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Braking stars in the Young Magellanic Cloud Massive Clusters

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Abstract. The presence of extended main sequence turnoff (eMSTO) regions in the Young Massive Clusters in the Magellanic Clouds was explained either as due to an "age spread", or to "rotational spread". Both models presented points of strength and flimsiness. The rotational model is becoming now favored, because if explains both the increase of the apparent age spread with the cluster age, and the presence of a split main sequence in the younger clusters (age <400Myr), interpreted with the presence of a scarcely rotating blue main sequence and a rapidly rotating red main sequence, this latter ending into an extended main sequence turnoff (eMSTO) region. The slowly–rotating bMS always includes stars which are apparently $\sim$30% "younger" than the rest. We show that, in a coeval stellar sample, this feature signals the presence of stars caught in the stage of braking from an initial rapidly rotating configuration; these stars are thus in a "younger" nuclear evolution stage (less hydrogen consumed in core burning) than stars directly born slowly–rotating in the same star–formation episode. "Braking" at different stages of the main sequence life also helps to explain the eMSTO, as the dimmer, apparently "older", stars, could be stars which have been braked at an earlier phase in the cluster life. This leads us to conclude that all the age spreads in Magellanic Cloud clusters may be understood as a manifestation of rotational stellar evolution.

Key words. Stars: intermediate mass – Stars: rotation– Local System: massive young globular clusters

1. Introduction

The color magnitude diagrams of many Magellanic Cloud clusters (with ages up to 2 billion years) display extended main sequence turnoff (eMSTO) regions, suggesting the presence of multiple stellar populations with ages which may differ up to hundreds million years (Mackey et al., 2008; Milone et al., 2009; Girardi et al., 2011). At first sight, the age spread could be an analogous of the different star formation epochs underlying the formation of multiple populations in ancient Globular Clusters (e.g. Carretta et al., 2009; Piotto et al., 2015), for which the most popular scenarios attribute the observed chemical abundance variations to a second generation of stars that formed out of gas clouds polluted, to varying extents, by winds of first–generation stars, during a period spanning from tens up to a hundred or more of Myr, depending on the nature of the polluters (Decressin et al., 2007; D'Ercole et al., 2008). An attempt to quantify this model was proposed by Goudfrooij et al. (2011) in the "escape velocity threshold" scenario, suggesting that eMSTOs can only be present when the escape velocity from the cluster is higher than the wind velocities of polluter stars thought to provide the material out of which the second stellar generation was formed, at the time such stars were present in the cluster.

The age spread hypothesis, and the opposite view, that such an eMSTO is instead due to coeval stars with different stellar rotations (Bastian & de Mink, 2009) were strongly debated in recent years (e.g. Girardi et al., 2011; Rubele et al., 2013; Goudfrooij et al., 2014; Li et al., 2014).

Today the rotational hypothesis favored by two new elements:

1) there is a direct correlation between the cluster age and the extension of the eMSTO area (Brandt & Huang, 2015) —and consequently with the desumed age spread (Niederhofer et al., 2015). This can be interpreted in terms of coeval stars covering a wide range of rotation rates;
2) a 'split' main sequence has been discovered in some younger (∼ 80–400 Myr) clusters. Such a feature is only consistent with slowly (rapidly) rotating stellar models populating the red (blue) side of the MS (D'Antona et al., 2015).

Nevertheless, still the analysis of data seem to indicate that a complete theoretical characterization of the observed color-magnitude diagram require also an age spread (Milone et al., 2017; Correnti et al., 2017; Goudfrooij et al., 2017).

We show here that a further feature is present in the color magnitude diagram of the youngest clusters, which can be also interpreted in the framewok of rotation, adding support to the rotational case.

2. The split main sequence

The split MS was first observed in the HST data for the cluster NGC 1856. Milone et al. (2015) revealed its presence thanks to the color baseline extending from UV to near IR. This feature could not be ascribed to age or metallicity differences, 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: a red main sequence (rMS) containing ∼65% of *rapidly rotating* stars, and a blue main sequence (bMS) including ∼35% of non–rotating or slowly rotating stars. In a coeval sample, bMS stars evolve off the main sequence at a turnoff luminosity *smaller* than for the rotating population, as expected from the tracks and isochrones for rotating stars[1], In fact, 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 which deeply affects the evolutionary times in the H–core burning phase. Thanks to mixing, the convective H–burning core gathers H-rich matter from the surrounding layers, extending the main sequence lifetime (e.g. Meynet & Maeder, 2000; Ekström et al., 2012; Georgy et al., 2013). Stars with the same mass but different rotation rates have different evolutionary times and different turnoff luminosities, and this effect may produce an eMSTO (Brandt & Huang, 2015; Niederhofer et al., 2015).

