Discovery of Extended Main Sequence Turnoffs in Galactic Open Clusters

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Abstract

The color–magnitude diagrams (CMDs) of Galactic open clusters are widely considered to be the prototypes of single stellar populations. By using photometry in ultraviolet and optical bands we discovered that the nearby young cluster NGC 6705 (M11) exhibits an extended main-sequence turnoff (eMSTO) and a broadened main sequence (MS). This is the first evidence of multiple stellar populations in a Galactic open cluster. By using high-resolution Very Large Telescope (VLT) spectra we provide direct evidence that the multiple sequences along the CMD correspond to stellar populations with different rotation rates. Specifically, the blue MS (bMS) is formed of slow-rotating stars, while red-MS (rMS) stars are fast rotators. Moreover, we exploit photometry from Gaia data release 2 (DR2) to show that three Galactic open clusters, namely NGC 2099, NGC 2360, and NGC 2818, exhibit the eMSTO, thus suggesting that it is a common feature among these objects. Our previous work on the Large Magellanic Cloud star cluster NGC 1818 shows that slowly and rapidly rotating stars populate the bMS and rMS observed in its CMD. The similarities between M11 and the young clusters of the Magellanic Clouds (MCs) suggest that rotation is responsible for the appearance of multiple populations in the CMDs of both Milky Way open clusters and MCs young clusters.

Key words: Hertzsprung–Russell and C–M diagrams – open clusters and associations: individual (NGC 6705, NGC 2099, NGC 2360, NGC 2818)

1. Introduction

The Galactic open clusters are considered to be the prototypes of simple stellar populations. This assumption was supported by color–magnitude diagrams (CMDs) often well reproduced by single isochrones (e.g., Kalirai et al. 2003; Bedin et al. 2010). In contrast, the CMDs of young and intermediate-age star clusters in both Magellanic Clouds (MCs) are not consistent with single isochrones. Nearly all of these clusters with ages between ~700 Myr and ~2 Gyr exhibit extended main sequence turnoff (eMSTO; e.g., Mackey & Broby Nielsen 2007; Milone et al. 2009; Goudfrooij et al. 2011, 2014); and clusters younger than ~700 Myr show both split main sequence (MS) and eMSTO (e.g., Milone et al. 2013, 2015, 2018; Correnti et al. 2015, 2017; Bastian et al. 2017; Li et al. 2017).

Stellar rotation plays a major role in the split MS and the eMSTO. The comparison between the observed CMDs of young MCs clusters and isochrones indicates that the blue MS (bMS) is consistent with a population of non-rotating or slow-rotating stars, while red-MS (rMS) stars rotate close to the critical value. According to this scenario, the fainter part of the main sequence turnoff (MSTO) is mainly populated by fast rotators, while the upper MSTO should host slow rotators (e.g., D’Antona et al. 2015). This scenario is confirmed by the large fraction of Be stars in young MCs clusters (e.g., Keller et al. 2000; Bastian et al. 2017), mostly populating the rMS and the faint MSTO (Milone et al. 2018). Spectroscopic analysis of the Large Magellanic Cloud (LMC) cluster NGC 1866 has provided direct evidence that its eMSTO hosts stars with different rotations, and that the faint MSTO is mostly populated by fast rotators (Dupree et al. 2017). High-resolution spectra have shown that the split MS of the LMC cluster NGC 1818 hosts a bMS made of slow rotators, and a rMS of stars with high rotation (Marino et al. 2018).

Stellar rotation is a common phenomenon that affects many aspects of stellar evolution, in particular for stars with \( M > 1.5-1.7 \ M_\odot \) (Meynet & Maeder 2000, and references therein). Stars with rotation rates from slow to nearly critical have been indeed reported both in field and open cluster stars (e.g., Huang et al. 2010), and the possible role of stellar rotation in causing color spreads in some open clusters was suggested by Brandt & Huang (2015a, 2015b).

We combine Strömgren photometry and spectra of the Galactic open cluster NGC 6705 (M11) to investigate its MSTO and upper MS. As estimated by Cantat-Gaudin et al. (2014), the age of this cluster ranges from 250 to 320 Myr, and its mass is between 3700 and 11,000 \( M_\odot \). We further exploit photometry, proper motions, and parallaxes from Gaia data release 2 (DR2; Gaia Collaboration et al. 2018) to search for multiple populations in Galactic open clusters NGC 2099, NGC 2360, and NGC 2818.

