The Astrophysical Journal Letters, 876:L33 (8pp), 2019 May 10 https://doi.org/10.3847/2041-8213/ab1b75

A Triple Origin for Twin Blue Stragglers in Close Binaries

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Received 2019 January 22; revised 2019 April 8; accepted 2019 April 22; published 2019 May 13

Abstract

We propose that twin blue stragglers (BSs) in compact binaries evolve through mass transfer from a giant outer tertiary companion on to the inner binary. We apply this scenario to the twin BS binary WOCS ID 7782 in the old open cluster NGC 188. This binary has two comparable-mass main-sequence stars in a $\lesssim$10 days almost circular ($e \lesssim 0.1$) orbit. 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 tertiary's liberated mass accretes onto the inner binary via a circumbinary disk, turning both stars into BSs. Relatively stable mass transfer occurs for donors with $\sim 1.4\,M_\odot$ that overfill their Roche lobe before ascending the asymptotic giant branch. The system is best reproduced if this tertiary is in an 220–1100 days orbit around an inner binary composed of an $1.1\,M_\odot$ primary and a $m_2 = 0.7$–$0.9\,M_\odot$ secondary in an 8.6–24 days orbit. The tertiary eventually turns into a 0.43–0.54 $M_\odot$ white dwarf in a relatively wide $\gtrsim$5.8 yr orbit. The scenario is generic, but requires some fine-tuning to achieve parameters comparable to WOCS ID 7782. We predict that twin BSs formed through mass transfer from a Roche-lobe overfilling tertiary are generally comparable in mass with aligned spins, which are in turn aligned with the tertiary white dwarf's orbit. If the two inner stars were initially unequal in mass the less massive star will accrete more, becoming more enhanced in CNO-processed material.

Key words: binaries: general – blue stragglers – globular clusters: general – scattering

1. Introduction

Most blue straggler (BS) stars are brighter and bluer than the main-sequence (MS) turn-off in a cluster color–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; Geller & Mathieu 2011; Leigh & Sills 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 an 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 (van den Berg et al. 2001; Sandquist et al. 2003). 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 $\sim$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). In addition, 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 (Fujii & Portegies Zwart 2011; Leigh & Sills 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

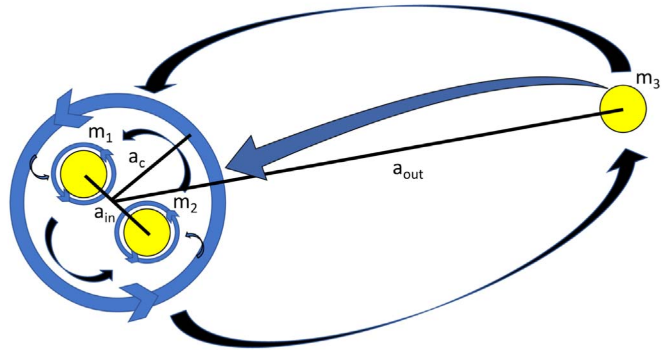

Figure 1. Cartoon depiction of our proposed scenario for the formation of WOCS 7782, specifically mass transfer from an evolved outer tertiary companion on to a compact inner binary via a circumbinary disk. The outer tertiary component has mass m_3, whereas the inner binary components have masses m_1 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.

