The Effects of Rotation on Extended Main Sequence Turnoff of Galactic Open Clusters from LAMOST View (Postprint)

Authors: Yuan-Hao Wen, A-Li Luo, Jing Zhong, Songmei Qin, Xiaoting Fu, Li Chen and Yong-Heng Zhao

Date: 2025-09-28T12:14:26+00:00

Abstract

Recent studies have increasingly identified extended main sequence turn-off (eMSTO) phenomena in Galactic open clusters, yet the number of such clusters with sufficient spectroscopic information for member stars remains limited. Unlike most studies that rely on fitting isochrones based on color-magnitude diagram (CMD) morphology to account for varying rotational velocities, our approach leverages LAMOST spectral data to compute actual rotational velocity distributions for confirmed cluster members, along with parameters such as metallicity, differential extinction, and rotational inclination, to utilize PARSEC isochrones for fitting the cluster CMDs. We systematically surveyed all known Galactic open clusters and selected 12 clusters where rotational velocity distributions could be reliably calculated for detailed fitting. Our results successfully reproduced the eMSTO phenomenon observed in these clusters. For the majority of clusters, considering only differential extinction and variations in rotational velocity adequately explains the position and morphology of the MSTO. For some intermediate-age clusters, incorporating rotational inclination additionally accounts for the broadening of the MSTO. This study underscores the importance of spectroscopic data in understanding eMSTO phenomena and provides a probable explanation for interpreting the combined effects of differential extinction, rotation, and inclination on the CMDs of Galactic open clusters.

Full Text

Preamble

Research in Astronomy and Astrophysics, 25:075021 (14pp), 2025 July

are reserved. Printed in China.
https://doi.org/10.1088/1674-4527/addf00
CSTR: 32081.14.RAA.addf00

The Effects of Rotation on Extended Main Sequence Turnoff of Galactic Open Clusters from LAMOST View

Yuan-Hao Wen[1],[2], A-Li Luo[1],[2], Jing Zhong[3], Songmei Qin[2],[3],[4], Xiaoting Fu[5], Li Chen[2],[3], and Yong-Heng Zhao[1],[2]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; wenyh@bao.ac.cn, lal@nao.cas.cn
[2] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China
[3] Astrophysics Division, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
[4] Institut de Ciències del Cosmos, Universitat de Barcelona (ICCUB), Martí i Franquès 1, 08028 Barcelona, Spain
[5] Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China

Received 2025 January 17; revised 2025 April 7; accepted 2025 April 14; published 2025 June 30

Abstract

Recent studies have increasingly identified extended main sequence turn-off (eMSTO) phenomena in Galactic open clusters, yet the number of such clusters with sufficient spectroscopic information for member stars remains limited. Unlike most studies that rely on fitting isochrones based on color-magnitude diagram (CMD) morphology to account for varying rotational velocities, our approach leverages LAMOST spectral data to compute actual rotational velocity distributions for confirmed cluster members, along with parameters such as metallicity, differential extinction, and rotational inclination, to utilize PARSEC isochrones for fitting the cluster CMDs. We systematically surveyed all known Galactic open clusters and selected 12 clusters where rotational velocity distributions could be reliably calculated for detailed fitting. Our results successfully reproduced the eMSTO phenomenon observed in these clusters. For the majority of clusters, considering only differential extinction and variations in rotational velocity adequately explains the position and morphology of the MSTO. For some intermediate-age clusters, incorporating rotational inclination additionally accounts for the broadening of the MSTO. This study underscores the importance of spectroscopic data in understanding eMSTO phenomena and provides a probable explanation for interpreting the combined effects of differential extinction, rotation, and inclination on the CMDs of Galactic open clusters.

Key words: stars: evolution –stars: rotation –(Galaxy:) open clusters and associations: general

1. Introduction

For a long time, it was believed that star clusters formed from a single burst of star formation during the pre-main-sequence stage, with all cluster members thought to be gravitationally bound within a specific region and assumed to have the same age and chemical composition. However, several studies have challenged this notion by revealing that many old globular clusters host multiple stellar populations with differing chemical compositions (Gratton et al. 2012; Milone & Marino 2022). Spectroscopic features, such as the Na-O anti-correlation observed in massive globular cluster stars, suggest these variations in light element chemical abundances occurred over a specific timescale, possibly originating during the early evolutionary stages through processes like stellar winds (Carretta et al. 2009; Milone & Marino 2022).

Thanks to high-quality observations from the Hubble Space Telescope and Gaia (Brown et al. 2018; Gaia Collaboration et al. 2021, 2023), it has become evident that young (<600 Myr) and intermediate-age (1-2 Gyr) open clusters (Milone et al. 2009, 2017, 2018; Goudfrooij et al. 2017; Li et al. 2017; Bastian et al. 2018) exhibit multiple discrete components in their color-magnitude diagrams (CMDs). Recent studies of some Large Magellanic Cloud (LMC)/Small Magellanic Cloud (SMC) open clusters, such as NGC 1866 (Milone et al. 2017), NGC 1856 (Milone et al. 2018), and NGC 1755 (Milone et al. 2016), have shown that it is a common property for young open clusters' CMDs to harbor split main sequences (MSs) or extended main sequence turn-offs (eMSTOs). However, while multiple stellar populations in old clusters involve differing chemical abundances, eMSTOs in young clusters do not imply multiple populations with different chemical compositions (Milone et al. 2018). Both the presence of multiple stellar populations in old clusters and the multiple components phenomenon in young clusters' CMDs challenge the single stellar population paradigm and the view that young and intermediate-age star clusters are best described by a single isochrone, providing new insights into the evolution of young and intermediate-age clusters.

