Mem. S.A.It. Vol. 87, 483

Memorie della

The origin of the two populations of blue stragglers in M30

S. Portegies Zwart and A. Rimoldi

Leiden Observatory, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, Netherlands e-mail: spz@strw.leidenuniv.nl

Abstract. We analyze the two populations of blue stragglers in the globular cluster M30. One population of *blue* blue stragglers is concentrated along the zero-age main-sequence of the cluster isochrone whereas the other (red) population is elevated in brightness (or color) by $\sim$ 0.75 mag. Based on stellar evolution and collision simulations we argue that the red population is formed between 2 and 10 Gyr ago, at a net constant rate of $\sim$ 2.8 blue stragglers per Gyr. The blue population is formed over the last 3.2 Gyr but at two distinct rates. About $\sim$ 60 % of this population is formed in a burst that started 3.2 Gyr ago and has a power-law decay with a time scale of 0.9 Gyr, whereas 40% of this population of formed at a constant rate of $\sim$ 1.8 Gyr^{-1}. We argue that the burst resulted from the core collapse of the cluster at an age of about 9.8 Gyr, whereas the constantly formed population is the result of mass transfer and mergers through binary evolution. In that case about half the binaries in the cluster effectively result in a blue straggler.

Key words. stars: kinematics and dynamics – methods: numerical

1. Introduction

The population of blue stragglers (Sandage 1953) in M30 appear to be split in two distinct populations (Ferraro et al. 2009, F09). One population along and near the zero-age main sequence (which F09 call the blue population) and a second (red) population that is brighter by about 0.75 mag. Both populations are centrally concentrated. The majority (90%) of *blue* blue stragglers and all *red* blue stragglers are within the projected half-mass radius of the cluster. F09 conjecture that both populations ware formed only 1-2 Gyr ago in a relatively short bursts instead of the continuous formation process. They further argue that the blue population resulted from stellar collisions, and the majority of the red population (60 %) has been attributed to binary mass transfer (Xin et al. 2015). We test these hypotheses by conducting a series of stellar collision calculations in order to reconstruct the collisional history of the star cluster. We adopt the hypothesis that a blue straggler is the product of a merger between two stars that merged to a single star (with mass $M_{\rm bss}$) at some moment in time $t_{\rm merge}$. Such a merger can either result from a direct collision during the dynamical evolution of the star cluster or from an unstable phase of mass transfer (Bailyn 1992, F09), we do not make a distinction in our models between these two scenarios. The moment of collision is determined by finding a collision product that is consistent with the blue straggler's position in the Hertzsprung-Russel diagram. For this we evolve two stars to the anticipated moment of collision t_{merge}. After applying a stellar merger model we continue the evolution of the merger product up to 13 Gyr, which corresponds to the age of the cluster (Harris 1996).

2. The experimental setup

We adopted the `MESA` Henyey stellar evolution code (Paxton et al. 2011) to model the evolution of the stars with [Fe/H]= −1.9, which is consistent with the cluster's metallicity). Both stars are initialized at the zero-age main-sequence and evolved to t_{merge}. At that moment we merge the two stars using Make-Me-A-Massive-star (Gaburov et al. 2008), which uses Archimedes' principle to calculate the structure of the star resulting from a merger between two stars. After this we continue to evolve the merger product using `MESA` to the age of the cluster M30. The numerical setup is realized with the Astronomical Multipurpose Software Environment (AMUSE, Pelupessy et al. 2013). Our analysis is comparable with the method described in Lombardi et al. (2002), but then our procedure is completely automated. We tentatively limit ourselves to head on collisions, such a described in Sills et al. (1997) because off-center collisions do, except from some additional mass loss, not seem to result in qualitative differences in the collision product (Sills et al. 2001). We initialize a grid of primary masses between 0.5 $M_\odot$ and the turn-off mass of 0.85 $M_\odot$ in steps of 0.05 $M_\odot$ and secondary masses between 0.2 $M_\odot$ with the same upper limit in steps of 0.005 $M_\odot$. The collision time is chosen between 0.1 Gyr and the age of the cluster with steps of 0.98 Gyr. The evolutionary state of the merger product at any time after the collision is predominantly determined by the total mass of the merger product m_{bss}. Small variations in the mass lost during the collision therefore have little effect on our determination of the collision time, because the location in the Hertzsprung-Russel diagram then depends on the total mass of the merger product and the moment of collision, rather than on the masses of the two stars that participate in the merger.