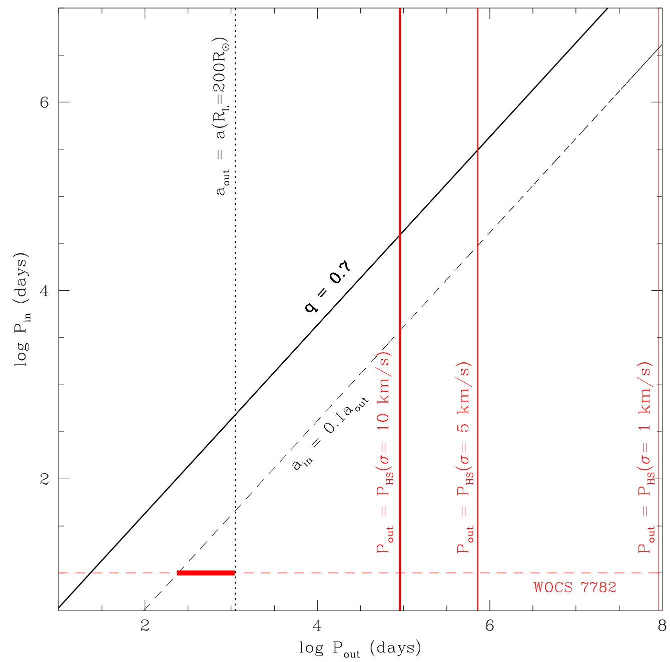

Figure 2. Parameter space in the $P_{\rm out}$–$P_{\rm in}$-plane allowed for the hypothetical outer tertiary orbit of WOCS 7782 before Roche-lobe overflow. The solid diagonal black line shows the period corresponding to the circularization radius $a_{\rm c}$ for the mass transfer stream coming from 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., $a_{\rm in} < 0.1 a_{\rm out}$ 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.

parameters that, according to our expectations, are most promising for the progenitors of the twin BS 7782. The calculations are performed using the Astrophysical Multi-purpose Software Environment (AMUSE; 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 semimajor axes are denoted $a_{\rm in}$ and $a_{\rm out}$, respectively. For specificity, 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 (AGB). We constrain the inner orbit by requiring the triple system to be dynamically stable, for which we adopt Equation (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 semimajor axis of the orbit 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 center of mass corresponding to the tertiary defined by the Roche lobe is given by Equation (2) in Eggleton (1983). Combining Equation (2) in Eggleton (1983; with mass ratio $q = m_3/(m_1 + m_2)$) with Equation (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 that are similar to WOCS 7782. We compare the circularization radius to the semimajor axis of the inner binary, for which we require $a_c > a_{in}$, 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_{in} corresponding to a contact state for the inner binary lies outside the range of plotted values for P_{in} (for components with radii of 1 $R_\odot$), as it does not contribute to constraining the outer orbital properties. The thick horizontal solid red line shows the allowed range of outer semimajor 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 $\leqslant P_{out} \leqslant 1.1 \times 10^3$ 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., $\sim$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 $m_3 = 1.4\,M_\odot$, 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 $m_{core} \sim 0.5\,M_\odot$, 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 $m_1 = 1.1\ M_\odot$ and $m_2 = 0.9\ M_\odot$, we can calculate the outer orbital separation at the onset of Roche-lobe overflow a_{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 leftover 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

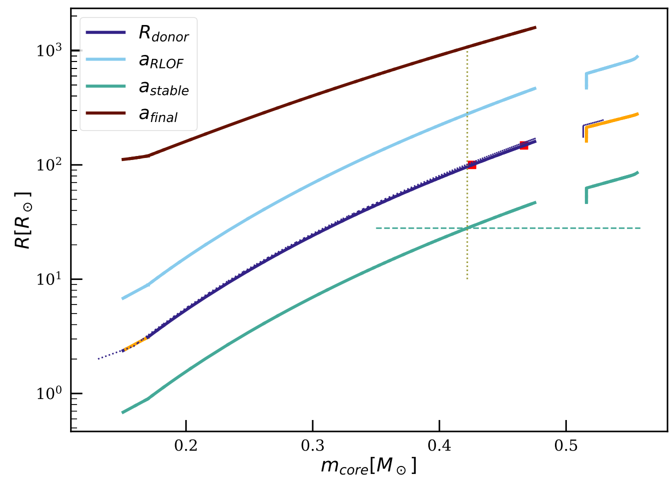

Figure 3. Giant radius as a function of the mass of the core of the Roche-lobe-filling outer star (dark blue curve). The first and last parts of this curve are orange to indicate that the star at these masses and radii is on the Hertzsprung-gap (to the left) or after core helium burning stage (to the right). 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 Section 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 colored curve. Donors that 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 leftmost 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) $M_\odot$.

and m_3', respectively, the total mass in the inner binary before (m_{in}) and after accretion (m_{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) and Portegies Zwart (1995) by matching the orbital evolution and birthrate of Be-type X-ray binaries that experience non-conservative 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 days 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)

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

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 outermost star fills its Roche lobe. First-order constraints for the initial conditions are derived in the previous section. 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 its 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 smoothed particle hydrodynamics (SPH) particles and 12 at 80k.