3. The evidence

A new feature emerged from the analysis of the color magnitudes diagram of the youngest LMC clusters in the plane of the HST near infrared magnitude m_{F814W} versus the color $m_{F336W}-m_{F814W}$(D'Antona et al., 2017). In Figure 1 we show, from left to right: NGC 1755 (Milone et al., 2016) (∼80 Myr); NGC 1866 (Milone et al., 2017) (∼ 200 Myr) and NGC 1856 (Milone et al., 2015) (∼400 Myr).

[1] The Geneva database created by C. Georgy and S. Ekström (Georgy et al., 2014) available at `http://obswww.unige.ch/Recherche/evoldb/index/wasused`.

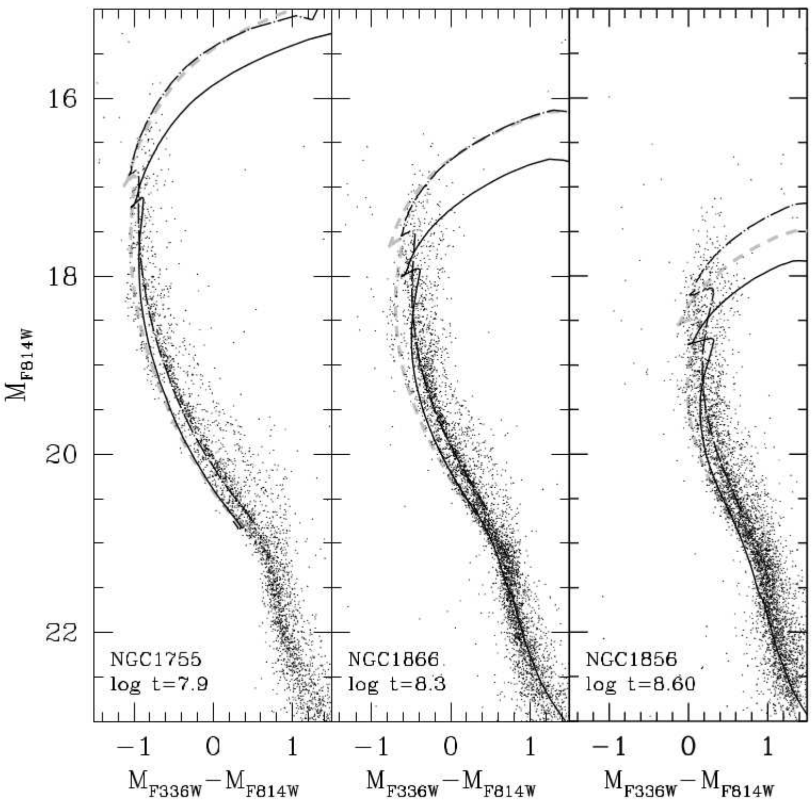

Fig. 1. Color-magnitude diagram for three young LMC clusters at different ages. At the bottom of each panel we report the clusters names and the adopted logarithm of the age (in years). All diagrams are characterized by an evident split of the MS, although the split extent in magnitude decreases as the cluster age increases. Coeval isochrones for $\omega_{\rm in}$=0 (solid) and $\omega_{\rm in}$=0.9$\omega_{\rm crit}$ (dash–dotted), where $\omega_{\rm crit}$ is the break up angular velocity, are shown. Dashed lines are non–rotating isochrones *younger* by 0.1 dex than ages labelled at bottom. So it appears that younger slow–rotating isochrones are needed to account for the blue upper main sequence stars. See text for details.

