Stellar Rotation and the Extended Main-sequence Turnoff in the Open Cluster NGC 5822

Weijia Sun1, Richard de Grijs2,3, Licai Deng4,5,6, and Michael D. Albrow7

1 Kavli Institute for Astronomy & Astrophysics and Department of Astronomy, Peking University, Yi He Yuan Lu 5, Hai Dian District, Beijing 100871, People’s Republic of China
2 Department of Physics and Astronomy, Macquarie University, Balalacla Road, Sydney, NSW 2109, Australia
3 International Space Science Institute—Beijing, 1 Nanertiao, Hai Dian District, Beijing 100190, People’s Republic of China
4 Key Laboratory for Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, People’s Republic of China
5 School of Astronomy and Space Science, University of the Chinese Academy of Sciences, Huairou 101408, People’s Republic of China
6 Department of Astronomy, China West Normal University, Nanchong 637002, People’s Republic of China
7 School of Physical and Chemical Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

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Abstract

The origin of extended main-sequence turnoffs (eMSTOs) in intermediate-age (1–3 Gyr) clusters is one of the most intriguing questions in current star cluster research. Unlike the split main sequences found in some globular clusters, which are caused by bimodal populations in age and/or chemical abundances, eMSTOs are believed to be due to stellar rotation. We present a spectroscopic survey of MSTO stars in a nearby, intermediate-age (0.9 Gyr), low-mass (≈1.7 × 105 M⊙) Galactic open cluster, NGC 5822. We derive a clean sample of member stars based on Gaia proper motions and parallaxes and confirm the existence of an eMSTO. Using medium-resolution (R ≈ 4000) Southern African Large Telescope spectra, we derive the rotational velocities of 24 member stars (representing 20% completeness around the eMSTO region) and find that the loci of the main-sequence stars in the eMSTO region show a clear correlation with the projected rotational velocities in the sense that fast rotators are located on the red side of the eMSTO and slow rotators are found on the blue side. By comparison with a synthetic cluster model, we show that the stellar rotational velocities and the eMSTO of NGC 5822 can be well reproduced, and we conclude that stellar rotation is the main cause of the eMSTO in NGC 5822.

Key words: galaxies: star clusters: general – open clusters and associations: individual (NGC 5822) – stars: rotation

1. Introduction

The extended main-sequence turnoff (eMSTO) phenomenon, i.e., the notion that the main-sequence turnoff (MSTO) in the color–magnitude diagram (CMD) is much wider than the prediction from single stellar population modeling—first discovered in NGC 1846 by Mackey & Broby Nielsen (2007), is a common feature found in a large fraction of young and intermediate-age (≤2 Gyr) massive Large and Small Magellanic Cloud clusters (e.g., Mackey et al. 2008; Milone et al. 2009, 2015; Goudroojit et al. 2011; Li et al. 2014b; Correnti et al. 2017).

In the past few years, our understanding of the eMSTO phenomenon in these clusters has been enriched and enhanced significantly. Rather than due to intrinsic age spreads, stellar rotation is believed to play an important role in shaping the morphology of the eMSTO (e.g., Bastian & de Mink 2009; Li et al. 2014a; Niederhofer et al. 2015). This theory is further reinforced by multiple lines of photometric and spectroscopic evidence. Using narrowband photometry, Bastian et al. (2017) detected a large fraction (∼30%–60%) of Be stars in the MSTO regions of NGC 1850 (∼80 Myr) and NGC 1856 (∼280 Myr), favoring the interpretation that their split main sequences are caused by the effects of fast rotators. Similar mechanisms were later confirmed in NGC 1866 (∼200 Myr) and NGC 1818 (∼40 Myr) through high-resolution spectroscopic surveys, suggesting that these clusters host a blue main sequence composed of slow rotators and a red one composed of fast rotators (Dupree et al. 2017; Marino et al. 2018b).
they found in the young cluster NGC 6705 correspond to stellar populations with different rotation rates.

