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Blue straggler stars: formation channels

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Abstract. I review formation channels for blue stragglers. I consider how they may be produced via collisions between two single main-sequence stars, or via collisions during encounters involving binary stars. Further, I discuss how blue stragglers may be produced via the evolution of isolated binaries. Observations of globular clusters suggest that both mechanisms are contributing.

Key words. Stellar clusters – Stars: blue stragglers – Stars: binaries

1. Introduction

Blue stragglers are found on the main-sequence in an H-R diagram but at a position above the turn-off mass. Their presence is a surprise: it would seem that somehow these stars have longer lives than one would expect given their apparent masses. In fact, we think today that these stars have been made (or at least rejuvenated) relatively recently, either via collisions (and mergers) between two lower-mass main-sequence stars, or by mass transfer within a binary. We will discuss both channels here.

We will show that collisions between main-sequence stars occur interestingly often within the dense cores of globular clusters. Because the relative velocity of stars within globular clusters is much less than the surface escape speed of main-sequence stars, collisions lead to the merger of the two stars, with very little mass loss (e.g. Benz & Hills 1987). The post-collision evolution of such merger products is, however, complex. Merger products are likely to possess relatively large amounts of angular momentum. Spin could lead to mixing within the star thus prolonging the merger-product's life. Encounters involving binary stars can be as frequent as those involving only single stars as a binary is a much larger target than a single star. Thus even if only a small fraction of stars are in binaries, the event rate for strong encounters between binaries and single stars can be comparable to that between two single stars. Stars pass close together during such encounters, and collisions are possible, producing blue stragglers.

Blue stragglers may also be produced through the evolution of isolated binaries without the external influence of other stars. Tight binaries will merge if they are able to lose angular momentum via winds. In other binaries, mass transfer will occur as the primary evolves off the main sequence and fills its Roche Lobe. Providing the mass ratio of the two stars within the binary is sufficiently close to unity, this phase of mass transfer may stably transfer material onto the secondary, increasing its mass, and potentially transforming it into a blue straggler.

As we will see in the final section of this paper, blue stragglers are made both via collisions, and via mass transfer/mergers within isolated binaries. Collisions are relatively more important in the cores of dense globular clusters, whereas the populations derived from isolated binaries dominate elsewhere.

2. Stellar collisions

In order for collisions to produce blue stragglers, collisions must occur at a sufficiently high rate and the collisions themselves must lead to a merger, with relatively little mass loss.

The cross section for two stars, having a relative velocity at infinity of V_∞, to pass within a distance $R_{\rm min}$ is given by

$$\sigma = \pi R_{\rm min}^2 \left(1 + \frac{V^2}{V_\infty^2}\right) \tag{1}$$

where V is the relative velocity of the two stars at closest approach in a parabolic encounter (*i.e.* $V^2 = 2G(M_1 + M_2)/R_{\rm min}$, where M_1 and M_2 are the masses of the two stars). The second term is due to the attractive gravitational force, and is referred to as gravitational focussing. If $V \gg V_\infty$ as will be the case in systems with low velocity dispersions, such as globular and open clusters, the gravitational focussing terms dominates and $\sigma \propto R_{\rm min}$. In this situation, collisions involving main-sequence stars will be more frequent that collisions involving red giants.

One may estimate the timescale for a given star to undergo an encounter with another star, $\tau_{\rm coll} = 1/n\sigma v$. For clusters with low velocity dispersions, we thus obtain

$$\tau_{\rm coll} \simeq 10^{11}{\rm yr}\left(\frac{10^5{\rm pc}^{-3}}{n}\right)\left(\frac{V_\infty}{10{\rm km/s}}\right)\times \left(\frac{R_\odot}{R_{\rm min}}\right)\left(\frac{M_\odot}{M}\right) \tag{2}$$

where n is the number density of single stars of mass M. For an encounter between two single stars to be hydrodynamically interesting, we typically require $R_{\rm min} \sim 3R_\star$ for $V_\infty = 10$ km/s (see for example, Davies et al. 1991). We thus see that for typical globular clusters, where $n \sim 10^5$ stars/pc^3, up to 10% of the stars in the cluster cores will have undergone a collision at some point during the lifetime of the cluster.

