Can rotation explain the multiple main sequence turn-offs of Magellanic Cloud star clusters?

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ABSTRACT

Many intermediate age star clusters in the Magellanic Clouds present multiple main sequence turn-offs (MMSTO), which challenge the classical idea that star formation in such objects took place over short timescales. It has been recently suggested that the presence of fast rotators among main sequence stars could be the cause of such features (Bastian & de Mink 2009), hence relaxing the need for extended periods of star formation. In this letter, we compute evolutionary tracks and isochrones of models with and without rotation. We find that, for the same age and input physics, both kinds of models present turn-offs with an almost identical position in the colour-magnitude diagrams. As a consequence, a dispersion of rotational velocities in coeval ensembles of stars could not explain the presence of MMSTOs. We construct several synthetic colour-magnitude diagrams for the different kinds of tracks and combinations of them. The models that best reproduce the morphology of observed MMSTOs are clearly those assuming a significant spread in the stellar ages – as long as \( \sim 400 \) Myr – added to a moderate amount of convective core overshooting. Only these models produce the detailed “golf club” shape of observed MMSTOs. A spread in rotational velocities alone cannot do anything similar. We also discuss models involving a mixture of stars with and without overshooting, as an additional scenario to producing MMSTOs with coeval populations. We find that they produce turn-offs with a varying extension in the CMD direction perpendicular to the lower main sequence, which are clearly not present in observed MMSTOs.

Key words: Stars: evolution – Hertzsprung-Russell (HR) and C-M diagrams

1 INTRODUCTION

There is now conclusive evidence that many star clusters in the Magellanic Clouds present double or multiple main sequence turn-offs (MMSTO). The first hints of this phenomenon have been advanced by Bertelli et al. (2003) and Baume et al. (2007), and were based on ground-based data for the LMC clusters NGC 2173 and NGC 2154. Much more impressive and conclusive, however, were the evidences brought by Mackey & Broby Nielsen (2007), Mackey et al. (2008), Goudfrooij et al. (2009) for the clusters NGC 1846, NGC 1806, and NGC 1783 in the LMC, and Glatt et al. (2008) for NGC 419 in the SMC, based on much deeper photometry obtained with the Advanced Camera for Surveys (ACS) onboard the Hubble Space Telescope (HST). In all these cases, the presence of a broad or MMSTO clearly stands out even from a visual inspection of the CMDs. Milone et al. (2009) revised the available ACS photometry for 16 intermediate-age LMC clusters, finding evidence for broad turn-offs in about 70% of them.

The easiest interpretation of MMSTOs is that these clusters contain two or more generations of stars formed one after the other, over a time span of a few hundreds of Myr. This is indeed the interpretation adopted by the above-mentioned works. In support of this interpretation, there is the fact that a subsample of the intermediate-age clusters contain a dual clump of red giants (Girardi et al. 2009), indicative of both the onset of electron degeneracy in stellar cores, and of a \( \sim 0.15 \) M\(_{\odot}\) spread in turn-off masses which is compatible with the one indicated by the color spread in the turn-off region (Rubele et al. 2010, and work in preparation).

This interpretation however is not an easy one, when one considers the challenges it poses to the theory of star and cluster formation (see e.g. Goudfrooij et al. 2009, Conroy & Spergel 2010). Note also that the prolonged star formation probably occurred in situ, within the relatively shallow potential well of \( \lesssim 10^5 \) M\(_{\odot}\) clusters, and are not due to the merging of different clusters (Goudfrooij et al. 2009).

There is, however, an amazing coincidence regarding the age scales in all these cases. For all LMC clusters with the clear presence of MMSTOs in the above-mentioned papers, the age interval between the youngest and oldest turn-off ranges from about 150 to \( \sim 300 \) Myr, whereas the clusters themselves have all ages between 1 and 2 Gyr (see Milone et al. 2009). NGC 419 in the SMC indicates a maximum age spread of 700 Myr, but again for a mean age
of 1.5 Gyr (Rubele et al. 2010). In terms of CMD features, the MMSTOs always cover a magnitude range of about $\sim 0.5$ mag in passbands like $V$ or $I$, and $\sim 0.15$ mag in colours like $V-I$. The MMSTO phenomenon is observed in star clusters located overall over the LMC disk and also in the SMC, although it seems to be preferentially observed in the most massive objects (Conroy & Spergel 2010). The homogeneity in the mean ages of clusters with MMSTOs could be indicating dramatic large-scale events in the past history of the Magellanic Clouds, that could have affected the formation of many of its more massive clusters in a similar way. Or, perhaps, this coincidence is simply suggesting us to look for a completely different interpretation to the MMSTO phenomenon.