2. Data and Analysis

To search for multiple sequences along the CMD of M11 we used images collected with the Isaac Newton Telescope (INT) through the uvby filters as part of the Strömgren survey for asteroseismology and Galactic archeology (Casagrande et al. 2014).
Specifically, we used $10 \, \text{s} + 2 \times 20 \, \text{s} + 2 \times 50 \, \text{s} + 2 \times 120 \, \text{s}$ $u$ band, $5 \, \text{s} + 2 \times 10 \, \text{s} + 2 \times 40 \, \text{s} + 2 \times 120 \, \text{s}$ $v$ band, and $3 \times 3 \, \text{s} + 2 \times 5 \, \text{s} + 2 \times 50 \, \text{s}$ $y$ band images; stellar parallaxes and proper motions are from Gaia DR2.

The photometry and astrometry of the INT images was carried out using kitchesync (Anderson et al. 2008) modified for INT images. For each exposure we derived a grid of $3 \times 3$ empirical point spread functions (PSFs) by using the available isolated, bright, and non-saturated stars. We accounted for the spatial variation of the PSF by assuming that each star of each image is associated to a bi-linear weighted interpolation of the four nearest PSFs (Anderson & King 2000).

The fluxes of bright and faint stars have been derived by using distinct procedures. Bright stars have been measured in each exposure independently by using the best PSF model, and then averaged together. To derive fluxes and positions of faint stars, poorly constrained in the single exposures, we fitted all pixels of all exposures simultaneously (see Anderson et al. 2008). The photometry has been calibrated as in Casagrande et al. (2014, see their Section 2).

Cluster members have been selected by using proper motions and parallaxes from Gaia DR2 (see Section 3). The photometry of the cluster members has been corrected for differential reddening as in Milone et al. (2012).

The spectroscopic data consist of Fibre Large Array Multi Element Spectrograph (FLAMES)/GIRAFFE data (Pasquini et al. 2002), with setup H665 ($R \sim \lambda / \Delta \lambda \sim 17,000$), collected under the Gaia-European Southern Observatory (ESO) Survey (Gilmore et al. 2012) and publicly available on the ESO archive. From the available sample of stars observed in M11, we have selected those in the magnitude range $12.0 \leq v \leq 14.5$, which is the interval where the spread MS and MTO is observed (see Section 3). At the $H\alpha$ line wavelength, the typical signal-to-noise of the fully reduced spectra is $\sim 100$.

Projected rotational velocities $(v \sin i)$ were determined by fitting the $H\alpha$ core. A grid of hybrid non-local thermodynamic equilibrium (non-LTE) model spectra was computed using the approach discussed by Przybilla & Butler (2004a, 2004b) based on ATLAS9 model atmospheres (Kurucz 1993). Non-LTE level populations were calculated using DETAIL and synthetic spectra using SURFACE (Giddings 1981; Butler & Giddings 1985; both updated by K. Butler). The grid covers effective temperatures $T_{\text{eff}}$ from 6400 to 8800 K (step width of 200 K), with surface gravity fixed to log $g = 4.0$, which is the typical value found in the Gaia-ESO survey for these stars. The consideration of non-LTE effects, yielding a pronounced strengthening of the $H\alpha$ core, is important for avoiding a systematic bias of the $v \sin i$ in particular for slower rotators. The model spectra were convolved with a Gaussian profile to account for instrumental broadening and a rotational profile $v \sin i$ from 0 to 300 km s$^{-1}$ (step width of 200 km s$^{-1}$).

We employed a $\chi^2$ minimization of each observed spectrum around the $H\alpha$ line to simultaneously infer $T_{\text{eff}}$, primarily affecting the wings, and $v \sin i$, which has a major impact on the core. The inferred $v \sin i$ values are listed in Table 1.

