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 a 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[1]. 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[2] than those at the turn-off point on the main sequence and therefore must be the result of either a collision[3,4] or a mass-transfer event[5–7]. 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[9]) but with very different structural properties (and hence possibly at different stages of dynamical evolution). Although significant variations in the radial distribution of BSSs among clusters are already known[10,11], we have found that, when the radial distance is expressed in units of the core radius (to permit a meaningful comparison among 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; see Supplementary Information).

Preliminary results[12,13] have shown that the observed radial distribution of BSSs is primarily modelled by the long-term effect of dynamical friction acting on the cluster binary population (and its progeny) since the early stages of cluster evolution. In fact, whereas BSSs generated by stellar collisions are expected to be the main or sole contributors to the central peak of the distribution[14], the portion beyond the cluster core, where the minimum of the distribution is observed, is entirely due to BSSs generated by mass transfer or merger in primordial binary systems, in agreement with what is found to be the dominant formation channel in other low-density environments such as open clusters[15]. In particular, what we call mass-transfer BSSs today are the by-product of the evolution of a $\sim 1.2 M_{\odot}$ primordial binary that has been orbiting the cluster and suffering the effects of dynamical friction for a significant fraction of the cluster's lifetime. Hence, the radial distribution of BSSs that is now observed simply reflects the underlying distribution of $1.2 M_{\odot}$ binaries, which has been shaped by dynamical friction for several billion years (see Supplementary Information).

Dynamical friction has the effect of driving objects that are more massive than the average towards the cluster centre, with an efficiency that decreases for increasing radial distance as a function of the velocity dispersion and mass density[13,16]. Hence, as time passes, heavy objects orbiting 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 ($r_{\rm min}$; 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_{min} in a few globular clusters[13,17]. The progressive outward drift of r_{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 $1.2M_{\odot}$ 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[18,19]. 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[1] (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 quantization into distinct age-families is of course an oversimplification: in nature a continuous behaviour is expected and the position of $r_{\rm min}$ should vary with continuity as a sort of clock hand. This allows us to push our analysis further and define the first empirical clock able to measure the dynamical age of a stellar system from pure observational quantities (the 'dynamical clock'): in the same way as the engine of a chronometer advances a clock hand to measure the flow of time, in a similar way dynamical friction moves $r_{\rm min}$ within 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 ($r_{\rm min}$) and two theoretical estimates commonly used to measure the dynamical evolution timescales of a cluster, namely the central and the half-mass relaxation times, $t_{\rm rc}$ and $t_{\rm rh}$, respectively[1] (see Supplementary Information), here expressed in units of the Hubble time ($t_{\rm H}$). The best-fit relations to the data,

$\log(t_{\rm rc}/t_{\rm H}) = -1.11 \log(r_{\rm min}) - 0.78$ (r.m.s. = 0.32)

$\log(t_{\rm rh}/t_{\rm H}) = -0.33 \log(r_{\rm min}) - 0.25$ (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 $t_{\rm rc}$ and $t_{\rm rh}$ 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 $r_{\rm min}$ as a function of the cluster's dynamical age in billions of years.

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1. Meylan, G. & Heggie, D. C. Internal dynamics of globular clusters. *Annu. Rev. Astron. Astrophys.* **8,** 1–143 (1997).

2. Shara, M. M., Saffer, R. A. & Livio, M. The first direct measurement of the mass of a blue straggler in the core of a globular cluster: BSS19 in 47 Tucanae. *Astrophys. J.* **489,** L59–L63 (1997).

3. Hills, J. G. & Day, C. A. Stellar collisions in globular clusters. *Astrophys. J.* **17,** 87–93 (1976).

4. Sills, A., Adams, T., Davies, M. B. & Bate, M. R. High-resolution simulations of stellar collisions between equal-mass main-sequence stars in globular clusters. *Mon. Not. R. Astron. Soc.* **332,** 49–54 (2002).