Concerning the origin of the split MS, the nature is gradually becoming more certain (Milone et al. 2018), but the nature of the eMSTO has long been considered complex and is still highly debated. Early studies interpreted that the extension of cluster CMDs in the MSTO stage originated from a prolonged star formation history (SFH) or a second burst of star formation (Mackey & Broby Nielsen 2007; Milone et al. 2009). However, this interpretation gradually proved inconsistent with much research, as SFH theory or a second burst of star formation cannot explain the width and location of subgiant branches of the cluster and red clump area in the CMD (Li et al. 2014; Bastian & Niederhofer 2015). It is also contradicted by the fact that the bottom of the cluster' s CMD, which consists of unevolved stars with the lowest mass in the cluster, already somewhat exhibits a persisting color difference (Wang et al. 2022). This argument points out that a single age-spread scenario cannot well explain the presence of eMSTO.

Instead of age spread, it is suggested that the dichotomy of rotation velocity of cluster members is more significant in shaping the eMSTO. The improvement of cluster spectroscopic observations has greatly advanced the study of how stellar rotation rates shape the morphology and extension of the MSTO (Kamann et al. 2023; Cordoni et al. 2024). The main sequence is divided into blue MS (bMS), which is consistent with a population of non-rotating or slow-rotating stars, and red MS (rMS), which is consistent with rapidly and critically rotating stars. More studies focus on the measurement of the average rotation velocity of bMS and rMS. Marino et al. (2018) represent the first spectroscopic exploration of rotation velocities in young clusters with split MS, confirming that split MS of young GCs is connected with different rotational regimes. Sun et al. (2019) also use spectral observations to measure vsini of stars in NGC 5822, finding that faster rotators are located on the red side of the eMSTO and slower rotators on the blue side in the CMD. Sun et al. (2019) also focus on revealing a dichotomy in stellar rotation rates that correlate with the bifurcated main sequence via spectroscopic observations, additionally suggesting that tidal locking by low-mass-ratio companions in binary systems slows down initially rapid rotators. Furthermore, the model by Wang et al. (2023a) specifically points out that the $\omega/\omega c$ of bMS stars is approximately 0.35, while that of rMS stars is approximately 0.65. Further studies, such as Kamann et al. (2023) based on actual observations, indicate that these values evolve with stellar evolution, and the $\omega/\omega c$ of bMS and rMS stars in the young LMC cluster NGC 1850 are found to be in the ranges of 35%-40% and 67%-79%. These studies suggest the effect of stellar rotation on the morphology of the cluster' s CMD is becoming increasingly quantified.

The main reason why differential rotation can shape the eMSTO is the synergistic effect of gravitational darkening and mixing caused by rotation. The former is due to the hydrodynamic equilibrium of the cluster star with geometric distortions caused by maintaining high-speed rotation (Bastian & De Mink 2009; Milone & Marino 2022). The surface temperature will be redistributed and adjusted, causing the star to appear darker and redder in most of the observation orientations. The latter will bring materials from the outer layers to the star' s core as fuel to expand the core' s burning life, making the stars appear younger (Yang et al. 2013). Also, projected inclination plays an unignorable role in shaping the morphology of eMSTO. This is not only because the precision of rotation velocity measurement will be affected due to the unknown projected inclination angle (Costa et al. 2019), but also because the gravitational darkening will induce fluctuation of the star' s color. However, the high-precision quantitative measurement and analysis of projection inclination is still in great demand.

The physical mechanisms creating the bimodal rotation rates are complex and still under debate and development. One scenario proposed before, considering the spin-down effect of tidal braking produced by extremely tight binary systems (D' Antona et al. 2017), can only explain part of the phenomenon but is not sufficient, as tidal braking is a continuous process, not a bimodal one. It would require extremely short tidal-locking timescales for a significant fraction of binary systems and thus a high amount of radial velocity (RV) variables in a 150 million years age cluster, which is not supported by observations (He et al. 2023). Another scenario suggests that pre-main-sequence stars' rotational speeds may interact with their protoplanetary disks in ways that either slow down or prevent the retention of the disk, leading to a bimodal distribution of rotation rates that could persist into the main-sequence phase (Bastian et al. 2020). However, this scenario has not been thoroughly tested or confirmed. The scenario validated by the analysis of mass distribution and isochrone fitting by Wang et al. (2022) provides another explanation. It suggests that the origin of rMS is the inheritance of angular momentum by star clusters in their giant molecular cloud stage, while the primary origin of bMS is the magnetic stellar wind torque effect during stellar mergers that lead to blue-straggler stars. Still, they only account for a small part of the whole cluster as the number of blue-straggler stars formed through dynamical binary interactions is insufficient to explain the observed population of bMS stars (Li et al. 2024). This series of explanations sheds light on the research of MSTO and calls for a large number of observations to further promote the verification of these scenarios.