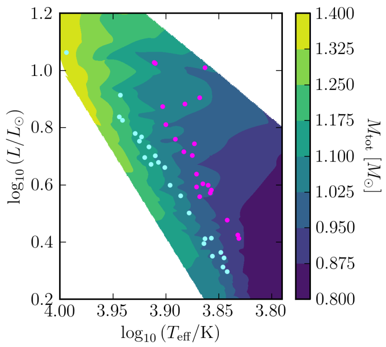

Fig. 1. Hertzsprung-Russel diagram of the M30 blue stragglers. The original data is from Ferraro 2015, but this was convoluted to the temperature-luminosity plane. With effective temperature and luminosity from Ferraro et. al. 2009. The *blue* and *red* blue stragglers are indicated as such. The solid curve is the isochrone at 13 Gyr.

3. Results

The Hertzsprung-Russel diagram of the blue stragglers is presented in Fig. 1. Over plotted in in color is the total mass of the collision products that remain on the main-sequence until an age of 13Gyr. A similar analysis was carried out in Rimold et al. (2016), who conclude that the moment of the collision and the mass of the collision product are well determined for the post-collision evolution of the merger product. Information about the masses of the two stars is largely lost in the merger process, and can hardly be used for diagnostics (see also Lombardi et al. 2002). We therefore use the total blue straggler mass and the collision time as a diagnostic tool. In fig. 2 we present the same data as in fig. 1, but now over plotted in color is the time since collision. The lightest shades indicate the most recent collisions. The *blue* blue stragglers tend to cluster around a time since collision between 2 Gyr and 4 Gyr, whereas the *red* blue stragglers span a much wider range of collision times. We quantify this statement in figs. 3, where we present the cumulative distribution of collision times for the blue and *red* blue stragglers together (colors) and separately (solid curves). We fitted both distribution with a constant blue straggler formation rate combined with a burst and exponential decay. The

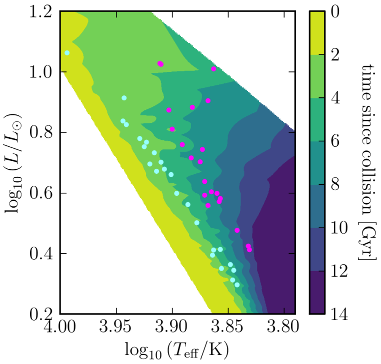

Fig. 2. Same as Fig. 1, except for the time since collision, which is color coded here.

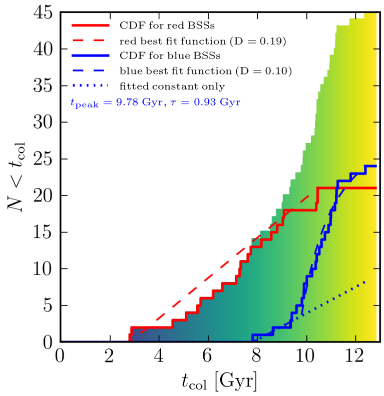

Fig. 3. The cumulative distribution of collision times for all the blue stragglers (blue plus red as the color shaded area where the color corresponds to that in Fig. 2). The solid blue and solid red curves give the cumulative distribution for the blue and *red* blue stragglers, respectively. The dashed and dotted blue curves give the two-line fit to the *blue* blue stragglers (the dotted curve gives the linear fit and dashes give the summ of the exponential and linear curves). The red dashed curve gives the linear fit to the *red* blue stragglers.

best fits are obtained using the Nelder-Mead simplex optimization (Nelder & Mead 1965) to find the minimum Kolmogorov–Smirnov (KS) statistic over the free parameters $t_{\rm merge}$, and e-folding time scale τ, in combination with a line describing the constant formation rate. The best fit (with KS statistics $D = 0.10$) to the *blue* blue stragglers is obtained for $t_{\rm merge} = 9.8$ Gyr, $\tau = 0.93$ Gyr with a peak formation rate of 30 blue stragglers per Gyr and an additional constant formation rate of 1.8 ± 0.6 per Gyr. Fitting the *red* blue straggler formation rate with the same set of functions (a constant rate plus a power-law) did not result in a satisfactory fit, but a single linear formation rate did produce the KS statistic of $D = 0.19$ with a constant formation rate of only 2.8 ± 0.5 per Gyr between 4 Gyr and 10 Gyr. It is interesting to note that the formation rate for the red population levels off when the blue population reaches is maximum rate.

Interpretation The majority of blue stragglers in star clusters are thought to originate from either stellar collisions (Leonard 1989) or from mass transfer in a close binary system (Collier & Jenkins 1984). We will argue here that the two distinct populations found in M30 can be attributed to these different formation channels. We argue that the red population is consistent with being formed continuously and through mass transfer and mergers in binary systems, whereas the blue population is mainly the result of collisions during the core collapse of the star cluster. In that perspective we attribute the burst population to the collision scenario, whereas the continuously formed population is the result from binary evolution.

