Stars caught in the braking stage in young Magellanic Cloud clusters

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The colour–magnitude diagrams of many Magellanic Cloud clusters (with ages up to 2 billion years) display extended turnoff regions where the stars leave the main sequence, suggesting the presence of multiple stellar populations with ages that may differ even by hundreds of millions of years1–3. A strongly debated question is whether such an extended turnoff is instead due to populations with different stellar rotations3–4. The recent discovery of a ‘split’ main sequence in some younger clusters (~80–400 Myr) added another piece to this puzzle. The blue side of the main sequence is consistent with slowly rotating stellar models, and the red side consistent with rapidly rotating models2–5. However, a complete theoretical characterization of the observed colour–magnitude diagram also seemed to require an age spread6. We show here that, in the three clusters so far analysed, if the blue main-sequence stars are interpreted with models in which the stars have always been slowly rotating, they must be ~30% younger than the rest of the cluster. If they are instead interpreted as stars that were initially rapidly rotating but have later slowed down, the age difference disappears, and this ‘braking’ also helps to explain the apparent age differences of the extended turnoff. The age spreads in Magellanic Cloud clusters are thus a manifestation of rotational stellar evolution. Observational tests are suggested.

When Hubble Space Telescope (HST) observations of the Magellanic Cloud cluster NGC 1856 extended the colour baseline from the ultraviolet to the near-infrared, they revealed the presence of a split main sequence. This feature could not be ascribed to age or metallicity differences4, and was not even compatible with a spread of rotation rates, but it could be well understood by assuming the presence of two coeval populations: ~65% of rapidly rotating ‘redder’ stars, and ~35% of ‘bluer’ non-rotating or slowly rotating stars that were evolving off the blue main sequence at a turnoff luminosity lower than that of the rotating population7, as expected from the results of calculations of stellar evolution tracks and isochrones calculated with the Geneva code11. In coeval populations, the evolution is faster (and the turnoff less luminous) for stars with slower rotation rate. In rotating models, the changes due to nuclear burning and rotational evolution are intertwined, as the transport of angular momentum through the stellar layers is associated with chemical mixing by which the convective hydrogen-burning core gathers hydrogen-rich matter from the surrounding layers, extending the main-sequence lifetime13–15. Stars with the same mass but different rotation rates have different evolutionary times and different turnoff luminosities; this effect helps to produce an extended main-sequence turnoff8 but may be insufficient to explain the whole spread observed9.

Figure 1 shows the HST colour–magnitude diagram in the plane of the near-infrared magnitude $m_{F814W}$ versus the colour $m_{F814W} - m_{F555W}$ for NGC 1856 (~400 Myr; Fig. 1d) and for three younger clusters in the Large Magellanic Cloud (LMC): NGC 1755 (~80 Myr; Fig. 1a); NGC 1850 (~100 Myr; Fig. 1b); and NGC 1866 (~200 Myr; Fig. 1c)10. In all cases, a split main sequence is present. The interpretation of this split in terms of stellar rotation requires the rotation distribution to be bimodal1–4, and much more skewed towards high rotation rates than in the field of the Galaxy and of the LMC1–2 or in low-mass galactic open clusters16,17, possibly suggesting an environmental effect18. The split finishes at magnitudes corresponding to a kink in the main sequence due to the onset of surface turbulence at $T_{\text{eff}} \leq 7,000$ K (ref.19), where rotational evolution begins to be dominated by the presence of the convective surface layers.

Remarkably, Fig. 1 shows that, in all three younger clusters, a coeval slow-rotating population does not adequately fit the colour–magnitude diagram: the blue main sequence is populated beyond the coeval non-rotating turnoff by stars resembling the ‘blue stragglers’ present in some standard massive clusters (for example in the old galactic globular clusters19). These can only be explained with younger non-rotating isochrones—at least ~25% younger, according to the orange dashed isochrones plotted in Fig. 1.