Also NGC 1850 (Bastian et al., 2017; Correnti et al., 2017) (∼100 Myr) displays similar features. The MS split is present, requiring the presence of both rapidly–rotating and a slow–rotating populations, but, in the younger clusters, a coeval slow–rotating population does not adequately fit the color-magnitude diagram: the bMS is populated, beyond the coeval non-rotating turnoff, by stars resembling the "blue stragglers" present in some standard massive clusters (e.g. in the old galactic globular clusters, Ferraro et al., 2009). These stars can only be explained with *younger* non-rotating isochrones (at least ∼25% younger, according to the thick dashed grey isochrones plotted in Figure 1).

The results has been confirmed by detailed simulations of the color magnitude diagrams:

the brighter part of the bMS can not be reproduced with a coeval ensemble of rotating and non rotating stars[2]. In NGC 1755, inclusion of stars on a younger isochrone provides a better fit for the entire non rotating sample, managing to also account for the bluer stars at luminosity 18 $\lesssim m_{F814W} \lesssim 19$. In the clusters NGC 1866 and NGC 1850 there are also multiple turnoffs, and the simulations require both a younger blue main sequence and the presence of stars on older isochrones.

Although the fraction of 'younger' stars is only 10–15%, understanding the origin of this population may be crucial to solve the puzzle of stellar populations in Magellanic Cloud clusters. A key question here is why only slow or non–rotating stars were born in the second star formation episode. Since these main sequence stars belong to type B and early A, one should expect this population to be dominated by rapidly–rotating stars (e.g. Dufton et al., 2013), but simulations show that a younger rapidly–rotating component would be revealed by the presence of —at least a few— main sequence stars more luminous than the upper red turnoff.

4. A model proposal

We show that the "blue stragglers" in the Young Massive Clusters might 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.

Non–rotating tracks follow a similar evolution of central temperature T_c and convective core mass M_{core} *as a function of the core-hydrogen mass fraction* X_c. Mainly the *time* evolution of $X_c$is different. We then suggest that transition from fast to slow rotation will produce an adjustment of the external layers, but will not result in a dramatic readjustment of the star interior. But a star moving from the rotating to the non–rotating evolutionary track *at fixed* X_c will appear *younger*.

Figure 2 illustrates this 'age' effect. We show in 2**b** the time evolution of X_c for a few masses which evolve at the age of NGC 1866, whose color magnitude diagram is shown in 2**a**, where the location of some (labelled) masses is highlighted along the isochrones, In 2**b**, the upper and lower curves for each mass (thick lines) show, respectively, the time evolution of X_c for ω_{in}=0.9$\omega_{crit}$and for ω_{in}=0. At the cluster age (marked by a vertical line), each given mass is at a particular nuclear burning stage: less advanced for the ω_{in}=0.9ω_{crit} case (open circles), more advanced for the ω_{in}=0 case (full circles). With the rapid braking we have hypothesized, the mass location would shift from the rotating to the non rotating evolution *a fixed* X_c, so that, immediately after full braking, a star of a given mass appears "younger" than a star with the same mass but formed with no rotation. In panel **c** we show X_c versus mass for non–rotating models at the cluster age (dashed) and for an isochrone 25% younger (grey, full line). Braking of a rotating stars produces a non-rotating star approximately falling on the the nuclear evolution track of non-rotating stars 25% younger than stars non-rotating from formation.

Of course, the X_c evolution will depend on the time at which braking occurs. We have schematically considered this in 2**b**, by assuming a simple shift of the non-rotating X_c versus time evolution, starting at different times along the *rotating* evolution (dashed grey lines). For a given cluster age, 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. This is particularly important for the upper main sequence (the stars above the coeval non-rotating isochrone, which we have called "blue stragglers"). These indeed must have been fully braked "recently" (say, less than 25% of the cluster age ago), otherwhise they would have been already out of the main sequence. The braking path is shown in 2**a**, by the lines connecting the rotating location (full dots) to the braked location (open dots). Multiple turnoff stars will represent the turnoff evolution of stars which have been braked at the right time to be now in the latest phases

[2] For this and following results see the Extended Data in D'Antona et al. (2017).

of core H–burning, such as, for example, the 3.5 $M_\odot$. This mass will be on the younger blue main sequence of NGC 1866 if it has been braked very recently, or in post–turnoff if braked within an age of $\sim 1.2\times 10^8$yr (see the location of the star symbol in the panels of Figure 2), reaching $X_c<0.1$ at the cluster age of 200 Myr. The piling up of slowly-rotating stars braked at different ages is the reason why the turnoff of the non rotating stars is significantly populated, at the age of NGC 1856 (D'Antona et al., 2015), while it is not present in the younger clusters.

