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Extended main-sequence turnoffs in young massive clusters in the Magellanic Cloud

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Abstract. The extended main-sequence turnoff region (eMSTO) shown as a common feature of young massive cluster (YMCs) in the Magellanic Clouds. Here we report the UV-optical colour-magnitude diagrams of four Large and Small Magellanic Cloud YMCs, NGC 330, NGC 1805, NGC 1818, and NGC 2164, based on high-resolution Hubble Space Telescope observations. We found that they all exhibit eMSTOs, which cannot be explained by stellar rotation alone. Adopting an age spread of 35–50 Myr can relax this difficulty. We suggest that stars in these clusters may be characterised by different ages and rotations, but the origin of the age spread remains unclear.

Key words. globular clusters: individual: NGC 330, NGC 1805, NGC 1818, NGC 2164 – Hertzsprung-Russell and C-M diagrams – Magellanic Clouds

1. Introduction

Recently, lots of studies have found that the colour-magnitude diagrams (CMDs) of some young massive clusters (YMCs, with ages $\leq$300 Myr) in the Large and Small Magellanic Cloud (LMC, SMC) harbour an extended main-sequence turnoff (eMSTO) region (e.g., Milone et al. 2015, 2016, 2017). These findings have challenged the traditional picture that the CMD of star clusters can be described by a simple isochrone. The explanation for the eMSTO is various. A prevailing scenario suggests that the observed eMSTO stars belong to a coeval stellar population with different stellar rotation rates (Li et al. 2014a,b; Bastian et al. 2016). It is also suggested that for at least some clusters, the eMSTO is caused by a degree of age difference among their MSTO stars (Piatti & Cole 2017).

In this article, we present our recent observations of the CMDs for four YMCs, NGC

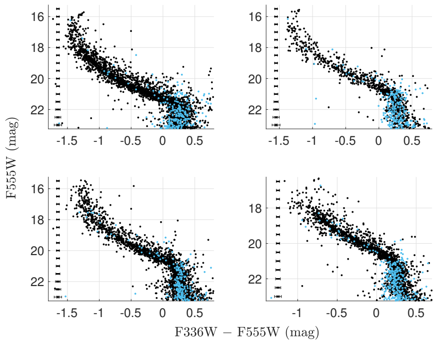

Fig. 1. Processed CMDs of NGC 330 (top-left), NGC 1805 (top-right), NGC 1818 (bottom-left), and NGC 2164 (bottom-right). The reference field stars are indicated by blue circles as well. The average (1σ) photometric uncertainties are shown on the left-hand sides of all panels.

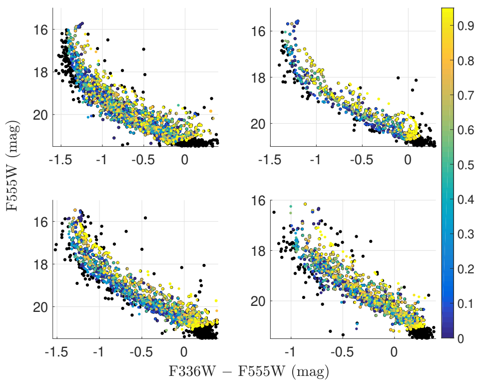

Fig. 2. Synthetic CMDs for NGC 330, NGC 1805, NGC 1818, and NGC 2164. Colours indicates the rotation rates of the simulated stars. The observed stars are attached as well (black dots).

330, NGC 1805, NGC 1818 and NGC 2164, which belong to the SMC and LMC. We found that all of them exhibit an eMSTO in both the ultraviolet (UV) and optical CMDs. We test whether the observations can be explained by assuming an age spread, a dispersion in stellar rotation rates, or a combination of both.

2. Main results

The data used in this work were obtained by the Hubble Space Telescope (*HST*) through the Ultraviolet and Visual Channel of the Wide Field Channel 3 (UVIS/WFC3) and the Wide Field and Planetary Camera 2 (WFPC2). The resulting CMDs are filtered in the passbands of F336W (based on UVIS/WFC3) and F555W (based on WFPC2). The photometry were performed by using the DOLPHOT 2.0 package[1]. The resulting stellar catalogues have been carefully corrected as regards sharpness, crowding and differential extinction. In Fig.1 we provide the CMDs of these four clusters, as well as the CMDs of their nearby referenced field.