We made detailed simulations (see Methods) of the colour–magnitude diagrams, excluding NGC 1856, because the (possibly younger) blue main-sequence stars are not clearly distinct from the turnoff stars. Simulations cannot reproduce the brighter part of the blue main sequence with a coeval ensemble of rotating and non-rotating stars. In NGC 1755 (Supplementary Fig. 1), inclusion of stars on a younger isochrone can reproduce the entire non-rotating sample better and account for the blue main sequence at $18 \leq m_{F555W} \leq 19$. In the other clusters (Supplementary Figs 2 and 3), the simulations require both a younger blue main sequence and the presence of stars on older isochrones (see Supplementary Table 1 and Supplementary Fig. 4) to match stars in the extended turnoffs, although the effect of non-sphericity (limb and gravity darkening) and random orientation accounts for a part of the spread in the case of high rotation (Supplementary Fig. 4).

Although, as discussed later, the fraction of ‘younger’ stars is only 10–15%, understanding the origin of this population is crucial. A younger rapidly rotating component would be easily revealed (Supplementary Fig. 5), so why does the ‘younger’ population include only slow or non-rotating stars?
We show here that these stars may represent a fraction of the initially rapidly rotating stars that have been recently braked: they are not younger in age, but simply in a younger (less advanced) nuclear burning stage.

The evolution of the core mass ($M_{\text{core}}$) and central temperature ($T_c$), as a function of the core hydrogen content ($X_c$), is very similar for non-rotating and rotating tracks (Supplementary Fig. 6). The main difference is the total time spent along the evolution, because, in rotating stars, mixing feeds the convective core with fresh hydrogen-rich matter and thus extends the main-sequence life at each given $X_c$. Therefore, a transition from fast to slow rotation does not require any marked readjustment of the star interior.

The angular momentum of the star may be subject to external, additional sinks, besides those included in the models. It is possible that the external layers are the first to brake (for example if they are subject to magnetic wind braking, as observed in the magnetic star ζ Orionis B, whose rotation period increases on a timescale of 1.34 Myr; ref. 23), and that the information propagates into the star by efficient angular momentum transport. Otherwise, braking first occurs into the core, for example by action of low-frequency oscillations, excited by the periodic tidal potential in binary stars (dynamical tides24), as proposed for the case of NGC 1856. We prefer the latter mechanism, as its timescale depends both on the stellar mass and its evolutionary stage, and on the parameters of the binary system, so braked stars (the upper blue main sequence) may be present in clusters over a wide range of ages. The stellar envelope will be the last to brake, and then the star will finally reach the location of the non-rotating configuration on the colour–magnitude diagram. If this latter stage takes place before the end of the main-sequence phase, the star will be placed on the blue main sequence. A star moving from the rotating to the non-rotating evolutionary track at fixed $X_c$ will appear younger as soon as braked, whereas its total main-sequence time will be shorter—simulating an older isochrone—than that of a star preserving its rotation rate, because full braking may prevent further core–envelope mixing. This produces two different effects: the presence of a younger blue main sequence and the presence of older stars showing up in the puzzling extended turnoff.

Both these ‘age’ effects are schematically illustrated in Fig. 2. Here we must keep in mind that the explanation shown here is based on existing stellar models, and a strong computational effort will be needed in future to confirm this suggestion. For the clusters NGC 1755 (left panels) and NGC 1866 (right), we plot the time evolution of core hydrogen $X_c(t)$ for selected masses, for models initially rotating with angular velocity $\omega_m = 0.9\omega_{\text{crit}}$ (where $\omega_{\text{crit}}$ is the breakup angular velocity required for the centrifugal force to counterbalance gravity at the equator) and for non-rotating models (initial angular velocity $\omega_m = 0$). A vertical line marks the location of these masses at the age of each cluster, where we see that the rapidly rotating star is in a less advanced nuclear-burning stage. The grey arrows show the age of a star born non-rotating and having the same $X_c$. ‘Rapid braking’ would shift the star to the non-rotating radius (and colour–magnitude location) corresponding to that same $X_c$, so it would appear ‘younger’ to us than a star with the same mass but formed with no rotation (blue squares). In fact, the braked masses will be approximately located on the $\omega_m = 0$ isochrone on a plot of mass versus $X_c$ (open circles on the green lines in Fig. 2b,d), 25% younger than the $\omega_m = 0$ isochrone at the clusters’ age (blue dashed line, on which the blue squares showing the stars non-rotating from the beginning are placed). The presence of stars on a ‘younger’ blue main sequence can thus be qualitatively understood. These stars must have been fully braked ‘recently’, less than 25% of the cluster age ago, otherwise they would have already evolved out of the main sequence.