Full braking of the external layers (corresponding to the bMS stage) is possibly achieved by only a fraction of braking stars, and the "older" stars of the extended turnoff may be directly evolving from the rotating main sequence and not from the bMS.

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 (Kopal, 1968), the synchronization time increases with the age of the binary system (Zahn, 1977, 2008), but we can expect that the detailed behavior of angular momentum transfer and chemical mixing at the edge of the convective core is 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 which may vary from cluster to cluster, possibly including the location of the star within the cluster. For instance, the bMS fraction increases in the external parts of NGC 1866 (Milone et al., 2017), while it does not vary with the distance from the cluster center in other clusters (Li et al., 2017; Correnti et al., 2017).

In conclusions, the braking hypothesis justifies both the presence of "younger" bMS stars, and the presence of "older" turnoffs, supporting the idea that rotation and its evolution, and not age differences, are at the basis of the split main sequences, the multiple turnoffs and the younger blue main sequence stars. Nevertheless, quantitatively the whole extension of the eMSTO is not justified by the differences accounted for by rotation in the Geneva isochrones (Goudfrooij et al., 2017) taken at face value. We should be aware that the evolution of rotating models depends on several parameters adopted in the description of the rotational mixing (Yang et al., 2013). The Geneva models adopted in the present work were calculated with values of parameters (in particular the parameters involved in the transfer and losses of angular momentum and associated chemical mixing, Ekström et al., 2012) falling in the range of possible reasonable choices but for which alternative options could be considered. Although the models provide a very good overall fit to the color-magnitude features of these clusters, slightly different assumptions for some of the model parameters may revise the quantitative analysis and solve this and other subtle problems posed by the data. For instance, if the projection effect is more extreme than modeled (Georgy et al., 2014), the displacement of observational points from the fast rotating isochrones would be larger, not only in $T_{\rm eff}$ (explaining the redder colors) but also in luminosity, and the rotating isochrones which best reproduce the data may result to be *older*. The non-rotating isochrones are not affected by projection, so older non–rotating isochrones will be needed for coevality.

Another possibility is that braking itself implies a mechanism for slowing down the stellar core, which, in the end, may cause strong shear in the outer layers, and produce even more mixing than in the standard rapidly rotating models. This would be a welcome feature, because the formal age of the blue turnoffs in NGC 1866 and NGC 1850 is much younger than predicted by the $\delta\log{\rm age}\simeq 0.1$ difference between the rapidly rotating and the non rotating isochrones. If chemical mixing effect in the braked stars is *more efficient*, the turnoff luminosity difference between the non-rotating and rotating isochrones would become larger, and explain why we need older isochrones to fit the dimmer turnoffs.

Our model works well for young clusters, where we see the evolution of stars of type B and early A. From Figure 1 we see that the bMS and rMS are no longer split at the magni-

