The Astrophysical Journal, 697:1048–1056, 2009 June 1 doi:10.1088/0004-637X/697/2/1048

ON THE TRIPLE ORIGIN OF BLUE STRAGGLERS

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Received 2009 January 27; accepted 2009 March 17; published 2009 May 8

ABSTRACT

Blue straggler stars (BSSs) are stars observed to be hotter and bluer than other stars with the same luminosity in their environment. As such they appear to be much younger than the rest of the stellar population. Two main channels have been suggested to produce such stars: (1) collisions between stars in clusters or (2) mass transfer between, or merger of, the components of primordial short-period binaries. Here we suggest a third scenario, in which the progenitors of BSSs are formed in primordial (or dynamically formed) hierarchical triple stars. In such configurations, the dynamical evolution of the triples through the Kozai mechanism and tidal friction can induce the formation of very close inner binaries. Angular momentum loss in a magnetized wind or stellar evolution could then lead to the merger of these binaries (or to mass transfer between them) and produce BSSs in binary (or triple) systems. We study this mechanism and its implications and show that it could naturally explain many of the characteristics of the BSS population in clusters, most notably the large binary fraction of long-period BSS binaries; their unique period–eccentricity distribution (with typical periods $>$ 700 days); and the typical location of these BSSs in the color–magnitude diagram, far from the cluster turnoff point of their host clusters. We suggest that this scenario has a major (possibly dominant) role in the formation of BSSs in open clusters and give specific predictions for the BSSs population formed in this manner. We also note that triple systems may be the progenitors of the brightest planetary nebulae in old elliptical galaxies, which possibly evolved from BSSs.

Key words: binaries: close – binaries: general – blue stragglers – open clusters and associations: general – stellar dynamics

Online-only material: color figures

1. INTRODUCTION

Blue Straggler Stars (BSSs) are stars that appear to be anomalously young compared to other stars of their population. In particular, BSSs lie along an extension of the main sequence (MS) in the color–magnitude diagram, a region from which most of the stars of equal mass and age have already evolved. Such stars appear to be brighter and bluer than the turnoff point of the stellar population in which they were observed. Their location in the color–magnitude diagram suggests that BSSs have typical masses of 1.2–1.5 $M_\odot$, that are significantly larger than those of normal stars in old stellar systems such as old open clusters (OCs) or globular clusters (GCs). Thus, they are thought to have increased their mass during their evolution. Two main mechanisms have been proposed for their formation: (1) the merger of two stars induced by stellar collision (Hills & Day 1976) and (2) coalescence or mass-transfer between two companions in a binary system (McCrea 1964). The roles of each of these mechanisms in producing the observed BSSs populations are still debated, as each of these scenarios were found to be successful in explaining some of the BSSs observations, but fail in others (e.g., Bailyn 1995). In fact, even when both these mechanisms are taken into account (e.g., in *N*-body simulations including stellar evolution), they have major difficulties explaining the observations, especially those of binary BSSs (Leonard 1996; Hurley et al. 2005): the period–eccentricity distribution of BSSs binaries produced through these mechanisms is in poor agreement with the observed distribution of BSS binaries (Section 4.1.3). Moreover, typical BSS binaries produced in combined *N*-body and stellar evolution simulations are produced in the inner regions of a cluster core (Hurley et al. 2005), whereas observations show many of the BSS binaries in clusters to exist much farther out (Geller et al. 2008; A. M. Geller et al. 2009, in preparation).

In the binary merger scenario for BSS formation, close binaries with periods shorter than 5–6 days evolve into mass transfer configuration or merger in less than 10 Gyr, thus producing a rejuvenated star (Andronov et al. 2006). As we point out in this work theoretical studies and observations suggest that most such close binaries form as the inner binaries in triple systems (Kiseleva et al. 1998; Eggleton & Kisseleva-Eggleton 2006; Tokovinin et al. 2006; Fabrycky & Tremaine 2007). A straightforward conclusion is that BSSs formed in close binaries are most likely to be (or to have been) members of triple systems. Such a scenario has strong implications on the properties of BSSs, their multiplicity and their orbital parameters. Here we raise this basic conclusion and follow its implications. We suggest a third mechanism for the origin of BSSs in which the progenitors of blue stragglers are formed in primordial (and also in dynamically formed) hierarchical triple stars. The inner binary in such triples can be rapidly driven into close or even contact configurations, due to the combined effects of Kozai cycles and tidal friction (KCTF mechanism: Kiseleva et al. 1998; Eggleton & Kiseleva-Eggleton 2001; Fabrycky & Tremaine 2007), as we discuss below. Such close binaries could then evolve through mass transfer or merger and produce BSSs. We show that such a scenario could explain and predict the characteristics of the BSS population in clusters, and could naturally explain the large fraction of long-period binary BSSs, their unique period–eccentricity distribution, and their location in the color–magnitude diagram, whereas previously proposed mechanisms cannot. This mechanism has some additional predictions that

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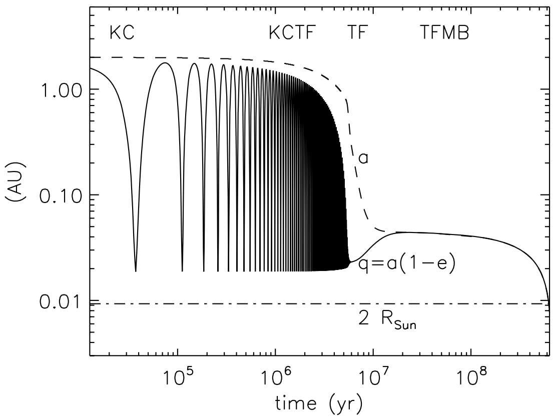

Figure 1. Merger of the two stars of an inner binary, accomplished by a combination of Kozai cycles (KC), tidal friction (TF), and magnetic braking (MB).

could discriminate it from other models for BSSs formation: (1) BSSs could have long-period *main-sequence* binary companions, (2) the spin axes of such BSSs are likely to be misaligned in a specific way from the orbital axes of the binary orbits, and (3) they may exist in regions where collisions between stars are unlikely; additional implications are discussed below. Such predictions differ from those of the previously suggested mechanisms for BSSs formation and could serve to further support and confirm the novel model suggested here.