A second consequence of the braking process is that the time evolution $X_c(t)$ of each ‘braked’ star will depend on the time at which braking is effective in changing the modalities of mixing at the border of the convective core to the $\omega_m = 0$ modality. Simplifying, the braked stars stop evolving on the $X_c(t)$ line for $\omega_m = 0.9\omega_{\text{crit}}$ and start evolving along the $X_c(t)$ line for $\omega_m = 0$, at different times (dashed grey lines in Fig. 2a and c; see Methods). The intersections of the dashed grey lines with the vertical line drawn at the cluster age show that each mass may, in principle, span the whole range of $X_c$ between the minimum value achieved by the non-rotating track and the maximum value of the rotating track.

Braking will, in reality, be much more complex than this exploratory outline. Two possibilities can help in the interpretation of the colour–magnitude diagram patterns. First, the mechanism for slowing down the stellar core might cause strong shear in the outer layers, and imply even more mixing than in the standard rapidly rotating models, before the star is finally fully braked. A more extended mixing explains why some of the upper blue main-sequence stars in NGC 1866 and NGC 1850 look younger than predicted by the ~25% difference between the rapidly rotating and the non-rotating isochrones (see Supplementary Table 1 and Supplementary Fig. 4).

Second, full braking of the external layers (corresponding to the blue main-sequence stage) is possibly achieved by only a fraction of the upper blue main-sequence stars at any given $X_c$, so coeval isochrones are apparently needed to account for the blue upper main-sequence stars.
whole cluster lifetime. This may indicate that stars much dimmer than the blue main-sequence turnoff have also reached full braking only recently, and that the aging effect of braking is seen mainly in the extended dimmer portions of the rotating turnoff. Piling up of slowly rotating stars braked at different ages produces a significantly populated turnoff of the blue main sequence only at the age of NGC 1856 (ref. 7), but it is not evident in the younger clusters.

These initial results may shed some light on the physical mechanism behind the braking. As both the 'blue stragglers' and the extended turnoff require braking in recent times, does braking accelerate for stars already in advanced core hydrogen burning? In the dynamical tide mechanism, the synchronization time increases with the age of the binary system 22,25, but we can expect that the detailed behaviour of angular momentum transfer and chemical mixing at the edge of the convective core will be more subject to small differences in the parameters when the structure is altered by expansion of the envelope and contraction of the core. In addition, the timescale will depend on parameters that may vary from cluster to cluster, possibly including the location of the star within the cluster. For instance, the blue main-sequence fraction increases in the external parts of NGC 1866 (ref. 10), whereas it does not vary with the distance from the cluster centre in other clusters 9,26.

We conclude that rotational evolution produces different timescales for the core hydrogen-burning phase which can be perceived as a mixture of stellar ages. The most direct indication in support of this interpretation comes from the presence of a small population of non-rotating stars that appear to be younger than the bulk of stars. Stars whose envelope is not fully braked may instead show up as older and be seen in the dimmer part of the extended turnoff. 'Complete' simulation of the colour–magnitude diagram