Most studies of eMSTO have focused on massive LMC and SMC clusters with Hubble Space Telescope observations, since the relatively larger numbers of stars that can be observed, higher precision measurement of stellar parameters and membership probabilities, and less background and foreground confusion (Milone et al. 2018; Wang et al. 2022). The uniqueness of the galaxy' s chemical environment and gravitational field intensity emphasizes the importance of the study of the eMSTO phenomenon in galaxy open clusters (Bastian et al. 2018). Several models have predicted that different metallicity leads to stars with even contrary evolution in rotation velocity (Amard & Matt 2020). The research indicates that stars with higher metallicity exhibit a more pronounced slowdown in rotation beyond 1 billion years than those with lower metallicity, with the discrepancy being enough for modern observational tools to ascertain. Specifically, models resembling the Sun in mass and age, but with a metallicity of [Fe/H] = -0.3, will exhibit a rotation period shorter than 20 days. These pieces of evidence all suggest that studying open clusters within the Milky Way is also of great value, potentially providing new insights into the origin and nature of eMSTOs.

Cluster isochrone grids calculated by 1D stellar evolution models like SYnthetic CLusters Isochrones & Stellar Tracks (SYCLIST; Bressan et al. 2012; Nguyen et al. 2022) can indicate a lot of information about the cluster' s eMSTO property or rotation velocity distribution. The direct calculation of cluster members' relative angular rotation velocity ω/ωc derived from the combination of direct spectroscopic observation and photometric observation as supplements can provide valuable cluster eMSTO knowledge from another view. The comprehensive adoption of the two methods is of great significance, and it will bring a new view of this area and give new evidence of some existing theories. All isochrones used in this article are generated from the PARSEC.

With these goals in mind, the structure of this paper is as follows. Section 2 lists the sources of data we use to perform our analysis. Section 3 presents all our data analysis skills. In Section 4, we interpret each cluster’ s results and discuss the broader inferences about star formation that our series of papers affords us. Finally, we offer concluding thoughts and future outlooks in Section 5.

2. Observations

To accurately identify the cluster member stars for our study, we utilized the open cluster membership table from Cantat-Gaudin et al. (2018). This membership table, derived using the unsupervised method UPMASK (Krone-Martins & Moitinho 2014), yields more precise results. It leverages both the astrometric and photometric information from Gaia DR2, ensuring that all identified cluster members have better reliability in their origin. We updated this membership table using the Gaia DR2-to-EDR3 match table to benefit from the improved astrometry in Gaia DR3.

We obtained the atmospheric parameters of stars using LAMOST low-resolution spectra to measure a wide range of projected rotation velocities (Luo et al. 2015). We cross-referenced LAMOST DR10 with the galactic open cluster member catalog, selecting 14 open clusters and 7842 stars within the LAMOST field as our study targets from above 1400 galactic open clusters (Table 1). We derived the projected rotational velocities of stars through spectral line broadening. Additionally, to improve the accuracy of the absolute magnitude calculations, the posterior distance of each star is determined using its parallax, associated errors, HEALpixel number, and Gaia G band magnitude and color, based on a photogeometric model from Bailer-Jones et al. (2021).

3. Data Analysis

3.1. Star Selection

We refrained from adding more cluster members, as most newly identified stars are likely faint ones lacking high signal-to-noise ratio spectroscopic parameters (Healy et al. 2021). Including these could introduce field stars and potentially distort the distribution of our open cluster members’ rotation. We set a cutoff of 50% membership probability to exclude field stars that exhibit similar R.A. and decl. as cluster stars. We also checked whether some high membership probability stars exhibit extremely different parallax or proper motion compared to other stars that originated from the same cluster.

We note that binary systems originating from bMS would overlap with normally evolved rMS and be hard to distinguish. So we fitted the theoretical single-star reduced unit weight error (RUWE) distribution of each cluster (Belokurov et al. 2020; Healy & McCullough 2020). We first plot the probability density function of the RUWE value from the Gaia DR3 measurement. We believe that the portion of the probability density function (PDF) of which RUWE value is less than the value at the peak of the PDF, which in most clusters is nearly equal to 1, is the natural broadening of the RUWE parameter. The other part of the PDF represents the superposition of natural broadening and broadening induced by binaries. We folded the left portion of the PDF along its peak, creating the theoretical single-star RUWE distribution for the cluster, and we chose the threshold to reject stars with excessive RUWE value to be set to the 99% percentile of the PDF (Figure 1 [Figure 1: see original paper]).

We cross-matched the spectroscopic binary candidates catalog from the LAMOST MRS survey (SB2 Catalog) (Zhang et al. 2022) with the member stars catalog of Galactic open clusters to identify potential binary systems within cluster environments. During the selection process, we applied stringent binary criteria to ensure the reliability of candidates. Specifically, we required the predicted median probabilities in both the blue and red arms (P_{16}) to exceed 0.5, ensuring consistency across spectral bands. Additionally, we constrained the uncertainty range, defined by the 16%–84% confidence interval, to be less than 0.3, thereby excluding candidates with high prediction uncertainty. To minimize the impact of low signal-to-noise ratios on spectral quality, only spectra with $S/N > 5$ were retained. Furthermore, to eliminate contamination from cool giant stars (e.g., AGB stars), we restricted the color index (BP-RP) to less than 2.5. By applying these criteria, we identified a subset of high-confidence spectroscopic binaries within open clusters, providing a robust sample for subsequent investigations of binary dynamics in cluster environments.