Stellar collisions are complicated events requiring them to be modelled using 3-D hydrodynamics simulations. Much work has been done modelling such collisions, particularly involving low-mass main-sequence stars with relatively-low velocities which are relevant for the encounters of interest to us in globular clusters (including Benz & Hills 1987, 1992; Lombardi et al. 1995, 1996, 2002; Sills et al. 2002). There are two speeds to consider in a stellar collision: the relative speed of the two stars at infinity V_∞ and the surface escape speeds of the stars ($V_{\rm esc} = \sqrt{2GM_\star/R_\star}$). For globular clusters, $V_\infty \simeq 10$ km/s. In comparison, for low-mass main-sequence stars, $V_{\rm esc} \simeq 600$ km/s. We should not be surprised therefore to find that collisions in globular clusters lead to mergers having little mass-loss (typically 1-10 % of mass is lost (e.g. Benz & Hills 1987, 1992) as the ejection of a small fraction of the total mass can carry off the (small) positive energy contained in the collision.

3. Post-collision evolution

The post-collision evolution of a merger product is complicated, though much work has been done (e.g. Sills et al. 2005, 2009; Glebbeek et al. 2008). During a collision, the kinetic energy contained by the stars is converted into thermal energy. Thus immediately after the collision, the merger product is out of virial equilibrium. It will expand and cool, returning to the main sequence once sufficient angular momentum has been lost either through a disc or in winds (Sills et al. 2005).

Mixing within the merger product critically affects its subsequent evolution as the core is provided with fresh fuel for hydrogen fusion reactions. Thus the subsequent main-sequence lifetime of the merger product will be set in part by the degree of mixing which occurs. The lifetime of the collision products will be short unless fresh hydrogen can be brought in to the core of the merger product. Indeed, recent work suggests that blue stragglers have somewhat shorter lifetimes than regular main-sequence stars of similar masses (Sills et al. 2013).

4. Encounters involving binary stars

We now consider encounters between binary and single stars. The time scale for such encounters is given by

$$\tau_{2+1} \simeq 10^{11}\mathrm{yr}\left(\frac{10^5 pc^{-3}}{n}\right)\left(\frac{V_\infty}{10km/s}\right)\times \left(\frac{R_\odot}{a_{\rm bin}}\right)\left(\frac{M_\odot}{M}\right) \quad (3)$$

One can see how encounters between binaries and single stars can be as frequent as encounters between two single stars. For example, if a cluster possesses a binary fraction of around 0.05, then the encounter rates will be similar for binaries of separation $a_{\rm bin} \sim 60$ $R_\odot$.

Encounters between binaries and single stars have several possible outcomes: fly-bys occur where the binary retains its stellar components although the binding energy and eccentricity of the binary orbit may change; fly-bys may lead to the merger of the two stars within the binary; an intruder star may exchange into the binary with typically the least massive of the three stars being ejected; the system may form a (transient) triple system; two of the stars may merge but remain bound to the third star; or a common envelope system may form where two of the stars orbit inside a gaseous envelope made from the third star. For us here, considering blue straggler production in stellar clusters, we are particularly interested in the fifth possible outcome, where two stars merge. The outcomes for such mergers are likely to be similar to those seen for collisions between two single stars as described earlier.