We note that although triples have been suggested before to play a role in BSSs formation, they were not considered to have a major contribution to the BSSs population (Leonard 1996; Ivanova 2008), and the role of primordial triples has not been discussed. Here we study the triple origin scenario for BSSs and its general implications in detail. We show that current observations strongly support this model and confirm its predictions where other models fail.

In this paper, we begin with an overview of the dynamics of Kozai cycles and tidal friction in triples (Section 2). Then we compare the timescales for the KCTF mechanism and for binary disruption in different environments (Section 3) and describe the theoretical and observational implications of this formation mechanism for various environments (Section 4). We then summarize in Section 5.

2. TRIPLE DYNAMICS, KOZAI CYCLES, AND TIDAL FRICTION

To be stable for many orbital periods, triple systems usually require a hierarchical configuration in which two stars orbit each other in a relatively tight "inner binary," and the third star and the inner binary orbit their common center of mass as a wider "outer binary." Although such triples do not disrupt, their orbits may change shape and orientation on timescales much longer than the dynamical time. A particularly important change was discovered by Kozai (1962), who studied the orbital changes of asteroids due to the weak interactions with Jupiter (where the asteroid–Sun system serves as an inner binary in the Sun–Jupiter–asteroid triple). He found that if the asteroid's initial inclination relative to Jupiter's orbit is high enough, secular torques will cause its eccentricity and inclination to fluctuate out of phase with one another: these are called "Kozai oscillations." Lidov (1962) independently studied a similar process effecting the motion of artificial satellites of the Earth as they are perturbed by the Sun and Moon, and he noted the possibility of collision between a satellite and the Earth if the satellite's eccentricity becomes large enough.

Collisions were also prominent in the first application of these dynamical concepts to triple stars. Harrington (1968) noted that large initial inclination ($i_c \lesssim i \lesssim 180^\circ - i_c$, for a "Kozai critical angle" of $i_c \approx 40^\circ$) leads to large eccentricities, which could cause a tidal interaction, mass loss, or even collision of the members of the inner binary. Thus, Harrington reasoned that a triple star system with an inner binary mutually perpendicular to the outer binary should not exist for many secular timescales. However, as was noted by Mazeh & Shaham (1979), the inner binary stars coming close to one another will not merge immediately; instead, the tidal dissipation between them shortens the semimajor axis of the inner binary during these eccentricity cycles. They suggested that such inner binaries could therefore attain a very close configuration, in which mass transfer and accretion could occur, possibly forming cataclysmic variables or binary X-ray sources. Eggleton & Kisseleva-Eggleton (2006) discussed binary stellar evolution, including mergers, following KCTF. Recently, Ivanova (2008) discussed the possibility of forming BSSs in dynamically formed triples in dense clusters, showing that such newly formed triples may explain as much as 10% of the BSSs in such clusters.

The equations of motion from the equilibrium tide model, with arbitrary eccentricity of a binary system and arbitrary spin obliquities of its components, were coupled to triple star dynamics by Eggleton et al. (1998). This analysis led to further fruitful studies (Kiseleva et al. 1998; Eggleton & Kiseleva-Eggleton 2001), suggesting that a large percentage of close binaries may have become close through KCTF. Several observational studies verified that close binaries very often have tertiary components (Tokovinin 2004; Pribulla & Rucinski 2006; D'Angelo et al. 2006; Rucinski et al. 2007), showing a strong correlation between the binary period and the existence of a third companion (Tokovinin et al. 2006). In fact it was found that nearly all (∼96%) closest binaries ($P < 3$ days) have distant tertiary components (Tokovinin et al. 2006). Recently, Fabrycky & Tremaine (2007) used the equations of Eggleton et al. (1998) to verify that the observational results of Tokovinin et al. (2006) are consistent with KCTF acting on a population of triples. They found that the population of close binaries could be explained through evolution in triples, even if no such primordial binaries (with $P < 6$ days) exist. They also noticed that although eccentricity will have damped during the tightening of the close binary, the mutual inclination between inner and outer binaries should very often finish at either $i \approx 40^\circ$ or $i \approx 140^\circ$.

The connection to BSS comes when the inner binary merges to become a single, more massive star. We put the whole scenario together in Figure 1, assuming the mechanism for close binary merger is angular momentum loss through magnetized stellar winds. The initial system is an inner binary of two solar mass stars, at low eccentricity and $a = 2$ AU, orbited by a 0.5 $M_\odot$ star on a circular orbit at 50 AU with a mutual inclination of 84°. On short timescales, the eccentricity of the inner binary fluctuates (Kozai cycles; KC). On millions of year timescales, tidal friction seals in a large eccentricity (KCTF), then damps the binary at constant orbital angular momentum (TF). Lastly, on a timescale of ∼1 Gyr, magnetic braking (MB) of the stellar spins drains the orbital angular momentum because the spins stay tidally locked, causing the binary to come into contact. After a contact evolutionary phase (Andronov et al. 2006), the binary would merge to form a BSS accompanied by a main-sequence star in a very wide orbit. The contact phase may be rapid for low-mass ratio binaries ($q \leqslant 0.6$), but could extend to a few 10^8–10^9 yr for binaries with higher mass ratios, before the final merger and the formation of a BSS (Nelson & Eggleton 2001).

In this figure, we have used the equations and parameters for KCTF found in Fabrycky & Tremaine (2007) and the magnetic braking prescription of Eggleton (2006, Section 4.4), in which angular momentum is extracted from the spin Ω_i of each star $i = 1, 2$ at a rate

$$\frac{d\Omega_i}{dt} = -|\dot{M}_i| \left(\frac{2}{3} R_i^2 + R_{A,i}^2 \right) \Omega_i, \tag{1}$$

where $\dot{M}_i = 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$ are the mass-loss rates from each component, $R_i = R_\odot$ are the stellar radii, and $R_{A,i} = 10\ R_\odot$ are the Alfvén radii. This expression corresponds to a saturated magnetic field (Andronov et al. 2006), which is valid for quick rotation. In reality, the stars lose a small amount of mass which directly carries away a small amount of *orbital* angular momentum, but we have not explicitly computed those two effects.