The choice of atmospheric parameters has little impact on the $v \sin i$ determination. Varying log $g$ by $\pm 0.5$ dex has negligible effect, while changes in $T_{\text{eff}}$ by $\pm 200$ K result in $v \sin i$ variations of $\pm 20$ km s$^{-1}$. The major contribution to the errors is associated with the continuum placement, which introduces an internal uncertainty of $\pm 30$–40 km s$^{-1}$. Conservatively, we associate an internal error of $\pm 40$ km s$^{-1}$ to our $v \sin i$ estimates.

![Image of the document page](http://archive.eso.org/cms.html)
3. The Extended Main-sequence Turnoff of M11

The \(v-(u-v)\) CMD of stars in the M11 field is plotted in Figure 1(a). The vector-point diagram of proper motions plotted in Figure 1(b) reveals that M11 stars are clearly clustered around \((\mu_u, \cos \delta; \mu_v) = (\sim-1.57; -4.12)\) mas yr\(^{-1}\), while the proper motions of field stars exhibit a broadened distribution. As a further membership criterion, we estimated the median parallax of the proper-motion selected stars \(\sigma_{\pi} = 0.42\) mas and considered as members of M11 only stars with parallaxes within 0.17 mas (corresponding to three times the dispersion) from the median value. We verified that the selected sample of cluster members matches the M11 stars selected by Cantat-Gaudin et al. (2018).

The CMD of cluster members reveals that M11 hosts an eMSTO and a broadened, possibly split, upper MS, in close analogy with MC clusters at similar ages. The color and magnitude broadening of the eMSTO and of the upper MS are significantly larger than those expected by observational errors. The presence of these features is confirmed by the synthetic \(v\) versus \((u-v)\) CMD (Figure 1(c2)) corresponding to one single non-rotating population, which does not show any evidence of either eMSTO or spread MS. The MS region with \(v > 14.5\) is consistent with a single stellar sequence.

To further demonstrate that the eMSTO and the broadened MS are not artifacts due to residual differential reddening, we selected three groups of bMS stars, rMS stars, and eMSTO stars by hand in the \(v\) versus \(u-v\) CMD plotted in Figure 1(c1). In Figure 1(d) we plotted the magnitude combination \(u - 1.87 \cdot v + y\) against \(u - 1.58 \cdot v + 0.60 \cdot y\) for cluster members. This diagram is reddening-free by assuming for the M11 field of view the absorption coefficients by Schlegel et al. (1998). If the eMSTO and broadened MS are due to residual differential reddening, we would expect that the three stellar groups exhibit random values of the reddening-free quantities \(u - 1.87 \cdot v + y\) and \(u - 1.58 \cdot v + 0.60 \cdot y\). The fact that the three groups of bMS, rMS, and eMSTO stars are clearly separated in the reddening-free diagram demonstrates that eMSTO and broadened MS are intrinsic features of M11. Panel e shows the \(B\) versus \((U-B)\) CMD from Sung et al. (1999) corrected for differential reddening. The selected bMS, rMS, and eMSTO stars populate distinct regions of this diagram, thus corroborating the presence of multiple stellar populations in M11.

4. Rotation

The position of our spectroscopically analyzed stars on the \(v-(u-v)\) CMD is shown in the left-upper panel of Figure 2. They are distributed along the eMSTO and the broadened MS of M11, discussed in Section 3. The sidebar shows the color scale indicative of the inferred \(v\) \(\sin i\). Stars exhibiting an H\(\alpha\) emission core have been clearly indicated. Our projected rotational velocities results suggest that \(v\) \(\sin i\) values span a large range, from a few tens to more than 250 km s\(^{-1}\), and that stars with slower rotation are distributed on the bluer side of the CMD.

For comparison reasons, the synthetic CMD of Figure 1(c2) for a non-rotating stellar population has been reproduced in the left-bottom panel of Figure 2. To this non-rotating population we have added a synthetic coeval rapidly rotating population, with \(\omega = 0.9\omega_{\text{crit}}\) (Georgy et al. 2013). If a rotation regime close to the critical velocity can account for a spread in the MSTO, the split MS can only be reproduced by two stellar populations with intrinsic different stellar rotation rates.
The right panels of Figure 2 illustrate some examples of our spectral fitting. Specifically, the upper and middle panels show two bMS and rMS stars, respectively, chosen to have similar luminosities. The best-fit synthetic spectra are superimposed to each spectrum. The lower panels display the spectra of two Hα-emission stars in our sample, for which we could not infer any \( \nu \sin i \). A visual inspection of these spectra immediately suggests a different \( \nu \sin i \) for the bMS and rMS stars, having a similar luminosity but a different color. The spectral profiles of the two rMS stars are significantly broader than those of the bMS ones.