5. McCrea, W. H. Extended main-sequence of some stellar clusters. *Mon. Not. R. Astron. Soc.* **128,** 147–155 (1964).

6. Sollima, A., Lanzoni, B., Beccari, G., Ferraro, F. R. & Fusi Pecci, F. The correlation between blue straggler and binary fractions in the core of Galactic globular clusters. *Astron. Astrophys.* **481,** 701–704 (2008).

7. Knigge, C., Leigh, N. & Sills, A. A binary origin for 'blue stragglers' in globular clusters. *Nature* **457,** 288–290 (2009).

8. Marín-Franch, A. *et al.* The ACS survey of galactic globular clusters. VII. Relative ages. *Astrophys. J.* **694,** 1498–1516 (2009).

9. Dotter, A., Sarajedini, A. & Yang, S.-C. Globular clusters in the outer Galactic halo: AM-1 and Palomar 14. *Astron. J.* **136,** 1407–1414 (2008).

10. Ferraro, F. R. *et al.* Blue stragglers in the Galactic globular clusters M3: evidence for two populations. *Astron. J.* **106,** 2324–2334 (1993).

11. Ferraro, F. R. *et al.* the pure noncollisional blue straggler population in the giant stellar system ω Centauri. *Astrophys. J.* **638,** 433–439 (2006).

12. Mapelli, M. *et al.* The contribution of primordial binaries to the blue straggler population in 47 Tucanae. *Astrophys. J.* **605,** L29–L32 (2004).

13. Mapelli, M. *et al.* The radial distribution of blue straggler stars and the nature of their progenitors. *Mon. Not. R. Astron. Soc.* **373,** 361–368 (2006).

14. Davies, M. B., Piotto, G. & de Angeli, F. Blue straggler production in globular clusters. *Mon. Not. R. Astron. Soc.* **349,** 129–134 (2004).

15. Geller, A. M. & Mathieu, R. D. A mass transfer origin for blue stragglers in NGC188 as revealed by half-solar-mass companions. *Nature* **478,** 356–359 (2011).

16. Binney, J. & Tremaine, S. *Galactic Dynamics* (Princeton Univ. Press, 1987).

17. Lanzoni, B. *et al.* The blue straggler population of the globular cluster M5. *Astrophys. J.* **663,** 267–276 (2007).

18. Mapelli, M. *et al.* Blue straggler stars in dwarf spheroidal galaxies. II. Sculptor and Fornax. *Mon. Not. R. Astron. Soc.* **396,** 1771–1782 (2009).

19. Monelli, M. *et al.* The ACS LCID Project. VII. The blue stragglers population in the isolated dSph galaxies Cetus and Tucana. *Astrophys. J.* **744,** 157–170 (2012).

20. Ferraro, F. R. *et al.* Two distinct sequences of blue straggler stars in the globular cluster. *Nature* **462,** 1028–1031 (2009).

21. Trager, S. C., Djorgovski, S. & King, I. R. in *Structure and Dynamics of Globular Clusters* (eds Djorgovski, S. G. & Meylan, G.) (Astronomical Society of the Pacific Conference Series Vol. 50) 347–355 (Astronomical Society of the Pacific, 1993).

22. Heggie, D. C. & Giersz, M. Monte Carlo simulations of star clusters. V. The globular cluster M4. *Mon. Not. R. Astron. Soc.* **389,** 1858–1870 (2008).

23. Ferraro, F. R. *et al.* The puzzling dynamical status of the core of the globular cluster NGC 6752. *Astrophys. J.* **595,** 179–186 (2003).

24. Lanzoni, B. *et al.* The surface density profile of NGC 6388: a good candidate for harboring an intermediate-mass black hole. *Astrophys. J.* **668,** L139–L142 (2007).

25. Renzini, A. & Buzzoni, A. in *Spectral Evolution of Galaxies* (eds Chiosi, C. & Renzini, A.) 195–231 (Reidel, 1986).

26. Bekki, K. & Freeman, K. C. Formation of ω Centauri from an ancient nucleated dwarf galaxy in the young Galactic disc. *Mon. Not. R. Astron. Soc.* **346,** L11–L15 (2003).