3. TRIPLE-FORMED BLUE STRAGGLERS INTERACTING WITH CLUSTER MEMBERS

Before discussing the implications of the triple BSS progenitor model and its predictions for the BSSs properties, we need to insure that such a scenario is viable for OCs or GCs where the triple's evolution could be affected by encounters with other stars. One should also note that close binaries may also be formed through tidal capture encounters in the densest regions of GCs, i.e., in some cases they may not be formed from triples.

The studies of KCTF evolution of triples have usually dealt with isolated triples. Triples evolving in clusters may be influenced by encounters with other stars in the cluster (Aarseth & Mardling 2001; Ivanova et al. 2008). Several scenarios are then possible: (1) an encounter destroys the triple before an inner close binary forms; (2) an encounter occurs before an inner close binary forms, but only perturbs the triple and does not destroy it; (3) KCTF evolution produces an inner close binary before an encounter occurs, and then an encounter destroys the outer binary of the triple, leaving a close binary; (4) KCTF evolution produces an inner close binary before an encounter occurs, and then either the triple evolves as if it was isolated or it is perturbed but not destroyed.

In the first scenario, the fraction of BSS progenitors is reduced relative to their fraction in a similar population of isolated triples, since in this case the destroyed triples could not form close inner binaries.

The second scenario, however, suggests an interesting possibility. In this case, perturbed triples change their orbital parameters in a chaotic way due to the encounter (see, e.g., Heggie 1975; Hut 1983; Binney & Tremaine 1987 for the behavior in binary encounters), but are not destroyed. These could be thought of as new triples. These new triples are now subjected to the same possible scenarios as the primordial triples, i.e., some of them could now form close inner binaries, while others are perturbed or destroyed beforehand.

The third scenario would produce close inner binary progenitors of BSSs. Such binaries are very hard (i.e., have orbital energy $E \ll m\sigma^2$; where σ is the velocity dispersion in the cluster, and m is the mass of the binary system; Heggie 1975), and are not likely to suffer from further perturbations, and therefore effectively evolve in isolation, and contribute to the fraction of close binaries and the fraction of BSSs in the cluster. Though hard, these binaries did not contribute their orbital energy to the energy budget of the cluster to affect its dynamical evolution as a whole; rather, the energy was deposited as tidal heat and radiated away, as for tidally captured binaries. Binaries formed in this way are expected to be observed as close binaries or even contact binaries, without a triple companion and therefore reduce the fraction of such binaries with tertiary companions (which is close to unity for close binaries in the field; Tokovinin et al. 2006). A BSS formed in such binaries is likely to do so through coalescence and is therefore likely to be observed as a single BSS. Nevertheless, in some cases, they may be observed as very close binaries during a mass transfer epoch before coalescence. The observable predictions from such a scenario may be difficult to disentangle from the case of tidally formed binaries. However, tidally captured binaries are expected to form only in the densest regions of cluster cores, whereas the triple scenario could produce such binaries even in OCs or the outskirts of GCs, since triples may suffer encounters in these regions, but the rates of tidal captures are negligibly small.

The fourth scenario is maybe the most intriguing in terms of the observable implications. In this case, KCTF evolution produces a close inner binary in a system that survives as a triple in the cluster. The close inner binaries may form a BSS, either by angular momentum loss through magnetized winds, or by the primary evolving to its Roche lobe, prompting mass transfer and coalescence. Such systems would therefore be observable as long-period BSS binaries (or a triple if the inner binary has transferred mass but not yet coalesced), with period–eccentricity distribution similar to that of the outer binaries in triples. If the triple is later perturbed, a companion star is still predicted by the model, but the orbital configuration of the outer binary is not predictable by KCTF alone (as in Fabrycky & Tremaine 2007).

In order to estimate the importance of the different scenarios, we can compare the typical timescales of the isolated KCTF evolution and the typical timescales between encounters. In order to do so, we used the methods described in detail by Fabrycky & Tremaine (2007) to evolve a large population of triple systems in isolation. We ran a Monte Carlo simulation of the evolution of primordial triples drawn from appropriate distributions (as described in Fabrycky & Tremaine 2007, where all inner binaries were assumed to have initial periods of $P > 6$ days) and the triples were checked for stability using the criterion of Mardling & Aarseth (2001). About 40% of the selected triples failed to fulfill the condition. A total of 5×10^4 stable systems were then integrated in time up to 10 Gyr, while neglecting stellar evolution or angular momentum loss through magnetized stellar winds. In Figure 2, we show the typical timescale for the KCTF mechanism to form close inner binaries from triples of different periods. This timescale is defined as the median time close inner binaries take to become "close" (defined as $P_{\rm in} < 6$ days, where magnetic braking may become important). The feature apparent at $P_{\rm out} = 10^3$–10^4 days is a combination of (1) the assumed eccentricity distribution of outer binaries switches from a Raleigh distribution (moderate eccentricities) to a thermal distribution (generally large eccentricities) there (Duquennoy & Mayor 1991; Fabrycky & Tremaine 2007), and (2) inner binaries with companions at $P < 10^3$ days must be initially rather close to satisfy dynamical stability anyway, so they do not have far to travel before magnetic braking becomes important. Also shown are the typical encounter timescales for triples at different periods, calculated for several cases; typical conditions in GCs, OCs, GC cores, or OCs cores. The encounter timescale

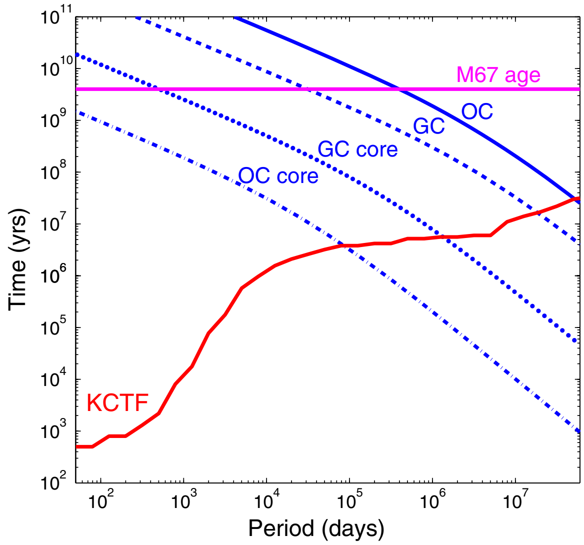

Figure 2. Timescales for encounters and Kozai cycles with tidal friction (KCTF) evolution of triples in clusters. The typical encounter time of triples of different outer periods is shown for different environments; OCs (upper solid), OC cores (dashed line), GCs (dotted line), GCs cores (dash-dotted line). The typical KCTF evolution time (see text) of triples with a range of outer period is also shown (lower solid line). The typical age of GCs and the age of the old OC M67 are denoted by vertical lines).