Figure 3 is a closer look at MS. The location on the CMD of the MS stars with available spectroscopy is displayed for stars 

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with $v \geq 13$. Our targets are clearly distributed on the split MS of M11, and the association with the bMS and rMS is straightforward (right-upper panel).

The $v \sin i$ histogram distributions, shown in the lower-left panel, illustrate the quite wide range for both the bMS and rMS. bMS stars do not show any value $\geq 150$ km s$^{-1}$. As $v \sin i$ values are lower limits to the real stellar rotation, depending on the inclination, more likely, a fast-rotating star has a higher $v \sin i$ than a slow rotator. Although a certain degree of overlap in $v \sin i$ between bMS and rMS might be expected because of projection effects, we cannot exclude some slower rotators among the rMS.

The left-upper panel of Figure 3 displays the $v$ magnitude versus $v \sin i$ for rMS and bMS stars. Clearly, bMS stars are slower rotators, while the rMS hosts stars with higher rotation. In the right panels we analyze the color of the MS stars as a function of $v \sin i$. To this aim we have drawn a fiducial line by eye defining the rMS on the $v-(u-v)$ CMD (upper-right panel). The difference in color between each star and the fiducial, $\Delta (u-v)$, within each of the two MSs, does not show any significant trend with $v \sin i$ (lower-right panel).

The average $v \sin i$ we obtain for the 12 bMS and the 23 rMS are $\langle v \sin i \rangle_{\text{bMS}} = 83 \pm 14$ km s$^{-1}$ ($\sigma = 46$ km s$^{-1}$) and $\langle v \sin i \rangle_{\text{rMS}} = 194 \pm 15$ km s$^{-1}$ ($\sigma = 68$ km s$^{-1}$), respectively, meaning that a difference in the rotation regimes of the two MSs exists. The mean $v \sin i$ difference is $\langle \Delta v \sin i_{\text{bMS}} - v \sin i_{\text{rMS}} \rangle = 111 \pm 21$ km s$^{-1}$.
5. Extended Main-sequence Turnoff as a Common Feature of Open Clusters: The Cases of NGC 2099, NGC 2360, and NGC 2818

Ultraviolet and optical filters are efficient tools to identify multiple sequences in the CMDs of young clusters. Although in optical filters the split MS and the eMSTO are less prominent than in the ultraviolet, these features can be detected also in purely optical photometric diagrams (e.g., Milone et al. 2013, 2016; Correnti et al. 2015). As an example, in the upper-left panel of Figure 4, we plot the \( G_{BP} \)-\( G_{RP} \) CMD of M11 cluster members from Gaia DR2 photometry. The three groups of bMS, rMS, and eMSTO stars exhibit different colors, further confirming that the CMD of M11 is not consistent with a single isochrone, and demonstrating that Gaia photometry is able to detect eMSTOs.

Driven by this result, we started inspecting the Gaia DR2 database to search for multiple populations in open clusters. Our first results are shown in Figure 4, where we plot the CMDs for three Galactic open clusters, namely NGC 2099, NGC 2360, and NGC 2818. As for M11, cluster members were selected from Gaia DR2 proper motions and parallaxes, and the CMDs were corrected for differential reddening. Noticeably, these clusters exhibit an eMSTO. The MS is much narrower than the eMSTO and its color spread is generally consistent with observational errors, thus demonstrating that the eMSTO is not due to photometric uncertainties or residual differential reddening.

The analysis of a large sample of MCs clusters with ages of \(~\text{40} \text{ Myr} - \text{2.5} \text{ Gyr}\) has demonstrated that eMSTOs are common among these objects, while split MSs are observed in clusters younger than \(~\text{700} \text{ Myr}\) (e.g., Milone et al. 2009, 2018), among stars with masses \( \geq 1.6 M_{\odot} \). Such mass corresponds to the MS kink associated with the onset of the envelope convection due to the opacity peak of partial H ionization (e.g., D’Antona et al. 2002).