27. Djorgovski, S. in *Structure and Dynamics of Globular Clusters* (eds Djorgovski, S. G. & Meylan, G.) (Astronomical Society of the Pacific Conference Series Vol. 50) 373–382 (Astronomical Society of the Pacific, 1993).

28. King, I. R. The structure of star clusters. III. Some simple dynamical models. *Astron. J.* **71,** 64–75 (1966).

29. Ferraro, F. R. *et al.* The giant, horizontal, and asymptotic branches of Galactic globular clusters. I. The catalog, photometric observables, and features. *Astron. J.* **118,** 1738–1758 (1999).

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

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Author Contributions F.R.F. designed the study and coordinated the activity. E.D., G.B., R.C., B.L., N.S. and A.M. analysed the data. M.P. and P.M. developed *N*-body simulations. F.R.F. and B.L. wrote the paper. E.V., A.S., S.S., M.M. and R.T.R. critically contributed to discussion and presentation of paper. All authors contributed to discussion of the results and commented on the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to F.R.F. (francesco.ferraro3@unibo.it).

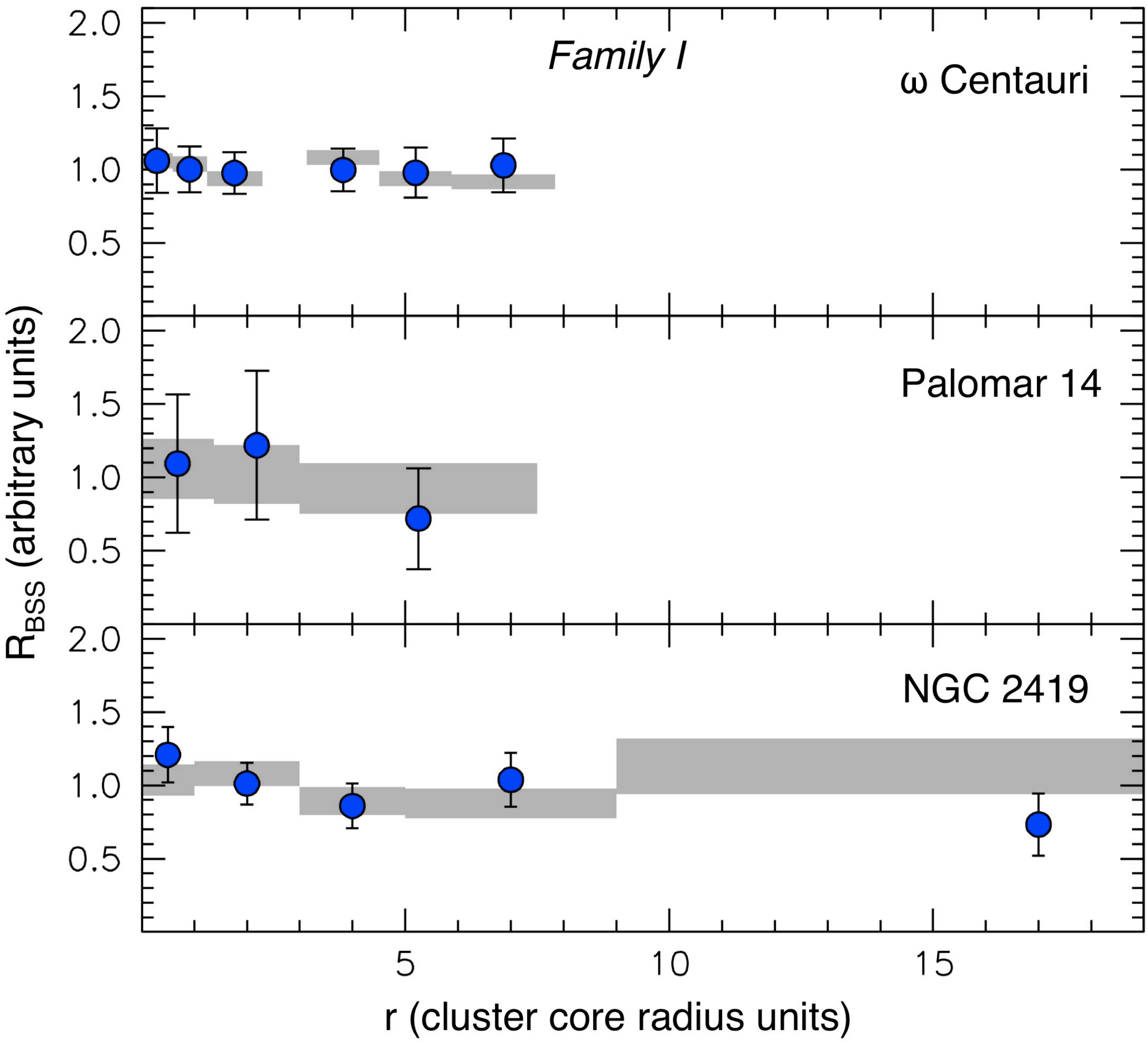

Figure 1 | The radial distribution of BSSs in three dynamically young stellar systems (family I). a, ω Centauri; **b**, Palomar 14; **c**, NGC 2419. The double-normalized ratio of BSSs (R_{BSS}; blue dots) is defined[10] as $R_{\mathrm{BSS}}(r) = [N_{\mathrm{BSS}}(r)/N_{\mathrm{BSS,tot}}]/[L_{\mathrm{samp}}(r)/L_{\mathrm{samp,tot}}]$, where $N_{\mathrm{BSS}}(r)$ is the number of BSSs measured in any given radial bin, $N_{\mathrm{BSS,tot}}$ is the total number of such stars, and $L_{\mathrm{samp}}(r)$ and $L_{\mathrm{samp,tot}}$ 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 (1σ) 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[25] 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 ω Centauri is not now considered to be a genuine globular cluster[26] but instead the remnant of a dwarf galaxy; in fact, no signs of mass segregation are expected in collisionless systems.

