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Blue straggler formation at core collapse

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Abstract. Among the most striking feature of blue straggler stars (BSS) in globular clusters is the presence of multiple sequences of BSSs in the colour-magnitude diagrams (CMDs) of several globular clusters. It is often envisaged that such a multiple BSS sequence would arise due a recent core collapse of the host cluster, triggering a number of stellar collisions and binary mass transfers simultaneously over a brief episode of time. Here we examine this scenario using direct N-body computations of moderately-massive star clusters (of order $10^4 M_\odot$). As a preliminary attempt, these models are initiated with $\approx 8 - 10$ Gyr old stellar population and King profiles of high concentrations, being "tuned" to undergo core collapse quickly. BSSs are indeed found to form in a "burst" at the onset of the core collapse and several of such BS-bursts occur during the post-core-collapse phase. In those models that include a few percent primordial binaries, both collisional and binary BSSs form after the onset of the (near) core-collapse. However, there is as such no clear discrimination between the two types of BSSs in the corresponding computed CMDs. We note that this may be due to the less number of BSSs formed in these less massive models than that in actual globular clusters.

Key words. galaxies: star clusters: general – methods: numerical – stars: kinematics and dynamics

1. Introduction

Blue Straggler Stars (hereafter BSS) of a stellar ensemble are main-sequence (hereafter MS) stars that are located on the colour-magnitude-diagram (hereafter CMD) as an extension of the regular MS, beyond its turn-off point. The most natural explanation for this stellar sub-population is that they are stars with rejuvenated hydrogen content so that they are still on the MS despite being more massive than the turnoff mass. There are two primary channels considered for this rejuvenation and mass gain, namely, (a) direct stellar collisions (Hills & Day 1976) and (b) mass transfer in a binary (Hurley et al. 2001, 2005). Being distinctly identifiable in the CMD and being more massive than the average stellar population, BSSs serve as excellent tracers of dynamical processes in open and globular clusters (Mathieu & Geller 2009; Ferraro et al. 2009); especially their radial profile, as governed by their mass segregation, serves as a "dynamical clock" for globular clusters (Ferraro et al. 2009).

The focus of this study is another remarkable feature of the BSSs, namely, the existence of a double sequence of BSSs in several globular clusters. Perhaps the best example of this is the BSSs' double sequence observed in the globular cluster M30 (Ferraro et al. 2009); another vivid example is that of the globular NGC 362 (Dalessandro et al. 2013). An intriguing explanation for this is the recent core collapse of the parent cluster that triggers both of the formation channels simultaneously so that the "red" sequence comprise binary (masstransferring) BSSs and the "blue" sequence comprise the collision products (Ferraro et al. 2009). Indeed, the presence of a central cusp in the density profile of M30 does indicate its post core collapse state (Ferraro et al. 2009). More recent and detailed study of mass transfer in binary evolution models only strengthens this notion and constrain the types of binaries that make up the red sequence (Xin et al. 2015). Generally, the red BSSs are found to be more centrally concentrated than the blue ones.

Motivated by the above possibility, the objective of the present work is to study the BSS formation following core collapse (Spitzer 1987; Heggie & Hut 2003) of a model star cluster. To allow the stars to collide "naturally" (*i.e.*, without any constructed collision-triggering procedure), a direct N-body approach is followed. This is for the first time stellar collisions and BSS formation following core collapse (or, speaking more generally, during the central energy-generation phase of a cluster; Spitzer 1987) is studied explicitly.

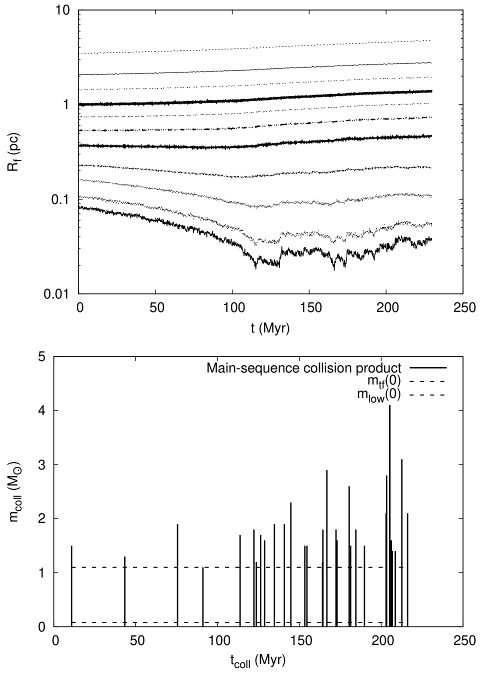

Fig. 1. The Lagrangian radii (top) and the time sequence of formation of MS collision products (bottom) for the computation with $M_{cl}(0) \approx 1.5\times10^4 M_\odot$, $W_0 = 7.5$ and $r_h(0) = 1$ pc with initially only single stars.