(A color version of this figure is available in the online journal.)

is given by (e.g., Ivanova et al. 2008)

$$t_{\rm enc} = 8.5 \times 10^{12}{\rm yr} \times P_{\rm out}^{-4/3} M_{\rm tri}^{-2/3} n_5^{-1} \sigma_{10}^{-1} \times \left[1 + 913 \frac{M_{\rm tri} + \langle M \rangle}{2 P_{\rm out}^{2/3} M_{\rm tri}^{1/3} \sigma_{10}^2}\right]^{-1}, \quad (2)$$

where $P_{\rm out}$ is the outer binary's period in days, $M_{\rm tri}$ is the total triple mass in $M_\odot$, $\langle M \rangle$ is the mass of an average single star in $M_\odot$, σ_{10} is the velocity dispersion $\sigma_{10} = \sigma/(10\,{\rm km\,s^{-1}})$, and n_5 is the stellar density in units of $10^5\,{\rm pc}^{-3}$. For simplicity, we assumed all triples have equal masses of $M_{\rm tri} = 3$ with the average mass of stars $\langle M \rangle = 1$. This timescale is for encounters between a single star and a binary (outer binary of a triple in our case). In binary–binary encounters, the cross section for the encounter is determined by the wider binary. In the following section, we compare the KCTF timescale to the encounter timescale in a variety of environments, allowing us to establish predictions for the observations.

4. IMPLICATIONS OF THE TRIPLE ORIGIN OF BSSs IN VARIOUS ENVIRONMENTS

4.1. *Low-density Environments (OCs and GC Outskirts)*

In relatively low-density environments such as OCs or at the outskirts of GCs, the timescales for close encounters are larger than the Hubble time (and could be much larger than the typical age of OCs). In these clusters, the triples effectively evolve in isolation. The only caveat is for very long outer period triples ($P_{\rm out} \gtrsim 5 \times 10^4$–$5 \times 10^5$ for the conditions in OCs). Such triples can form close inner binaries in $\sim 10^7$ yr that evolve into a BSS, but the outer binary may still encounter other stars in the cluster later on and therefore change its configuration. In particular, triples for which the KCTF mechanism was inefficient may be perturbed into a different configuration which is more favorable for KCTF evolution. Since the timescale for the Kozai cycles, when those occur (i.e., $40^\circ \lesssim i \lesssim 140^\circ$), is usually much shorter than the time between dynamical encounters, encounters are not likely to interfere with KCTF evolution and destroy potential BSSs progenitors. Encounters can, however, contribute to the formation of new BSSs progenitors. For example, if a triple is initially coplanar, it cannot evolve through KCTF evolution to form a close inner binary. However, if an encounter excites its mutual inclination sufficiently, then KCTF will rapidly operate before the next encounter. If the companion stays bound, it has a better chance of causing KCTF evolution. Therefore, encounters that do not destroy the triple tend to make KCTF evolution more likely (for a similar discussion in the context of the KCTF mechanism in dense environments, see Perets & Naoz 2008). Since tidally captured close binaries are not expected to form in these low-density regions, we can conclude that the majority of close binaries should be part of triple systems, and in particular, the majority of BSSs produced in close binaries should be part of triple systems. Such a conclusion has many implications for BSSs properties, some of which can be compared with currently available observations to test the triple scenario, while others can be checked by future observations. In the following, we list these implications and compare them with observations, when available. The triple origin of BSSs has many implications and direct falsifiable predictions.

4.1.1. *BSS Fraction*

The BSSs formed in the triple scenario mostly form through the merger of the inner close binary in a triple. As discussed above, it is likely that nearly all close binaries (defined as $P < 6$ days) are formed in triples. The BSS fractions we expect to be produced are therefore similar to those predicted in the close binaries merger scenario, where the only difference is that we expect the produced BSSs to have companions (see below). Andronov et al. (2006) studied the BSS fractions from mergers of close binaries. Their results for the BSS fractions, applicable also to the triple scenario, are that the expected BSS fractions are consistent with observations. Note, however, that such results require a relatively high fraction of close binaries to be assumed. Such caveat applies in general to other theoretical predictions in the literature (e.g., Hurley et al. 2005 that also assumed high fraction of close binaries). In the triple scenario such high fraction of close binaries is the result of KCTF evolution, and need not be primordial. This is important since it is not clear how can binaries with $\lesssim$6 days period form primordially, as the protostars of the binaries components are of comparable size to the size of such short binaries (Fabrycky & Tremaine 2007). Binary distributions containing large fractions of close binaries are indeed observed in very young clusters and are therefore reasonable assumptions (see the extended discussions in Hurley et al. 2005 and Andronov et al. 2006). Note however, that the field distribution of binaries in the binaries sample of Duquennoy & Mayor (1991) shows smaller fractions of close binaries than those observed in very young clusters, which is perhaps the signature of their merger.

4.1.2. *BSS Binaries Fraction*

BSSs formed following the merger of the inner binary of a triple should still have a companion following the merger. Although such binaries could later be destroyed through encounters with other stars, this is likely to happen mainly for very large period binaries (soft binaries). The binary fraction of BSSs should therefore be higher than the overall binary fraction in the environment where they are observed. Current observations of spectroscopic BSS binaries (Geller et al. 2008; A. M. Geller et al. 2009, in preparation; Latham 2007) could only detect binaries with periods of $\lesssim$3000 days to a good level of completeness, due to the finite duration of the surveys. Longer period binaries would be observed as single BSSs and could therefore lower the *observed* BSSs binary fraction. Nevertheless, hard BSS binaries with an initial $P_{\rm out} > 3000$ days could be affected by encounters and harden to become closer, and thus observable, binaries (since BSSs are more massive than other cluster stars, they are more likely to survive in binaries even in exchange encounters). In any case, the BSS binary fraction is expected to much exceed the general binary fraction (of all stars) in the cluster environment. Since the hardening of binaries is dependent on the age of the cluster and its density, we may expect the (detection limited) *observations* of BSS binary fraction to show higher fractions in older and/or denser environments, as long as the period detection limit is smaller than the expected final hardening period (Hills 1984). For example, for the typical conditions in NGC 188, hard binaries should harden down to periods of $\lesssim 10^4$ days (see Equation (5) in Hills 1984), this period is close to the detection limit of the binary periods, and therefore most of the BSS binaries should be observed as such, and the observed BSS binary fraction is expected to be high (>0.5), as indeed confirmed by observations (e.g., a binary fraction >76 % for BSS binaries in NGC 188, Geller et al. 2008). M67 is a younger and less dense cluster and, therefore, the expected BSS binary fraction is expected to be lower than that in NGC 188, but still higher than the general binary fraction in the cluster.