In this paper, we present a spectroscopic survey of MSTO stars in the nearby (~760 pc) intermediate-age (0.9 Gyr) open cluster NGC 5822. We find the presence of an eMSTO in this cluster and verify that it is not an artifact caused by differential extinction. The loci of the main-sequence stars in the eMSTO region show a clear correlation with the projected rotational velocities, with fast rotators lying on the red side of the eMSTO and slow rotators on the blue side. By comparison with a synthetic cluster within the framework of stellar rotation, we argue that the observed morphology of the eMSTO in the CMD can be properly explained by the model and that stellar rotation is likely the main contributor to the eMSTO morphology in NGC 5822.

This article is organized as follows. In Section 2 we present the observations, data reduction procedures, and membership determination. Section 3 reports our main results, showing a strong correlation between the stellar rotation rates and their loci in the CMD region covered by the eMSTO. A discussion and our conclusions are summarized in Section 4.

2. Data Reduction and Analysis

2.1. Spectroscopic Data

We selected spectroscopic candidates in NGC 5822 using the photometric survey in the UBVI and uvbyCaHβ systems undertaken by Carraro et al. (2011). These broadband observations were obtained with the Y4KCAM camera mounted on the Cerro Tololo Inter-American Observatory (CTIO) 1 m telescope and the intermediate- and narrowband imaging was carried out using the CTIO 0.9 m telescope. Through a cross-correlation with the UCAC3 database (Zacharias et al. 2000), these authors derived 136 probable photometric members and 322 probable nonmembers.

We obtained spectroscopic observations with the Southern African Large Telescope (SALT; Buckley et al. 2006) equipped with the Robert Stobie Spectrograph (RSS) using its multi-object spectroscopy (MOS) capability over nine nights from 2018 February 8/9 to August 14/15 under programs 2017-2-SCI-038 and 2018-1-SCI-006. Six masks were designed to cover 88 stars (including repetitions) in NGC 5822 as part of program 2017-2-SCI-038, with three masks observed for the second time the following semester (see Table 1). The PG2300 grating was used with a 1 arcsec wide short slit binned 2 × 2, offering a nominal spectral resolution of ~4000 with a per-pixel resolution of 0.33 Å at a central wavelength of 4884.4 Å. Regular bias, argon arc lamp, and quartz lamp flat-field calibration frames were taken as part of normal SALT operations. We used the PySALT package (Crawford et al. 2010) to perform the primary reduction and wavelength calibration. For all of our samples, we obtained spectra with a signal-to-noise ratio (S/N) per pixel in excess of 200.

Table 1

| Mask Name  | Program   | 102500 | 025000 | Nσ  | Exp. Time (s) | Date (UT) |
|------------|-----------|--------|--------|------|--------------|-----------|
| NGC5822p2  | 2017-2-SCI-038 | 15°04′33″43 | −54°26′33″16 | 13 | 600          | 2018 Feb 8 |
|            | 2018-1-SCI-006 | 15°04′33″43 | −54°26′33″16 | 13 | 764          | 2018 Aug 3 |
|            | 2017-2-SCI-038 | 15°04′19″43 | −54°16′44″52 | 10 | 600          | 2018 Apr 26 |
|            | 2017-2-SCI-038 | 15°03′11″44 | −54°16′22″93 | 11 | 600          | 2018 Feb 8 |
|            | 2017-2-SCI-038 | 15°03′11″44 | −54°16′22″93 | 11 | 600          | 2018 Jul 30 |
|            | 2017-2-SCI-038 | 15°03′09″95 | −54°31′46″39 | 9  | 600          | 2018 Feb 11 |
|            | 2017-2-SCI-038 | 15°03′09″95 | −54°31′46″39 | 9  | 764          | 2018 Aug 14 |
|            | 2017-2-SCI-038 | 15°05′10″13 | −54°19′41″91 | 7  | 600          | 2018 Feb 26 |
|            | 2017-2-SCI-038 | 15°04′36″35 | −54°34′51″48 | 5  | 600          | 2018 Apr 30 |

Note.