Figure 2 | Illustration of the role of braking at the age of NGC 1755 and NGC 1866. a,b,e, NGC 1755; c,d,f, NGC 1866. Panels e and f show the observed data, the isochrones at the cluster age (blue and red) and the isochrone 0.1 dex younger (green), on which the mass points corresponding to the $X_c(t)$ evolution of panels a and b and panels c and d, are highlighted. $X_c$ is the mass fraction of central hydrogen content. Panels a and c show $X_c$ as a function of time in units of 100 Myr, for different masses. For each mass, the upper line (red) is the $\omega_{\text{in}} = 0.9\omega_{\text{crit}}$ evolution, where $\omega_{\text{crit}}$ is the break-up angular velocity; the lower line (blue) is the $\omega_{\text{in}} = 0$ evolution. The nuclear burning stage reached at the age of the clusters is marked by red circles (blue squares) for the rotating (non-rotating) stage; dark green open circles are the locations of recently braked stars in the plane of $X_c$ versus mass (panels b and d). The corresponding locations in the colour–magnitude diagrams are shown in e (NGC 1755) and f (NGC 1866), where the mass is labelled in green, in solar units. The dashed grey lines represent schematic transitions from $\omega_{\text{in}} = 0.9\omega_{\text{crit}}$ to $\omega_{\text{in}} = 0$, occurring at different ages. As an example, the asterisks in panels c and d mark the evolutionary stage of a star that braked about 70 Myr ago, so that it is now evolving past the turnoff (asterisk in panel f).
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(see Supplementary Table 1) requires an age choice for the bulk of stars (the age defined by the most luminous rapidly rotating population) plus smaller samples of different ages (Supplementary Fig. 4): younger, to describe the blue main sequence, and older, to describe the multiple turnoff (Supplementary Figs 1, 2 and 3); but all the stars may in fact be a coeval ensemble.

The best test for the model of the blue and red main sequence in terms of different rotation rate will be to find low rotation velocities in the spectra of the blue main-sequence stars, and higher velocities in the red main-sequence stars. The Hα emission typical of rapidly rotating stars (Be stage) should be mostly confined to the red turnoff stars (as in NGC 1850; ref.11). A test for the braking model is possible by studying the surface anomalies of CNO elements. If the blue main-sequence stars are born non-rotating, we should expect CNO differences between the blue and red main-sequence spectra 

ref. P. Goudfrooij). These images were reduced by adopting the methods developed in three in F814W (durations: 7 s, 350 s, 440 s) from GO14147 (Principal Investigator F814W bands of the Ultraviolet and Visual Channel of the Wide-Field Camera 3 (UVIS/WFC3) on board the HST. The quoted references provide details on the data and the data reduction.

For NGC 1850, we used five UVIS/WFC3 images in F336W (durations: 260 s, 370 s, 600 s, 650 s, 675 s) from GO14069 (Principal Investigator N. Bastian) and three in F814W (durations: 7 s, 350 s, 440 s) from GO14147 (Principal Investigator P. Goudfrooij). These images were reduced by adopting the methods developed in ref.12 and used in our work on NGC 1755, NGC 1856 and NGC 1866. Photometry was corrected for differential reddening and small variations of the relevant photometric zero point13 and calibrated to the Vega system14 and using the zero points provided by the Space Telescope Science Institute official webpage.

To reduce the contamination from field stars, we only used stars in a small region centred on the cluster and with radius of 40 arcsec. In the case of NGC 1850, we minimized contamination from the nearby star cluster NGC 1850B by excluding stars with distances smaller than 20 arcsec from its centre.

Models and simulations. We make use of the tool SYCLIST (for Synthetic Clusters, Isochrones, and Stellar Tracks)13 Web facility available at http://obswww.unige.ch/Recherche/evoldb/index/, both for the stellar models and isochrones. Details of the physical treatment are contained in the relevant papers of this group12–14. Models with mass fraction of helium $Y = 0.26$, metals $Z = 0.006$, and-o-elements in the solar ratios are used, as this composition is the best available to study the LMC clusters. The models are available for any choice of the initial angular velocity $\omega_{0}$ from 0 to the break-up $\omega_{\text{break-up}} = GM(R_{\text{rot}}^{3})/R_{\text{rot}}$. The mixing efficiency15 depends on an effective diffusion coefficient, accounting both for the meridional circulation and horizontal turbulence16 and for the shear-mixing diffusion coefficient. Both radiative and mechanical (equatorial) mass loss are accounted for.