As shown in Fig.1, all clusters exhibit eMSTO regions. The contamination by field stars is minimal because the cluster's broadened MSTO regions are bright. Also we confirmed that the observed eMSTO regions cannot be explained by photometric uncertainties alone.

We used a sample of Geneva SYCLIST isochrones with different stellar rotation rates to fit our observations (Ekström et al. 2012; Georgy et al. 2014)[2]. Based on the best-fit isochrones, we constructed for each cluster a synthetic CMD where we have mimicked the same photometric uncertainties as pertaining to the real data.

Since the average binary fraction in these four clusters is ∼48% (Li et al. 2013a), we included in the synthetic CMDs 50% of unresolved binaries. By using these procedures, for each CMD, we generated more than 3×10^6 artificial stars. Then for each observed star, we randomly selected one of its 10 nearest fake stars as representative. Finally, each simulated CMD has been compared with the observed one. We expect that, if the clusters host a simple population of stars with different rotation rates, the resulting synthetic CMDs and the observed CMDs should be very similar. Our results are present in Fig.2.

Fig.2 shows that a coeval stellar population characterised by different stellar rotation rates alone can not fully explain the observed

[1] `http://americano.dolphinsim.com/dolphot/`

[2] `https://obswww.unige.ch/Recherche/evoldb/index/`

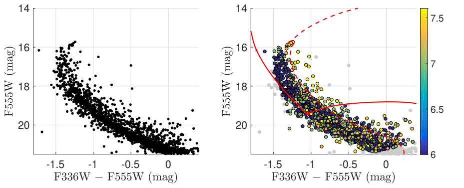

Fig. 3. (Left) Observed CMD of NGC 330. (Right) The corresponding synthetic CMD with different ages and rotational rates. The observed CMD is attached as well (grey dots). Colours represent the ages of the simulated stars (in logarithm scale).

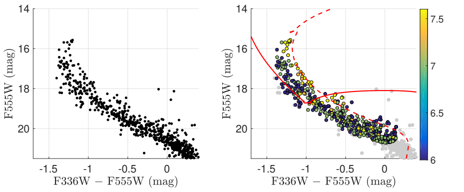

Fig. 4. The same as Fig.3, but for cluster NGC 1805.

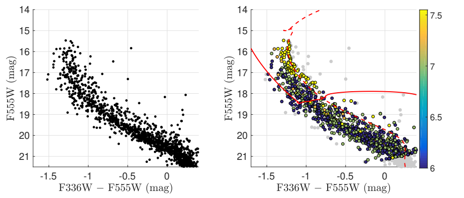

Fig. 5. The same as Fig.3, but for cluster NGC 1818.

eMSTOs. Indeed, in each cluster, there is an excess of blue MS stars that cannot be reproduced by the simulation. We subsequently explore if a combination of stellar rotation and age spread better reproduce the observations. To do this, we generated artificial stars that are both different in age and rotation, with the same photometric uncertainties as the observed CMDs and 50% unresolved binaries again. The performance of this combined model for NGC 330, NGC 1805, NGC 1818 and NGC 2164 are presented in Fig.3–6.

For both cluster, our simulation shows that the contributions s from the young and old population stars are very different in the MSTO region. Lots of young stars are located in the blue part of the MSTO region and old stars mainly

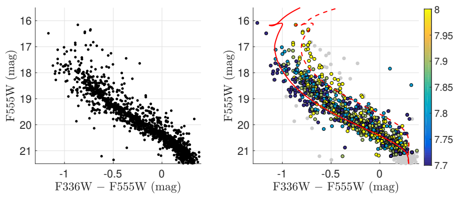

Fig. 6. The same as Fig.3, but for cluster NGC 2164.

located in the red part of the MSTO. Most blue-MS stars that are not consistent with simple stellar populations, as shown in Fig.2, are reproduced in our multi-aged stellar population models. These results demonstrate that in order to reproduce the bluest MS stars, a fraction of young stars is indeed required.

