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# A Triple Origin for Twin Blue Stragglers in Compact Binaries

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## ABSTRACT

In this Letter, we propose a potential formation mechanism for twin blue stragglers in compact binaries that involves mass transfer from an evolved outer tertiary companion on to the inner binary via a circumbinary disk. We apply our hypothetical scenario to the observed double blue straggler system Binary 7782 in the old open cluster NGC 188, and show that its observed properties are easily and even naturally reproduced within the context our proposed model. Within the context of the hypothetical formation mechanism proposed here, the presented work predicts the following properties for the post-mass transfer double BS tertiary: (1) For the outer tertiary orbit, the initial orbital period should lie between 220 days $\lesssim \mathrm{P_{out}} \lesssim$ 1100 days, assuming initial masses for the inner binary components of $\mathrm{m_1} = 1.1\ \mathrm{M_\odot}$ and $\mathrm{m_2} = 0.9\ \mathrm{M_\odot}$ and an outer tertiary mass of $\mathrm{m_3} = 1.4\ \mathrm{M_\odot}$. (2) Larger final WD masses, and hence core masses for the donor at the time of mass transfer, should correspond to larger final outer orbital periods for the tertiary. (3) For the inner binary, the rotational axes of the BSs should be aligned with each other and the orbital plane of the outer tertiary WD. (4) The BSs in the inner binary should have roughly equal masses, independent of their initial masses. This predicts that the initially lower mass MS star should accrete the most, and should hence be polluted more significantly by any accreted material. This could be observable in the surface layers of a radiative star (i.e., He, C and O if the donor is an RGB star, and/or s-process elements if the donor is an AGB star). (5) Twin BSs in compact binaries formed from the proposed mechanism should be more frequent in younger clusters with ages $\lesssim$ 4-6 Gyr, since the donor will have radiative envelope.

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

## 1. INTRODUCTION

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Blue straggler (BS) stars appear brighter and bluer than the main-sequence turn-off (MSTO) in a cluster colour-magnitude diagram (CMD) (e.g. Simunovic, Puzia & Sills 2014; Simunovic & Puzia 2016). Two primary channels for BS formation have been proposed; mass transfer from an evolved donor on to a main-sequence star in a binary star system (e.g. McCrea 1964; Knigge, Leigh & Sills 2009; Mathieu & Geller 2009; Leigh & Sills 2011; Geller & Mathieu 2011, 2012; Gosnell et al. 2014, 2015), and direct stellar collisions involving main-sequence stars mediated via direct interactions involving binaries (e.g. Hills 1975; Shara, Saffer & Livio 1997; Leigh, Sills & Knigge 2007; Leigh & Sills 2011; Leigh et al. 2013; Hypki & Giersz 2013). Other possible, albeit related, formation mechanisms include mergers of compact MS-MS binaries, and mergers of the inner MS-MS binaries of hierarchical triple star systems induced by Lidov-Kozai oscillations coupled with tidal damping (e.g. Perets & Fabrycky 2009).

In spite of these specific predictions for the expected properties of BSs formed from each of the above production mechanisms, there exist many BSs with observed properties that defy these simple scenarios. For example, in the old open cluster M67, there lurks a candidate triple system that is posited to host *two* BSs (van den Berg et al. 2001; Sandquist et al. 2003). The observations suggest that the outer tertiary is itself a BS, with a mass $\sim$ 1.7 $M_{\odot}$ and orbiting the inner binary with a period of 1188.5 days (Sandquist et al. 2003). The inner binary has a period of only 1.068 days (van den Berg et al. 2001), and hosts a BS of mass 2.52 $M_{\odot}$. Thus, in order to form this system after convolving its observed properties with its host cluster age, we require at least five stars in order to conserve the total system mass (Leigh & Sills 2011). As explained in Leigh & Sills (2011), this is strongly indicative of a dynamical origin for the system, and a single direct interaction involving a binary and a triple that resulted in two separate collision events is the most probable explanation for its origin (i.e., a single interaction involving two multiples with two or more stars is a more likely scenario to produce this system than two back-to-back direct binary-binary interactions).

Even more curious, there exists in the old open cluster NGC 188 a double BS binary, called Binary 7782. Specifically, 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* blue stragglers. During a given binary-binary interaction, the probability that not one but *two* direct MS-MS collisions occur is less than a percent (Leonard 1989; Leigh & Sills 2011; Leigh et al. 2012). Typically, such binaries are very wide with long orbital periods. Thus, dynamically, it is very difficult to form a compact binary composed of two collision products during a single direct interaction in a star cluster. So, how did Binary 7782 form? MENTION BIMODAL P-E DISTRIBUTION, AND HOW THIS COULD BE SUGGESTIVE OF A TRIPLE ORIGIN FOR SOME OF THE SUBSET OF OBSERVED BSs.

