Blue Straggler Formation in Clusters

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Abstract.

Blue stragglers are thought to be formed from the merger or coalescence of two stars, but the details of their formation in clusters has been difficult to disentangle. We discuss the two main formation mechanisms for blue stragglers (stellar collisions or mass transfer in a binary system). We then look at the additional complications caused by the stars living in the dynamically active environment of a star cluster. We review the recent observational and theoretical work which addresses the question “which mechanism dominates?” and conclude that the most likely answer is that both mechanisms are at work, although with different importances in different environments and at different times in the cluster lifetime. We conclude with a short discussion of some avenues for future work.

Keywords: Blue stragglers; open clusters; globular clusters; binary stars; multiple stars

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1. SEARCH FOR FORMATION MECHANISMS

Blue stragglers are stars which are bluer and/or brighter than the main sequence turnoff in clusters. They are found in all resolved stellar populations, including globular and open clusters, dwarf galaxies [27], and even the field [4]. They are main sequence stars, lying between the zero-age main sequence and the giant branch in clusters. Typically they do not lie on a tight sequence, but instead fill much of that region of the colour-magnitude diagram. Where we can identify companions, we know that blue stragglers often occur in binary systems or even in triples [28, 38]. Typically there are a few tens of blue stragglers in open clusters, and up to a few hundred in globular clusters. While they only represent 1% or less of the stellar population in any cluster, they are easily identified and provide a way to probe the history of the cluster and/or its binary population, depending on our understanding of how this unexpected population was formed.

Any formation mechanism for blue stragglers must find a way to either increase the mass of a normal (low-mass) cluster main sequence star, or delay the evolution of a higher-mass star such that it stays on the main sequence longer than its peers. Currently, the two main formation mechanisms which are thought to create blue stragglers are direct stellar collisions, or mass transfer in a binary system. We discuss each of them below, and then look at the importance of the cluster environment.

1.1. Stellar Collisions

In the simplest form of this scenario, two previously unrelated stars collide as they are moving through the cluster. A fairly dense environment is needed, but calculations of collisional cross sections in globular [12] and open [22] clusters have shown that collisions are common enough in these environments to produce approximately the right number of blue stragglers. In some clusters, it is expected that every star has undergone at least one close encounter. There is also evidence that another exotic population, cataclysmic variables, is a collision product and they are over-abundant in clusters [33]. Blue stragglers are also concentrated in the cores of clusters [e.g. 18], suggesting that they are more massive than the average star, but also indicative that they are formed in the densest environments.

Hydrodynamic simulations of stellar collisions [e.g. 23] show that for the relatively gentle collisions which occur in globular clusters, the collision product is a star-like object. Only a few percent of the total mass of the two parent stars is lost during the collision, and the rest settles into a spherical, hydrostatic object. The collision product is typically not fully mixed, but instead the cores of the parent stars end up at the core of the collision product [23]. Subsequent stellar evolution calculations of the collision product [34, 10] have shown that after some initial thermal-timescale relaxation, the star evolves relatively normally. One such example is shown in Figure 1. The red line is the evolutionary track of the product of a collision between a 2.4 and 1.9 $M_\odot$ star, and the blue line shows the evolution of a normal star of
FIGURE 1. Evolution of the product of a collision between a 2.4 \( M_\odot \) and a 1.9 \( M_\odot \) star (red), compared to the evolutionary track of a normal 4.3 \( M_\odot \) star (blue). Models courtesy of E. Glebbeek, based on the calculations in Glebbeek & Pols[10].

4.3 \( M_\odot \). The initial thermal relaxation of the collision product has not been shown. In general, collision products are quite similar to normal stars of the same mass. However, their main sequence lifetime is generally shorter than that of the normal star. Since the parents of the collision product have been evolving for some time before the collision, they have converted some of their hydrogen to helium, and so the collision product has a smaller hydrogen reservoir and a shorter main sequence lifetime. Their position in the colour-magnitude diagram is therefore usually above the zero-age main sequence, reflecting their advanced stage of evolution when they are formed. However, the collision products do typically spend considerable time in the appropriate region of the colour-magnitude diagram so that we would expect to see them as blue stragglers.