We expect some specific correlations between BSSs fraction and cluster properties in the triple KCTF scenario. The primordial triple fraction is expected to be directly related to the binary fraction, and we should therefore expect a correlation between the binary fraction in clusters and the BSSs fraction. Since close encounters do not have important effects on the BSSs formation in the triple KCTF scenario, the BSSs fraction should be related to the unperturbed evolution of triples, similar to scenarios of unperturbed evolution of binary stars, which is consistent with recent analysis of the correlations between cluster properties and BSS fractions (Davies et al. 2004; Sollima et al. 2008; Knigge et al. 2009).

4.1.3. The Period–Eccentricity Distribution of BSS Binaries

The triple origin scenario implies that the period and eccentricity distribution of the BSS binaries should be the same as that of the outer binaries of triple systems (observed in the field) that have close inner binaries. In Figure 3(d), we show such a sample of such triples. The inner binaries in such field triples with $P_{\rm in} < 6$ days should be directly comparable with BSSs progenitors, although we may miss some of the closest inner binaries in the field which may have already merged via magnetic winds. Systems seen as triples with close inner binaries now are likely to become BSS in binaries later. We therefore also show the sample of triples with larger inner periods ($P_{\rm in} \lesssim 10$ days), which is also likely to be comparable, and could add to our statistics. We choose an upper cutoff of 3000 days, comparable to the detection limit of binaries in the observations of M67 and NGC 188. All the triples were chosen from the multiple stars catalog. Only low-mass triples, i.e., triples not containing stars with masses larger than $\sim 3\,M_{\odot}$were chosen. Higher mass stars would evolve off the MS on short timescales and not contribute to the BSSs in older clusters such as M67 and NGC 188.

The period–eccentricity distribution of the outer binaries in the triples discussed above is in good agreement with the observed BSS binaries distribution in the OC M67 (see Figure 3(d)) and NGC 188 (full data will be available in A. M. Geller et al. 2009, in preparation). Although the triples sample is not large, one can still observe some very unique characteristics that would be expected for BSS binaries in the triple origin scenario; note that the general binary distribution in Figure 3(b) clearly shows a different behavior than that of the BSS binaries in Figure 3(a). In particular, we expect BSS binaries from the triple scenario to usually have large periods, typically with $P \gtrsim 700$ days (also true for the larger NGC 188 sample, where 12 out 15 BSS binaries have periods longer than this cutoff A. M. Geller et al. 2009, in preparation).[4] Such a lower cutoff for the period of the outer binaries in triples could be the result of their formation process. Closer triples may have formed with correlated angular momentum. In such a case, the relative inclination between the inner and outer binaries in the triple may be low or even close to zero, which will quench KCTF evolution. These triples could not then produce close inner binaries. Note also that the stability of the triples may also play a role in biasing against the formation of close triples (Tokovinin et al. 2006). We also note that observed BSS binaries with $P < 10$ days are more likely to be the inner binaries of triples in which the BSSs were rejuvenated through mass transfer and not through a full merger (similar to the close BSS binaries produced in Hurley et al. 2005 simulations). Since the rejuvenated BSSs have only accreted some of their companions' mass, such close BSS binaries are likely to have lower masses (and be fainter) than the typical BSSs observed in the cluster. Even within the triple scenario, then, it is no surprise that some short-period BSS binaries do not match the $P - e$ diagram of *outer* binaries; the scenario predicts that a third, yet unseen star orbits each of these binaries.

Regarding the eccentricity distribution of BSSs produced by the triple scenario, we note that the eccentricities of outer binaries are consistent with the distributions of regular binaries in the field (Duquennoy & Mayor 1991): generally low ($\lesssim$0.4) eccentricities for period of $P \lesssim 1000$ days and a wider distribution up to high eccentricities for periods of $P > 1000$ days (again also consistent with the larger sample in A. M. Geller et al. 2009, in preparation). For the triple to be initially dynamically stable, the periastron of the outer binary must not pass too close to the inner binary, and this constraint translates to an upper limit on the eccentricity of the outer binary (which becomes the BSS binary), although for individual systems this limit is difficult to evaluate as the orbit of the original inner binary is not known.

The unique properties of the outer binaries in triples which are consistent with the behavior of BSS binaries are difficult to reproduce by either the collisional or the binary mass transfer scenarios for BSSs formation, even when combined together with the full dynamics of the system (see Figure 3(c); high eccentricities are mainly due to exchange encounters). The observations of BSS binaries therefore serve as a good discriminator between different formation scenarios, and current observations clearly favor the triple scenario as the major formation route of BSSs.

[4] Interestingly, higher mass triples do show outer binary periods much shorter than ~700 days, which suggest very different characteristics of massive versus low-mass triples (see also Geller et al. 2008, Section 3.2.1, in this respect), which may suggest a very different BSS binary period distribution in very young OCs.