We used the Virtual Observatory SED Analyzer (VOSA) to build spectral energy distributions (SEDs, Bayo et al. 2008), opting to assemble for each star the available broadband photometry from the following large, all-sky catalogs: GALEX All-sky Imaging Survey (AIS): FUV and NUV (around 0.15–0.22 m) (Bianchi et al. 2017); All WISE: WISE 1-4 bands (around 3.37–22.19 m) (Wright et al. 2010); Two-Micron All-Sky Survey (2MASS): JHKs bands (around 1.24–2.26 m) (Skrutskie et al. 2006); Sloan Digital Sky Survey (SDSS): ugriz bands (around 0.2–1 m) (Alam et al. 2015); Johnson UBV bands (around 0.35–0.55 m) (Mermilliod 2006); Tycho-2: Tycho B and Tycho V bands (around 0.42–0.54 m) (Høg et al. 2000). To obtain more accurate SEDs, we tried to use a wider range of wavelengths for band selection as much as possible. Though relatively few stars have data in the near-ultraviolet bands, most stars have data with sufficiently small errors in the selected bands.

Our v sin i values in this study were from Zuo et al. (2024). This method generates synthetic reference spectra from the PHOENIX grid, convolves them with broadening kernels, and compares them to observed spectra using ^{2} minimization to determine v sin i of LRS spectra.

3.2. Extinction

Rather than calculating extinction by combining the morphology of the cluster CMD and isochrone grids, we implemented a systematic differential reddening correction method originating from Milone et al. (2012) to minimize observational biases caused by spatial variations in extinction, thereby enhancing the accuracy of binary star identification. Initially, we defined a reference coordinate system aligned with the reddening vector to standardize the CMD. Using a selected sample of main-sequence stars, we established a fiducial line representing the typical locus of single stars and computed each star' s displacement from this fiducial along the reddening direction. For each target star, we identified a local sample of neighboring reference stars within a defined spatial region and estimated the differential reddening value by averaging the displacements of these neighbors. This correction was iteratively applied to refine the CMD and the fiducial line until convergence was achieved. The resulting corrected CMD significantly reduced the impact of differential reddening on the main sequence width, allowing for more accurate identification and characterization.

3.3. Critical Rotation Velocity

There are different definitions of the critical rotational velocity in different one-dimensional stellar evolution models. According to PARSEC' s definition (Nguyen et al. 2022), our critical rotation velocity is derived from $v_{\text{crit}} = \sqrt{\frac{GM}{R_e}}$, in which R_e represents the radius of the star at the equator. To obtain the actual critical rotation speed of a star, we need to know the star' s radius and mass. We utilize the mass-T_{eff} relation, which is derived from the combination of high-precision empirical measurements of masses and radii of eclipsing binaries and simulations based on the TRILEGAL stellar mass (Torres 2010; Stassun et al. 2018). We then compare it with results obtained from Final Luminosity Age Mass Estimator (FLAME) models to establish a validation check (Gaia Collaboration et al. 2023).

For stellar radius, we apply the Stefan-Boltzmann law: $L = 4\pi R^2 \sigma T_{\text{eff}}^4$ to calculate it, which fundamentally relates the total luminosity of a star to its effective temperature and radius. This equation allows us to infer radius by incorporating a comprehensive SED constructed from multi-band photometric data. By utilizing the star' s extinction, distance, and the aforementioned multi-band photometric observations, we derived the SED for each star using VOSA. This method enables us to extract accurate stellar parameters, including the radius, which is crucial for understanding the star' s physical properties and its position on the Hertzsprung-Russell diagram (Figure 2 [Figure 2: see original paper]).

After obtaining all the parameters described in Section 2, we have derived the total rotation information for each source. Specifically, we calculate the ratio of angular velocity to critical angular velocity, as this dimensionless form effectively symbolizes the influence of rotation on evolutionary tracks within stellar evolution models. By plotting the kernel density estimation (KDE) of this ratio for each star cluster, we can visually analyze the distribution of rotational velocities.

3.4. eMSTO

For all significant members of the clusters we analyzed, we confirmed the membership of stars in the MSTO region. The range of the MSTO and the absolute magnitudes of the member stars are listed in Table 2. Additionally, we further validated these stars by examining their three-dimensional spatial kinematics. Using the RV provided by the Gaia-ESO spectroscopic survey for stars in the MSTO region, we found that the majority of stars exhibit similar RV values. Stars with significantly larger RVs were considered potential unresolved binary systems, and as a result, they were excluded from further analysis. We also estimated the uncertainty in the magnitudes of stars within this region, accounting for uncertainties in distance and extinction measurements. This allowed us to derive the uncertainties in the absolute magnitudes in the G, GBP, and GRP bands. Finally, we compared these uncertainties with the color spread (Δcolor) at the MSTO of the entire cluster. The results of this comparison are also presented in Table 2.

