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Francesco R. Ferraro, Giacomo Beccari, Emanuele Dalessandro, Barbara Lanzoni ...+6 more authors

Institutions: University of Bologna, McMaster University, University of Virginia, INAF

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LETTERS

Two distinct sequences of blue straggler stars in the globular cluster M 30

F. R. Ferraro[1], G. Beccari[2], E. Dalessandro[1], B. Lanzoni[1], A. Sills[3], R. T. Rood[4], F. Fusi Pecci[5], A. I. Karakas[6], P. Miocchi[1] & S. Bovinelli[1]

Stars in globular clusters are generally believed to have all formed at the same time, early in the Galaxy's history[1]. 'Blue stragglers' are stars massive enough[2] that they should have evolved into white dwarfs long ago. Two possible mechanisms have been proposed for their formation: mass transfer between binary companions[3] and stellar mergers resulting from direct collisions between two stars[4]. Recently the binary explanation was claimed to be dominant[5]. Here we report that there are two distinct parallel sequences of blue stragglers in M 30. This globular cluster is thought to have undergone 'core collapse', during which both the collision rate and the mass transfer activity in binary systems would have been enhanced[6]. We suggest that the two observed sequences are a consequence of cluster core collapse, with the bluer population arising from direct stellar collisions and the redder one arising from the evolution of close binaries that are probably still experiencing an active phase of mass transfer.

To investigate the blue straggler star (BSS) content in M 30, we used a time series of 44 high-resolution images obtained with the NASA Hubble Space Telescope (Supplementary Information). The colour–magnitude diagram (CMD) derived by combining data from these images has revealed the existence of two well-separated and almost parallel sequences of BSSs (hereafter 'red BSSs' and 'blue BSSs'; Fig. 1). The two sequences are similarly populated, consisting of 21 and 24 stars, respectively.

The detected BSSs are substantially more concentrated towards the cluster centre than are 'normal' cluster stars, either along the subgiant branch or the horizontal branch (Fig. 2a). According to a Kolmogorov–Smirnov test, the probability that the BSSs and the subgiant- or horizontal-branch populations are drawn from the same distribution is only $\sim 10^{-3}$ (that is, they differ at a significance level of more than 4σ). This result confirms that BSSs are more massive[2] than the majority of the cluster stars and that mass segregation has been active in this cluster. Moreover, when we consider the distribution of the two BSS subpopulations separately, we find that the red BSSs are more centrally segregated than are the blue BSSs. Indeed, no red BSSs are observed at an angular distance of $r > 30$ arcsec (corresponding to ~1.3 pc; see Supplementary Table 1) from the cluster centre (Fig. 2a). Even though in this case the level of significance (1.5σ) is marginal because of the small number of objects, this evidence is suggestive of different formation histories for BSSs belonging to the two sequences. Furthermore, whereas the radial distribution of BSSs in many clusters is found to be bimodal[7] (with a dominant peak at the centre, a dip at intermediate radii and a rising branch in the outer regions), in the case of M 30 there is no evidence of an increase at large distances from the centre: more than 80% of the entire BSS population is confined within the inner 100 arcsec (~4.2 pc), and the radial distribution then is nearly constant