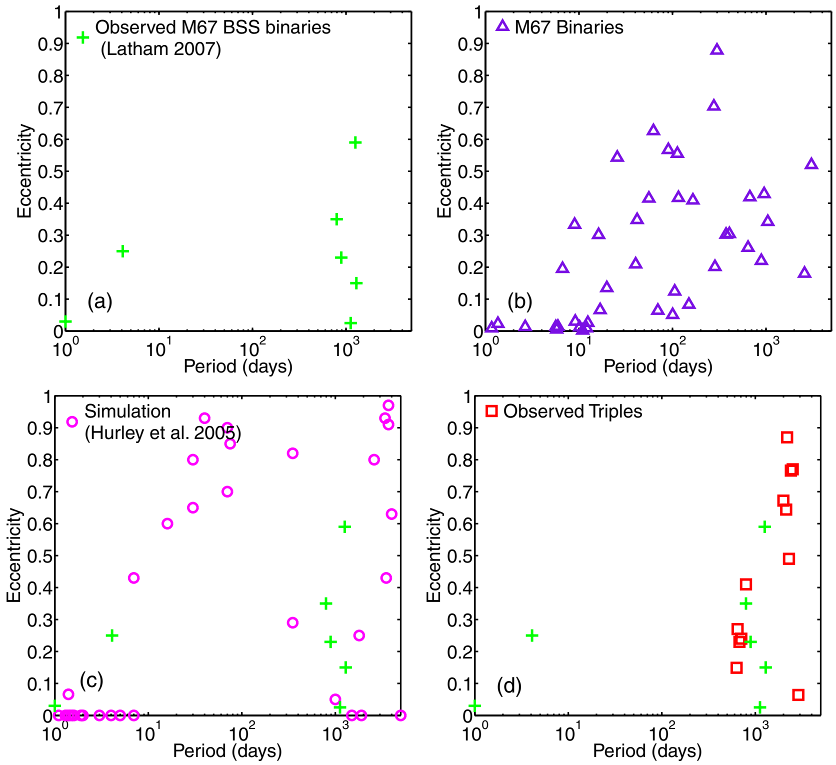

Figure 3. Period–eccentricity distribution of observed BSS binaries. (a) The period–eccentricity distribution of BSS binaries in M67 (+; Latham 2007), note that the larger sample of BSS binaries in NGC 188 (not shown; A. M. Geller 2009, in preparation) show similar behavior to that of M67 BSS binaries. (b) The period–eccentricity distribution of regular (non-BSS) binaries observed in M67 (△; Latham 2007). (c) The period–eccentricity distribution of BSS binaries produced in *N*-body simulations of M67 (○; Hurley et al. 2005) compared with the observed BSS binaries. (d) The period–eccentricity distribution of outer binaries in triple systems with close inner binaries (□; taken from the multiple stars catalog (Tokovinin 1997)) compared with the observed BSS binaries. Only binaries with periods shorter than 3000 days are shown (approximately the radial-velocity detection limit for the periods of the BSS binaries in the clusters). The good agreement between the distribution of outer binaries of triples to that of BSS binaries is evident. The comparison of BSS binaries to the other distributions (regular binaries in the same cluster or simulated BSS binaries in Hurley et al. 2005 simulation) is poor.

(A color version of this figure is available in the online journal.)

4.1.4. The Companions of Blue Straggler

The binary companions of long-period BSSs could be MS stars in the triple scenario (see also Eggleton & Kisseleva-Eggleton 2006, 2008 for a related discussion, and possible observations of such cases), which could not be the case for long-period BSS binaries produced following the post MS evolution of their companion, that are expected to be white dwarfs (WDs) at this stage. Another interesting discrimination method in this respect might be the comparison to CH stars found in clusters (which have low eccentricities and long periods, consistent with post-MS evolution in binaries; e.g., McClure 1997). If the triple KCTF scenario is the dominant mechanism for BSSs formation, one would expect very different distribution of CH binary stars and BSSs binaries, but very similar distribution if the mass transfer scenario is the dominant mechanism, and the former is apparently the case.

Since higher multiplicity systems are abundant (e.g., quadruples are $1/3$ as abundant as triples), one may find a similar fraction of the BSSs binaries to be in triple (or higher multiplicity) systems. In particular, two binaries in a double–double quadruple system (see, e.g., the doubly eclipsing light curves of Pilecki & Szczygiel 2007) could produce a long-period binary system containing two BSSs. This could happen if both inner binaries merged. Similarly a triple (or quadruple) system containing two BSSs could form in this way if one (or both) of the inner binaries transferred mass, but has not merged, yielding BSSs in the inner binaries. We therefore expect multiple systems containing more than one BSS to be observed.[5]

4.1.5. The Masses of Blue Stragglers and Their Location in Color–Magnitude Diagrams

Mass transfer in long-period binaries ($P > 700$ days, such as the BSS binaries observed) is highly inefficient. The total mass transferred from the post-MS companion to the formed BSS is likely to be small ($<0.3\ M_{\odot}$; and typically even lower) in this case, producing BSSs with masses not much larger than the turnoff mass of the cluster (i.e., $M_{\rm BSS} \lesssim M_{\rm turnoff} + 0.3\ M_{\odot}$). The triple scenario can produce a much more massive BSS, as it is the sum of the inner components of the triple ($M_{\rm BSS} \lesssim 2M_{\rm turnoff}$). Such a higher mass would therefore discriminate them from those formed through mass transfer. The latter binaries are expected to be composed of a low-mass (fainter) BSS with a WD companion at an intermediate period of a few hundred days as observed for field BSS binaries (see Preston & Sneden 2000 and Section 4.3.1). Such BSSs would be located close to the turnoff mass in the color–magnitude diagram of a given

[5] Interestingly, a triple containing two BSSs, one with a close companion, is observed in M67 (van den Berg et al. 2001; Sandquist et al. 2003). Such system could be formed, in principle, through the quadruple evolution we discuss. However, the large masses of s1082 components inferred from the orbital solution (Sandquist et al. 2003; but note the discrepancy with the position in the color–magnitude diagram) would require such system to be much younger (age of 1–1.5 Gyr) than the age of M67 (4 Gyr).

cluster, whereas the BSSs from the triple scenario can be distributed much further, typically far from the turnoff point of the cluster. Note that most BSSs in both NGC 188 and M67 are far from the turnoff point in the color–magnitude diagrams of the clusters (Geller et al. 2008; Liu et al. 2008), consistent with the predictions of the triples scenario and at odds with the binary mass transfer origin.