2. N-body calculations

To obtain a prompt but clear core collapse, systems with a moderate number, N, of stars and having high central concentration needs to be evolved — that way one "tunes" a cluster for core collapse. In this work, clusters initially with masses, $M_{cl}(0)$, between $1 - 3 \times 10^4 M_\odot$ following $W_0 = 7.5$ King (1962) density profiles and of half-mass radius $r_h(0) \approx 1$ pc are computed. Such concentrations are common in present-day Galactic and Local-Group globulars. To mimic an old stellar population like in globular clusters, low-mass stars between $0.1 - 1.0 M_\odot$ with a Kroupa (2001) mass function is assumed, which are pre-evolved for $\approx$ 8.8 Gyr (this corresponds to the "turn-off" age of $1.0 M_\odot$ stars at solar metallicity, when the giant branch on the CMD is just appearing). Such models are computed both with initially single stars and with $\approx$ 5% binaries following a Duquennoy & Mayor (1991) period distribution. No initial mass segregation is assumed as consistent with what is typically observed in globulars. All the N-body runs are done using the `NBODY7` code (Aarseth 2012; Nitadori & Aarseth 2012).

3. Results

Fig. 1 (top panel) shows the evolution of the Lagrangian radii of such a computed model with $M_{cl}(0) \approx 1.5 \times 10^4 M_\odot$ without initial binaries. The occurrence of core collapse is indicated by the abrupt halting of the inner region of the cluster, followed by a slow expansion. The high central density at and after the collapse boosts collisions among stars which can be called a "burst"; Fig. 1 (bottom) shows the timeline for collisions occurring among MS stars where BSSs are those whose final mass (Y-axis) exceeds the turn-off mass (upper horizontal line).

Fig. 3 shows the corresponding computed CMDs at t = 0 Myr and $t \approx$ 165 Myr evo-

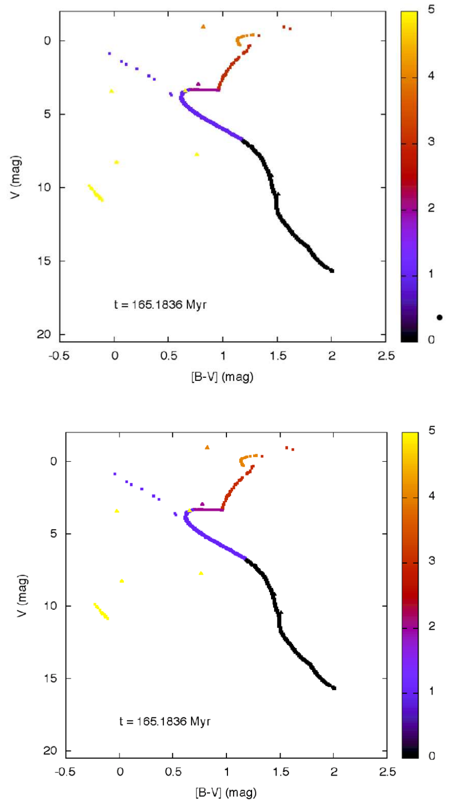

Fig. 2. CMDs corresponding to the calculation in Fig. 1. The colour coding represents the different stellar-evolutionary stages where 0=lower MS, 1=upper MS, 2=subgiant, 3=red giant, etc. A filled square indicates a single star and a filled triangle implies a binary (combined magnitudes used).

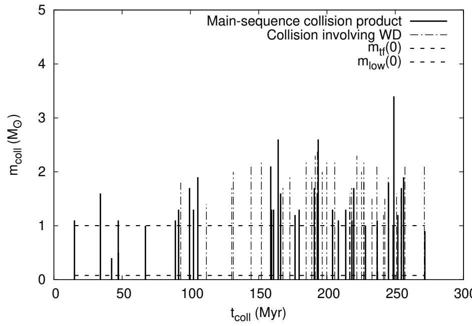

Fig. 3. Collision timeline for the calculation with $M_{cl}(0) \approx 3.0 \times 10^4 M_\odot$, $W_0 = 7.5$ and $r_h(0) = 1$ pc with initially only single stars.