For this work, we use the $\omega_{0} = 0.9\omega_{\text{crit}}$ models and the $\omega_{0} = 0$ isochrones, as they account for the colour separation of the blue (identified with the $\omega_{0} = 0$ models) and red (corresponding to the $\omega_{0} = 0.9\omega_{\text{crit}}$ models) main sequences in the four clusters of Fig. 1(a). A previous analysis of the NGC 1850 data17 shows that it is necessary to exclude stars with intermediate rotation, 0.5 < $\omega_{\text{ecl}}/\omega_{\text{crit}}$ < 0.9, to let the main sequence remain split. The rotational distribution of field stars17,18 is much more continuous, although it also shows signs of bimodality. A hypothesis is that all stars are born rapidly rotating. Preliminary confirmation comes from the presence of the Be type stars, which are all rapidly rotating19, in the red side in NGC 1850 (ref.19). Rotational braking may be due to a non-close companion (orbital period between 4 and 500 d), as these binaries, in the field, have rotational velocity significantly smaller than for single stars20, with about one-third to two-thirds of their angular momentum being lost, presumably by tidal interactions21.

We use the simulations provided by the SYCLIST facility for the rotating sample. This is mandatory for the high-$\omega_{0}$ simulations, because they account for the effect of gravity darkening (which arises because a rotating star are hotter and brighter than the equatorial region11) and limb darkening (due to the optical thickness of the atmosphere towards the central and peripheral regions11). Both effects are such that a star seen pole-on will look hotter and more luminous (bluer and brighter) than it would if seen equator-on. Therefore, the angle at which we view a star will influence its location in the colour–magnitude diagram. We use a random viewing angle distribution and the distance weight of the effect results in a spread in colour and luminosity for the turnoff region, in agreement with the observations. In Supplementary Fig. 4, for the case of NGC 1866, we compare the simulation from the same $\omega_{0} = 0.9\omega_{\text{crit}}$ isochrone in which the projection effect is included (yellow triangles) or not (violet triangles) to show this striking effect on the turnoff. We note, in any case, that the colour spread is not found for the blue sequence (for see ref. for discus. In Supplementary Fig. 4, we show that the whole turnoff spread is matched by adding rotating stars at ages 0.05 dex (red squares) and 0.1 dex larger (green squares).

The initial mass function in the Geneva database is fixed to a Salpeter’s power-law function with an index $\alpha = –2.35$. We produced $\omega_{0} = 0$ simulations with smaller values of $\alpha = –1.0$, to fit the blue main sequence better (see the discussion on number counts as a function of $M_{\text{crit}}$).

The data of all synthetic simulations were transformed into the observational planes using model atmospheres, convolved with the HST filter transmission curves. The points were reported to the observational planes by assuming the following colour shifts $\delta i = \delta i(M_{\text{ma}} - M_{\text{neq}})$ and distance modulus $d = 10 \log (M_{\text{F814W}}/M_{\odot}) - \delta M_{\text{F814W}}$, where $M_{\text{F814W}}$ is the absolute magnitude in the band F814W. NGC 1755: $\delta i = 0.37$ mag, $d = 18.50$ mag; NGC 1850: $\delta i = 0.52$ mag, $d = 18.70$ mag; NGC 1866: $\delta i = 0.32$ mag, $d = 18.50$ mag.

In the simulations, we take into account the combined photometry for a variable percentage of binaries15. Binaries are included both in the rotating and non-rotating sequence. The mass function of the secondary stars is defined from a Salpeter’s mass function, with a lower limit of 0.5 $M_{\odot}$. Only the photometric consequences of the presence of such binaries are monitored in the simulations.

Simulations for the three younger clusters: necessity of a ‘younger’ blue sequence. We plot in Supplementary Figs 1, 2 and 3 the Hess diagram of data (left), best simulation (ceny) and a simulation using only two coeval (rotating and non-rotating) isochrones (right), for the clusters NGC 1755, NGC 1850 and NGC 1866. Supplementary Table 1 lists the relative fraction of samples for the best simulation of the three clusters. The right panels show that the lack of a sample of younger non-rotating stars does not allow us to account for the morphology of the colour–magnitude diagram. The very evident discrepancy, when a unique coeval non-rotating population is assumed, confirms that it is not possible that rotating and non-rotating stars born at the same time account for the results.