For each cluster’ s CMD, we visually identified the eMSTO region. This region, a prominent feature in intermediate-age star clusters, is characterized by a spread in the main-sequence turn-off, likely caused by factors such as differential rotation, binarity, or stellar age spreads. To quantify this, we carefully analyzed the shape and extent of the eMSTO. In this study, we divided the cluster’ s CMDs into several luminosity bins based on stellar brightness. For each bin, we calculated the average color and magnitude, designating these as the representative reference points for the bin. A spline interpolation was then applied to all reference points to construct a smooth baseline, representing the typical color-magnitude relation of the cluster. Using this baseline, we measured the color offsets of all cluster member stars in the MSTO region relative to the baseline. These offsets were then used to quantify the color distribution in the MSTO region, providing a robust characterization of the cluster’ s photometric properties (Figure 3 [Figure 3: see original paper]).

To ensure uniformity across all clusters, we applied standardization procedures by correcting for distance and reddening effects in each cluster. This provided a consistent framework for comparing eMSTO widths. Subsequently, we constructed a KDE of the distance distribution within each cluster, offering a robust statistical representation of the spread. For this KDE, we performed a detailed statistical analysis on the full width at half maximum (FWHM) and central width. Furthermore, we aimed to investigate whether the color distribution could be explained by the presence of age variation and rotation variation. To test this hypothesis, we applied a Gaussian Mixture Model (GMM) to the color distribution of the eMSTO stars. The GMM assumes that the observed color distribution can be modeled as a combination of one or two Gaussian components, each representing a distinct population of stars. We take NGC 2168 as an example, and the analysis is plotted in Figure 3. The fit parameters and results of this GMM analysis are also summarized in Table 2.

3.5. Projected Rotation Speed Distribution

Variations in stellar rotational velocities are a key factor contributing to eMSTO in open clusters. To investigate the contributions of age and rotation to eMSTO formation, we constrained the isochrone fitting parameters using the v sin i data from cluster members. This approach allowed us to more accurately assess the contributions of rotation and age to the spread observed in the eMSTO region.

In the analysis, we studied the distribution of v sin i values and ωi values for all the clusters under study (Figure 4 [Figure 4: see original paper]). Our results show that most clusters exhibit a clear bimodal distribution in rotational velocities. The first peak is located around 50-100 km s^{-1}, while the second, broader peak is centered around 200-250 km s^{-1}. The distributions of v sin i and ωi are largely consistent, reflecting uniformity in the physical parameters of stars within each cluster. The detailed bimodal distribution parameters are all listed in Table 2. This bimodal distribution aligns with stellar evolution models, which predict that slower-rotating stars populate the lower left region of the cluster' s CMD, forming the bMS. Conversely, stars with higher rotational velocities are predominantly found in the upper right region of the CMD, making up the rMS.

We analyzed the rotational velocity distribution of slow and fast rotators in each cluster, marking individual stars on the CMD based on their v sin i and ωi values. An example from NGC 2168 is shown in Figure 5 [Figure 5: see original paper]. By annotating the CMD with different markers to distinguish slow rotators from fast rotators, we visually demonstrated the bimodal nature of the rotational velocity distribution and its effect on the positioning of stars within the CMD. Histogram analysis highlights that bMS stars, with lower rotational velocities, are separated from rMS stars, which rotate more rapidly. Analysis across clusters reveals a significant trend: populations with higher v sin i values tend to occupy redder positions within the MSTO region, while stars with lower v sin i are predominantly found in bluer positions. This distribution pattern of v sin i aligns closely with that of ωi, indicating a coherent relationship between rotational speed and stellar color. This bimodal distribution supports the hypothesis that the spread in the eMSTO region is strongly influenced by variations in rotation velocities, with slow rotators and fast rotators following distinct evolutionary paths that manifest as separate populations in the CMD.

We employed a GMM to fit the KDE of the rotational velocity distribution for each star cluster. The centers of the two Gaussian distributions in the KDE represent the rotational velocity parameters for two isochrones, capturing the rotational speed differences that shape the CMD morphology in the MSTO region. With consistent metallicity across the cluster and applied extinction corrections, we used isochrone fitting to examine how stellar rotation contributes to MSTO broadening. For each cluster analyzed, we generated KDE plots of the ωi distribution and overlaid the two-component Gaussian fit results (Figure 6 [Figure 6: see original paper]). Most clusters exhibit a bimodal distribution, with the slower rotational velocity peak around 0.2–0.3 and the faster peak around 0.5–0.7. Slow rotators generally outnumber fast rotators, with their distribution more tightly clustered. In NGC 1647 and NGC 1039, however, the rotational velocity does not exhibit a bimodal pattern; all MSTO stars belong to the slow-rotating population. In these cases, the double Gaussian fit may not represent the underlying distribution accurately, so we adopt $\omega\mathrm{i} = 0.5$ as a representative value for fitting the redder isochrone in the MSTO region. This approach enables us to incorporate rotational variations when fitting isochrones and to assess their impact on MSTO morphology across clusters.

4. Result and Discussion

To delineate the upper and lower bounds in our CMDs (Figure 7 [Figure 7: see original paper]), we utilized two isochrones—one rendered in blue, corresponding to the velocity distribution of slower rotators, and the other in red, indicative of faster rotators—both derived from previously fitted normal distributions. The average metallicity was adopted for each cluster, and the overall extinction was determined based on the position of the main sequence.