The burst population According to our analysis about one third (15) of the blue stragglers in M30 are formed in a rather short burst that started at 9.8 Gyr with power-law decay with a characteristic time scale of 0.9 Gyr. At the peak the blue stragglers in the burst formed at a rate of about 30 blue stragglers per Gyr. But due to the exponential we adopted (and satisfactorily fitted) this burst lasts only a short while, long enough to produce some 20 blue stragglers. We estimate the expected formation rate through stellar collisions in a phase of core collapse by calculating the collision rate. The collision rate in a star cluster with number density n and velocity dispersion v is $\Gamma_{\rm coll} = n\sigma v$, using the approximate gravitational-focused cross-section $\sigma = rv^2$.

Here $v \equiv v/v_\infty$ is the stellar velocity dispersion as fraction of the stellar escape speed (Binney & Tremaine 1987). Davies et al. (2004) derived a formation rate of blue stragglers for a star cluster through direct stellar collisions, using the above arguments. We can adopt their eq.4 to calculate the expected number of blue stragglers formed through collisions. By adopting the observed cluster parameters ($n \simeq 3.8 \cdot 10^5 \mathrm{pc}^{-3}$, $N = 1.6 \cdot 10^5$ stars, $r_{\rm core} \simeq 0.2$ pc and adopting a mean stellar mass of $0.5\,M_\odot$) we then arrive at an average blue straggler production rate through collisions of $20\,\mathrm{Gyr}^{-1}$.

The continuously formed blue stragglers

Mass transfer in binary systems are less likely to depend strongly on the cluster core density because binaries are present in the halo as well as in the cluster center, which causes them to be more homogeneously distributed across the cluster (Hut et al. 1992), whereas direct stellar collisions are predominantly occurring at the very center of the cluster. The binary collision rate is also not expected to be particularly affected by the cluster density profile. We therefore argue that the constant rate is a result of binary mass transfer and coalescence. We can constrain the underlying binary semi-major axis distribution and mass ratio distribution in order to produce a constant blue straggler formation rate (or a constant mass-transfer initiation rate). Mass transfer in a binary system is typically initiated by the primary star, which overfills its Roche lobe when it either ascends the giant branch or, for very tight binaries, along the main sequence. Since the time scale between the terminal-age main-sequence and the post-AGB phase is only a small fraction ($\lesssim 0.15$) of the main-sequence lifetime, we adopt the main-sequence lifetime as the limiting factor between zero age and the stars of Roche-lobe overflow. The lifetime of a main-sequence star $t_{\rm ms} \propto m^{2.5}$ (Spitzer 1962). A primary mass distribution of $f(m) \propto m^{-2.35}$ (Salpeter 1955) therefore would produce a roughly constant rate at which stars leave the main sequence, consistent with the observed constant blue straggler formation rate. M30 has a binary fraction of about 3% (Romani & Weinberg 1991), so with $1.6 \cdot 10^5$ stars the cluster has 4800 binaries. A standard Salpeter mass function has about 5.8% of the stars between $0.5\,M_\odot$ and $\sim 0.85\,M_\odot$. For a $0.5\,M_\odot$ star requires an equal mass secondary star to evolve into a blue straggler in an unstable phase of mass transfer, whereas a $0.85\,M_\odot$ star only requires a very low mass companion. On average about half the binaries in the appropriate mass range then produce blue stragglers, totaling the potential number of blue stragglers of 280. Roughly half of these binaries have a total mass that upon a merger results in a blue straggler. Binary separations range from a few $R_\odot$ and a maximum of 10^4 AU at the Heggie limit for hard-soft binaries (Heggie 1975). Roche lobe overflow on the main-sequence is most favorable for the formation of blue straggler, which is only applicable for binaries with an orbital separation $\lesssim 10\,R_\odot$, and with a flat distribution in the logarithm of the semi-major axis (Zinnecker et al. 2004) only about one in four binaries will be effectively producing a blue straggler (Chen & Han 2009). The entire binary reservoir then produces ~ 35 blue stragglers through mass transfer or coalescence.