* Number of science slits in each field.

2.2. Membership Determination

We exploited the Gaia DR2 (Gaia Collaboration et al. 2016, 2018) to analyze the stellar photometry, proper motions, and parallaxes, and to perform membership determination in the NGC 5822 field. First, we acquired the stellar catalog from the Gaia database within 2.5 times the cluster radius (35; Dias et al. 2002). In the vector-point diagram of stellar proper motions, NGC 5822 showed a clear concentration centered at (μv, cos θ, μb) ≈ (−7.44, 7.44, 5.52) mas yr⁻¹. The other overdensity located at (μv, cos θ, μb) ≈ (−3.67, 3.67, 2.52) mas yr⁻¹ corresponds to a nearby cluster, NGC 5823. Then, we derived the quantity μR = (√(μv cos θ − μb))² + (μb − μb)² and applied a cut of μR = 0.4 mas yr⁻¹ to conduct our primary membership selection. Next, we placed a further constraint on the parallaxes by estimating the mean parallax of the proper-motion-selected stars at (μv, cos θ, μb) = 1.18 mas yr⁻¹ and adopted stars with parallaxes within 0.115 mas yr⁻¹ as cluster members. Note that this approach is slightly different from that adopted by Cordoni et al. (2018), in the sense that we adopted a straight cut in both μv and cos θ rather than applying different selection criteria for stars of different brightnesses. One reason for this approach is that NGC 5822 is sufficiently close that its member stars can be easily separated from field stars using parallaxes (see the top right panel of Figure 1). On the other hand, the limited number of stars in NGC 5822 makes it hard to reliably calculate the corresponding rms for each magnitude bin. As we did not set out to compile a homogeneous database for multiple clusters, our approach is suitable for our analysis of this single cluster. We present the spatial distribution as well as the CMD of the member stars of NGC 5822, together with all stars in the field, in the bottom panels of Figure 1. We present the CMD of NGC 5822 color-coded by the stellar classifications based on their loci in Figure 2. Member stars classified as MSTO, MS, and giant stars are marked as green squares, blue triangles, and red diamonds, respectively. Member stars with spectroscopic data are presented using solid markers and field stars with
spectroscopic data are shown as gray circles. Following decontamination of the field stars, 24 member stars (21 MSTO and 3 MS stars) were left in our observational sample; 13 member stars were observed a second time. We estimate that the total number of member MSTO stars in this cluster is $\sim 10^7$, suggesting that the completeness of our observed sample is around 20% in the eMSTO region.

This cluster shows a clear eMSTO feature around $G \sim 11.5$ mag. To further demonstrate that this is not an artifact owing to residual differential reddening, we estimated the degree of the spatial variation of the reddening and found that its influence is negligible compared with the extent of the eMSTO. Given its close distance and low Galactic latitude, we found that we could not use a 2D reddening map (e.g., Schlafly & Finkbeiner 2011) to estimate the differential reddening. Instead, we adopted the method of Nataf et al. (2013), who assumed a two-component model for the distribution of the dust, including the mean density of dust along the plane $\rho_D$ and a scale height $H_D$. Therefore, the prediction for the reddening in
with effective temperatures, $T_{\text{eff}}$, ranging from 5000 K to 8000 K (in steps of 100 K), surface gravities from log $g = 3.5$ to log $g = 5.0$ (in steps of 0.1), and metallicities from [Fe/H] = −1.0 to [Fe/H] = 1.0 dex (in steps of 0.5 dex) from the Pollux database (Palacios et al. 2010). We applied the latest ATLAS12 model atmospheres (Kurucz 2005) where blanketed model atmospheres handle line opacity in stellar atmospheres using the Opacity Sampling technique. The models assume a plane parallel geometry, hydrostatic and radiative equilibrium, as well as local thermodynamic equilibrium. The microturbulent velocity was fixed to 2 km s$^{-1}$ for all models. Synthetic spectra were then generated using the SYNSPEC tool (Hubeny & Lanz 1992). Each model spectrum was convolved with the rotational profile for a given rotational velocity and implemented with an instrumental broadening as well as a radial velocity shift. Given that the light enters through off-axis slits (in the dispersion direction) in the MOS, the actual resolution may vary from slit to slit and from mask to mask. Therefore, we adopted the full width at half maximum (FWHM) of the corresponding arc lines as an indicator of the instrumental broadening effect. Then, we used the Markov chain Monte Carlo (emcee; Foreman-Mackey et al. 2013) method to sample the five-dimensional parameter space ($v \sin i$, $v$, $T_{\text{eff}}$, log $g$, [Fe/H]) to employ a $\chi^2$ minimization. For each of the 3000 runs of the MCMC procedures, $\chi^2$ values and their associated probabilities $e^{-\chi^2/2}$ were stored. Probability distributions were then generated by projecting the sum of the probabilities onto the dimension considered. A Gaussian fit to the distribution provides its width $\sigma$, which we adopt as the uncertainty.