The stellar-evolution model, including the structure, temperature, and composition profiles, is 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 outermost 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 being 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, Section 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 $\sim 250\ R_\odot$ for the $100\ R_\odot$ donor star and about $430\,R_\odot$ 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 modeled 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 $2\,R_\odot$ 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 Section 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 that 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, because 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, because an appreciable fraction may 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. In our simulations the accretion efficiency on the inner binary has to exceed ~80% for the two BSs to reach masses comparable to those observed in WOCS ID 7782. Over the relatively short timescale for which we performed these calculations, this efficiency is 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. (2019) concluded 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.

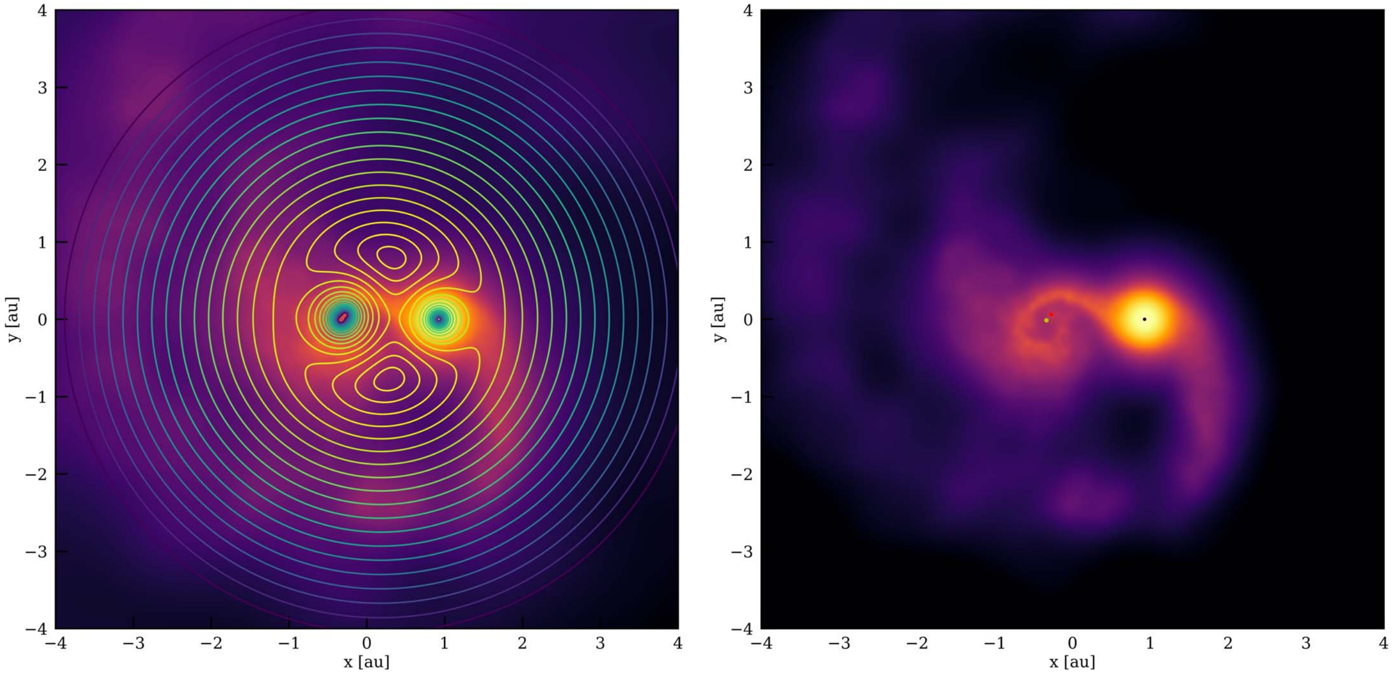

Figure 4. Top view of one of the simulated triple systems at an age of $t \simeq 1091$ days after the start of the simulation when the $100\,R_\odot$ outer star of $1.4\,M_\odot$ overfills its Roche-lobe. The star is represented by 80,000 SPH particles and a core particle of $\sim 0.4\,M_\odot$ (the black bullet in the middle of the rightmost yellow blob). The inner binary (to the left) is represented by the yellow and red bullets for, respectively, the $1.1\,M_\odot$ primary and $0.9\,M_\odot$ secondary stars in a circular orbit of 0.1 au. The $1.4\,M_\odot$ giant star is presented to the right in a circular orbit with semimajor axis $\sim 250\,R_\odot$ in the plane of the inner binary. The 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.

For most of our calculations we agree with this statement, but in Figure 5 we nevertheless present the results of six of our calculations, three for a $1.2\,M_\odot$ donor star and three for a $1.4\,M_\odot$ donor. The various colored 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 $1.2\,M_\odot$ donor. These systems are expected to result in a contact binary that eventually may merge to form a single BS with a mass that is more than twice the turn-off in orbit around 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 $1.2\,M_\odot$ 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 $1.4\,M_\odot$ 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 that are 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 accommodating the observed constraints. The longer thermal timescale 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 $1.4\,M_\odot$ 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 $1.4\,M_\odot$, 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 $90\overset{\circ}{.}0$ for the primary star and $93\overset{\circ}{.}4$ 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 after 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 after mass transfer are supported by other work (see, for example, de Vries et al. 2014), but the twin BSs 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 Letter, we propose a formation scenario for twin equal-mass BSs 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