For most analyzed clusters, we successfully simulated the position of the main sequence. However, for some clusters such as NGC 1245 and NGC 1817, the lower portion of the main sequence was not accurately matched. For example, in NGC 1817, the isochrones in the lower main sequence deviate from the observed stars, appearing redder than expected. This discrepancy may be attributed to errors in differential extinction estimates. In older open clusters, where dispersion is more pronounced and differential extinction is greater (Krause et al. 2020), the lower part of the main sequence exhibits increased broadening. During the correction for differential extinction, accurate positioning information of the cluster' s main sequence may be submerged, leading to systematic deviations among member stars. While fitting the MSTO accurately, this process might cause distortions in the fit for cluster members below the MSTO. However, we note that the MSTO region itself is less affected by differential extinction and thus requires less correction, preserving its positional accuracy. Therefore, the parameters derived from fitting the isochrones at the MSTO can be considered reliable.

We also consider the probability of the MS evolution track being wide enough to overlap with the binary star evolution tracks in the CMDs, leading to additional broadening. The inability to completely fit certain aspects of the main sequence broadening in these clusters may result in an underestimation of the overall differential extinction. The overlap between single-star and binary-star evolution tracks means that the main sequence appears redder and wider overall when correcting for differential extinction, further affecting the fit of the MS broadening. Given that there is no significant additional broadening at the MSTO compared to the main sequence in some clusters, such as NGC 2168, we conclude that invoking age differences to explain the eMSTO is not necessary. We additionally found that near the MSTO region in clusters NGC 1528 and NGC 1647, there is a small clump of stars that cannot be fitted by the two isochrones at the MSTO. These stars do not exhibit the characteristic features of typical eMSTO region members since they form an independent clump adjacent to the main sequence without any apparent evolutionary connection. Therefore, we believe this phenomenon may be due to binary stars or photometric errors, which does not affect the fitting of the isochrones to the main sequence and the MSTO.

Even after accounting for photometric errors and the effects of binaries and large differential extinction, the MSTO regions of two intermediate-age clusters, NGC 1245 and NGC 1817, remained poorly fitted. The two clusters exhibit significant spread in the MSTO region and substantial differential extinction, with a considerable number of member stars having reached the MSTO phase. In these clusters, some members approaching the horizontal branch could not be adequately modeled, which we believe is related to variations in rotational inclination. We found that among the members of these two clusters, slow rotators and fast rotators have different effective temperatures. According to von Zeipel' s Law (Maeder 1999), fast-rotating stars produce varying effective temperature distributions at different inclinations due to their ellipsoidal deformation (Equation 3). We argue that $T_{\text{eff}}(\theta) = T_{\text{eff}}(1 - \epsilon \cos^2 \theta)$, where $T_{\text{eff}}(\theta)$ represents fast rotators' effective temperature, and T_{eff} represents slow rotators' effective temperature. ϵ is equal to 0.3 in the case of no extremely fast rotations. Under the above assumptions, we estimate the average inclination angles for NGC 1245 and NGC 1817 to be 78° and 79°. By adopting PARSEC isochrones for rapid rotators with an inclination angle of 75°, we successfully reproduced the additional broadening observed in the MSTO regions of the two clusters (Figure 8 [Figure 8: see original paper]).

Therefore, our conclusion aligns with previous discussions: age differences are not a critical factor in shaping the MSTO morphology in Milky Way open clusters. Considering parameter uncertainties, we can reproduce the observed CMD shapes of the clusters through differential extinction corrections and variations in rotational inclination. In the following section, we will present a preliminary analysis and discussion of the possible mechanisms underlying the differences in rotational speeds among cluster stars.

One possible origin of slow rotators in star clusters is the presence of low-mass-ratio tidally locked binary systems. Unresolved low-mass-ratio binaries may evade detection using the methods described in Section 3. In such systems, tidal forces between the primary star and its companion lead to deformations, forming tidal bulges. These tidal forces gradually dissipate angular momentum from the system, causing the star' s rotational speed to synchronize with the orbital motion. During this process, if the star' s rotational velocity exceeds the orbital angular velocity, tidal friction transfers angular momentum from the star' s rotation to the orbit, resulting in a gradual decrease in the star' s rotation until it matches the orbital angular velocity (de Mink et al. 2013). Due to the effects of mass segregation in star clusters, if a substantial number of tidally locked binaries have evolved into slow rotators, they are expected to be concentrated in the inner regions of the cluster.

We initially considered the comparison between the timescales of binary tidal-locking and mass segregation with the age of the cluster, in order to explore the possibility that tidal-locking could lead to the formation of slow rotators. We estimated tidal-locking timescale by following Hurley et al. (2002) and the formula is as follows:

$$t_{\mathrm{sync}} = \frac{I_p \omega_p}{3GM_pR_p^2E_2}\left(\frac{a}{R_p}\right)^6 \frac{1}{q^2(1+q)}$$

Here, M_p, R_p, and I_p represent the mass, radius, and moment of inertia of the primary star, respectively, while G is the gravitational constant. The term q refers to the mass ratio of the binary system, and a indicates the separation between the two components. The parameter E_2, known as the second-order tidal coefficient, originates from Zahn (1975). We adopted the empirical relationship between R_p and M_p mentioned in Demircan & Kahraman (1991), and the final synchronization time only depends on M_p, q, and a. Using the average mass of the cluster as a probe, we attempted a grid search and concluded that for M_p of 1.5 $M_\odot$, binaries with $q > 0.5$ and $a < 6R_\odot$ correspond to tidal-locking timescales shorter than the ages of all the clusters analyzed. We believe that a significant number of member stars in our clusters have completed tidal locking.