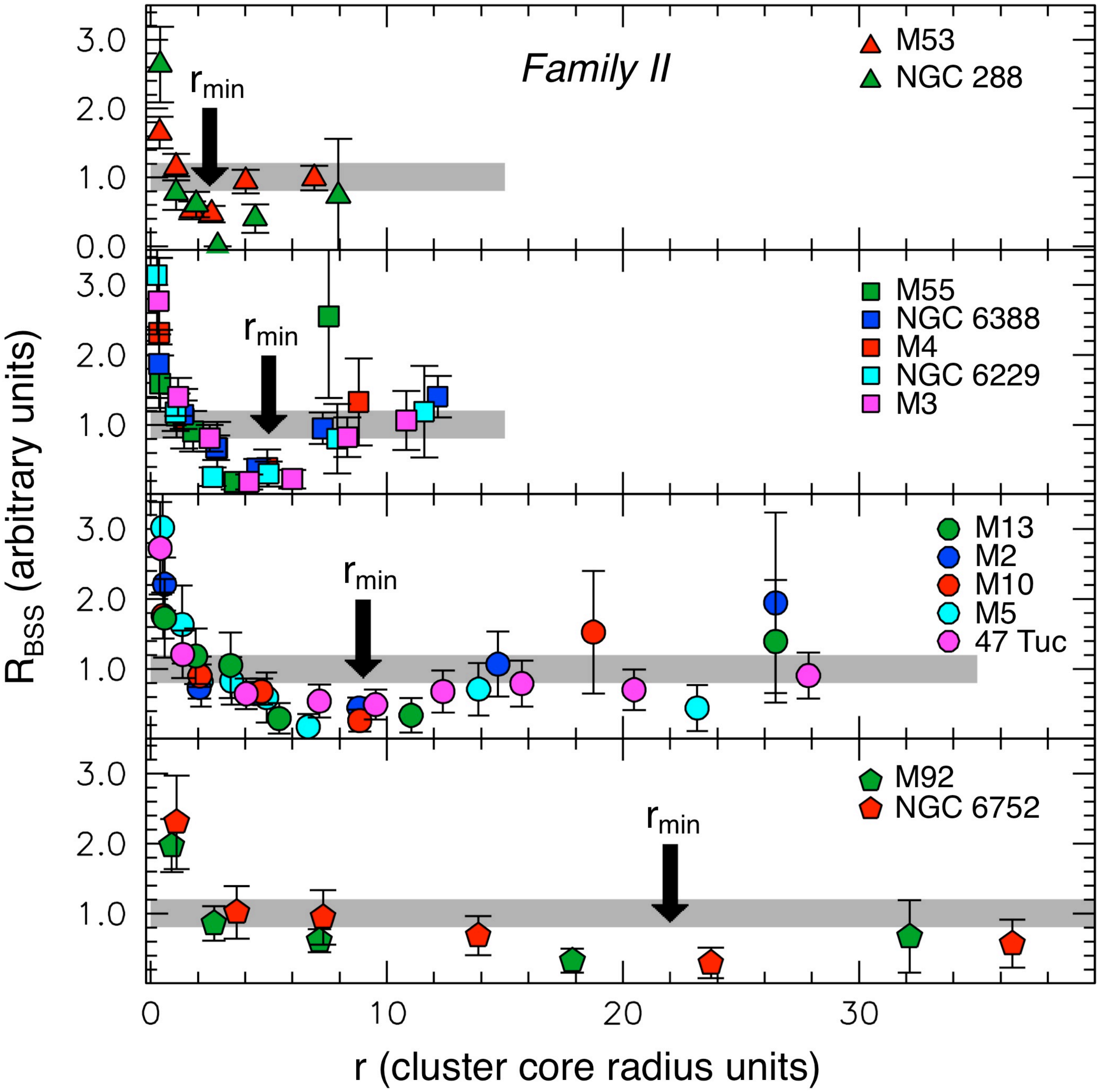

Figure 2 | The radial distribution of BSSs in systems of intermediate dynamical ages (family II). For the sake of clarity, the grey strips schematically represent the reference population distributions (which are shown in Supplementary Fig. 1 and in specific papers describing each individual cluster[10–13,17,20,24]). 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 ($r_{\rm min}$; see Supplementary Information) and a rising branch in the outskirts. Clusters have been grouped according to the value of $r_{\rm min}$ (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 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 $r_{\rm min}$; 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, $r_{\rm min}$ is well detected in all cases and these drawbacks do not affect the conclusion of the paper.