To estimate the influence of instrumental broadening on the determination of the rotational velocities, we generated a set of mock spectra by sampling the projected rotational velocities $v \sin i$ from 20 to 200 km s$^{-1}$, assuming a uniform $S/N = 200$ and a reasonable uncertainty for the instrumental broadening ($\sigma_{\text{FWHM}} = 0.1 \, \AA$), and we measured the best-fitting parameters from those mock spectra. We repeated this procedure 100 times and estimated the median values and the 68th percentiles of the velocity distribution. In Figure 4 we present a comparison of the rotational velocities of the mock data with those derived through profile fitting. The blue shadowed region corresponds to $1\sigma$ and the one-to-one relation is indicated by an orange solid line. Given the intermediate spectral resolution, it is hard to differentiate the effect of rotational from instrumental broadening for slow rotators. Therefore, we defined the detection limit of the rotational velocity to be the velocity where its uncertainty is around half of the actual value and, for slow rotators with $v \sin i \lesssim 55$ km s$^{-1}$, the uncertainties of the measurements are comparable to their actual values, while the uncertainty is less than 5% and 3% for the mock spectra with $v \sin i \gtrsim 100$ km s$^{-1}$ and $v \sin i \gtrsim 150$ km s$^{-1}$, respectively.

### 3. Extended MSTOs and Stellar Rotation

The eMSTO of NGC 5822, if interpreted as an age difference, is around 300–350 Myr. Cordoni et al. (2018) estimated the ages of the stars around the eMSTO region by linearly interpolating a grid of isochrones and calculated the FWHM of the cluster’s age distribution, which gives a spread of 270 ± 52 Myr. They also showed that the FWHM of the NGC 5822 eMSTO follows the correlation between the width of the eMSTO and cluster age applicable within the framework of stellar rotation.
In Figure 5, we present the CMD of NGC 5822, with the member stars color-coded by their rotational velocities. We found that their loci in the CMD region covered by the eMSTO strongly depend on stellar rotation, in the sense that rapid rotators tend to lie on the red side of the eMSTO while slow rotators are usually found on the blue side. Similar results have also been discovered in young and intermediate-age clusters in the Magellanic Clouds (Dupree et al. 2017; Kamann et al. 2018), as well as in Galactic open clusters (Bastian et al. 2018; Marino et al. 2018a). The stellar structural parameters as well as the inferred projected rotational velocities are listed in Table 2.

We also compared the observed cluster data with a synthetic cluster data set that included the effects of stellar rotation. The synthetic cluster data were derived from the SYCLIST models (Georgy et al. 2013, 2014), assuming a metallicity of $Z = 0.014$, an age of $\log(t \text{ yr}^{-1}) = 8.95$, and a binary fraction of 0.13, with a rotational distribution derived from Huang et al. (2010) and a random rotation axis distribution. The model also accounts for the limb-darkening effect (Claret 2000) as well as for the gravity darkening law of Espinosa Lara & Rieutord (2011). In the left panel of Figure 6, the synthetic cluster is superposed onto the CMD of NGC 5822 and the eMSTO feature is well reproduced and consistent with coeval stellar populations with different rotation rates. The projected rotational velocity of the synthetic cluster follows a similar trend as the real member stars, which become redder as the stellar rotation rates increase. In the middle panel we present a realistic synthetic cluster with a number of stars comparable to that in the observed CMD.