Bastian & de Mink (2009) have so far advanced the only alternative explanation for such CMD features, namely that the MMSTOs appear in aggregates of coeval stars, due to the color dispersion caused by the presence of fast rotators among the main-sequence stars. Their suggestion is based on simple considerations about the shape of stellar evolutionary tracks with and without rotation, on some observational facts, and on some less well-justified assumptions, namely that:

- a significant fraction of main sequence stars rotate with velocities of about $\sim 0.4$ times the critical break up velocity, $\Omega_{\text{crit}}$ (see Royer et al. 2007);
- rotation causes stars to shift, in general, to redder colours and slightly brighter luminosities in CMDs;
- for the most massive stars, close to the MSTO, the effect of rotation is quite similar throughout the main-sequence evolution, so that the effects are considered as displayed when stars reach the end of the main sequence;
- the effect of rotation gets less important at smaller masses, and disappears for masses smaller than $\sim 1.2 \, M_\odot$.

Note that the combination of all these different effects is required to explain the shape of the observed MMSTOs. In addition, strongly bi-modal distributions of rotational velocities are needed to explain the few cases in which the turn-off appear as a double feature.

In this paper, we investigate whether rotation does really behave in the way suggested by Bastian & de Mink (2009). Our analysis is based on isochrones computed with detailed models of rotating stars (Sect. 2), and do not suffer from the approximations adopted by them. In Sect. 3 we compare the performance of coeval models with a dispersion of rotation, with that of non rotating models with a dispersion of ages, in producing the MMSTO feature observed in the LMC cluster NGC 1846. The basic conclusions are discussed in Sect. 4.

2 MODELS OF ROTATING STARS AND ISOCHRONES

We start computing a series of evolutionary tracks with initial masses in the interval relevant for MMSTOs. An initial heavy elements mass fraction of $Z = 0.008$, suitable for LMC populations of young-to-intermediate ages, is adopted.

The main-sequence evolution of models with and without rotation is computed by using the Geneva stellar evolution code (Eggenberger et al. 2008). The standard mixing-length formalism for convection (Böhm-Vitense 1958) is used with a solar calibrated value of the mixing-length parameter. Overshooting from the convective core into the surrounding radiatively stable layers is not included. Rotating models are computed with an initial velocity on the ZAMS of 150 km s$^{-1}$, which corresponds to a typical value for rotating stars in the mass interval between 1.5 and 3 $M_\odot$ studied here (e.g. Royer et al. 2007). Note that the ratio $\omega = \Omega/\Omega_{\text{crit}}$ of these models remains always inferior to 0.7, so that the effects related to the variation with colatitude of the effective temperature are negligible (Ekström et al. 2008). These models include a comprehensive treatment of shellular rotation (Zahn 1992) and meridional circulation is treated as a truly advective process (for more details, see e.g. Eggenberger et al. 2010). The rotating and non-rotating models share the same initial parameters except for the inclusion of shellular rotation.

These two sets are complemented by one without rotation but with overshooting from the convective core, computed with the same code. The overshooting parameter is set to $\alpha_{\text{ov}} = 0.25$ pressure scale heights (see Maeder & Meynet 1988 for details).

The tracks are presented in Fig. 1. They cover all evolutionary

![Figure 1. The evolutionary tracks computed for this work (dark solid lines), together with isochrones derived from them (narrow lines, in color in the electronic version), for the non-rotating, rotating, and overshooting cases (from left to right, respectively). The isochrones ages go, from top to bottom, from $\log(t/\text{yr}) = 8.5$ to 9.3 at steps of 0.1 dex. As a reference to the eye, the isochrones with ages of 0.5, 1 and 2 Gyr are marked with a different colour.](image)
stages from the zero-age main sequence (ZAMS) up to either He-ignition, or the RGB-bump of less massive stars.

The same figure presents a set of isochrones derived from them. Despite the relatively large mass interval between clusters, the interpolation algorithm (the same as in Girardi et al. 2000) works very well and produces isochrones with all the fine details of the original tracks, especially along the MSTO region. In order to include the lower main sequence in the isochrones, the new grids of tracks have been complemented with Girardi et al. 2000 non-rotating tracks of $M < 1.0 M_\odot$, which, for the ages considered in this work, are always very close to the ZAMS.

The two sets of tracks without overshooting make the basic set with which we will discuss the effect of rotation on the CMDs. We recall that these tracks do follow, qualitatively, the changes in the stellar $T_{\text{eff}}$ due to rotation that are at the base of Bastian & de Mink (2009) work.