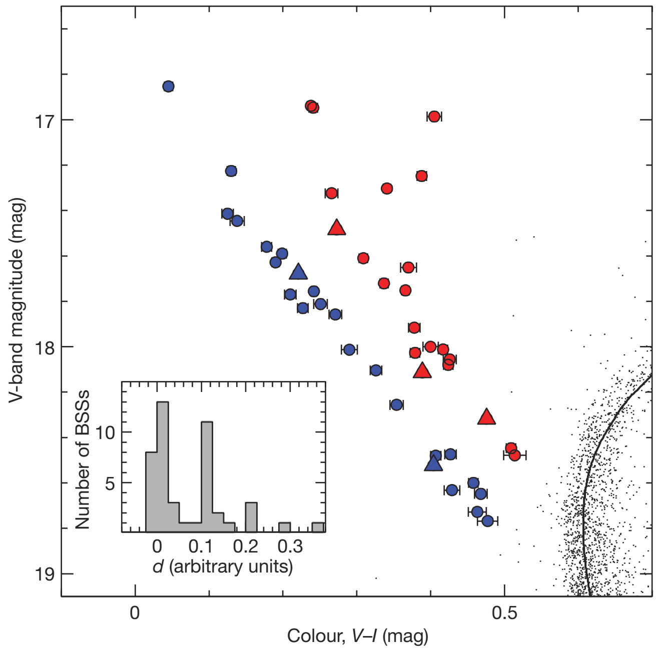

Figure 1 | The two blue straggler sequences of M 30. BSS region of the (V, $V-I$) CMD. The selected BSSs are plotted as circles, with the red and blue colours distinguishing the red and the blue BSS sequences, respectively. A series of 44 images (22 in each filter), made using the Hubble Space Telescope's Wide Field Planetary Camera 2 (WFPC2) through the F814W (I band) and the F555W (V band) filters, has been analysed using point-spread-function-fitting photometry[21,22]. Errors (1 s.e.m.) in magnitude and colour have been computed from repeated measurements and are also plotted (they are typically less than 0.01 mag; in most cases the error bars are smaller than the point size). The two sequences are separated in magnitude by $\Delta V \approx 0.4$ mag and in colour by $\Delta(V-I) \approx 0.12$ mag. Using these time series, we have tested the variability of the selected BSSs and found five candidate variables (triangles): on the basis of the light-curve characteristics, the three brightest variables have been classified[23] as W Ursae Majoris (W UMa) contact binaries. The two faintest candidates have quite scattered light curves that prevent a reliable classification. W UMa stars are binary systems losing orbital momentum as a result of magnetic braking. These shrinking binary systems, which are initially detached, evolve to the contact stage and finally merge into a single star. The evolution of W UMa systems is thought to be a viable channel for the formation of BSSs[20,24]. Inset, distribution of the geometrical distances, d, of the selected BSSs from the straight line that best fits the blue BSS sequence. Two well-defined peaks are clearly visible. A dip test[25] applied to this distribution demonstrates that it is bimodal at a significance level of more than 4σ, confirming that the two sequences are nearly parallel to each other.

[1]Department of Astronomy, University of Bologna, Via Ranzani 1, 40127 Bologna, Italy. [2]ESA, Space Science Department, Keplerlaan 1, 2200 AG Noordwijk, Netherlands. [3]McMaster University, Department of Physics and Astronomy, 1280 Main Street West, Hamilton, Ontario L8S 4M1, Canada. [4]Astronomy Department, University of Virginia, PO Box 400325, Charlottesville, Virginia 22904, USA. [5]INAF, Osservatorio Astronomico di Bologna, Via Ranzani 1, 40127 Bologna, Italy. [6]Research School of Astronomy and Astrophysics, Mt Stromlo Observatory, Weston Creek, Australian Capital Territory 2611, Australia.

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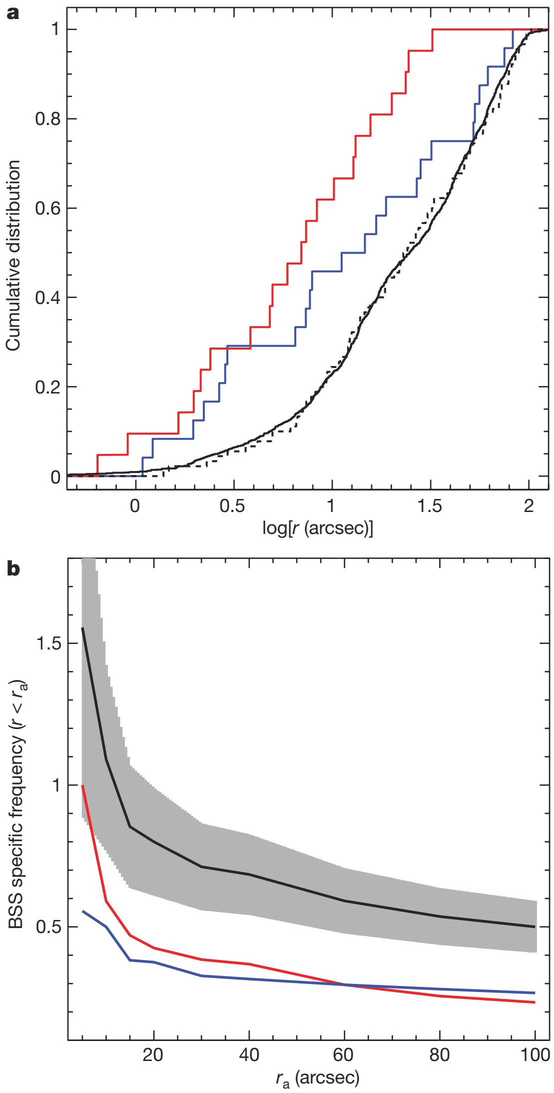

