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Stellar rotation bifurcation caused by tidal locking in the open cluster NGC 2287?

Weijia Sun[1,2], **Chengyuan Li**[3,2], **Licai Deng**[2,4,5] and **Richard de Grijs**[6,7,8]

[1]Kavli Institute for Astronomy & Astrophysics and Department of Astronomy, Peking University, Yi He Yuan Lu 5, Hai Dian District, Beijing 100871, China
email: swj1442291549@gmail.com

[2]Key Laboratory for Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China

[3]School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519082, China

[4]School of Astronomy and Space Science, University of the Chinese Academy of Sciences, Huairou 101408, China

[5]Department of Astronomy, China West Normal University, Nanchong 637002, China

[6]Department of Physics and Astronomy, Macquarie University, Balaclava Road, Sydney, NSW 2109, Australia

[7]Research Centre for Astronomy, Astrophysics and Astrophotonics, Macquarie University, Balaclava Road, Sydney, NSW 2109, Australia

[8]International Space Science Institute–Beijing, 1 Nanertiao, Hai Dian District, Beijing 100190, China

Abstract. We present a detailed analysis of the projected stellar rotational velocities of the well-separated double main sequence (MS) in the young, ∼200 Myr-old Milky Way open cluster NGC 2287 and suggest that stellar rotation may drive the split MSs in NGC 2287. We find that the observed distribution of projected stellar rotation velocities could result from a dichotomous distribution of stellar rotation rates. We discuss whether our observations may reflect the effects of tidal locking affecting a fraction of the cluster's member stars in stellar binary systems. The slow rotators are likely stars that initially rotated rapidly but subsequently slowed down through tidal locking induced by low-mass-ratio binary systems. However, the cluster may have a much larger population of short-period binaries than is usually seen in the literature, with relatively low secondary masses.

Keywords. stars: rotation — open clusters and associations: individual: NGC 2287 — galaxies: star clusters: general.

1. Introduction

Discoveries of extended main-sequence (MS) turnoffs (eMSTOs) in intermediate-age clusters (e.g. Mackey *et al.* 2008; Milone *et al.* 2009) and split MSs in young clusters (e.g., Milone *et al.* 2015; D'Antona *et al.* 2015) have generated great interest in the formation mechanisms of these phenomena in clusters. These features, which are primarily found in the Magellanic Clouds, strongly challenge our understanding of star cluster formation and evolution.

Multiple scenarios have been proposed to explain the observational results, including an extended star formation history (Goudfrooij *et al.* 2011), variable stars (Salinas *et al.* 2016), stellar rotation, and convective overshooting (Yang & Tian 2017). Thus far,