In this Letter, we propose a potential formation channel for Binary 7782, and compact double BS binaries in general, which involves mass transfer from an outer tertiary companion on to an inner MS-MS binary. 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 our hypothetical triple system, computed using the `AMUSE` software package, in order to study the evolution of the inner and outer orbital parameters during mass transfer. 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 7782

Consider a hierarchical triple system with component masses $m_1$ and $m_2$ for the inner binary, and mass $m_3$ for the outer tertiary companion. The inner and outer binary orbital semi-major axes are denoted $a_{in}$ and $a_{out}$, respectively. We assume circular orbits for both the inner and outer orbits, and co-planar triples only since this is what has been observed for low-mass tertiaries (e.g. Moe & Kratter 2018; Tobin et al. 2018).

We consider a scenario where the outer tertiary companion is filling its Roche lobe and is hence transferring mass to the inner binary. The mass transfer stream gathers at the circularization radius $a_c$, and forms a circumbinary disk. Using conservation of angular momentum, we can equate the specific angular momentum of the accreted mass at the inner Lagrangian point of the donor star to the final specific angular momentum of the accretion stream at the circularization radius about the inner binary:

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

where $R_L$ is the radius of the Roche lobe of the outer tertiary companion, $a_c$ is the semi-major axis of the orbit about the inner binary corresponding to the circularization radius and $v_{orb,c}$ is the orbital velocity at $a_c$. The distance from the center of mass corresponding to the outer tertiary companion defined by the Roche lobe is given by (?):

$$R_{\rm L} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})} a_{\rm out}, \tag{2}$$

where the mass ratio q is defined as q = $m_3/(m_1 + m_2)$. Combining Equation 2 with Equation 1, we can solve for the circularization radius as a function of $a_{\rm out}$ and the assumed stellar masses:

$$a_{\rm c} = a_{\rm out}(1 - R_{\rm L}). \tag{3}$$

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

Figure 1 shows the parameter space in the $P_{\rm out}$-$P_{\rm in}$-plane for Binary 7782. 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 $m_3 = 1.4$ $M_\odot$ for the outer tertiary. 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, an outer tertiary that is Roche lobe-filling, and a dynamically hard outer tertiary orbit. Note that the range of plotted orbital periods $P_{\rm in}$ corresponding to a contact state for the inner binary, assuming $R_1 = R_2 = 1$ $R_\odot$, lies outside the range of plotted values for $P_{\rm in}$, since it does not contribute significantly to constraining the outer orbital properties of a hypothesized outer WD tertiary. The thick horizontal solid red line shows the allowed range of outer semi-major axes, after folding in all of the aforementioned criteria. As is clear, this makes a relatively narrow prediction for the allowed ranges of outer tertiary orbits, namely $2.2 \times 10^2$ days $\leq P_{\rm out} \leq 1.1 \times 10^3$ days, for our assumed final donor mass.

## 3. NUMERICAL SIMULATIONS

### 3.1. *AMUSE*

We use smoothed-particle hydrodynamics (SPH) simulations to compute the time evolution of the mass transfer process. We adopt the same initial particle masses as in Figure 1, namely 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. The initial orbital eccentricities are set to zero. The inner and outer binary orbital semi-major axes are set to 0.1 AU and 1 AU, respectively (CORRECT).

### 3.2. *Initial Conditions*

In this section, we describe and justify our choice of initial conditions for both our analytic calculations and smoothed-particle hydrodynamics simulations.

We adopt 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. This choice for the initial mass of the outer tertiary is critical since it ensures that the donor star during the mass transfer process will have a radiative envelope (e.g. Maeder 2009). In turn, this ensures that the mass transfer will be maximally conservative, such that the accretion stream will be maximally stable, accreting at a stable and constant rate (e.g. Iben 1991).

## 4. RESULTS

## 5. SUMMARY AND DISCUSSION

In this Letter, we have proposed a formation scenario for double BS equal-mass compact binaries, as observed for Binary 7782 in the old open cluster NGC 188. The proposed scenario involves mass transfer from an evolved outer tertiary companion, which is accreted by the inner binary via a circumbinary disk. 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 present-day semi-major axis 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 outer tertiary mass of $m_3 = 1.4$ $M_\odot$.