Figure 2 | The BSS radial distribution. **a**, Cumulative radial distributions of red BSSs (red line) and blue BSSs (blue line), as functions of the projected distance, r, from the cluster centre of gravity. The distributions of subgiant-branch stars (solid black line) and horizontal-branch stars (dashed black line) are also plotted, for comparison. **b**, BSS specific frequency computed in circular areas of increasing radius r_a. The lines correspond to the overall BSS population (black) and to the red BSS (red) and blue BSS (blue) subpopulations separately. The grey area around the black line shows the 1σ uncertainty in the specific frequency. BSSs are substantially more numerous than horizontal-branch stars in the cluster centre. Although the small number of stars in the sample prevents statistical robustness in our results, we note that in the innermost 5–6 arcsec (~0.2 pc) the red BSSs tend to be as numerous as the horizontal-branch stars and dominate the ratio.

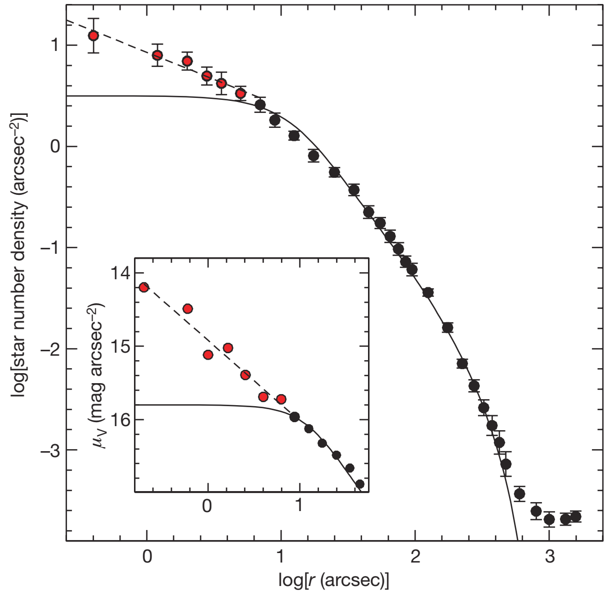

Figure 3 | The star density profile of M 30. Profile (errors, 1 s.e.m.) obtained from resolved star counts over the entire cluster extension: the WFPC2 data set was combined with Hubble Space Telescope Advanced Camera for Surveys data and with wide-field ground-based observations secured at the European Southern Observatory New Technology Telescope (La Silla Observatory, Chile) and the Canada–France–Hawaii Telescope MegaCam (Hawaii). The single-mass King model[26] that best fits the observed profile excluding the innermost ($r < 5$ arcsec) points is shown as a solid line. The points that deviate from the King model (red) are well fitted by a power law with slope $\alpha \approx -0.5$ (dashed line). Inset, surface brightness profile derived from the WFPC2 V-band images within the innermost 40 arcsec, with the two lines having the same meaning as above. The measured central surface brightness is $\mu_V \approx 14.2$ mag arcsec^{-2}. This value is significantly lower (corresponding to greater brightness) than that listed in currently used cluster catalogues[27], but is fully consistent with that obtained in most recent studies[28]. Following the procedure described in the literature[29] and assuming a distance of 8.75 kpc and a reddening of $E(B-V) = 0.03$ mag (ref. 16), we derive $\nu \approx 9.6 \times 10^4 L_\odot$ pc^{-3} for the luminosity density within the density cusp (that is, for $r < 5$ arcsec; $L_\odot$, solar luminosity). Under the assumption of a mass-to-light ratio of three and a mean stellar mass of $0.5M_\odot$, this corresponds to a star number density of $n \approx 5.8 \times 10^5$ pc^{-3} (Supplementary Table 1; $M_\odot$, solar mass). Both profiles were computed with respect to the newly determined cluster centre of gravity (Supplementary Table 1), which is located ~3 arcsec southeast of the centre listed in commonly used catalogues of globular-cluster parameters[27].