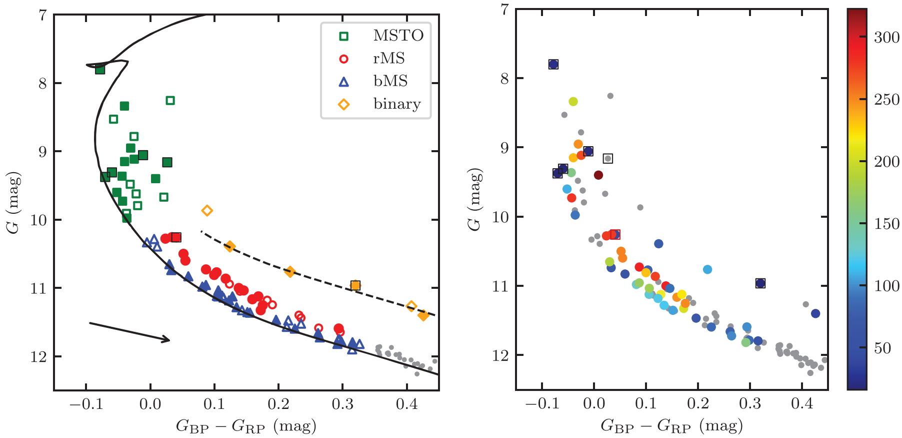

Figure 1. (left) CMD of NGC 2287 around its eMSTO and split-MS regions. bMS, rMS, MSTO, and binary stars are represented by blue triangles, red circles, green squares, and yellow diamonds, respectively. Spectroscopically analyzed stars are marked with solid symbols. The black solid and dashed lines represent the best-fitting PARSEC isochrone and the corresponding equal-mass binary sequence, respectively. The black arrow indicates the direction of the reddening vector. (right) CMD of NGC 2287 with stars color-coded according to their projected rotational velocities. Squares represent spectroscopic binaries. Adapted from Sun *et al.* 2019.

the stellar rotation interpretation is most favored by a range of observations, including the detection of a population of Be stars based on narrow-band photometry (Bastian *et al.* 2017; Milone *et al.* 2018) and rapidly rotating stars based on direct spectroscopy (Dupree *et al.* 2017; Marino *et al.* 2018), although contributions from other channels cannot be completely ruled out.

Recent studies have revealed that these features are not exclusive to Magellanic Clouds clusters, but they are quite common in Galactic open clusters (Cordoni *et al.* 2018; Sun *et al.* 2019). These results provide us with a great opportunity to study cluster evolution under different physical conditions. The cluster we selected to study is NGC 2287. It is an open cluster that is known to have an eMSTO. This study aims to verify whether there is a connection between the MS stars' loci in the color–magnitude diagram (CMD) and their stellar rotation properties, and study the formation mechanism(s) responsible for its peculiar rotation distribution.

2. Stellar rotation and split MSs in NGC 2287

Following standard procedures to select member stars using proper motion and parallax analysis, we derived a 'clean' membership determination for NGC 2287 based on *Gaia* DR2. The *Gaia*-based CMD of the cluster's member stars is presented in the left-hand panel of Fig. 1. A clearly defined split MS is shown for G-band magnitudes from 10.5 mag to 11.5 mag. We also overplotted the best-fitting isochrone with an age of 150 Myr based on the PARSEC 1.2S models (Bressan *et al.* 2012) for solar metallicity, $Z = 0.0152$, and an extinction $A_{\rm V} = 0.217$ mag. By checking the MS region that is not parallel to the reddening direction, we confirmed that the split MS and eMSTO in NGC 2287 are not artifacts caused by differential extinction.

We downloaded archival high-resolution ($R \approx 29,000$) spectra observed with the European Southern Observatory's (ESO) Very Large Telescope (VLT) equipped with

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the FLAMES/GIRAFFE spectrograph. The data were collected as part of program 380.D-0161 (PI: Gieles). We studied 53 bright stars of the full 166 member-star sample observed, covering the eMSTO, the red and blue MSs (rMS, bMS), and the equal-mass binary sequence (see Fig. 1, left). Using the absorption-line profiles of the Mg I triplet, we calculated the projected rotational velocities, $v \sin i$, by comparing the observed spectra with synthetic stellar spectra convolved with various rotational velocities from the Pollux database (Palacios *et al.* 2010). As for stars with multiple observations, we confirmed that most do not show any variations in their stellar parameters, including radial and rotational velocities. There are a handful of exceptions that may be attributed to spectroscopic binaries (black squares in Fig. 1).

The right-hand panel of Fig. 1 presents the CMD of NGC 2287 with stars color-coded according to their $v \sin i$. bMS and rMS stars are clearly separated in projected rotational velocity, in the sense that bMS stars are mainly dominated by slow rotators while rMS stars are rapid rotators. The mean projected rotational velocities of bMS and rMS are $\langle v \sin i\rangle_{\rm bMS} = 111 \pm 13\,{\rm km\,s^{-1}}$ $(\sigma = 46\,{\rm km\,s^{-1}})$ and $\langle v \sin i\rangle_{\rm bMS} = 255 \pm 10\,{\rm km\,s^{-1}}$ $(\sigma = 26\,{\rm km\,s^{-1}})$, respectively, if possible unresolved binaries are excluded. A similar trend is observed for MSTO stars, i.e., stars are getting redder as their rotation rates increase.