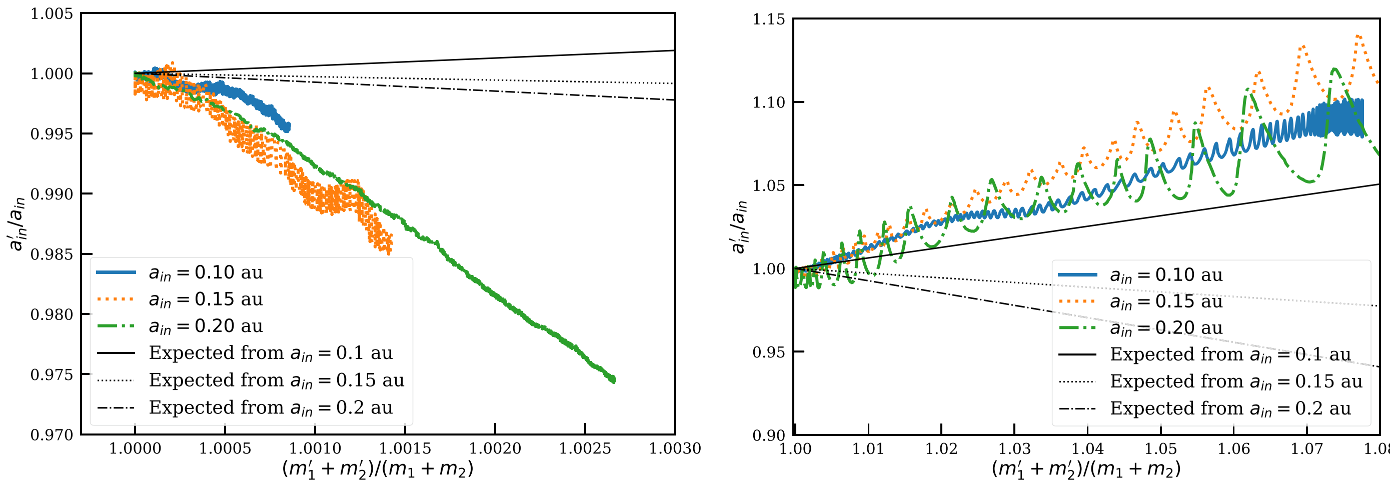

Figure 5. Evolution of the orbital separation as a function of the total mass of the inner binary for six calculations with somewhat different initial conditions (see the legend). The left panel shows the result for a 1.2 $M_{\odot}$ donor star, and the right panel for a 1.4 $M_{\odot}$ donor. The initial binary shown by the blue curve of the right-hand panel is presented in Figure 4, where 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 toward the observed orbital separation of 0.13 au at a total binary mass of 2.8 $M_{\odot}$.

several predictions for the observed properties of a hypothetical outer triple companion, now a WD. These are as follows.

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 BS should 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 ≳6.4 yr for a ∼0.42 $M_{\odot}$ white dwarf to ≳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 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, as 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 $m_3 = 0.5\ M_{\odot}$ to $0.7\,M_{\odot}$ and $0.9\,M_{\odot}$. In Figure 6 we present the evolution of the normalized mass ratio in these binaries. With these calculations we demonstrate that a low-mass ratio initially tends to evolve toward an equal-mass ratio.

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 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 ≳20 $M_{\odot}$, which could be promising sources for gravitational wave detectors once both twins evolve into a binary black hole (de Mink & Mandel 2016).

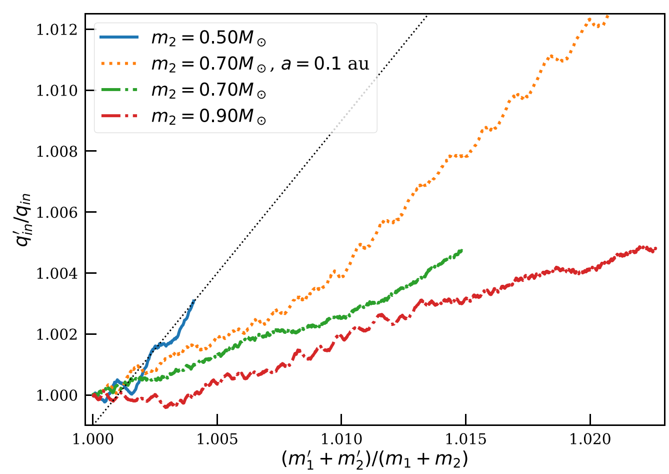