However, contradicting our previous analysis, there is no evidence that the bMS occupies a more central position within the clusters. Moreover, for the vast majority of clusters, with the exception of the two intermediate-age clusters NGC 1817 and NGC 1245, there is also no evidence that slow rotators are more centrally located. We believe that the reason is as follows: in young clusters, such as 300 Myr open clusters, tidally locked binaries are predominantly high-mass-ratio systems, which occupy the redder side of the MS on the CMD (Wang et al. 2023b). In Wang et al. (2023b)' s simulations, low-mass-ratio binaries appear very early in the cluster' s lifetime (such as 40 Myr), and their primary star masses are all greater than 5 $M_\odot$. Such samples are lacking in our observations. Therefore, we argue that tidal locking cannot serve as the origin of the bMS in our observed clusters. On the other hand, the low-mass-ratio binaries may still be the reason for the spin-down of bMS stars of the eMSTO (Maurya et al. 2024). For our clusters, except for NGC 1245 and NGC 1817, most are young clusters. In these clusters, binaries with low-mass-ratios and primary star masses in the range of 1-2 $M_\odot$ are insufficient to complete tidal locking (Equation 4). As for NGC 1245 and NGC 1817, even though smaller values of a could allow cluster members with $q < 0.2$ to complete tidal locking at their current age, the initial proportion of low-mass-ratio binaries in the cluster is relatively low (Wang et al. 2023b). Additionally, there is also a lack of sufficient fast rotators for comparison in our observations. Therefore, we were unable to reach the theoretically predicted conclusion that slow rotators would be closer to the cluster center due to mass segregation. Further follow-up observations of individual clusters are urgently needed to verify the spatial distribution of slow and fast rotators.

We are still unclear about the origin of the bimodal rotation velocity distribution of Galactic open cluster members. This is partly due to the lack of sufficiently high-quality observational data, especially for fast-rotating stars. The number of Galactic open clusters covered by the LAMOST field of view is relatively small and needs to be further increased. Sufficient observational data might provide a clearer understanding of the eMSTO phenomenon and its origin in the Galactic open cluster CMD.

5. Conclusion

In this study, we investigated the main sequence and eMSTO phenomena across a sample of Galactic open clusters, analyzing the contributions of stellar rotation, age spread, and differential extinction. By incorporating precise measurements of projected rotational velocities and CMD morphology, we aimed to understand the underlying mechanisms driving the eMSTO broadening. Our results further confirm that rotation, rather than age, plays a significant role in shaping the CMD morphology across clusters. We observed that fast rotators generally populate the red side of the eMSTO, while slow rotators occupy the blue side. The projected rotation velocity distribution supports this finding, revealing a bimodal structure in rotational speeds, with fast-rotating stars often exhibiting signatures of gravity darkening. We provide a fit for all clusters. We conclude that the main sequence broadening in clusters is primarily due to differential extinction. After eliminating differential extinction by rotating the coordinate system and fitting the reference line, we were able to roughly match the main sequence position and broaden the clusters.

Based on this, we find that for younger clusters (below 600 Myr), broadening due to stellar rotation is sufficient to allow synthetic isochrones to fit the position and morphology of the MSTO. However, for some older clusters (above 600 Myr), it is necessary to consider the clusters' average rotation inclination for a successful fit. Age differences are not a critical factor in shaping the MSTO morphology in Milky Way open clusters. We attempted to use the photometric data from Swift and GALEX to construct the CMD morphology in the ultraviolet band, in order to investigate whether the rMS exhibits additional circumstellar extinction. However, we found that the clusters in our observations lack sufficient data, particularly for fast rotators, to draw any conclusions.

Furthermore, our radial distribution analysis provides insights into the spatial arrangement of stars within clusters, but we did not observe any distinct patterns in the spatial distribution of slow rotators and fast rotators or bMS and rMS within the clusters. Finally, our findings suggest that eMSTO features in

Galactic open clusters are shaped predominantly by a combination of rotational effects, including rotation velocities and rotation inclination. Further observational data are needed to study the specific origins of the eMSTO and the differentiated distribution of rotational velocities in each cluster. This will help clarify the individual contributions of age spread and rotation to the eMSTO phenomenon and provide a deeper understanding of rotational effects within each star cluster.

Acknowledgments

This work is supported by the National Natural Science Foundation of China, No. 12261141689.

This work has made use of data from the Guo Shou Jing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope, LAMOST), a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by the National Astronomical Observatories, Chinese Academy of Sciences.

