Dynamical age differences among coeval star clusters as revealed by blue stragglers

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Globular star clusters that formed at the same cosmic time may have evolved rather differently from the dynamical point of view (because that evolution depends on the internal environment) through a variety of processes that tend progressively to segregate stars more massive than the average towards the cluster centre. Therefore clusters with the same chronological age may have reached quite different stages of their dynamical history (that is, they may have different ‘dynamical ages’). Blue straggler stars have masses greater than those at the turn-off point on the main sequence and therefore must be the result of either a collision or a mass-transfer event. Because they are among the most massive and luminous objects in old clusters, they can be used as test particles with which to probe dynamical evolution. Here we report that globular clusters can be grouped into a few distinct families on the basis of the radial distribution of blue stragglers. This grouping corresponds well to an effective ranking of the dynamical stage reached by stellar systems, thereby permitting a direct measure of the cluster dynamical age purely from observed properties.

We have analysed the entire database of blue straggler stars (BSSs) collected by our group for a sample of 21 globular clusters (see Supplementary Information). Such a data set contains clusters with nearly the same chronological age (12–13 Gyr (ref. 8); the only exception is Palomar 14, which formed ~10.5 Gyr ago) but with very different structural properties (and hence possibly at different stages of dynamical evolution). Although significant variations in the radial distribution of BSSs between clusters are already known, we have found that, when the radial distance is expressed in units of the core radius (to permit a meaningful comparison between the clusters), the BSS distributions seem surprisingly similar within distinct subsamples. These similarities are so striking that clusters can be efficiently grouped on the basis of the shape of their BSS radial distribution, and at least three distinct families can be defined. The observational panorama is summarized in Figs 1–3, in which the BSS distribution is compared with that of a reference population (typically red giants or horizontal-branch stars) whose radial distribution follows that of the cluster’s structural properties (and hence possibly at different stages of dynamical evolution). This is the most direct evidence that these stellar systems are dynamically unevolved, with mass segregation not yet being established even in the central regions. Our conclusions are further strengthened by the fact that essentially the entire radial extension is sampled by the analogous quantities for the sampled luminosity. Grey regions correspond to the double-normalized ratio measured for the reference population (red giants or horizontal-branch stars). Error bars and the width of the grey bands (σ) have been computed from the error propagation law, by assuming Poissonian number counts and a few per cent uncertainty in the fraction of sampled luminosity, respectively. For a meaningful cluster-to-cluster comparison, the distance from the centre (r) is expressed in units of the cluster core radius. Simple theoretical arguments demonstrate that the double-normalized ratio is equal to unity for any population (such as red giants and horizontal-branch stars) whose radial distribution follows that of the cluster’s integrated luminosity. In the three cases plotted here, BSSs show no evidence of mass segregation with respect to the reference population at any distance from the centre (note that essentially the entire radial extension is sampled by the observations). This is the most direct evidence that these stellar systems are dynamically unevolved, with mass segregation not yet being established even in the central regions. Our conclusions are further strengthened by the fact that a Centauri is not now considered to be a genuine globular cluster but instead the remnant of a dwarf galaxy; in fact, no signs of mass segregation are expected in collisionless systems.