The best simulation is obtained first by choosing the samples of single-age synthetic clusters that best map the colour–magnitude patterns. This is shown in Supplementary Fig. 4, where the different colours mark the choices for NGC 1866. Another example is given in Supplementary Fig. 5, in which we show in yellow the isochrones of the simulation of $\omega_{0} = 0.9\omega_{\text{crit}}$ sample compared to the turnoff stars (and, together with a dating for the cluster, establishes the distance modulus and reddening). We add synthetic populations based on $\omega_{0} = 0.9\omega_{\text{crit}}$ isochrones younger than the yellow dots, and see that these points do not correspond to the locations of cluster stars, so we omit them from consideration. Following this first choice, we base the quantitative comparison on number counts. We first restrict the sequence of the three clusters19, which helps to separate the blue and red side of the sequences. We then calculate the number of stars in each of the bins described in the first column of Supplementary Table 2 for both observational sequences. We associate to each bin count $N$ a Poissonian error $\sigma = \sqrt{N}$. We repeat the procedure for the synthetic clusters and choose the combination of parameters (Supplementary Table 1) that gives the minimum discrepancy in the ratio between the observed and theoretical sequences. An outcome of this procedure is to find the population fraction of blue main-sequence stars. Examples are shown in Supplementary Fig. 7, and Supplementary Table 2 lists the results for each cluster.

The error value associated to the ratio in each bin is calculated from Poisson statistics (where $\sigma = \sqrt{N}$) and through standard error propagation procedures.

Results and comparisons: how to justify a ‘braking’ track-shift. In this work, we make a simplified hypothesis: we assume that a rapid braking of the stellar layers may shift the evolution from the $\omega_{0} = 0.9\omega_{\text{crit}}$ track to the $\omega_{0} = 0$ track for the same mass. This naive assumption relies on the comparison of the different evolutionary paths shown in Supplementary Fig. 6. The $\omega_{0} = 0.9\omega_{\text{crit}}$ tracks are the lines with squares, and non-rotating tracks are simple lines. We show the masses 3.5 and 6 $M_{\odot}$. As a function of the core hydrogen content $X_{c}$ we show the age (Supplementary Fig. 6a), the convective core mass $M_{\text{conv}}$ (panel b), $T_{\text{eff}}$ (panel c) and luminosity (panel d). The ranges of values of the physical quantities differ for the different masses, but the behaviour is similar. Only the $M_{\text{conv}}$ evolution is slightly different in the first phases of core hydrogen burning. In fact, its size relies on two counteracting physical processes linked to rotation. In the first phase, rotation generates an additional support against gravity owing to the centrifugal
force, so the rotating core and the stellar luminosity are smaller. In the subsequent evolution, the rotational mixing at the edge of the core progressively brings fresh material into the core, increasing its mass and hence its luminosity. The resulting time evolution is very different: in the rotating tracks, the total main-sequence phase lasts about 25% longer, despite the luminosity being larger. Thus, a fixed cluster age, fast-rotating evolving stars have larger masses than the non-rotating ones (for example, at $t = 100$ Myr, the turnover masses are ~4.6 and ~4.4 $M_\odot$, respectively).

If the rotational mixing stops because of external factors that cause braking, the fact that $T$ and $M$, do not differ, at the stage of evolution defined by a value of $X$, means that we may expect that the shift from the rotating to the non-rotating configuration mainly implies a readjustment of the radius and luminosity, which become smaller, and the star moves to the location of the $\omega = 0$ model on the colour–magnitude diagram, with its $X$, value. Computation of specific models including braking is necessary, but the important point that will remain true is that a braked mass will find itself in a less advanced stage of core hydrogen consumption with respect to the evolution at constant zero rotation rate. Other physical phenomena that cause ingestion of hydrogen may remain active, for example those linked to the ‘overshooting’ due to the finite velocity of convective elements at the convective borders.