To provide a better comparison with the simulation, we introduced the pseudo-color $D_{\text{BP}} - \text{BP}$ as the normalized color difference with respect to the blue ridgeline in the direction determining how stellar rotation may change the locus of a star in the CMD (black arrow) to represent the deviation in color that may be caused by stellar rotation. We adopted the blue edge of the synthetic cluster, which represents the population of nonrotating stars, as the fiducial ridgeline. In the right panel of Figure 6, the $D_{\text{BP}} - \text{BP}$ versus $v \sin i$ diagram for all stars with projected rotational velocity measurements is shown, and the gray dots represent the same distribution for the synthetic cluster. We found that most of our targets follow the trend predicted by the stellar rotational model, where the pseudo-color is close to zero for slow rotators and it increases significantly as the rotational velocity increases. Two outliers in the right panel of Figure 6 (Gaia IDs: 5887669198096568960 and 5887671397119565312), which have relatively large pseudo-colors compared with their rotational velocities, may result from contamination by binary stars. Since their locations in the CMD coincide with the equal-
For each spectrum, the best-fitting isochrone is shown as the red curve. A clear trend between stellar rotation and their loci in the CMD region is seen, in the sense that the rapid rotators (yellow) tend to lie on the red side of the eMSTO while the slow rotators (blue) are usually found on the blue side. (Right) Two sample spectra of a slow rotator (top) and a fast rotator (bottom). H$\beta$ and Mg I triplets of the same object are shown in the left- and right-hand columns, respectively. For each spectrum, the best-fitting models are presented as orange curves.

NGC 5822 is an intermediate-age (0.9 Gyr) Galactic open cluster exhibiting an eMSTO. Through membership determination based on Gaia proper motions and parallaxes, we investigated the CMDs of NGC 5822 and confirmed that the eMSTO is not likely an artifact caused by differential extinction. By exploiting SALT/RSS data, we derived the projected rotational velocities of 24 member stars and found that stellar rotation is strongly correlated with the stellar loci in the CMD in the MSTO region. The red side of the eMSTO is occupied by fast rotators while the blue side is mainly composed of slow rotators. By comparison with a synthetic cluster, we have shown that the eMSTO of NGC 5822 can be properly reproduced and the rotational velocities of the eMSTO stars follow the same pattern as that predicted by the stellar rotation model.

Combined with NGC 6705 (Marino et al. 2018a) and NGC 2818 (Marino et al. 2018b), we have confirmed the existence of slowly and rapidly rotating populations and found that these two subgroups are well separated in projected rotational velocity, with a difference in mean $\nu\sin i$ greater than 100 km s$^{-1}$. Meanwhile, in the intermediate-age clusters NGC 2818 (Bastian et al. 2018) and NGC 5822, such a result is barely seen, which may due to small number statistics and selection effects. Therefore, we estimated the rotational velocities for all MSTO stars in NGC 5822 based on our synthetic cluster to check the distribution of the stellar rotation rates. On the basis of previous analyses, we argue that the synthetic cluster can properly reproduce the observed results and that it can be taken as a reasonable approximation to the real cluster. Thus, for each member star in the NGC 5822 MSTO region, we inferred the rotational velocities by taking the average velocities of the nearest 50 stars in the synthetic CMD.