The fraction of binary-single encounters which lead to collisions between stars depends on the binary separation. For binaries having separations around 1 AU, the fraction of strong binary-single encounters where two stars pass within some distance $r_{\rm min}$ is found, through numerical experimentation, to be $f \propto (r_{\rm min}/a_{\rm bin})^\gamma$ where $\gamma \simeq 1/2$ (Davies et al. 1993, 1994). So, for example, collisions and mergers occur in 10-20% of encounters involving solar-like stars and a binary of separation 1 AU. Thus stellar mergers occurring during a binary-single encounter may make a significant contribution to the total merger rate within a stellar cluster providing the binary fraction is large. In typical globular clusters, where the binary fraction is perhaps around 10% or smaller (e.g. Milone et al. 2012), the collision rate derived from single-single collisions is likely to exceed that derived from encounters involving binaries.

5. Making blue stragglers via binary evolution

We now consider the production of blue stragglers via the evolution of isolated binaries. It is important to note that binaries may evolve *in isolation* even within a stellar cluster providing the evolutionary time scale is shorter than the time scale for perturbing encounters with other stars.

Binaries may produce blue stragglers from one of two distinct pathways. Firstly, if the binary is sufficiently tight, the binary may merge as angular momentum is lost via stellar winds. The subsequent evolution of the merger product is likely to be rather similar to that described earlier for objects produced via stellar collisions. Here, as before, the object is likely to be spinning rapidly, which may help provide the stellar core with fuel. Clearly the merger product will be a single star, unless the tight binary is itself a component of a wider binary.

Binaries too wide to merge as described above will undergo mass transfer once the primary evolves off the main sequence. If this mass transfer proceeds in a stable fashion, then the secondary will gain mass possibly exceeding the mass of the primary, and thus becoming a blue straggler. In order for the mass transfer to proceed stably, the initial mass ratio must be close to unity, as mass transfer from more-massive donors tends to reduce the binary separation and thus increase the mass-transfer rate which, if continued, would lead to a binary smothered by a common envelope of gas, producing a single merged object.

6. Comparing primordial and collisional formation rates in clusters

In this final section we consider the likely formation rates of blue stragglers produced either by collisions or by binary evolution as described earlier.

The stellar collision rate within the cluster core is given by $\Gamma_{\rm coll} \propto \rho^2 r_{\rm c}^3/\sigma$, where ρ is the mass density of stars within the cluster core, $r_{\rm c}$ is the core radius, and σ is the velocity dispersion of the stars which is $\propto \sqrt{M_{\rm tot}/r_{\rm h}}$, where $M_{\rm tot}$ is the cluster total mass and $r_{\rm h}$ is the radius containing half of the cluster's total mass. Assuming for simplicity all clusters have similar properties (i.e. radii, fraction of mass in core, etc.), we find that the number of blue stragglers produced by collisions increases with the cluster mass as

$$N_{\rm bs,coll} \propto M_{\rm tot}^{1.5} \tag{4}$$

Blue stragglers produced via binary evolution will be visible today provided the rejuvenating mass transfer occurred sufficiently recently. This in turn implies that the primary masses were only *slightly* above the current turn-off mass. If the binaries which produce blue stragglers are allowed to evolve in globular clusters without any interactions with other stars, then we would simply expect that the number of blue stragglers derived from these primordial binaries would be proportional to the cluster mass

$$N_{\rm bs,bin} \propto f_{\rm bs,bin} M_{\rm tot} \tag{5}$$

where $f_{\rm bs,bin}$ is the fraction of the original binary population contributing to the blue straggler population today. We would expect the blue straggler population to be a sum of these two terms, i.e. to scale with cluster mass with a power-law index somewhere between 1.0 and 1.5. However, the blue straggler population is observed to be *roughly independent of cluster mass* (Piotto et al. 2004). How can this be? The solution lies, it seems, in understanding how encounters will change the binary population. Encounters systematically leave more-massive stars within the binaries which will have undergone mass transfer in the (too) distant past. They will also break up some binaries. Together these processes will act to reduce the fraction of binaries which contained a primary in the mass range necessary to produce a blue straggler which would be visible today. When combined with the number of blue stragglers produced by collisions, the total number of blue stragglers produced is found to be relatively independent of cluster mass (Davies et al. 2004).

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