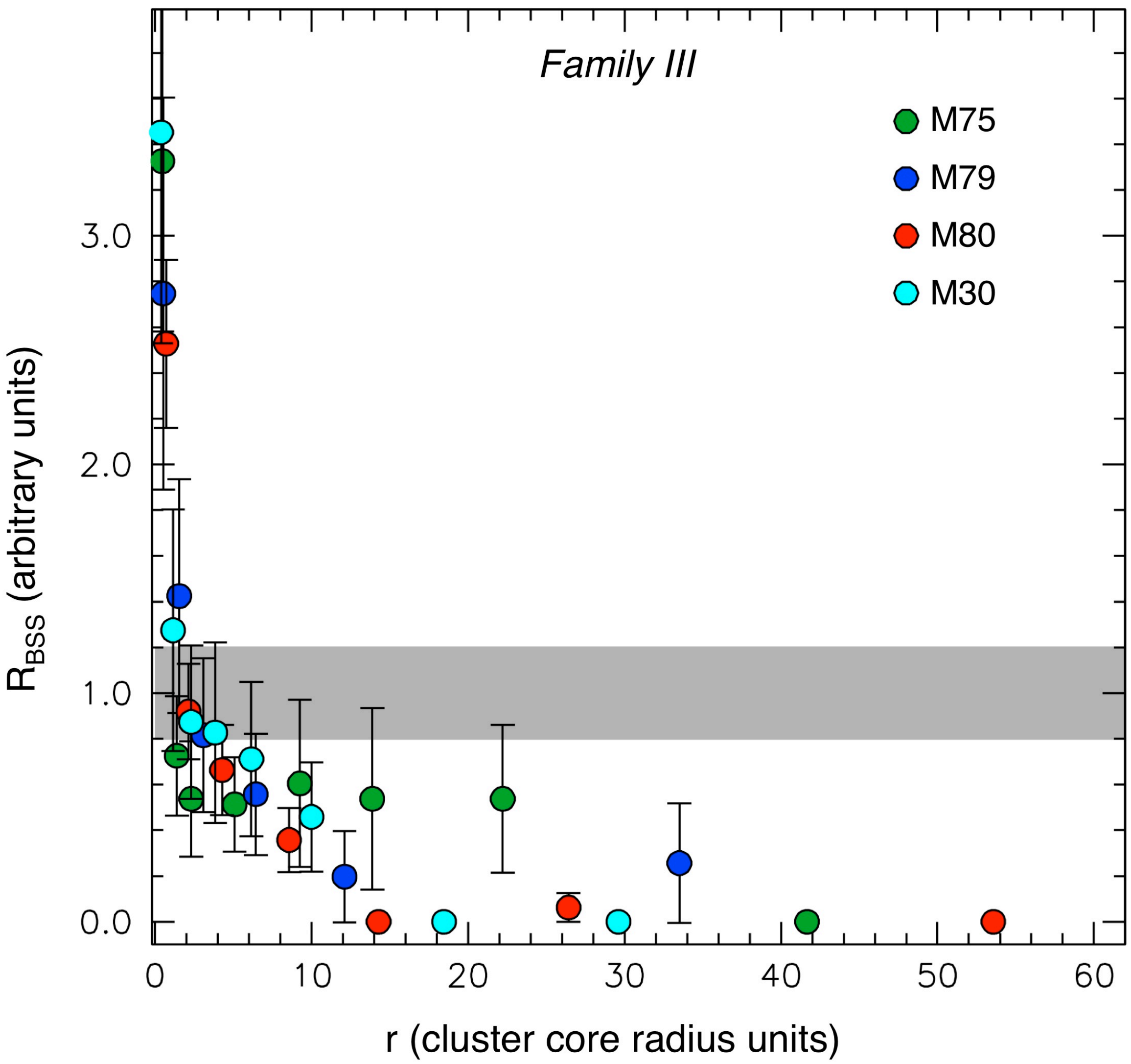

Figure 3 | The radial distributions of BSSs in dynamically old clusters (family III). The grey strip is as in Fig. 2. The BSS radial distributions in this family of clusters are monotonic, with only a central peak followed by a rapid decline and no signs of an external rising branch; these systems therefore show the highest level of dynamical evolution, with even the farthest BSSs already sunk towards the cluster centre. Even if in this regime the dynamical clock were to start to saturate, a ranking could still be attempted on the basis of the shape of the BSS distribution: M75 (green dots), where some BSSs are still orbiting at $r \approx 20$ and the slope of the decreasing branch is flatter, could be the dynamically youngest cluster within the family; M80 (red dots), with very sharply decreasing distribution, could have the highest dynamical age. Because our observations sample almost the entire radial extension of each cluster, we are confident that no BSS rising branch is present beyond the limit reached by the data. Error bars indicate 1σ.