lutionary time, which are obtained from the simulation data using a slightly modified version of the `GalevNB` program (Pang et al. 2016). The BSS formation rate from stellar collisions is much higher after the core collapse (*c.f.* Fig. 1) owing to the high central density and the rapid mass segregation (at least locally, close to the cluster's center) of the most massive (MS) stars that occurs nearly simultaneously to the collapse. The mass segregation is important here without which there would not have been the marked increase of BSS formation right after the collapse. Some BSSs as well get ejected from the cluster due to dynamical interactions; this is likely as they are the most massive members of the cluster and therefore are most likely to participate in close encounters. The above condition is to some extent fine tuned as the most massive member ($\approx 1.0 M_\odot$) is chosen to be at the MS turn-off point by adjusting the stellar pre-evolution age. This has also made the cluster initially free of white dwarfs (WDs) which can be more than or similarly massive as the turn-off mass and might suppress the collision rate of MS stars close to the turn-off, that generates the BSSs. To examine the role of the WDs, a $M_{cl}(0) \approx 3.0 \times 10^4 M_\odot$ cluster (no initial binaries) is computed with $0.08 - 8.0 M_\odot$ stars which are pre-evolved for ≈ 10 Gyr; that gives $\approx 1 M_\odot$ turn-off mass and a large number of WDs. Although the collisions between between WDs and MS stars (resulting in red giants and AGBs) are frequent in this calculation, BSSs continue to form and its rate boosts after the core collapse. This is demonstrated in Fig. 3.

In one final demonstration, a $M_{cl}(0) \approx 1.5 \times 10^4 M_\odot$ cluster with $\approx 5\%$ binaries (see Sec. 2) is computed. The corresponding CMD after $t \approx 143$ Myr evolution is shown in Fig. 3. A hint of double BSS sequence is apparent although the number of BSSs in the red sequence is much less than that in the blue sequence. On closer inspection of the computation, it is found that both the binaries in the red sequence contain a BSS and a red giant in a close binary having

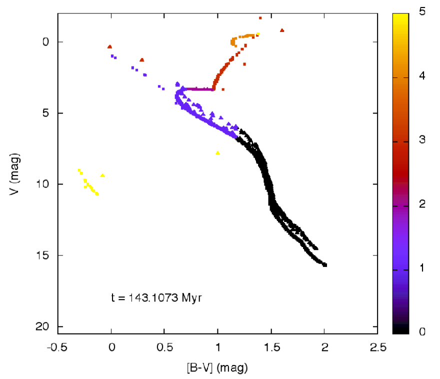

Fig. 4. The CMD at $t \approx 143$ Myr evolution for the calculation with $M_{cl}(0) \approx 3.0 \times 10^4 M_\odot$, $W_0 = 7.5$ and $r_h(0) = 1$ pc with initially $\approx 5\%$ binaries. The meanings of the symbols and the colours are same as in Fig. 3.

residual eccentricity. This indicates a recent dynamical origin of these involving encounters with the giant's envelope. This is consistent with what has been envisaged so far. However, given that only two of such binaries plus a third MS-MS binary (close to the MS turn-off; see Fig. 3) define the red BSS sequence in this computed model, this is only a marginal case of formation of a double BSS sequence. This double BSS sequence is found to last for ≈ 80 Myr, after which the binary BSSs evolve off. Computations of more massive clusters would potentially provide more concrete outcomes. The radial distribution of the BSSs in the model with primordial binaries is also inspected where the members of the red BSS sequence is found to be radially more concentrated then the blue ones, as observed. Again, given that there are only three red members, this comparison is only marginal. Interestingly, in the computations without any initial binaries, the BSSs are much more centrally concentrated than their counterparts in the model with binaries — the super-elastic encounters involving binaries (Heggie & Hut 2003) and the resulting kicks make the BSSs more radially spread out in the latter case.

4. Conclusions and outlook

From the above preliminary study suggest that:

- A "burst" of BSSs appears when an old (GC-like) cluster approaches core collapse. This is true despite the presence of primordial binaries (of a few percent) and a significant population of white dwarfs, as long as "some form of" core collapse happens.
- BSSs continue to form (and evolve/get ejected) during post core collapse phase.
- A "second" binary BSS sequence can appear in the presence of primordial binaries which are typically outcomes of recent dynamical interactions.
- Primordial binaries also seem to determine the radial distribution of BSS.

Computing more massive models with primordial binaries is necessary to consolidate the above results and to better understand the properties of post core collapse BSSs, which will be the forthcoming step of this study.

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