2. Larger final WD masses, and hence 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.

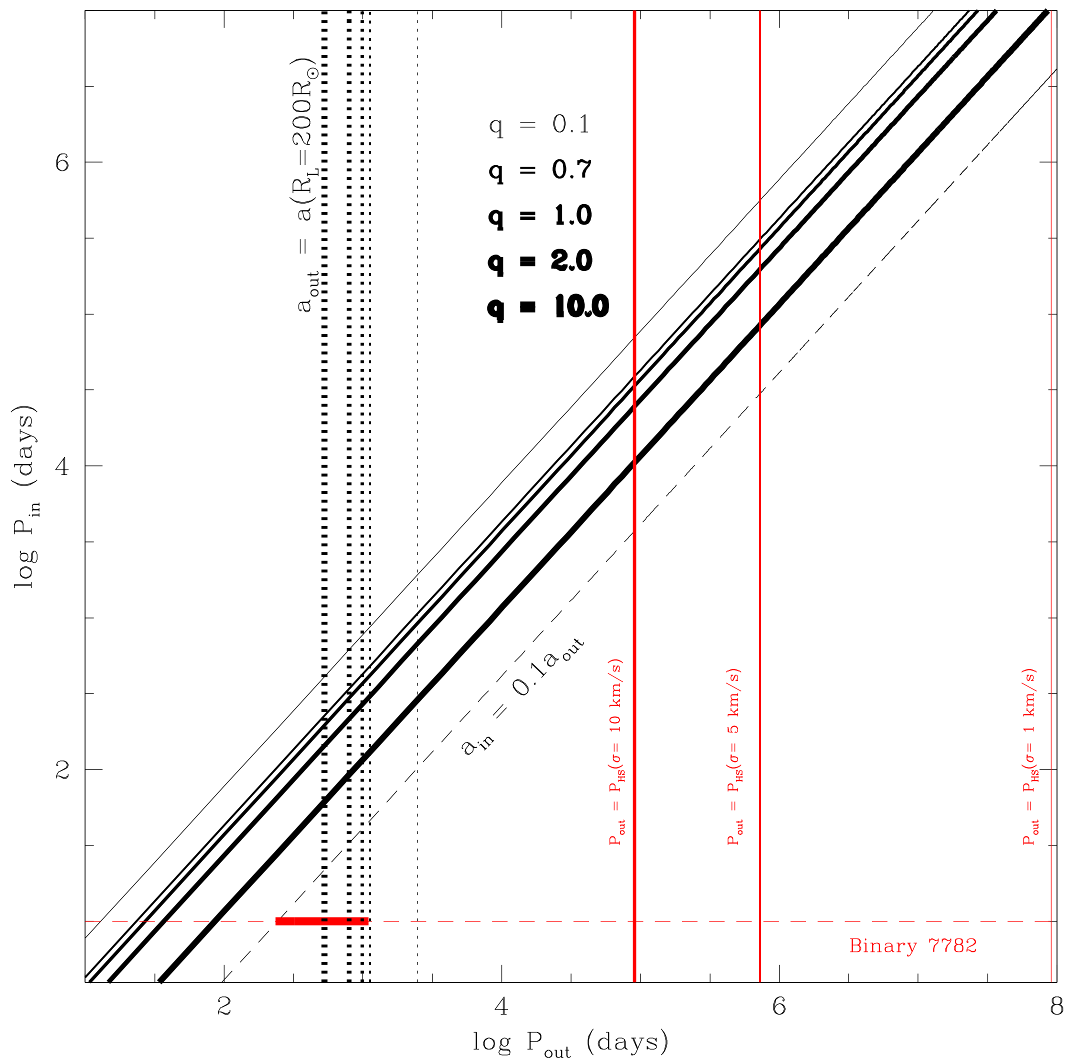


**Figure 1.** Parameter space in the $P_{out}$-$P_{in}$-plane allowed for the hypothetical outer tertiary orbit of Binary 7782. The solid diagonal black lines show the period corresponding to the circularization radius $a_c$ for the mass transfer stream coming from the outer tertiary, for different values of the mass ratio, namely q = 0.1, 0.7, 1, 2 and 10. 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., $a_{in} < 0.1a_{out}$ 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 lines show the maximum outer orbital period $P_{out}$ for which the outer tertiary companion is Roche lobe-filling, assuming a stellar radius of $R_3 = 200$ $R_\odot$ (CHANGE, POSSIBLY USING MESA CALCULATIONS?!). The horizontal dashed red line shows the observed orbital period for Binary 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 $P_{out}$ allowed after considering all of the aforementioned criteria.

3. For the inner binary, the rotational axes of 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. Haiman et al. 2009; Farris et al. 2015; Rafikov 2016; Kelley et al. 2017). This quickly brings the mass ratio toward unity. This predicts that the initially lower mass MS star should accrete the most, and should hence be polluted more significantly by any accreted material. This could be observable in the surface layers of a radiative star. If the donor is an RGB star, the accretor will be enriched in mostly carbon, oxygen and helium. If the accretor is an AGB star, it will be enriched in mostly s-process elements.

5. Twin BSs in compact binaries formed from the proposed mechanism should be more frequent in younger clusters with ages $\lesssim$ 4-6 Gyr. This is because clusters with a main-sequence turn-off mass $\lesssim 1.2$ M$_{\odot}$ have convective envelopes (e.g. Iben 1991; **?**), and a radiative envelope for the donor in a mass transferring binary ensures stable accretion on to the accretor.

   WHAT ELSE? SOMETHING RELATED TO TIMESCALES AND THE PROBABiLitY OF OBSERVING THE WD?

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