1.2. Binary Mass Transfer

The other plausible mechanism for blue straggler formation involves mass transfer in a binary system. We know that binaries exist in all stellar populations, and we also know that if the orbits are small enough, mass will be transferred from one star to another. Binary mass transfer has been invoked to explain a wide variety of unusual stars, starting with the Algol system and encompassing objects at all evolutionary stages. Blue stragglers are seen in all well-studied stellar populations, including sparse clusters and the field. Stellar collisions are not expected to contribute to blue stragglers in these environments, and therefore binary mass transfer provides an obvious and likely alternative formation mechanism.

If the accreting star is a main sequence star, then the product will be a blue straggler. Not all of the donor star needs to become part of the blue straggler – only enough mass to significantly change the accretor’s position in the colour-magnitude diagram needs to be transferred. For relatively high-mass accretors near the turnoff, this could be only a few tenths of a solar mass. The other extreme is a mass transfer event in which the entire donor star is accreted onto the blue straggler. Some authors refer to the latter as “binary coalescence” or “binary merger”. For the purposes of this review, we will consider any amount of mass transfer as belonging to this mechanism.

The position of the blue straggler in the colour-magnitude diagram and its main sequence lifetime depend heavily on the masses and evolutionary states of the two stars involved. The initial binary orbit also determines how much mass will be transferred, and when. The parameter space of binary mass transfer blue stragglers has not yet been fully
explored. The most comprehensive studies to date follow binaries which are appropriate for producing blue stragglers in old open clusters like M67 [39, 2]. Both case A and case B mass transfer have been studied. Again, the evolutionary tracks for these objects spend a significant amount of time in the blue straggler region of the colour-magnitude diagram. Interestingly, many of the mass transfer systems spend the majority of their time at or near the equal-mass binary line (0.75 magnitudes above the zero age main sequence), regardless of the actual mass ratio of the system.

The present-day appearance of binary mass transfer products will depend strongly on when the mass transfer began, whether the mass transfer was conservative, and whether the mass transfer was complete. Incomplete mass transfer will result in a blue straggler in a binary system, and the nature of that companion star can tell us a lot about the initial configuration. For example, a main sequence companion means that case A mass transfer was the cause, while a helium white dwarf points to a giant branch donor instead.

1.3. Influence of the cluster environment

In the discussion above, we have considered the effects of stellar dynamics and of binary evolution separately. In clusters, however, this simplification is invalid. We know that all clusters have a population of binaries, and these binaries can interact dynamically with each other and with single stars. These interactions will modify our expectations for the blue straggler populations in clusters in a number of ways.

Dynamical interactions will modify the binary population in clusters. The standard wisdom can be summarized as “hard binaries harden” [11]. In other words, during long-range encounters with other objects in the clusters, binaries whose orbital energy is larger than the average kinetic energy of stars in the cluster will have their orbital energy increased. Soft binaries, on the other hand, have their orbital energy decreased by encounters, even to the point of disruption of the binary completely. What implications will this have for those binaries which would have formed blue stragglers through mass transfer? In order to produce a blue straggler that we identify at the current time, mass transfer needs to have happened in the somewhat recent past. Also, the accretor needs to be a main sequence star of the appropriate mass. Otherwise, the blue straggler will have had time to leave the main sequence and evolve off to the giant branch. If the distribution of binary orbital energies (and hence separations) is being modified by interactions, then the number of appropriate binaries which would have undergone mass transfer at the appropriate time will have changed. Some systems will be hardened to the point where mass transfer will happen earlier and we will not see them as blue stragglers at the current time. Other, wider systems, which would not have become blue stragglers, may be hardened enough that those objects will contribute to the blue straggler population. However, we must also consider the evolutionary state of the donor when determining which objects will become blue stragglers – the initial orbital separation is not enough information.

In addition to long-range, gentle encounters, binaries in clusters undergo close encounters with single stars or other binaries which result in much more violent outcomes. Binaries can be broken apart entirely, which means that those objects cannot later produce blue stragglers. These close encounters are typically resonant encounters [15], meaning that the individual stars spend a long time involved in a complicated dance around each other. Exchange interactions are quite common, and the typical outcome is that the heavier stars are exchanged into the resultant binary. Therefore, the stellar evolution timescale of this new binary is shorter than the original one. Even if the new binary does produce a blue straggler, it will do so sooner and the blue straggler is likely to have evolved away to the giant branch before the present day [3].