Figure 1 | The radial distribution of BSSs in three dynamically young stellar systems (family 1). a, α Centauri; b, Palomar 14; c, NGC 2419. The double-normalized ratio of BSSs (R_BSS) is defined as $R_{\text{BSS}}(r) = \frac{N_{\text{BSS,rad}}(r)}{N_{\text{BSS,tot}}}/\frac{L_{\text{BSS,rad}}(r)}{L_{\text{BSS,tot}}}$, where $N_{\text{BSS}}(r)$ is the number of BSSs measured in any given radial bin, $N_{\text{BSS,tot}}$ is the total number of such stars, and $L_{\text{BSS,rad}}$ are the analogous quantities for the sampled luminosity. Grey regions correspond to the double-normalized ratio measured for the reference population (red giants or horizontal-branch stars). Error bars and the width of the grey bands (σ) have been computed from the error propagation law, by assuming Poissonian number counts and a few per cent uncertainty in the fraction of sampled luminosity, respectively. For a meaningful cluster-to-cluster comparison, the distance from the centre (r) is expressed in units of the cluster core radius. Simple theoretical arguments demonstrate that the double-normalized ratio is equal to unity for any population (such as red giants and horizontal-branch stars) whose radial distribution follows that of the cluster’s integrated luminosity. In the three cases plotted here, BSSs show no evidence of mass segregation with respect to the reference population at any distance from the centre (note that essentially the entire radial extension is sampled by the observations). This is the most direct evidence that these stellar systems are dynamically unevolved, with mass segregation not yet being established even in the central regions. Our conclusions are further strengthened by the fact that α Centauri is not now considered to be a genuine globular cluster but instead the remnant of a dwarf galaxy; in fact, no signs of mass segregation are expected in collisionless systems.

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LETTER

For the sake of clarity, the grey strips schematically represent the reference population distributions (which are shown in Supplementary Fig. 1 and in specific papers describing each individual cluster\(^{16,15,13,17,26,19}\)). The radial distributions of BSSs (large coloured symbols, 1σ errors) are clearly incompatible with that of the reference populations: they appear bimodal, with a well-defined peak in the cluster centre (testifying to a strong central segregation), a dip at intermediate radii (\(r_{\text{min}}\); see Supplementary Information) and a rising branch in the outskirts. Clusters have been grouped according to the value of \(r_{\text{min}}\) (thick arrows): from top to bottom, the minimum is observed at progressively larger distances from the centre. This radius marks the distance at which dynamical friction has already been effective in segregating BSSs towards the cluster centre. Hence, in contrast with those plotted in Fig. 1, these systems show evidence of dynamical evolution, progressively increasing from top to bottom. According to this interpretation, M53 and NGC 288 should be the dynamically youngest of the clusters of progressively increasing from top to bottom. According to this interpretation, M53 and NGC 288 should be the dynamically youngest of the clusters of intermediate dynamical age. Note that, in spite of its possible appearance, there is no correlation between the extent of the observations and the value of \(r_{\text{min}}\) in a few cases the most external point is not plotted (M53, 47 Tuc and M3) for the sake of clarity. Moreover, as a result of insufficient quality of data or strong contamination by Galactic field stars, the most external part of the radial distribution of BSSs is lacking in a few clusters (NGC 6388, M4 and NGC 6229). However, \(r_{\text{min}}\) is well detected in all cases and these drawbacks do not affect the conclusion of the paper.

orbits at larger and larger distances from the cluster centre are expected to drift towards the core and their radial distribution to develop a peak in the cluster centre and a dip (that is, a region devoid of these stars) that progressively propagates outwards. As the dynamical evolution of the system proceeds, the portion of the cluster where dynamical friction has been effective increases and the radial position of the minimum of the distribution (\(r_{\text{min}}\); see Supplementary Information) increases. In spite of the crude approximations, even a simple analytical estimate\(^{16}\) of the radius at which dynamical friction is expected to segregate 1.2\(M_\odot\) stars over the lifetime of the cluster has been found to be in excellent agreement with the observed value of \(r_{\text{min}}\) in a few globular clusters\(^{3,17}\). The progressive outward drift of \(r_{\text{min}}\) as a function of time is fully confirmed by the results that we obtained from direct N-body simulations that followed the evolution of 1.2\(M_\odot\) objects within a ‘reference’ cluster over a significant fraction of its lifetime (see Supplementary Information).