3 SYNTHEtic CMDS AND COMPARISON WITH DATA

Let us now consider the effect that rotation has in the CMDs of star clusters. Let us assume for the moment that all the stars in clusters with multiple turn-offs have exactly the same age and initial chemical composition. The theoretical entities suitable to describe such a situation are the stellar isochrones. In the following, we will center our discussion on isochrones computed for a single age of 1.58 Gyr, however we advance that very similar conclusions would be obtained for any age between 1 and 2 Gyr.

In the left panel of Fig. 2, we superpose isochrones of the same age computed for the 3 cases mentioned in Sect. 2 in the HR diagram. The result is somewhat surprising: contrarily to what sustained in Bastian & de Mink (2009), models with rotation do not present a cooler and fainter turn-off with respect to their non-rotating counterparts. Instead, they have a slightly hotter and brighter turn-off. This result cannot be easily inferred while looking only at the evolutionary tracks in Fig. 1 which at first sight seem to suggest that rotating models have a broader main sequence, hence being able to extend to cooler temperatures, as sustained in Bastian & de Mink (2009). This is true only for pairs of evolutionary tracks of the same mass. What we see in the isochrones is different, it is the combined effect of changes in the morphology of the evolutionary tracks, and of the changes in their lifetimes.

The increase in the main sequence lifetimes caused by rotation, in particular, is quite remarkable (see Palacios et al. 2003, Eggenberger et al. 2010) and constitutes one of the main factors in play here. As discussed in Eggenberger et al. 2010, classical models with a $v_{\text{rot}} = 150$ km/s have a similar increase in their main sequence lifetimes as models with a moderate amount of overshooting, that is $v_{\text{rot}} = 0.1$. Such an increase in the lifetimes of rotating stars has been ignored in Bastian & de Mink (2009), and this has been determinant in leading to their different conclusions.

In the right panel of Fig. 2, we present synthetic HR diagrams corresponding to 1.58-Gyr old clusters with and without rotation – in this latter case assuming that all stars rotate with the same initial velocity – and with overshooting, for a total mass of $10^4 M_\odot$ following the Chabrier (2001) log-normal IMF. This panel clearly evinces what are the regions of the diagram effectively populated by stars. In particular, one may notice that the differences between non-rotating and rotating models is not dramatic, if one considers only the region where the MSTO is drawn.

Then, using the TRILEGAL code (Girardi et al. 2005), we simulate populations in the CMD in which MMSTOs are usually observed, namely the F555W vs. F555W − F814W (approximately $V$ vs. $V − I$) diagram for the filters in the the ACS/WFC camera onboard HST. Such simulations are shown in Fig. 3. The bolometric correction tables in use are described in Girardi et al. 2005. The simulated photometry is displaced by the absolute distance modulus of 18.5 mag and a $V$-band foreground extinction 0.2 mag, which are values typical of LMC star clusters. Then, photometric errors of $\sigma = 0.01$ mag are applied to the photometry, so as to help in the visualisation of the densest parts of the CMDs without however modifying their morphology in any appreciable way. All simulations include a fraction of 20% of binaries with mass ratios uniformly distributed between 0.4 and 1. The total mass is assumed to be of $2.4 \times 10^4 M_\odot$, following a Chabrier (2001) log-normal IMF.

The models in the top row of Fig. 3 from (a) to (c), are for a single age of 1.58 Gyr, and using each one of the 3 sets of tracks presented in this work. These top panels illustrate the modest effect that binaries have in these CMDs, in a way similar to the synthetic CMDs already presented by many authors (e.g. Bertelli et al. 2003, Kerber et al. 2007, Mackey et al. 2008).

Panels in the second row of Fig. 3 represent attempts to produce MMSTOs by adding stellar models with different properties but again for the same single age. Panel (d) shows the case of models with and without rotation and otherwise identical physics. This

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2 Throughout this paper, turn-off is intended as the tip of the locus continuously populated by stars along the main sequence.
Figure 3. Panels (a)–(i) present synthetic CMDs illustrating the effect of different prescriptions regarding the distributions of initial rotational velocities \( v_{\text{rot}} \), overshooting efficiency \( \alpha_{\text{ov}} \), and ages \( t \) among the clusters stars. All these models assume a modest fraction of binaries and small photometric errors. For comparison, panel (j) shows the ACS/WFC data for the central region of the LMC star cluster NGC 1846 (from Goudfrooij et al. 2009), with its well defined MMSTO. For each panel, we provide the number of objects in the turn-off region defined by \( 19 < F814W < 21.5 \) and \( 0.2 < F555 - F814W < 0.8 \). The top row shows models for a single age and for (a) no rotation without overshooting, (b) rotation without overshooting, and (c) no rotation without overshooting. The second row show mixed models, again for a single age: a mixture of (d) rotating and non rotating stars, without overshooting, (e) stars with and without overshooting, without rotation, and (f) non-rotating stars with overshooting, together with rotating stars without overshooting. It is evident that none of these cases produces the peculiar “golf club” shape of the observed MMSTO. In the third row, from (g) to (i), we have the same models as on the top row, but now with the star formation spanning and interval of 400 Myr. The similarity with the observed MMSTO is evident, especially in the panel (i), corresponding to models with a moderate efficiency of convective overshooting but no rotation.
corresponds to the situation favoured by Bastian & de Mink (2009) as being at the origin of MMSTOs. As can be noticed, our results produce a dramatically narrow MSTO, clearly very different from both the observed one and those illustrated in Bastian & de Mink (2009).