In case a close BSS binary did not fully merge, i.e., a close companion could still be detected, the BSS product should be less massive than the product of a full merger, as mentioned before, and would be observed closer to the turnoff point of the cluster than a merged BSS. The binary companion of such BSSs is likely to be an evolved star, and the system could be a close or even contact binary (possibly an Algol-like system, e.g., Jeon et al. 2006; Kaluzny et al. 2007). The frequency of such BSS Algols and other close BSS binaries is still unknown, but is likely to be small (Tian et al. 2006). In addition, one should then expect to find a triple companion, as is observed in close binary systems in the field (see Sepinsky et al. 2000 for possible observation of such systems).

In some cases, the companion of the KCTF-formed BSS may evolve off the MS during the lifetime of the BSS, in which case the BSS may accrete some of its mass, and become a more massive BSS, possibly even extending beyond twice the turnoff mass of the cluster. This could possibly explain the existence of some overmassive BSSs observed in clusters. In such cases, we might expect the binary companion to be a WD, probably on a rather circular orbit.

4.1.6. Spin–Orbit Correlation in BSS Binaries

In their theoretical analysis, Fabrycky & Tremaine (2007) found that the distribution of the relative inclination between the inner and outer binary orbits of KCTF triples should be in the range 30°–150°, with peaks at 40° and 140°. This distribution is therefore expected for BSS triples with nonfully merged inner close binaries. If the inner binaries did merge, it is likely that the angular momentum of the premerged inner binary would leave its signature on the spin of the merged BSS. It is therefore possible that the typical relative inclination distribution found by Fabrycky & Tremaine could still be detectable in relative inclination between the *spin* of the BSS and the binary orbit (i.e., the *obliquity* of the BSS), which is observationally accessible (although currently only through an overall statistical analysis; e.g., Hale 1994).

4.1.7. Radial Distribution of BSSs in Clusters

Since our triple scenario suggests the same progenitors for BSSs and close binaries, we expect the radial distribution (from the cluster center) of BSSs in clusters to be similar to that of close binaries. This prediction may seem natural also in the scenario of BSS production from primordial close binaries not evolved in triples; however, there are few differences between the two predictions. In principle, triple systems are likely to be more massive than binary systems, and therefore be somewhat more mass segregated in clusters, and possibly have different formation efficiency in different parts of a cluster, than that of binaries. These could possibly make a priori differences in the radial distribution of BSSs compared with regular binaries, although it is not clear whether enough statistics exist for making such a signature significant. In addition, in the triple scenario, we would also expect BSS binaries with long periods (i.e., with the inner binaries fully merged, see Section 4.1.3) to have a similar radial distribution to that of regular (non-BSS) close binaries in the cluster. If short- and long-period binaries have different radial distributions, the BSSs distribution should also reflect this.

Possible differences in the radial distribution may also serve as good discriminators between the triple scenario and the combined effects of all other suggested scenarios such as studied in N-body simulations (Hurley et al. 2005), since the latter suggest that BSSs and especially BSS binaries form only in the inner regions of the cluster, whereas the triple scenario could also form BSSs and BSS binaries in the outskirts of clusters[6].

4.1.8. A General Relation Between BSSs and Close Binaries

A more general prediction of the triple KCTF scenario is the close relation between close binaries and the BSSs population. This relation suggests that the predictions and implications described in the previous points regarding BSSs should be applicable also to the general population of close binaries in clusters (e.g., eclipsing binaries, contact binaries W UMa binaries, etc.) which may also be expected to have third companions in many cases. We note however that some close binaries populations such as X-ray binaries and cataclysmic variables were likely to form in a different route. In such populations, the close binaries form only after the main-sequence evolution of the compact object progenitor, and the binary separation must have been large during this time (e.g., Ritter 2008 and references therein), i.e., excluding the possibility of KCTF evolution in which the binaries must have a very small pericenter distance during their evolution.

4.2. High-density Environments (GCs Cores)

As can be seen in Figure 2, the timescales for close encounters with triples are larger than the typical KCTF time even in the dense environments of GCs, and therefore close binaries could form through KCTF even in such environments. Therefore, the primordial triples (and dynamically formed triples; see Ivanova 2008; Ivanova et al. 2008; Trenti et al. 2008) should be taken into account when studying BSSs formation scenarios in GCs. Nevertheless, given the high encounter rates in GCs, even close KCTF-formed binaries may be involved in close encounters which could destroy them, change their configuration or cause collisions, and possibly forming BSSs. The outer binaries in such triples are even more likely to be involved in several encounters at some stage during the GC evolution, which may even disrupt the triple, if the outer binary's periastron sinks too close to the inner binary (see, e.g., Heggie 1975; Hills 1984; Aarseth 2004). Given that the BSSs that do form would have a long-period binary companion, they are most likely to be involved in many encounters, following which they are still expected to be in relatively wide binaries (for the hard triples), even in the case of an exchange. According to Trenti et al. (2008), $\sim$1% of binaries have tertiary companions at any given time by dynamical formation, but this population continually evolves, so up to $\sim$10% of binaries have a chance to evolve through KCTF. The complex dynamics of high-density environments (see, e.g., de La Fuente Marcos et al. 1997; Aarseth 2004)

[6] Note that observation of a bimodal radial distribution of close binaries in a cluster would be highly interesting, since such a distribution is usually thought to be quite unique for BSSs. Following this prediction, we searched the literature for any evidence of such bimodal radial distribution of close binaries in clusters, and indeed found two examples for such a distribution in the clusters ω Centauri and Tuc 47 (Weldrake et al. 2004, 2007, this is by no means a complete list, and many others may exist). The analysis of this phenomena is, however, beyond the scope of this paper and will be discussed elsewhere.

and the need to include stellar evolution in old system such as GCs make it difficult to make clear predictions for the BSSs population without more elaborate dynamical analysis and/or N-body simulations; it is beyond the scope of this work.

In addition, given the old ages of GCs, BSSs formed from primordial triples in the triple scenario may already evolve off the MS in these clusters (see also the following section), and possibly only the dynamically formed triples could then directly form BSSs at later stages of the cluster evolution (see also Ivanova 2008; Ivanova et al. 2008). In this case, BSS binaries observed in GCs would have a different distribution than that of BSS binaries in lower density environments, with likely more eccentric and shorter period orbits.

4.3. Halo Environment

Now we discuss BSS formation, including the triple scenario, within the old populations of the halo of the Milky Way and of early-type galaxies, which have properties similar to old OCs and the outskirts of GCs.