For NGC 330, NGC 1805, NGC 1818 and NGC 2164, the required age ranges are 0–40 Myr, 0–40 Myr, 0–35 Myr and 50–100 Myr, respectively. In the right panels of Fig.3–6, we have plotted the corresponding isochrones with these boundary ages. However, although the synthetic CMDs with different ages and stellar rotations can ideally reproduce our observations, their corresponding isochrones reveal serious issue. A zero-age stellar population should contain a large number of massive O-type and pre-MS stars. However, we did not found any obvious evidence of such objects in our clusters.

3. Physical discussion

D'Antona et al. (2017) proposed that the observed blue-MS stars were initially fast rotators but were recently braked. These decelerated stars would be less advanced in their nuclear burning stage than those were initially non-rotating stars. If their explanation were on the right track, stellar rotation would be still a viable scenario that is responsible for the observed eMSTO regions of our sample clusters.

In our test models we invoked simple-aged stellar populations. But if this would imply that all of our sample clusters have extended star-formation histories remains unclear. The absence of O-type and pre-MS stars contradicts the ongoing star-formation hypothesis. To reproduce the observed MSs, we have to adopt a mass truncation for the young stellar population in our model, which is contrived indeed. Also our sample clusters are too light to retain long star-formation episodes by accreting their initial gas. By using the equation from Georgiev et al. (2009),

$$M_{\rm cl} \approx 100 v_{\rm esc}^2 r_{\rm h}, \tag{1}$$

we estimated that the minimum masses required to retain the initial gas are more than 100 times larger than their current masses. The dynamical evaporation would not dramatically affect our clusters since the typical timescale for such mass loss is expressed in units of billions of years (McLaughlin & Fall 2008; Li et al. 2016b).

Another possible explanation is that these puzzling blue MS stars are blue straggler stars (BSSs). Because BSSs are produced through binary evolution or stellar collisions, their maximum mass would not exceed twice the mass of TO stars. Also because BSSs were not formed through the collapse of a giant molecular cloud, they would not experience the pre-MS stage. This may explain the absence of O-type and pre-MS stars in our sample clusters.

As suggested by D'Antona et al. (2015, 2017), the observed blue-MS stars may hide a binary component. Their period may range from 4 to 500 days, corresponding to a distribution of semi-major axis that spans from a = 0.06 to 3.23 au. This would indicate a potential population for mass-transfer BSS candidates. This was also suggested by Yang et al. (2011), who suggested that the eMSTO regions in intermediate-age star clusters (e.g., Milone et al. 2009) may include significant contributions from binary evolutions. A disadvantage of this scenario is that the fraction of BSSs with respect to the bulk-population stars is usually small (e.g., for the old LMC GCs, see Li et al. 2013b; Mackey et al. 2006). Although there are no direct observations of BSSs in YMCs, Xin et al. (2007) found that the specific frequency of BSSs of Galactic open clusters ranges from 1% to 20%. This is also reported by numerical simulations (Lu et al. 2011; Hypki & Giersz 2013).

4. Summary

In this article, we have studied the CMDs of the clusters NGC 330, NGC 1805, NGC 1818, and NGC 2164. Our main results are summarised below:

* All our sample clusters exhibit eMSTO regions, which cannot be explained by a coeval stellar populations with homogeneous chemical content and unresolved binaries.
* A coeval population of stars with a spread in the stellar rotation velocities can not reproduce the observed wide MSs. To match our observations, an age spread of 35–50 Myr is required.
* The apparent age spread is unlikely owing to continuous star formation. Because we did not detect any evidence of ongoing star formation in these clusters. In their CMDs, there are neither very massive O-type stars nor pre-MS stars, which are predicted by the extended star formation scenario. In addition, these clusters' masses are too small to sustain extended star-formation episodes.

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