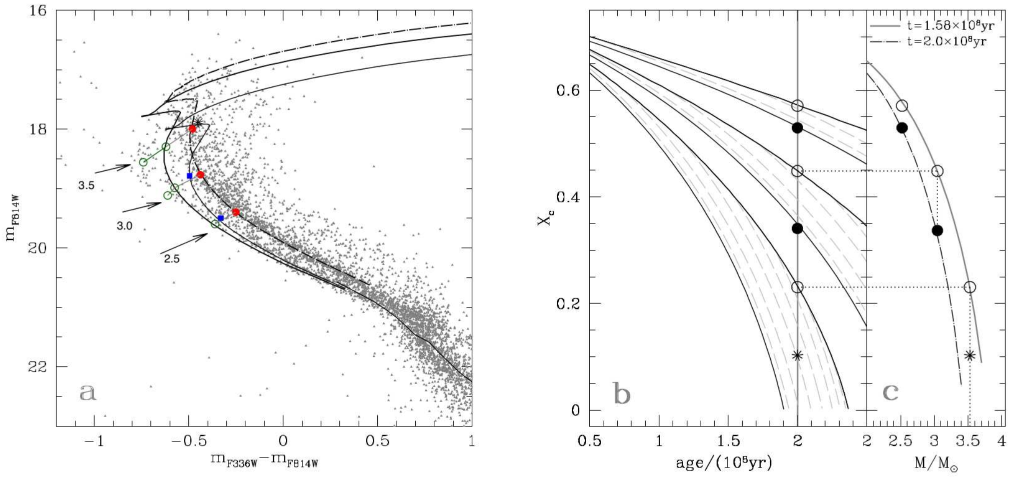

Fig. 2. Panel **a** shows the observed data, the isochrones at the cluster age (dashed with red dots for ω_{in}=0.9ω_{crit}, where ω_{crit} is the break up angular velocity, full line with blue squares for ω_{in}=0) and the ω_{in}=0 isochrone 0.1 dex younger (full line with green open circles), on which the mass points corresponding to the X_c(t) evolutions of the panels b and c are highlighted. **b**: core hydrogen content X_c as function of time in units of 100 Myr, for masses 2.5, 3 and 3.5 $M_\odot$, from bottom to top. For each mass, the upper line corresponds to ω_{in}=0.9ω_{crit}; the lower line is the ω_{in}=0 evolution. The nuclear burning stage reached at the age of the clusters is marked by open (full) dots for the rotating (non rotating) stage; the dots are also shown in **c**, in the plane X_c versus mass, where we see that the rotating (open dots) location is along a younger *non rotating* isochrone, labelled at the top. The asterisks in **b** and **c** mark the evolutionary stage of a star that braked about 70 Myr ago, so that it is now evolving past the turnoff (asterisk in **a**).

tudes where the main sequence shows a kink, which is due to the appearance of convective surface layers at $T_{eff}\lesssim$7000 K (e.g. D'Antona et al., 2002). Both the initial distribution of rotational velocities and the temporal evolution of angular momentum will be different for these stars (M$\lesssim$ 1.7 $M_\odot$), so we can not directly extend the model to the ages of 1–3 Gyr, where typical clusters with extended main sequence turnoffs are found. On the other hand, a distribution of initial stellar rotations will imply also here different evolutionary times for each mass, and may result in an apparent spread of ages, like in the younger clusters. Even if no large rotational differences are still present at 1–3 Gyr of age, the nuclear evolution differences already set into the evolution will cause the turnoff spread.

5. Conclusions

Concerning the ancient globular cluster issue, two considerations are due:

1) if there is no age spread in young globulars, the phenomena we are looking for are very different. We remarked that an age difference (from a few to a hundred million years) is required by present models for the formation of chemical differences among the ancient clusters populations;
2) the present analysis shows that the evolution of stars of intermediate – high mass in proto globular clusters depends on rotation and its braking to an extent which may affect the timing and modalities of multiple population formation, and can not be ignored.

The conclusion of our analysis suggests a single answer to the many questions raised by the puzzling features observed in the color magnitude diagrams of clusters in the Magellanic Clouds. All the observed features are due to stellar evolution in a coeval population of stars which begin their life rotating: either rapidly, if they are B or early A stars, or with a rotational spread, if they are stars of smaller mass. Our model predicts that the bMS stars should be slowly rotating, contrary to the rMS stars. A confirmation of this comes from observations: the Hα emission typical of these stars (Be stage) is mostly confined to the red turnoff stars, as seen in the spectrophotometric observations by Bastian et al. (2017), and mainly in the spectroscopic Hα detection in the redder TO stars only in NGC 1866 (Dupree et al., 2017). On the contrary, surface abundance anomalies due to the effect of rotational mixing should be expected also for the luminous bMS stars, if they are not slowly rotating from the birth, but have indeed been braked.

Rotational evolution produces different timescales for the core–H 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 which appear to be *younger* than the bulk of stars, dated on the basis of the rotating turnoff. Existing set of models describing rotation are in qualitative good agreement with this interpretation, but we warn that further modeling is necessary. The evolution in older (one to two billion years) clusters is similar, although the initial rotation distribution may have been different in stars born with smaller initial masses, below $\sim 1.7\, M_{\odot}$.

Multiple populations in ancient globular clusters are not the same as those in the Magellanic Cloud young clusters, but what we have learned about evolution of intermediate mass stars in these latter must be kept in mind when modeling the first phases of evolution of the former ones.

Future observations are needed to study in more detail the percentage of slow versus fast populations, so that also the physics of the braking process will be highlighted.

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