References

Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, *ApJS*, 219, 12
Amard, L., & Matt, S. P. 2020, *ApJ*, 889, 108
Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., & Andrae, R. 2021, *AJ*, 161, 147
Bastian, N., & De Mink, S. E. 2009, *MNRAS: Letters*, 398, L11
Bastian, N., Kamann, S., Amard, L., et al. 2020, *MNRAS*, 495, 1978
Bastian, N., Kamann, S., Cabrera-Ziri, I., et al. 2018, *MNRAS*, 480, 3739
Bastian, N., & Niederhofer, F. 2015, *MNRAS*, 448, 1863
Bayo, A., Rodrigo, C., Barrado, Y., Navascués, D., et al. 2008, *A&A*, 492, 277
Belokurov, V., Penoyre, Z., Oh, S., et al. 2020, *MNRAS*, 496, 1922
Bianchi, L., Shiao, B., & Thilker, D. 2017, *ApJS*, 230, 24
Bressan, A., Marigo, P., Girardi, L., et al. 2012, *MNRAS*, 427, 127
Brown, A. G. A., Vallenari, A., Prusti, T., et al. 2018, *A&A*, 616, A1
Cantat-Gaudin, T., Jordi, C., Vallenari, A., et al. 2018, *A&A*, 618, A93
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2009, *A&A*, 505, 117
Cordoni, G., Casagrande, L., Yu, J., et al. 2024, *MNRAS*, 532, 1547
Costa, G., Girardi, L., Bressan, A., et al. 2019, *MNRAS*, 485, 4641
D' Antona, F., Milone, A. P., Tailo, M., et al. 2017, *NatAs*, 1, 0186
de Mink, S. E., Langer, N., Izzard, R. G., Sana, H., & de Koter, A. 2013, *ApJ*, 764, 166
Demircan, O., & Kahraman, G. 1991, *Ap&SS*, 181, 313
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, *A&A*, 649, A1
Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2023, *A&A*, 674, A1
Girardi, L., Groenewegen, M. A. T., Hatziminaoglou, E., & da Costa, L. 2005,

A&A, 436, 895
Goudfrooij, P., Girardi, L., & Correnti, M. 2017, *ApJ*, 846, 22
Gratton, R., Carretta, E., & Bragaglia, A. 2012, *A&ARv*, 20, 50
He, C., Li, C., Sun, W., et al. 2023, *MNRAS*, 525, 5880
Healy, B. F., & McCullough, P. R. 2020, *ApJ*, 903, 99
Healy, B. F., McCullough, P. R., & Schlaufman, K. C. 2021, *ApJ*, 923, 23
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, *A&A*, 355, L27
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, *MNRAS*, 329, 897
Kamann, S., Saracino, S., Bastian, N., et al. 2023, *MNRAS*, 518, 1505
Krause, M. G. H., Offner, S. S. R., Charbonnel, C., et al. 2020, *SSRv*, 216, 64
Krone-Martins, A., & Moitinho, A. 2014, *A&A*, 561, A57
Li, C., de Grijs, R., & Deng, L. 2014, *ApJ*, 784, 157
Li, C., de Grijs, R., Deng, L., & Milone, A. P. 2017, *ApJ*, 844, 119
Li, C., Milone, A. P., Sun, W., & de Grijs, R. 2024, arXiv:2401.08062
Luo, A.-L., Zhao, Y.-H., Zhao, G., et al. 2015, *RAA*, 15, 1095
Mackey, A. D., & Broby Nielsen, P. 2007, *MNRAS*, 379, 151
Maeder, A. 1999, *A&A*, 347, 185
Marino, A. F., Przybilla, N., Milone, A. P., et al. 2018, *AJ*, 156, 116
Maurya, J., Samal, M. R., Amard, L., et al. 2024, *MNRAS*, 532, 929
Mermilliod, J. C. 2006, Homogeneous Means in the UBV System, VizieR Online Data Catalog: II/168., ubvmeans.dat 64x72 Catalog Data
Milone, A. P., Bedin, L. R., Piotto, G., & Anderson, J. 2009, *A&A*, 497, 755
Milone, A. P., & Marino, A. F. 2022, *Univ*, 8, 359
Milone, A. P., Marino, A. F., D' Antona, F., et al. 2016, *MNRAS*, 458, 4363
Milone, A. P., Marino, A. F., D' Antona, F., et al. 2017, *MNRAS*, 465, 4363
Milone, A. P., Marino, A. F., Di Criscienzo, M., et al. 2018, *MNRAS*, 477, 2640
Milone, A. P., Piotto, G., Bedin, L. R., et al. 2012, *A&A*, 540, A16
Nguyen, C. T., Costa, G., Girardi, L., et al. 2022, *A&A*, 665, A126
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163
Stassun, K. G., Oelkers, R. J., Pepper, J., et al. 2018, *AJ*, 156, 102
Sun, W., Li, C., Deng, L., & de Grijs, R. 2019, *ApJ*, 883, 182
Torres, G. 2010, *AJ*, 140, 1158
Wang, C., Hastings, B., Schootemeijer, A., et al. 2023, *A&A*, 670, A43
Wang, C., Langer, N., Schootemeijer, A., et al. 2022, *NatAs*, 6, 480
Wang, L., Li, C., Wang, L., He, C., & Wang, C. 2023, *ApJ*, 949, 53
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, *AJ*, 140, 1868
Yang, W., Bi, S., Meng, X., & Liu, Z. 2013, *ApJ*, 776, 112
Zahn, J. P. 1975, *A&A*, 41, 329
Zhang, B., Jing, Y.-J., Yang, F., et al. 2022, *ApJS*, 258, 26
Zuo, F., Luo, A.-L., Du, B., et al. 2024, *ApJS*, 271, 4

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.