The distributions of projected rotational velocity $\nu\sin i$ and $v_{\text{rot}}$ are presented in Figure 7. We found that the projected rotational velocities show a dip around 150 km s$^{-1}$, similar to the results for NGC 1818 and NGC 6705. However, we suggest that this is an artifact caused by projection effects. In Figure 7 the “slow” rotators have a peak at 100 km s$^{-1}$ and they have a dearth of stars with $\nu\sin i \sim 50$ km s$^{-1}$, which is different from the results for the young clusters where the slowly rotating populations have lower mean velocities and do not show a gap in slowly rotating stars. The distribution of the true rotational velocities is also shown in Figure 7, and the fact that it shows a single peak around 200 km s$^{-1}$ further confirms that the equatorial velocities in NGC 5822 should follow a unimodal distribution. On the other hand, projection effects are unlikely to explain the large difference in projected rotational velocities found in young clusters, and the true rotation rates of MSTO stars in young clusters should in all probability show a bimodal distribution given the fact that the split MSs can be separated into distinct sequences in the CMD. Since the typical masses of the split MSs in young clusters ($\approx 2.5 M_\odot$) and eMSTOs in intermediate-age clusters ($1.4 M_\odot - 2 M_\odot$) are different, if a split MS and eMSTO are present in the evolutionary sequence of

**4. Discussion and Conclusions**

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star clusters, these two distributions of stellar rotation may coexist in the same cluster. This may hint that the stellar rotation distribution in clusters follow a similar pattern as the field population in the sense that stars more massive than $2.5 \, M_\odot$ show a bimodal equatorial velocity distribution while less massive stars have a unimodal rotation distribution (Zorec & Royer 2012). However, spin alignment in clusters may play an overlooked role. Corsaro et al. (2017) found evidence of spin alignment among the red giant stars in the two old open clusters NGC 6791 and NGC 6819. Lim et al. (2018) inferred the $v_{\text{rot}}$ and the inclination angles $i$ of MSTO stars in NGC 6705 from Monte Carlo simulations where $v_{\text{rot}}$ has a linear distribution and $i$ a Gaussian distribution. They argued that cluster members have highly aligned spin axes, which implies a link between stellar rotation and rotational kinetic energy in the progenitor molecular cloud.

We also estimated the stellar masses following similar procedures as Sun et al. (2018). In essence, we generated a synthetic cluster of 10,000 stars with the initial masses generated through Monte Carlo sampling of a Kroupa stellar initial mass function (Kroupa 2001). Then, we calculated the ratio of the number of member stars with $G$ magnitudes from 12.5 to 13.5 mag to that of the synthetic cluster for the same magnitude range. We multiplied the integrated mass obtained for the synthetic cluster by this ratio to estimate the total stellar mass in the cluster, $1.7 \pm 0.3 \times 10^4 \, M_\odot$. We confirmed that changing the magnitude range will not affect the estimation of the total mass significantly. Bastian et al. (2018) reported a mass of $2800 \, M_\odot$ for NGC 2818. These results suggest that eMSTOs are not exclusive to massive clusters ($10^5$–$10^7 \, M_\odot$).

One possible source that could also give rise to a broadened MSTO is stellar variability. Salinas et al. (2016) argued that the instability strip intersects with the MSTO region of a cluster
with an age of $\approx$1–3 Gyr and can make a significant contribution to the observed eMSTOs. Follow-up observations of NGC 1846 revealed the presence of a group of (mainly $\delta$ Scuti) variable stars around the eMSTO region. However, the number fraction of variable stars was not sufficient to produce the observed width of the eMSTO (Salinas et al. 2018). Certain types of variable or binary stars (e.g., EA-type eclipsing binaries) exhibit large changes in radial velocity over time and can be detected through multi-epoch observations. However, we did not find such candidates in our sample because of the limited spectral resolution and the small number of observations. Follow-up photometric and spectroscopic observations are required to further investigate the role of variability in shaping the morphology of the eMSTO region.

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ORCID iDs

Weijia Sun @ https://orcid.org/0000-0002-3279-0233
Richard de Grijs @ https://orcid.org/0000-0002-7203-5996
Licai Deng @ https://orcid.org/0000-0001-9073-9914
Michael D. Albrow @ https://orcid.org/0000-0003-3316-4012

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