4. Discussion

The 13 Gyr–old globular cluster M30 has a rich population of blue stragglers, which appear to be distributed bimodially in the Hertzsprung-Russel diagram. We tested the hypothesis that all these blue stragglers are the result of some form of quick mass transfer in a binary system or due to a stellar collision. We therefore simulate the formation of a blue straggler as the collision between two stars with a total mass of $M_{\rm merger}$, which are evolved to some merger time $t_{\rm merge}$ to the age of the cluster. For each point in the Hertzsprung-Russel diagram we then obtain a unique solution for the mass of the blue straggler and the moment of merger. The two masses of the stars that merge are not well discriminated in the results, because the memory of the two stellar masses is mainly lost in the collision process. The collision time distribution for the *blue* blue stragglers is best described by a constant formation rate of $1.8\,\mathrm{Gyr}^{-1}$ between 8 Gyr and the age of the cluster, superposed with an exponential decay with a peak of $\sim$ 30 Gyr^{-1} at $t_{\rm merge}$ = 9.8 Gyr with an e-foulding time scale of 0.93 Gyr. The population of *red* blue stragglers is best described with a constant formation rate of 2.8 Gyr^{-1} between an age of 2 Gyr and 10 Gyr. We interpret the this bimodal distribution of blue straggler formation with the two distinct channels in which they form. The continuously formed population is consistent with originating from mass transfer in primordial binaries. In that case about 10-15% of any binary leads to the formation of a blue straggler. The exponential decay is suggestively the result of the core collapse of the star cluster, whereas the constant formation of blue stragglers is the result of the natural global evolution of the cluster, possibly from binary mass transfer. The *blue* blue stragglers then have a contribution from the collision produced as well as from those formed through binary evolution, whereas the red population is almost exclusively produced via the latter channel. We attribute the start of the blue straggler formation burst to the moment of core collapse in the star cluster, at an age of 9.9 Gyr, which is consistent with the inverse cluster evolution analysis of Pijloo et al. (2015). In an independent reconstructing the evolution of M30 by means of Markov-Chain Monte Carlo simulations, she conclude that M30 has experience core collapse at an age of about 9.5 ± 0.4 Gyr, which is consistent with the start of the blue straggler formation burst (Pijloo, private communication). We therefore tentatively suggest that the core collapse of the cluster was associated with a burst in the formation of blue stragglers. The exponential decay is a result of the relatively extended period during which the cluster remains in a collapsed –or semi-collapsed– state following the primary collapse (Heggie & Ramamani 1989). This could indicate a prolonged period of gravothermal oscillations following the primary collapse of the cluster core (Heggie et al. 1994). We argue that this phase lasted for about a Gyr. This would bring the cluster in a relatively low-density post-collapse evolutionary state today.

Acknowledgements. We are grateful to Francesco Ferraro who provided us with the data on the blue stragglers in M30, and for organizing the conference on blue stragglers, during which this paper was written. We further like to thank Tjibaria Pijloo for providing us the reconstructed core-collapse data for M30. This work was supported by the Netherlands Research Council (NWO grant numbers 612.071.305 [LGM] and 639.073.803 [VICI]), by the Netherlands Research School for Astronomy (NOVA) by the Interuniversity Attraction Poles Programme (initiated by the Belgian Science Policy Office, IAP P7/08 CHARM) and by the European Union's Horizon 2020 research and innovation programme under grant agreement No 671564 (COMPAT project).

References

Bailyn, C. D. 1992, ApJ, 392, 519
Binney, J. & Tremaine, S. 1987, Galactic dynamics (Princeton Univ. Press, Princeton, NJ)
Chen, X. & Han, Z. 2009, MNRAS, 395, 1822
Collier, A. C. & Jenkins, C. R. 1984, MNRAS, 211, 391
Davies, M. B., et al., 2004, MNRAS, 349, 129
Ferraro, F. R., et al. 2009, Nature, 462, 1028
Gaburov, E. et al., 2008, MNRAS, 383, L5
Harris, W.E. 1996, AJ, 112, 1487
Heggie, D. C. 1975, MNRAS, 173, 729
Heggie, D. C., et al. 1989, MNRAS, 237, 757
Heggie, D. C., et al. 1994, MNRAS, 271, 706
Hut, P. et al., 1992, ApJ, 389, 527
Knigge, C., et al. 2009, Nature, 457, 288
Leonard, P. J. T. 1989, AJ, 98, 217
Lombardi, J. C., et al. 2002, ApJ, 568, 939
Nelder, J. & Mead, R. 1965, The Computer Journal, 7, 4
Paxton, B., et al. 2011, ApJS, 192, 3
Pelupessy, F. I., et al. 2013, A&A, 557, A84
Pijloo, J. T., et al. 2015, MNRAS, 453, 605
Rimoldi, A., et al. 2016, submitted to MNRAS
Romani, R. W., & Weinberg, M. D. 1991, in The Formation and Evolution of Star Clusters, ed. K. Janes (ASP, San Francisco), ASP Conf. Ser., 13, 443
Salpeter, E. E. 1955, ApJ, 121, 161
Sandage, A. R. 1953, AJ,58, 61
Sills, A., et al. 1997 ApJ, 487, 290
Sills, A., et al. 2001, ApJ, 548, 323
Spitzer, L. 1962, Physics of Fully Ionized Gases (Interscience Publ., New York)

Xin, Y., et al. 2015, ApJ, 801, 67
Zinnecker, H., Köhler, R., & Jahreiß, H. 2004, Rev. Mex. Astron. Astrofis. Conf. Ser., 21, 33