Although an eMSTO is displayed by all of the clusters shown in Figure 4, remarkably a broadened MS is present only in M11 and NGC 2099. By comparing the CMDs of Figure 4 with isochrones from Marigo et al. (2017), we find that these two clusters have ages of \(~\text{30} \text{ Myr} - \text{500} \text{ Myr}\), respectively; NGC 2818 and NGC 2360 are well fitted by \(~\text{800} \text{ Myr} - \sim\text{1.1} \text{ Gyr}\) isochrones. This fact corroborates the conclusion that the eMSTOs and broadened/split MSs observed in the Milky Way clusters originate from the same physical mechanism responsible for the appearance of similar features in the MCs clusters.

6. Conclusions

The eMSTO was first discovered to be a common feature in the CMD of the Large and Small MCs clusters younger than \(~\text{2.5} \text{ Gyr}\) (e.g., Mackey & Broby Nielsen 2007; Glatt et al. 2008; Milone et al. 2009, 2018; Goudfrooij et al. 2011, 2014). This finding and the evidence of split MSs in MC clusters younger than \(~\text{800} \text{ Myr}\) (e.g., Milone et al. 2015, 2018; Bastian et al. 2017; Correnti et al. 2017) has challenged the theories on the formation and evolution of these objects.

The eMSTO was initially interpreted as the signature of an extended star formation history, with young MC clusters considered to be the counterparts of the old GCs with multiple populations (e.g., Conroy & Spergel 2011; Keller et al. 2011). Alternatively, the eMSTO could be due to coeval stellar populations with different rotation (e.g., Bastian & de Mink 2009).

Recent studies have provided strong evidence that rotation plays a major role in shaping the split MS and the eMSTO. Direct evidence that the rMS is populated by fast rotators, while the bMS hosts stars with low rotation, comes from spectroscopic measurements of MS stars in the LMC cluster NGC 1818 (Marino et al. 2018); evidence for the connection between the eMSTO and stars with different rotation rates has been provided for NGC 1866 (Dupree et al. 2017).

We have combined \textit{uvby} Strömgren photometry and \textit{Gaia} DR2 proper motions and parallaxes to search for multiple populations in the Galactic open cluster M11. The \( v - \langle u - v \rangle \) CMD shows an eMSTO and a broadened, possibly split, MS in the magnitude interval \( 12.0 \lesssim v \lesssim 14.5 \). We have demonstrated that these are intrinsic features of the M11 CMD, in close analogy with what was previously observed in nearly all of the young clusters of both MCs. This is the first evidence of a connection between the eMSTO in MCs and in Galactic open clusters.

We have exploited GIRAFFE data to derive projected rotational velocities for a sample of stars in M11. Our analysis shows a clear difference in the mean \( v \sin i \) between bMS and rMS stars, having average values of \( \langle v \sin i \rangle_{\text{rMS}} = 83 \pm 14 \text{ km s}^{-1} \) (\( \sigma = 46 \text{ km s}^{-1} \)) and \( \langle v \sin i \rangle_{\text{bMS}} = 194 \pm 15 \text{ km s}^{-1} \) (\( \sigma = 68 \text{ km s}^{-1} \)). A large range in \( v \sin i \) is also present among eMSTO stars, with some of them showing H\alpha emission.

We show that the eMSTO of M11 is visible in the \( G_{BP} - G_{RP} \) CMD from Gaia DR2 photometry. Driven by this finding, we started to search for multiple populations in Galactic open clusters by using this data set and found eMSTOs in NGC 2099, NGC 2360, and NGC 2818.

Our results indicate that the eMSTO is not a peculiarity of the extragalactic MC clusters but is a common feature of Galactic open clusters, thus challenging the traditional idea that these objects are the proxy of a single isochrone. High-resolution spectroscopy has provided direct evidence that stellar rotation is the major factor responsible for the split MS and the eMSTO in open clusters, making these objects similar to MCs clusters.

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