collision or in the ejection of (probably) the lowest mass star. This evolution could result in a single ejected BS, with the other BS left in a relatively close and eccentric orbit with a WD (the left-over core of the tertiary star). ~~Such a close~~ As discussed in Section 1, BS-WD ~~binary would be hard to explain in another way.~~ binaries are predicted to be the products of the binary mass transfer hypothesis (ignoring a common envelope phase) for BS formation. However, this mechanism tends to predict wide orbits, which is consistent with the observed BS-WD systems in NGC 188. If, on the other hand, such a dynamical instability engages relatively late in the mass-tranfer phase, the white dwarf (maybe with a little left-over envelope) is expected to be ejected. This would lead to a relatively wide twin blue-straggler binary and a single low-mass white dwarf.

When we adopt an inner orbit of 0.10 au the expansion eventually matches the observed orbital separation (i.e., 0.13 au) of the observed twin BS WOCS 7782 and the observed masses of the two stars of about $1.4\,M_\odot$.

In order to study the T-tauri binaries V4046 Sgr and DQ Tau, de Val-Borro et al. (2011) perform a series of 2D hydrodynamical simulations of circumbinary disks. These authors studied the two observed T-tauri systems V4046 Sgr and DQ Tau, to which we compare our results here. For V4046 Sgr, for which the two stars have comparable masses as in our calculation for a circular orbit with a period of only 2.4 days, they find that the inner binary accretes at a rate of $\sim 0.028\,M_\odot$/Myr. For DQ Tau, which is composed of lower-mass stars ($m_1 = m_2 \simeq 0.55\,M_\odot$) in an eccentric ($e \simeq 0.556$) orbit of ~ 15.8 days, they find an accretion rate onto the inner binary of $\sim 0.027\,M_\odot$/Myr. These values are in the same range as in our calculations, which results in an accretion rate for the inner binary of 0.027–0.058 $M_\odot$/Myr (i.e., the average measured over a period of about 3000 days in our simulations). Interestingly, however, de Val-Borro et al. (2011) find that the primary star in V4046 Sgr accretes at an 8% higher rate than the secondary star, whereas in our case the secondary star accretes at a higher rate than the primary star by about 1% to 12%. Higher accretion rates in the secondary star are realized for eccentric and retrogade inner orbits. We performed an extra series of calculations to further study this, but they all lead to the merger of the inner binary.

The authors kindly thank two anonymous reviewers for their considerable insight and suggestions for improvement. N.W.C.L. acknowledges support from a Kalbfleisch Fellowship at the American Museum of Natural History. SPZ would like to thank Norm Murray and CITA for their hospitality during my long-term visit. This work was supported by the Netherlands Research School for Astronomy (NOVA). In this work we use the matplotlib (Hunter 2007), numpy (Oliphant 2006), AMUSE (Portegies Zwart et al. 2018), SeBa (Portegies Zwart & Verbunt 2012), Huayno (Pelupessy et al. 2012), MESA (Paxton et al. 2010), and GadGet2 (Springel 2000) packages. The calculations ware performed using the LGM-II (NWO grant # 621.016.701) and the Dutch National Supercomputer at SURFSara (grant # 15520).

REFERENCES

Bate, M. R. 2000, MNRAS, 314, 33

de Mink, S. E., & Mandel, I. 2016, MNRAS, 460, 3545

de Val-Borro, M., Gahm, G. F., Stempels, H. C., & Pepliński, A. 2011, MNRAS, 413, 2679

de Vries, N., Portegies Zwart, S., & Figueira, J. 2014, MNRAS, 438, 1909

Eggleton, P. P. 1983, ApJ, 268, 368

Frank, J., King, A., & Raine, D. J. 2002, Accretion Power in Astrophysics: Third Edition, 398

Fujii, M., Iwasawa, M., Funato, Y., & Makino, J. 2007, PASJ, 59, 1095

Fujii, M. S., & Portegies Zwart, S. 2011, Science, 334, 1380

Geller, A. M., & Mathieu, R. D. 2011, Nature, 478, 356

Geller, A. M., Mathieu, R. D., Harris, H. C., & McClure, R. D. 2009, AJ, 137, 3743