The major effect of the cluster environment is to blur the distinction between the two formation mechanisms for blue stragglers. Direct collisions are much more likely between two binary stars rather than two single stars, since the cross section of a binary star goes as its semi-major axis instead of the stellar radius. During resonant interactions, two or more of the stars involved could run into each other. Even though the velocities are larger than in the single star case (because of the addition of the orbital velocities of the binaries), the collisions are still sufficiently gentle that our models of collision products still apply. Therefore, identifying an individual blue straggler as a collision product or a binary product may not be an easy, or even a valid, distinction.

2. WHICH MECHANISM DOMINATES?

Standard practice in science, when presented with two likely explanations for any phenomenon, is to figure out which explanation is correct. In astronomy, observations are made in many wavelengths and modes; theorists produce detailed
models of individual objects and of whole populations. Comparisons are made, and after a while, one explanation emerges triumphant over the other. However, in the question of blue straggler formation, we are not yet at the final stage of this story. In fact, it seems that the question we need to answer is not “which mechanism dominates” but rather “does one mechanism dominate?” And, in fact, we many need to look for different dominant mechanisms in different environments in the universe and perhaps even in different regions in the same star cluster.

As we have discussed above, both collisions and mass transfer can reproduce observed properties of blue stragglers. These mechanisms create main sequence stars, more massive than the turnoff, with lifetimes that are long enough that we expect to see significant numbers of these objects in present-day clusters. Therefore, in order to distinguish between the different formation mechanisms, we must look at the entire population of blue stragglers in clusters. Can either mechanism correctly predict the distribution of blue stragglers in the cluster, and in the colour-magnitude diagram? Which mechanism can correctly predict the number of blue stragglers found in each cluster, or predict the sizes of populations as a function of global cluster properties? Thanks to both increasingly detailed observations of blue stragglers, and to more and more models, we are starting to be able to answer these questions.

An early comparison of collisional blue straggler populations to observations of cluster populations was done for 6 globular clusters [6] with a range of central densities. The authors compared the luminosity functions of blue stragglers with collisional models, as well as their distribution in temperature. Because these were HST observations, only core blue stragglers were included in the comparison. The collisional models could fit the data reasonably well for most clusters, but not for the lowest-density cluster in the sample (NGC 288). This was expected since the collision rate in that cluster is quite low. Most of the clusters have a population of blue stragglers which are redder than the collisional models can explain, as it is very difficult to get a star to remain in the Hertzsprung gap for any substantial length of time.

A similar study of the blue straggler population throughout the nearby cluster 47 Tucanae [30] made use of HST and ground-based data, thereby covering the entire extent of the blue straggler population in this cluster. In this case, the blue straggler population was assumed to be collisional, and the models allowed for two free parameters: the mass function of the main sequence stars which went into the collisions, and the duration over which the collisions could occur. The collisional models fit the observations very well. Interestingly, the blue straggler models implied that the mass function in the core of the cluster is very heavily weighted towards high mass stars, and that it becomes shallower towards the cluster edge. This result is consistent with the direct measurement of the main sequence mass function as a function of radius in 47 Tuc. Therefore, using blue stragglers as tracers of the dynamical state of the cluster seems plausible, which is really only possible if collisions contribute significantly to the formation of these objects.

However, around the same time, some completely contradictory evidence was published. By comparing the fraction of blue stragglers in clusters to the current collision rate, Piotto et al. [32] showed that there was not the expected correlation. In fact, there seemed to be an anti-correlation. That paper concluded that collisions could not be the dominant mechanism for producing blue stragglers. A consistent selection of core blue stragglers, and comparison to many cluster properties (e.g. velocity dispersion, central density, etc), concurred with that result [19, 20]. Finally, a robust correlation with a cluster property was found [16]: The number of core blue stragglers is proportional to the cluster’s core mass. The authors conclusively proved that the number of blue stragglers could not be proportional to the collision rate. In addition, they showed that the blue straggler number was not linearly proportional to the core mass, but instead goes as \( M_*^{0.5} \). If the binary fraction in globular clusters also depends on the (core) mass as \( M_*^{-0.5} \), then it seems reasonable that the number of blue stragglers in globular cluster cores is proportional to the number of binaries in the core, \( f_b M_* \). In fact, preliminary evidence does show approximately this dependence of binary fraction on cluster mass [36, 29]. In addition, a correlation between blue straggler populations and binary fraction was found for some sparse globular clusters [37]. Therefore, binary stars must be involved in the formation of blue stragglers, even in the cores of clusters.