4.3.1. Field BSSs

In the galactic halo, the stellar population is expected to be very old, so apparently younger stars are conspicuously blue; these are called Field BSSs (Preston & Sneden 2000; Carney et al. 2001, 2005). Such a noncluster stellar population is expected to evolve in isolation, and therefore field BSSs are not expected to form through collisions. Field BSSs could be explained by the binary stellar evolution of isolated binaries with periods of at most a few thousands days which evolve through mass transfer to form binaries with typical periods of a few hundred days (100–800; McCrea 1964). In such binaries, one of the components would evolve and expand, leading to a mass transfer to its companion which could become a BSS. Such stellar evolution would usually lead to circularization of the binary orbit and its shrinkage and leave a WD companion to the BSS. The field BSSs identified by Preston & Sneden (2000) and Carney et al. (2001) are single-lined spectroscopic binaries, so the companions are consistent with being WDs, and the orbital period distribution is consistent with that expected from mass transfer in evolved binaries. One may ask whether triple systems could also contribute to the formation of field BSSs.

When it operates, the KCTF mechanism leads to a rapid formation ($\lesssim 10^7$ yr) of a close inner binary. Stellar evolution of such a close binary is likely followed by its merger.[7] A merger product is usually much more massive than a star which accreted some mass from its companion (see Section 4.1.5). Therefore, such a rejuvenated star is very likely to evolve off the MS relatively early, and not be currently observed as a field BSS. When evolved such a star may transfer mass to its long-period companion (originally the star in the outer period of the triple), forming a low-mass BSS (i.e., at $M_{\rm BSS} \lesssim M_{\rm turnoff} + 0.3\, M_\odot$). Such a scenario may still show a weak signature on the BSS binary.

Since the outer period of triples is usually larger than $\sim$700 days (see Section 4.1.3), field BSS binaries from triples may have larger periods, on average (although these may be somewhat shortened during the mass transfer evolution). The more massive BSSs may also produce more massive WDs, on average. Combined together we might observe wider period field BSS binaries to have more massive WD companions (see O'Brien et al. 2001 for a related scenario). The most massive (and luminous) field BSSs could be the product of a full merger of the inner binary in triples with very long KCTF timescales. Observation of a field BSS binary with a main-sequence companion could serve as a strong evidence for a triple origin in this noncollisional environment, where an exchange scenario for the MS star origin is not possible. Such a BSS is likely to be one of the brightest, most massive field BSSs. Nevertheless, the signature of triple-formed field BSSs is not strong, and it is possible that in most cases triple-formed BSS binaries would be indistinguishable from the other field BSS binaries produced in binaries. We conclude that triples may contribute to the formation of field BSS binaries, but their contribution is not likely to be dominant, and would leave only a weak signature, unless very massive BSSs are observed ($\geqslant 2\, M_\odot$).

4.3.2. Bright Planetary Nebulae

Ciardullo et al. (2005) suggested that the progenitors of bright planetary nebulae (PNe) observed in old stellar population are BSSs formed in close binaries, since the progenitor mass of these bright PNe is thought to be larger than $2\, M_\odot$. Such high mass is much beyond the turnoff mass of stars in old stellar populations, such as in early-type galaxies and in galactic halos. Moreover, high-mass BSSs are likely to form only through mergers or strong mass transfer (see Section 4.1.5) which are only produced in close binaries or in collisions in dense environments. Since in the triple origin for BSSs we suggest such close binaries and their merged BSS product are formed in triples, a straightforward conclusion is that the progenitors of bright PNe are also triple stars. We therefore predict that such PNe may still have a long-period binary companion after the inner binary in the triple produced the BSS which evolved to become a PN. The further evolution of the BSS to a PN could affect the binary orbit, possibly circularizing it, due to low-mass transfer from the evolved BSS to its companion. Likewise, the presence of the binary companion could affect the morphology of the nebula. The details of such evolutionary process are beyond the scope of this work.

5. SUMMARY

In this paper, we have studied the possible formation scenario of BSSs in primordial and dynamically formed triple systems and its implications for the evolution and observations of BSSs. The direct relation between triple stars and BSSs in this scenario suggests a strong connection between BSSs properties and those of triples stars. Many specific predictions for the BSSs populations are implied by this relation and described mainly in Section 4, some of which are unique predictions that can discriminate it from the two other BSSs formation scenarios: stellar collisions and mass transfer in or merger of binaries. Possibly the strongest signature expected from this scenario is the expected high binary fraction of long-period BSS binaries and their unique period–eccentricity distribution with its strong bias toward long-period orbits (>700 days). This distribution is not likely to be produced by any other single scenario for BSSs formation, and not even through their combined effect as studied in N-body simulations with stellar evolution. We showed

[7] We do caution, however, that for wide systems for which the TF timescale is too long initially, stellar evolution can play an important role in the KCTF evolution, leading to a complicated interplay of mass transfer and eccentricity driving. The analysis of such combined KCTF and stellar evolution processes, however, is beyond the scope of this work. See Iben & Tutukov (1999) for foundational considerations on this subject.

that the recent observations of the BSS binaries population in the open clusters M67 and NGC 188 (the only clusters for which we have a wealth of data on BSSs binaries) could naturally be explained by the triple scenario, where all other currently suggested scenarios for BSS formation and evolution encounter major difficulties (see Figure 3). The triple scenario is likely to play a more minor role in the formation of field BSSs and in other low density *old* stellar populations, but could be important for the production of the most massive BSSs in these environments. The brightest planetary nebulae observed could be the product of such massive field BSSs, and may therefore have long-period binary companions as expected for BSSs in this scenario. In the cores of globular clusters, the interplay between triple evolution and other dynamical effects may become more complex, and both processes are likely to play a role in the BSSs formation. However, in open clusters, the triple origin scenario is possibly the most dominant mechanism for the formation of blue stragglers and currently the only model explaining the BSS binary properties in these environments.

We thank Bob Mathieu and Aaron Geller for helpful discussions and for supplying us with their prepublished data on BSS binaries in NGC 188. We thank Scott Tremaine and the referee Peter Eggleton for helpful comments and discussions. H.B.P. is supported by ISF grant 928/06 and gratefully acknowledges support from a Michelson Fellowship, which is supported by the National Aeronautics and Space Administration and administered by the Michelson Science Center.

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