for greater radii. This suggests that dynamical friction has already affected a large portion of the cluster, with the result that almost the entire population of BSSs has sunk into the centre[8].

There is further evidence that M 30 is a highly evolved cluster from a dynamical point of view. The density profile has a steep power-law cusp in the central 5–6 arcsec (~0.2 pc; Fig. 3), suggesting that M 30 has already undergone core collapse (Supplementary Information)[9]. M 30's dynamically evolved state, combined with several suggestions[4,7,10,11] that cluster dynamics and BSS formation processes could be linked, indicates that the dual BSS sequence is probably connected to the cluster's dynamical history. In particular, during core collapse the central density rapidly increases, bringing a concomitant increase in gravitational interactions[6] able to trigger the formation of new BSSs through both direct stellar collisions and enhanced mass transfer activity in dynamically shrunk binary systems. When considering the entire population of detected BSSs (population size, $N_{BSS} = 45$) and horizontal-branch stars ($N_{HB} = 90$), the BSS specific frequency, $F^{BSS} = N_{BSS}/N_{HB}$, is equal to 0.5, a value not particularly high in comparison with that of other clusters[12]. However, the value of F^{BSS} varies significantly over the surveyed area, reaching ~1.55 when only the central cusp of the star density profile (5–6 arcsec) is considered (Fig. 2b). So far, this is the highest value measured for the BSS specific frequency in a globular cluster, and it further supports the possibility that in M 30 we are observing the effect of enhanced gravitational interactions on single and binary stars.

To investigate this possibility, we have compared the observations with the predictions of evolutionary models of BSSs formed by direct collisions between two main-sequence stars[13] with metallicities of $Z = 10^{-4}$ and masses ranging from between $0.4M_\odot$ and $0.8M_\odot$ (thus producing BSSs with masses of between $0.8M_\odot$ and $1.6M_\odot$). As shown in Fig. 4, the blue BSS sequence is well fitted by collisional isochrones corresponding to ages of 1–2 Gyr, with the brightest blue BSS being slightly less luminous than the collision product of two turn-off-mass stars ($0.8M_\odot + 0.8M_\odot$). The observed number of stars in the blue BSS sequence is in good agreement with the expected[14]

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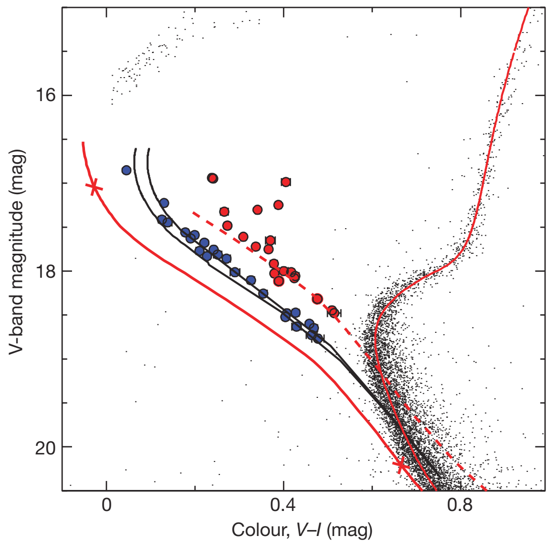