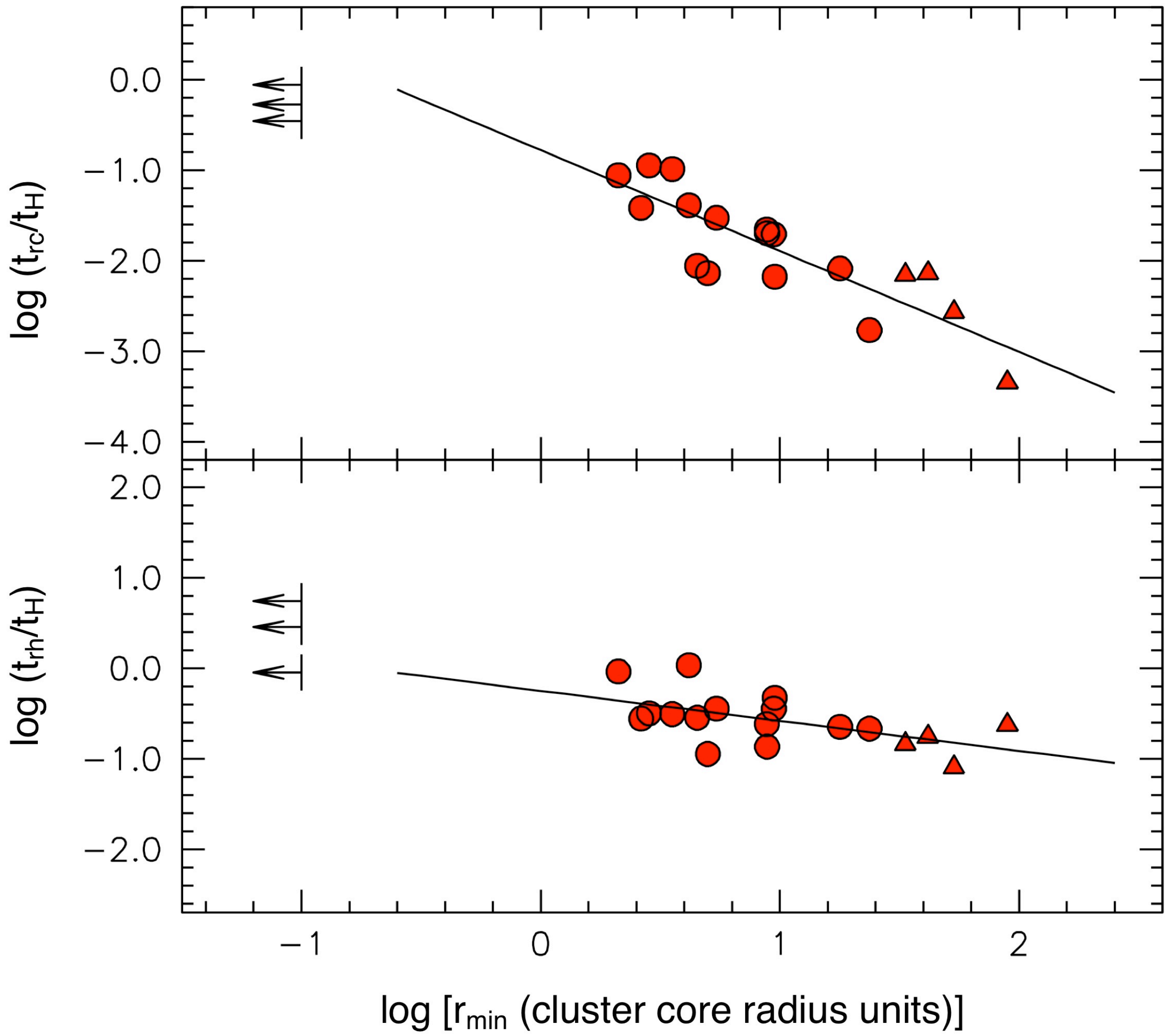

Figure 4 | A first calibration of the clock. The relaxation times at the cluster centre (t_{rc}) and at the half-mass radius (t_{rh}), normalized to the age of the Universe (t_H = 13.7 Gyr), are plotted as a function of the hand of our clock (r_{min}, in units of the cluster core radius). Relaxation times have been computed by following the literature[27], using accurately re-determined values of the structural parameters (derived from the King-model[28] fit to the observed star density profiles[11,17,20,24]) and a homogeneous distance scale[29]. The dynamically young systems (family I), showing no minimum, are plotted as lower-limit arrows at r_{min} = 0.1 and are not used to derive the best-fit relations (solid lines). For dynamically old clusters (family III, red triangles) we adopted $r_{min} = r_0$, where r_0 is the distance from the centre of the most distant bin where no BSSs are found. As expected for a meaningful clock, a tight anticorrelation is found: clusters with relaxation times of the order of the age of the Universe show no signs of BSS segregation (hence the radial distribution of BSSs is flat and r_{min} is not definable; see Fig. 1), whereas for decreasing relaxation times the radial position of the minimum increases progressively.