Additional evidence supporting a binary evolution for blue stragglers comes from detailed observations of surface chemical abundances in these stars. Ferraro et al. [7] did a spectroscopic survey of blue stragglers in 47 Tuc, and found some evidence for mass transfer – a subset of the blue stragglers were depleted in both carbon and oxygen compared to normal stars in the cluster. One way to do this is to have CNO-processed material from the inner regions of a star be dumped onto the surface of a companion, where it is now visible. Unfortunately, a similar study of blue stragglers in M4 [25] found no evidence of such a population so this signature seems not to be ubiquitous.

So, collisions can explain the observations of blue stragglers and can predict cluster properties...except that blue stragglers cannot be formed through collisions and must have a binary origin. The picture is not becoming clearer. And, indeed, we have evidence that both mechanisms are going on in the same cluster. First, we have the long-known “bimodal distribution” of blue stragglers in globular clusters. HST plus ground-based observations of a number of clusters, starting with M3 [5], have shown that the blue straggler population is largest in the centre of the cluster. Then
there is a significant drop of blue straggler numbers with increasing cluster radius, and after some point the numbers go back up again, although not usually to values as high as the central value. The best explanation for this distribution was presented by Mapelli et al. [26]. A blue straggler population which consists of a collisional population and a binary population was allowed to react dynamically with the underlying cluster stars for the typical lifetime of a blue straggler. The collisional population was initially found only in the core of the cluster, where the binary population was initially spread evenly throughout the cluster. These binary blue stragglers started to fall into the core, because of mass segregation. But because of the finite lifetime of blue stragglers, not all of them have a chance to reach the core in the lifetime of the cluster. The radius of the minimum of the blue straggler population is called the “zone of avoidance”, and is where the dynamical friction timescale is short enough that the blue stragglers can have reached the core. Outside of that radius, the blue stragglers remain more-or-less at their initial radii. As shown in Mapelli et al. [26] and later papers [17, 1], the predicted zone of avoidance matches the minimum blue straggler position within a factor of 2 for most clusters.

The second strong piece of evidence for two formation mechanisms at work in the same cluster comes from HST observations of M30 [8]. In the core of this cluster, two distinct sequences of blue stragglers can be seen (see figure 2). The bluer sequence lies slightly above the ZAMS, with the brightest of these blue stragglers further from the ZAMS than the fainter stars on this sequence. It is extremely well-modeled with an isochrone of collision products, approximately 1 Gyr after the collisions have occurred. The red sequence consists of stars which are at least 0.75 magnitudes brighter than the ZAMS, and some are substantially brighter than that and lie in the Hertzsprung gap. These stars are consistent with the mass transfer models from [2]. The redder blue stragglers are more centrally concentrated than the blue ones, which has interesting implications for the binary properties of the two progenitor populations. In another Gyr or so, normal stellar evolution will blur the distinction between the two sequences. The fact that we see two sequences at the present time suggests that the formation of this population of blue stragglers was both recent and short-lived. It is interesting to consider that this may be an indication of core collapse or some other clearly-defined dynamical event.

Finally, evidence that we must include both (or hybrid) formation mechanisms comes from “kitchen-sink” dynamical models of globular cluster evolution. This result was first presented in the context of N-body models of the old open cluster M67 [14], where the blue stragglers were found to have very complicated formation histories involving both dynamics and binary evolution. Recently, we have been investigating the blue straggler populations of approximately 100 globular cluster models using the Northwestern Monte Carlo code (Sills, Chatterjee & Glebbeek, in preparation). Our preliminary results are shown in figure 3. Here we show the observed trend of core blue straggler number with core mass (open circles), and the results of our simulations overplotted (squares). These models, which reproduce the observations very nicely, require a cluster binary fraction of 5-10%. Cluster with no initial binaries simply do not produce enough blue stragglers, especially in the high-mass clusters. We can also look at the formation histories of all our modeled blue stragglers, and we find that very few of them are purely collision products or purely binary mass transfer products. Almost all of them have both dynamical encounters and binary evolution in their history. We can also distinguish between blue stragglers formed in a binary encounter from those formed from direct collision, and we find that the binary encounters significantly outnumber both direct collisions and binary mass transfer.