Figure 6. Evolution of the mass ratio for initial triples with an inner orbital separation of 0.1 au (orange dotted curve) and 0.2 au (all other curves). The initial primary mass was $m_1 = 1.4\ M_{\odot}$ overfilling it is Roche lobe at a radius of 100 $R_{\odot}$. The companion masses are $m_2 = 0.9\ M_{\odot}$ and the mass of the tertiary are indicated in the legend. The dotted black line indicates the required mass-ratio evolution in order to eventually reach an equal-mass-ratio BS binary.

6. Summary

In this Letter, 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 that 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 days binary with an eccentric orbit of ∼0.10.

With an original outer star of mass ∼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 leftover core of the tertiary star). As discussed in Section 1, BS–WD 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-transfer phase, the white dwarf (maybe with a little leftover envelope) is expected to be ejected. This would lead to a relatively wide twin BS 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) performed 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 $\sim 0.028\,M_\odot\,\mathrm{Myr}^{-1}$. 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 $\sim 0.027\,M_\odot\,\mathrm{Myr}^{-1}$. 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 $M_\odot\,\mathrm{Myr}^{-1}$ (i.e., the average measured over a period of about 3000 days in our simulations). Interestingly, however, de Val-Borro et al. (2011) found 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%–12%. Higher accretion rates in the secondary star are realized for eccentric and retrograde 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. S.P.Z. would like to thank Norm Murray and CITA for their hospitality during a 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 No. 621.016.701) and the Dutch National Supercomputer at SURFSara (grant No. 15520).

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