Figure 4 | Comparison with collisional and binary-evolution models. Magnified portion of the CMD of M 30. The solid black lines correspond to the collisional isochrones[13] corresponding to 1 and 2 Gyr, respectively, which accurately reproduce the blue BSS sequence. The solid red lines correspond to the single-star isochrones[15] respectively corresponding to 13 Gyr (well fitting the main cluster evolutionary sequences) and to 0.5 Gyr (representing the reference cluster zero-age main sequence (ZAMS)). The two crosses mark the respective positions of a $0.8M_\odot$ star and a $1.6M_\odot$ star along the ZAMS. The dashed red line corresponds to the ZAMS shifted by 0.75 mag, marking the position of the 'low-luminosity boundary' predicted[17] for a population of mass-transfer binary systems. This line well reproduces the red BSS sequence.

number of BSSs formed by direct collisions during the last 1–2 Gyr in a cluster with total absolute magnitude comparable to that of M 30 (Supplementary Table 1). Hence, we conjecture that 1–2 Gyr ago some dynamical process (possibly core collapse) produced the BSS population that is now observable along the blue BSS sequence. The origin of the red BSSs should be different, as this sequence is too red to be properly reproduced by collisional isochrones corresponding to any age. Figure 4 also shows the location in the CMD of single-star isochrones[15] computed for a metallicity of $Z = 2 \times 10^{-4}$ and shifted by the distance modulus and reddening of M 30[16]. The 13-Gyr single-star isochrone fits the main cluster evolutionary sequences quite well, whereas the BSS sequences are significantly offset with respect to the 0.5-Gyr single-star isochrone, which can be adopted as the cluster ZAMS. Of particular note is the fact that the red BSS sequence is ~0.75 mag brighter than the reference ZAMS. According to the results of recent binary-evolution models[17], during the mass-transfer phase (which can last several gigayears, that is, a significant fraction of the binary evolution timescale), a population of binary systems defines a low-luminosity boundary ~0.75 mag above the ZAMS in the BSS region (see fig. 5 of ref. 17). Hence, the BSSs that we observe along the red BSS sequence could be binary systems still experiencing an active phase of mass exchange.

As a result of normal stellar evolution, in a few gigayears both collisional and mass-transfer products will populate the region between the two sequences. The fact that we currently see two well-separated sequences supports the hypothesis that both the blue and the red BSS sequences were generated by a recent and short-lived event instead of a continuous formation process. A picture in which the two BSS sequences were generated by the same dynamical event is therefore emerging. As suggested by the shape of the density profile and by the location of the blue BSSs in the CMD, 1–2 Gyr ago M 30 may have undergone core collapse. This is known to increase the gravitational interaction rate significantly and it may therefore have boosted the formation of BSSs: the blue BSSs arise from direct stellar collisions, whereas the red BSSs are the result of the evolution of binary systems that first sank into the cluster centre because of dynamical friction (or were already present in the cluster core) and were then brought into the mass-transfer regime by hardening processes induced by gravitational interactions during core collapse. The detected double BSS sequence could be the signature imprinted onto a stellar population by core collapse, with the red BSS sequence being the outcome of the 'binary-burning' process expected to occur in the cluster core during the late stages of the collapse[18,19]. The proposed picture leads to a testable observational prediction: the red BSS sequence should be populated by binaries with short orbital periods.

A recent paper[5] suggested that the dominant BSS formation channel is the evolution of binary systems, independent of the dynamical state of the parent cluster. Our discovery shows that binary evolution alone does not paint a complete picture: dynamical processes can in fact play a major part in the formation of BSSs. An appropriate survey of the central regions of other core-collapsed clusters would help to clarify whether the double BSS sequence is a common signature of the core-collapse phenomenon. Moreover, detailed spectroscopic investigations are worth performing to obtain a complete characterization of the BSS properties (orbital periods, rotational velocities and so on). In this respect, particularly promising is the search for the chemical signature[20] of the mass-transfer process of the BSSs along the red sequence, even though these observations represent a challenge for the current generation of high-resolution spectrographs mounted at 8–10-m-class telescopes.

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Author Contributions F.R.F. designed and coordinated the study. G.B., E.D. and S.B. analysed the data. A.S. and A.I.K. developed collisional models. B.L. and P.M. computed the surface density profile and performed comparisons with a single-mass King model. F.R.F. and B.L. wrote the paper. F.F.P., A.S. and R.T.R. critically contributed to discussions on, and the presentation of, the paper. All the authors contributed to discussions of the results and commented on the manuscript.

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