3. FUTURE WORK AND OPEN QUESTIONS

We are converging on an explanation for the formation of blue stragglers in clusters. Unfortunately it seems to be a complicated explanation, involving multiple formation mechanisms which act with different weights in different environments and at different times in the cluster evolution. However, we are certainly making progress with a combination of detailed observations and more sophisticated models of both individual blue stragglers and cluster populations. As always, there are still a number of additional complications and considerations that we still need to consider. The following is a combination of a “wish list” and a nod to additional physics we may still need to include in our models.

For the most part, we have completely ignored the effects of any system more complicated than binary stars. However, there has been some promising research recently pointing to the importance of triple systems, particularly for blue straggler populations in old open clusters [31, 21]. Modeling the dynamical effects of triples is extremely computational intensive in N-body codes, and they are completely neglected in currently Monte Carlo codes, but we may have become cleverer if we really wish to investigate all possible formation mechanisms of blue stragglers and other stellar exotica in clusters in the context of full-blown cluster models.
In the mid-90’s, there was a concerted effort to understand single-single and single-binary encounters. Calculations of encounter outcomes and cross sections were automated and parameterized, and so we have a fairly good understanding of these kinds of encounters. However, because the parameter space of binary-binary encounters was so large, and because it is much harder to determine when an encounter is “finished”, we know much less about the outcomes of higher order encounters. And, of course, very little work has been done on triples and higher order multiples, as discussed above. Special-purpose codes such as FEWBODY [9] have been built to follow encounters of a small number of stars, and could be harnessed for this purpose. Brute force, however, is unlikely to cover the interesting parameter space in a useful amount of time, and so the problem of being selective in initial conditions is likely to remain.

I have not mentioned the rotation rates of blue stragglers in clusters, and the information that those measurements can give us. There are very few measured rotation rates of blue stragglers, particularly in globular clusters. The situation is rather better in open clusters, where the fields are sparser and spectroscopic studies have been going on for longer (e.g. for characterization of the binary populations in those clusters[28]). The indications are that blue stragglers do not rotate extremely rapidly, but that they rotate more rapidly than normal stars of the same temperature (typically 10-40 km/s for blue stragglers, compared to 2-10 km/s for normal stars). Have they been spun up by collisions or mass transfer? Have they had a chance to spin down from a very significant rotation rate? Can the rotation rates tell us anything about their time of formation? Does the rotation mix the stars significantly, so that their evolutionary tracks are different from non-rotating stars? Models of the angular momentum evolution of both collision products e.g. [35] and binary mass transfer products are required before we can use these pieces of observational evidence to understand anything more about blue straggler formation in clusters.

We have detailed evolutionary models of some binary mass transfer products. However, the (very large) parameter space has not yet been sufficiently explored. We need to understand enough about the evolution of mass transfer
Number of blue stragglers in the core of globular clusters, vs. core mass. Observations are shown as open circles, model calculations are dark squares. The models require a binary fraction of 5-10%, and contributions from both collisions and binary evolution, to match the observations.

products that we can approximate their evolution in binary evolution codes like BSE [13]. This has been done for collision products, to some extent – the Make Me A Star code (MMAS) [24] will produce a collision product from two parents, without the need for the detailed hydrodynamic calculation. The subsequent evolution of this collision product can be calculated using a stellar evolution code, or the lifetime and CMD location can be estimated based on the core hydrogen fraction of the product. We are not yet at this stage for binary mass transfer models.

And finally, it would be of great interest to a large population of researchers to know the binary properties in globular clusters. Does the binary fraction depend on the mass of the cluster, as suggested by preliminary work? Does it depend on the location in the cluster? The answer to this question seems to be “yes”, based on some scant observations and a number of dynamical models. Does it depend on which stellar population one observes? Of particular interest to understanding the formation of blue stragglers, we’re looking for two answers to this question. One, what is the binary fraction of main sequence-main sequence binaries, which could form blue stragglers later? Two, what is the binary fraction of the blue stragglers themselves? And, of course, any information we can glean about the mass ratio, semi-major axis, and eccentricity distributions of any of these binaries will be crucial for many of us. Will there be a multi-object spectrograph on a telescope with sufficient resolution to disentangle the crowded conditions of globular clusters any time soon? I know of no such instrument in the planning stages, so we may be using approximations and indirect methods for a long time.

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