In view of these considerations, the families defined in Figs 1–3 correspond to clusters of increasing dynamical ages. The signature of the parent cluster’s dynamical evolution encoded in the BSS population has now been finally deciphered: the shape of the radial distribution of BSSs is a powerful indicator of dynamical age. A flat radial distribution of BSSs (consistent with that of the reference population, as found for family I in Fig. 1) indicates that dynamical friction has not yet had a major effect even in the innermost regions, and the cluster is still dynamically young. This situation is confirmed by observations of dwarf spheroidal galaxies: for these collisionless systems we do not expect dynamical friction to be efficient, and indeed no statistically significant dip in the distribution of BSSs has been observed\(^{16,19}\). In more evolved clusters (family II in Fig. 2), dynamical friction starts to be effective and segregates heavy objects that are orbiting at distances still relatively close to the centre; as a consequence, a peak in the centre and a minimum at small radii appear in the BSS distribution. Meanwhile, the most remote BSSs have not yet been affected by the action of dynamical friction (this generates the rising branch of the observed bimodal BSS distributions). Because the action of dynamical friction extends progressively to larger and larger distances from the centre, the dip of the distribution moves progressively outwards (as seen in the different groups of family II clusters). In highly evolved systems we expect that even the most remote BSSs were affected by dynamical friction and started to drift gradually towards the centre. As a consequence the external rising branch of the radial distribution disappears (as observed for family III in Fig. 3). All the clusters showing BSS distribution with only a central peak can therefore be classified as ‘dynamically old’. This class includes M30, a system that has already experienced core collapse\(^{20,21}\), which is considered to be a typical symptom of extreme dynamical evolution’ (see Supplementary Information).

The proposed classification is also able to shed light on several controversial cases that have been debated in the literature, thus further demonstrating the importance of a reliable determination of the cluster’s dynamical age. In fact, in contrast with previous studies\(^{22}\) suggesting that the core of M4 might have collapsed, we find that M4 belongs to a family of clusters of intermediate dynamical age. NGC 6752 turns out to be in a relatively advanced state of dynamical evolution, possibly on the verge of core collapse, as also suggested by its double King profile indicating that the cluster core is detaching from the rest of the cluster structure\(^{23}\). Finally, this approach might provide the means of discriminating between a central density cusp due to core collapse (as for M30)\(^{20}\) and that due to the presence of an exceptional concentration of dark massive objects (neutron stars and/or the long-sought and still elusive intermediate-mass black holes; see the case of NGC 6388 (ref. 24)).
the cluster centre, providing a measure of the overall dynamical evolution of the system. In fact, the relaxation timescales at specific radial distances from the cluster, measuring its dynamical age. Confirmation that this is indeed the case is provided by the tight correlations (see Fig. 4) obtained between the clock hand ($r_{\text{min}}$) and two theoretical estimates commonly used to measure the dynamical evolution timescales of a cluster, namely the central and the half-mass relaxation times, $t_{\text{c}}$ and $t_{1/2}$, respectively (see Supplementary Information), here expressed in units of the Hubble time ($t_{H}$). The best-fit relations to the data, \[
\log(t_{c}/t_{H}) = -1.11 \log(r_{\text{min}}) - 0.78 \quad (\text{r.m.s.} = 0.32) \\
\log(t_{1/2}/t_{H}) = -0.33 \log(r_{\text{min}}) - 0.25 \quad (\text{r.m.s.} = 0.23) \]
where r.m.s. is root mean square, can be assumed to be a preliminary calibration of the dynamical clock. Although $t_{c}$ and $t_{1/2}$ are indicative of the relaxation timescales at specific radial distances from the cluster centre, the dynamical clock here defined is much more sensitive to the global dynamical evolutionary stage reached by the system. In fact, the radial distribution of BSSs simultaneously probes all distances from the cluster centre, providing a measure of the overall dynamical evolution and a much finer ranking of dynamical ages. In the near future more realistic N-body simulations will provide a direct calibration of $r_{\text{min}}$ as a function of the cluster’s dynamical age in billions of years.

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Supplementary Information is available in the online version of the paper.

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