3. Discussions

To unravel the underlying distribution of equatorial rotational velocities, $v_{\rm eq}$, and the inclination angles, i, we compared the cumulative distribution of the projected rotational velocities $v \sin i$ with three distribution models. Model 1 has a uniform distribution of both $v_{\rm eq}$ and orientation in three-dimensional space. Model 2 is characterized by a uniform distribution of $v_{\rm eq}$ and a Gaussian distribution of i, which is the representative scheme for 'spin alignment' (see Corsaro *et al.* 2017; Mosser *et al.* 2018). Model 3 adopts a uniform distribution of i and a bimodal distribution of $v_{\rm eq}$ to represent the slowly and rapidly rotating populations, $v_{\rm s}$ and $v_{\rm r}$, respectively.

We found that model 3 performs significantly better than the other two models. It yields two rotating populations with peak velocities of $v_{\rm r} = 280\,{\rm km\,s^{-1}}$ and $v_{\rm s} = 100\,{\rm km\,s^{-1}}$. These values are within $1\,\sigma$ of $\langle v \sin i\rangle_{\rm rMS}$ and $\langle v \sin i\rangle_{\rm bMS}$, suggesting a relationship between fast/slow rotators and rMS/bMS stars. This represents the first evidence in support of a dichotomous distribution of real rotational velocities in star clusters. It raises an important question as to the origin of such a bimodal rotational velocity distribution.

Although a similar bimodal distribution of rotation has been detected in early-type field stars (Royer *et al.* 2007; Zorec & Royer 2012), there are substantial differences in terms of mass and velocity. On the one hand, the census of field stars found a bimodal distribution only for stars more massive than $2.5\,{\rm M_\odot}$, while the lowest-mass end of the split MS in NGC 2287 is around $1.7\,{\rm M_\odot}$. On the other hand, the peak rotational velocities we derived for slow and fast rotators in NGC 2287 are both slightly larger than the values reported by Zorec & Royer (2012) for a similar mass range.

D'Antona *et al.* (2017) proposed a possible scenario that could explain the bimodal rotational distribution in NGC 2287. They argued that bMS in young clusters might be the outcome of fast braking of the rapidly rotating population. Magnetic-wind braking or tidal torques owing to a binary companion can, in theory, rapidly decelerate a star's rotation rate and transfer the star's evolution from the rapidly rotating to the non-rotating track. Here, we explore whether the bMS stars in NGC 2287 could be composed of a population of slow rotators ($\sim$100 km s^{-1}) which may have slowed down from their initial state of rapid rotation by low-mass-ratio ($q \leqslant 0.4$) binary companions.

Using the equations given by Hurley *et al.* (2002), we estimated the synchronization timescale for a typical star in the split MS region of NGC 2287. We confirmed that the synchronization timescale of a close binary system is relatively short compared with the age of NGC 2287. And the possible distribution of binary separations, a, and mass ratios, q, overlap significantly with the expected relation between a and q for slow rotators, based on Kepler's Third Law. Such a population of close binaries with low-mass-ratio companions could explain the existence of the bMS. In the meantime, the higher-mass-ratio ($q \geqslant 0.5$) unresolved binaries will become significantly reddened and therefore appear on the rMS rather than the bMS. However, there are some possible flaws in the scenario. The best-fitting result of Model 3 requires a bMS-to-rMS number ratio of close to unity, which is not found in the field survey (Moe & Di Stefano 2017). Another peculiar feature is the mass ratio distribution of NGC 2287. The well-defined equal-mass binary sequence implies that they have mass ratios close to unity. Our observational evidence shows that in NGC 2287 binary systems have either very low or very high (near unity) mass ratios since no objects with intermediate-mass ratios appear to be present in the CMD.

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