Data availability. The observational data published in this study are available from A.M. upon reasonable request. The tracks, isochrone data and simulations that support the theoretical plots within this paper were retrieved by the authors from the CYCLIST Web facility available at http://obswww.unige.ch/Recherche/evoldb/index/ and created by C. Georgy and S. Ekström.

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References

1. Mackey, A. D., Broby Nielsen, P., Ferguson, A. M. N. & Richardson, J. C. Multiple stellar populations in three rich Large Magellanic Cloud star clusters. Astrophys. J. Lett. 681, L17–L20 (2008).

2. Milone, A. P., Bedin, L. R., Piotto, G. & Anderson, J. Multiple stellar populations in Magellanic Cloud clusters. I. An ordinary feature for intermediate-age globulaires in the LMC. Astron. Astrophys. 497, 755–771 (2009).

3. Girardi, L., Eeggbensegger, P. & Miglio, A. Can rotation explain the multiple main-sequence turn-offs of Magellanic Cloud star clusters? Mon. Not. R. Astron. Soc. 412, L103–L107 (2011).

4. Goudfrooij, P., Puzia, T. H., Chandar, R. & Kozhurina-Platais, V. Population parameters of intermediate-age star clusters in the Large Magellanic Cloud. III. Dynamical evidence for a range of ages being responsible for extended main-sequence turnoffs. Astrophys. J. 737, 4 (2011).

5. Rubele, S. et al. The star formation history of the Large Magellanic Cloud star clusters NGC 1846 and NGC 1783. Mon. Not. R. Astron. Soc. 430, 2774–2788 (2013).

6. Li, C., de Grijs, R., Deng, L. & Milone, A. P. The radial distributions of the two main-sequence components in the young massive star cluster NGC 1856. Preprint at https://arxiv.org/abs/1611.04659 (2016).

7. Anderson, J. et al. Deep Advanced Camera for Surveys imaging in the globular cluster NGC 6397: reduction methods. Astron. J. 135, 2114–2128 (2008).

8. Milone, A. P. et al. The ACS survey of Galactic globular clusters. XII. Photometric binaries along the main sequence. Astron. Astrophys. 540, A16 (2012).

9. Bedin, L. R. et al. Transforming observational data and theoretical isochrones into the ACS/WFC Vega-mag system. Mon. Not. R. Astron. Soc. 357, 1038–1048 (2005).

10. Chaboyer, B. & Zahn, J.-P. Effect of horizontal turbulent diffusion on transport by meridional circulation. Astron. Astrophys. 253, 173–177 (1992).

11. Zorec, J. & Boyer, F. Rotational velocities of A-type stars. IV. Evolution of rotational velocities. Astron. Astrophys. 537, A120 (2012).

12. Rivinius, T., Carciofi, A. C. & Martayan, C. Classical Be stars. Rapidly rotating B stars with viscous Keplerian decretion disks. Astron. Astrophys. Rev. 21, 69 (2013).

13. Abt, H. A. & Boonyarak, C. Tidal effects in binaries of various periods. Astrophys. J. 616, 562–566 (2004).

14. Espinosa Lara, F. & Rieutord, M. Gravity darkening in rotating stars. Astron. Astrophys. 533, A43 (2011).

15. Claret, A. A new non-linear limb-darkening law for LTE stellar atmosphere models. Astron. Astrophys. 363, 1081–1190 (2000).

16. Salpeter, E. E. The luminosity function and stellar evolution. Astrophys. J. 121, 161 (1955).

17. Castelli, F. & Kurucz, R. L. New grids of ATLAS9 model atmospheres. Preprint at https://arxiv.org/abs/astro-ph/0405087 (2004).

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Author contributions

ED. and A.M. jointly designed and coordinated this study. ED. proposed and designed the rotational evolution model. E.D., E.V., A.M. and P.W. worked on the theoretical interpretation and implications of the observations. M.T. and M.D.C. carried out the simulations and the analysis. All authors read, commented on and approved submission of this article.

Additional information

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