Gualandris, A., Portegies Zwart, S., & Eggleton, P. P. 2004, MNRAS, 350, 615

Hills, J. G. 1975, AJ, 80, 809

Hunter, J. D. 2007, Computing in Science and Engineering, 9, 90

Hypki, A., & Giersz, M. 2013, MNRAS, 429, 1221

Iben, Jr., I. 1991, ApJS, 76, 55

Knigge, C., Leigh, N., & Sills, A. 2009, Nature, 457, 288

Krtička, J., Owocki, S. P., & Meynet, G. 2011, A&A, 527, A84

Leigh, N., & Geller, A. M. 2012, MNRAS, 425, 2369

Leigh, N., Knigge, C., Sills, A., et al. 2013, MNRAS, 428, 897

Leigh, N., & Sills, A. 2011, MNRAS, 410, 2370

Leigh, N., Sills, A., & Knigge, C. 2007, ApJ, 661, 210

Leiner, E., Mathieu, R., Gosnell, N., & Sills, A. 2018a, arXiv e-prints, arXiv:1812.02181

Leiner, E., Mathieu, R. D., Gosnell, N. M., & Sills, A. 2018b, ApJL, 869, L29

Leiner, E., Mathieu, R. D., Stello, D., Vanderburg, A., & Sandquist, E. 2016, ApJ, 832, L13

Leonard, P. J. T. 1989, AJ, 98, 217

Maeder, A. 2009, Physics, Formation and Evolution of Rotating Stars, doi:10.1007/978-3-540-76949-1

Manser, C. J. e. a. 2019, Science, in press

Mardling, R., & Aarseth, S. 1999, in NATO Advanced Science Institutes (ASI) Series C, Vol. 522, NATO Advanced Science Institutes (ASI) Series C, ed. B. A. Steves & A. E. Roy, 385

Mathieu, R. D., & Geller, A. M. 2009, Nature, 462, 1032

McCrea, W. H. 1964, MNRAS, 128, 147

Miranda, R., Muñoz, D. J., & Lai, D. 2017, MNRAS, 466, 1170

Moe, M., & Kratter, K. M. 2018, ApJ, 854, 44

Mösta, P., Taam, R. E., & Duffell, P. C. 2018, arXiv e-prints, arXiv:1812.08175

Oliphant, T. E. 2006, A guide to NumPy, Vol. 1 (Trelgol Publishing USA)

Paxton, B., Bildsten, L., Dotter, A., et al. 2010, MESA: Modules for Experiments in Stellar Astrophysics, Astrophysics Source Code Library, ascl:1010.083

—. 2011, ApJS, 192, 3

Pelupessy, F. I., Jänes, J., & Portegies Zwart, S. 2012, NewA, 17, 711

Perets, H. B., & Fabrycky, D. C. 2009, ApJ, 697, 1048

Pols, O. R. 2007, in Astronomical Society of the Pacific Conference Series, Vol. 367, Massive Stars in Interactive Binaries, ed. N. St.-Louis & A. F. J. Moffat, 387

Pols, O. R., Cote, J., Waters, L. B. F. M., & Heise, J. 1991, A&A, 241, 419

Portegies Zwart, S. 2019, A&A, 621, L10

Portegies Zwart, S., & McMillan, S. 2018, Astrophysical Recipes: the Art of AMUSE (AAS IOP Astronomy (*in press*))

Portegies Zwart, S., McMillan, S. L. W., van Elteren, E., Pelupessy, I., & de Vries, N. 2013a, Computer Physics Communications, 183, 456

Portegies Zwart, S., van Elteren, A., Pelupessy, I., et al. 2018, AMUSE: the Astrophysical Multipurpose Software Environment, doi:10.5281/zenodo.1443252

Portegies Zwart, S. F. 1995, A&A, 296, 691

Portegies Zwart, S. F., Hut, P., McMillan, S. L. W., & Verbunt, F. 1997a, A&A, 328, 143

Portegies Zwart, S. F., Hut, P., & Verbunt, F. 1997b, A&A, 328, 130

Portegies Zwart, S. F., McMillan, S. L., van Elteren, A., Pelupessy, F. I., & de Vries, N. 2013b, Computer Physics Communications, 184, 456

Portegies Zwart, S. F., & Verbunt, F. 1996, A&A, 309, 179

—. 2012, SeBa: Stellar and binary evolution, Astrophysics Source Code Library, ascl:1201.003

Sandage, A. R. 1953, AJ, 58, 61

Sandquist, E. L., Latham, D. W., Shetrone, M. D., & Milone, A. A. E. 2003, AJ, 125, 810

Shi, J.-M., Krolik, J. H., Lubow, S. H., & Hawley, J. F. 2012, ApJ, 749, 118

Simunovic, M., & Puzia, T. H. 2014, ApJ, 782, 49

Springel, V. 2000, GADGET-2: A Code for Cosmological Simulations of Structure Formation, Astrophysics Source Code Library, ascl:0003.001

Tokovinin, A. 2010, VizieR Online Data Catalog, 738, 90925

van den Berg, M., Orosz, J., Verbunt, F., & Stassun, K. 2001, A&A, 375, 375