Panel (e) instead explores the case in which there is a mixture of stars with different efficiencies of core overshooting, but observed at the same age. In this case the MSTO opens into a composite feature, with two distinct MSTOs. However, the brighter MSTO (corresponding to the overshooting models) is clearly much more extended to larger radii (towards the top-right corner of the figure) than the fainter MSTO. This again contrasts with observations, in which the MMSTOs are seen to have about the same extension in the direction perpendicular to the lower main sequence.

Finally, the panel (f) shows the combination of non-rotating stars with overshooting, together with rotating stars without overshooting, so as to simulate a hypothetical reduction of the extent of the overshooting region driven by rotation. This combination produces CMDs slightly more similar to the observed one, but does not reproduce its detailed shape; in particular, it can be noticed that the fainter turn-off, corresponding to rotating models without overshooting, is again less extended in the direction perpendicular to the main sequence than the brighter one. This discrepancy cannot be remediated imposing that the fast rotators have some residual velocities, which could produce a CMD-fitting that even approaches the observed MMSTO.

The third row of Fig. 3, from (g) to (i), presents the models derived from each set of homogeneous tracks, but now assuming that star formation proceeded at a constant rate in the age interval from 1.3 to 1.7 Myr. The similarity with the observed MMSTO is now evident, especially in the panel (i), corresponding to models with a single efficiency of overshooting but no rotation.

4 FINAL CONSIDERATIONS

The present work demonstrates that stellar rotation, as predicted by detailed evolutionary models, produces features in CMDs which are quite different from those illustrated in Bastian & de Mink (2009). We find that, despite the changes that rotation causes in the HR diagram of evolutionary tracks, their longer lifetimes make the isochrones derived from these tracks to have a MSTO position almost indistinguishable from those derived from non-rotating models. It follows that coeval isochrones derived from rotating plus non-rotating tracks – with otherwise identical physics – are not able to describe the detailed shape of the observed MMSTOs in Magellanic Cloud clusters.

On the other hand, Fig. 3 and the careful CMD-reconstruction work by Rubele et al. (2010) and Rubele et al. (2011) demonstrate that the other possible explanation for the origin of MMSTOs – namely prolonged histories of star formation taking place in the clusters – does provide excellent qualitative and quantitative fits of the CMD in the clusters NGC 419 and NGC 1751. This despite these latter clusters present dual red clumps in addition to MMSTOs, which represents a big additional challenge to CMD-fitting algorithms. It is hardly conceivable, after the results from this work, that a coeval population of stars with a dispersion in their rotational velocities, could produce a CMD-fitting that even approaches the quality reached in those CMD-fitting works. We are left with no better alternative, for the moment, than accepting that prolonged star formation has probably occurred in these clusters, although we are aware of the great challenges it represents for dynamical models of stellar and cluster formation.

We are also aware that stellar rotation – and fast rotators – occurs anyway among the cluster stars. What is evinced by our models is simply that the effect of fast rotation on CMDs is modest and more likely similar to the colour and magnitude dispersion caused by binaries, rather than the dramatic drawing of MMSTOs advocated by Bastian & de Mink (2009). Following our reasoning, the detection of fast rotators at the MMSTOs is just expected, and would not support Bastian & de Mink (2009) hypothesis unless the fast rotators are all observed at the reddest MSTO. This is an aspect to be tackled by future observations of rotation in cluster stars, as those recently announced by Platais et al. (2010) for the open cluster Tr 20.

In conclusion, the explanation based on prolonged periods of SFH seems to be the only surviving one, in this moment, to explain the origin of MMSTOs in Magellanic Cloud clusters. Despite the perplexities and difficulties it may cause to star formation theories, the presence of dual red clumps in some clusters (Girardi et al. 2009) and the high quality of the results obtained from the modelling of their CMDs (Rubele et al. 2010; Rubele et al. 2011) strongly favour this interpretation. Detection of chemical self-enrichment in clusters with MMSTOs would likely be the decisive data to confirm or disprove this explanation.

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