Massive Stars Near and Far
Proceedings IAU Symposium No. 361, 2024
J. Mackey, J. S. Vink, & N. St-Louis, eds.
doi:10.1017/S1743921322002836

The impact of binary interaction on the main-sequence morphology of young star clusters

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Abstract. Since massive stars form preferentially as members of close binary systems, we use dense grids of detailed binary evolution models to explore how binary evolution shapes the main-sequence morphology of young star clusters. We propose that binary mergers might be the origin of the blue main sequence stars in young star clusters. Our results imply that stars may either form by accretion, or through a binary merger, and that both paths lead to distinctly different spins, magnetic fields, and stellar mass distributions.

Keywords. stars: early-type, stars: binaries, Hertzsprung-Russell diagram

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1. Introduction

Recent high-precision Hubble Space Telescope (HST) photometry reveals that the main sequences (MSs) of young star clusters in the color-magnitude diagram are split into several components (Milone et al. 2009, 2018). This challenges the traditional view

https://doi.org/10.1017/S1743921322002836 Published online by Cambridge University Press

of star clusters containing coeval stars born with identical initial conditions. These MS components are characterized by a split MS and an extended MS turn-off (eMSTO).

There is a growing consensus that the split MS is caused by a bi-modal rotation velocity distribution, with the red MS containing fast rotators and the blue MS containing slow rotators. This is supported by the spectroscopic measurements of the rotation velocity of the red and blue MS stars in the Large Magellanic Cloud (LMC) cluster NGC 1818 (Marino et al. 2018). This bi-modal velocity distribution also agrees well with the previous spectroscopic studies of the velocity of B/A type stars (Zorec & Royer 2012; Dufton et al. 2013). Fast rotation is expected from star formation theory, as stars increase their spins during the contraction and accretion phases in their formation, whereas the origin of the slowly rotating stars is still unknown.

About 70% of massive stars are shown to have close companions (Sana et al. 2012). However, the impact of binary interaction in shaping the MS morphology of young star clusters has not been studied in detail so far, due to the lack of proper binary models. We provide such detailed binary models and propose a self-consistent theory to explain all these discrete MS components with co-eval stars.

2. Methods

We use the one-dimensional stellar evolution code MESA (Paxton et al. 2011, 2013; Paxton et al. 2015), version 8845, to compute our binary evolution models. We use the same physics assumptions as the single star models of Brott et al. (2011) and Schootemeijer & Langer (2018). For the details of our binary star models, we refer to Wang et al. (2020).

We consider a Small Magellanic Cloud (SMC) like metallicity ($Z_{\rm SMC} = 0.002179$) for our binary models, such that stellar winds, which are one of the important uncertainties in stellar astrophysics, are weak. We build more than 50 000 binary evolution models, with the primary star mass ranging from $5M_{\odot}$ to $100M_{\odot}$, initial mass ratio ranging from 0.3 to 0.95 and initial orbital periods ranging from 1 day to ~8.6 yr. We consider constant parameter intervals and do not include statistical probabilities, such as the IMF and initial binary parameter distributions, because we only mean to show which parts of the HRD are covered by binary models in different evolutionary stages.

In order to perform isochrone fits to young star clusters, we also compute single star models with MESA version 12115 (Paxton et al. 2019), as this new version allows building star models with rotational velocities as high as 90% of critical rotation. For the details of our single star models, we refer to Wang et al. (2022).

3. Results

3.1. *Binary evolutionary induced main-sequence features*

Figure 1 shows the location of our binary models in the HRD at 30 Myr. Each dot corresponds to the visually brighter component in one binary system. The pre-interaction binaries (blue dots) in this figure are located on a single line, which represents the corresponding single-star isochrone. The binary merger products (yellow dots) are located on the upper left side of the HRD. We assume that the binary merger products have slow rotation according to Schneider et al. (2019). The merger products appear bluer and younger than the other binary systems because of rejuvenation. The post-mass transfer binaries (red dots) form a discrete main sequence on the upper right side of the HRD. They are the accretors that have experienced stable mass transfer and have reached near-critical rotation during accretion. We assume that they will be observed as Be stars, which may have disks and thus have emission lines in the spectrum and IR excess in photometry (Rivinius et al. 2013). The semi-detached binaries (green dots) are those that are

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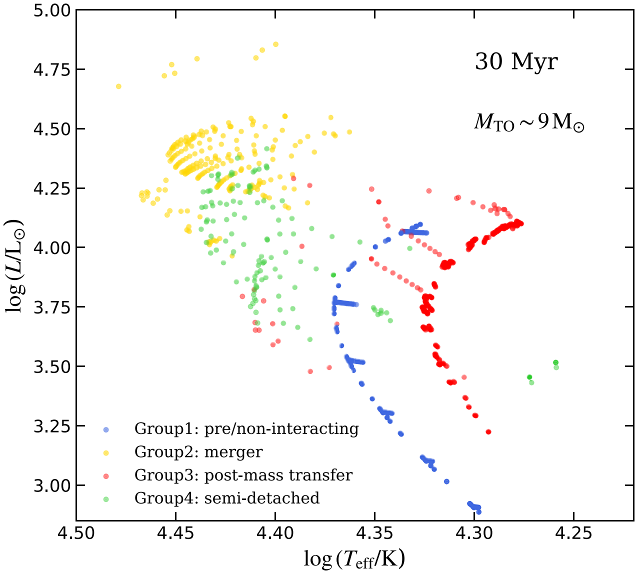

Figure 1. Distribution of our binary models in the Hertzsprung-Russell diagram at 30 Myr. Only the visually brighter component of each binary is plotted. Blue dots are the stellar models that have not yet interacted with a companion. Yellow dots are the binary merger products, while red dots correspond to post-interaction stellar models. Green dots represent the stellar models that are undergoing mass transfer at this time. The MS turnoff mass for the non-interacting stars in a cluster at this age is $\sim 9\,M_\odot$. (Colors can only be seen in the online version.)

undergoing nuclear timescale mass-transfer phase. We stress here that the colors in this figure only mean to indicate different binary evolutionary stages. The red and blue dots do not correspond to the observed red and blue MS stars in young star clusters.

Figure 1 indicates that binary evolution leads to multiple MS components in young star clusters, by producing a population of blue stragglers via binary mergers and a population of red Be stars from stable mass transfer.

3.2. *The origin of the blue main-sequence*

Our detailed binary evolution models show that binary merger products can explain the blue stragglers observed in young star clusters. However, the origin of the blue MS stars below the cluster turn-off, which are also believed to have slow rotation, is yet unknown. We use the LMC cluster NGC 1755 as an example to investigate the origin of the blue MS. In Fig. 2 we show the CMD of the MS stars in NGC 1755 and the isochrone fit. We identify the red and blue MS stars according to the method in Wang et al. (2022). We examine the mass function of the red and blue MS stars in this cluster. The masses of the stars are derived according to the mass-luminosity relation contained in the isochrones in the right panel of Fig. 2.

We plot the cumulative number distribution of the red and blue MS stars in NGC 1755 as a function of mass in Fig. 3. We use a power-law mass function $N(m)dm \propto m^\gamma$ to fit the obtained distribution. For the red MS stars, the derived power law exponent of $\gamma = -2.17 \pm 0.15$ is close to that of a Salpeter law ($\gamma = -2.35$) in the mass range of 2 to 5.5 $M_\odot$. However, in the same mass range, the power law exponent of the blue MS stars is $\gamma = -1.03 \pm 0.32$, representing a much flatter mass distribution. We find similar results in other young Magellanic Cloud clusters (< 100 Myr) that exhibit a split MS feature.

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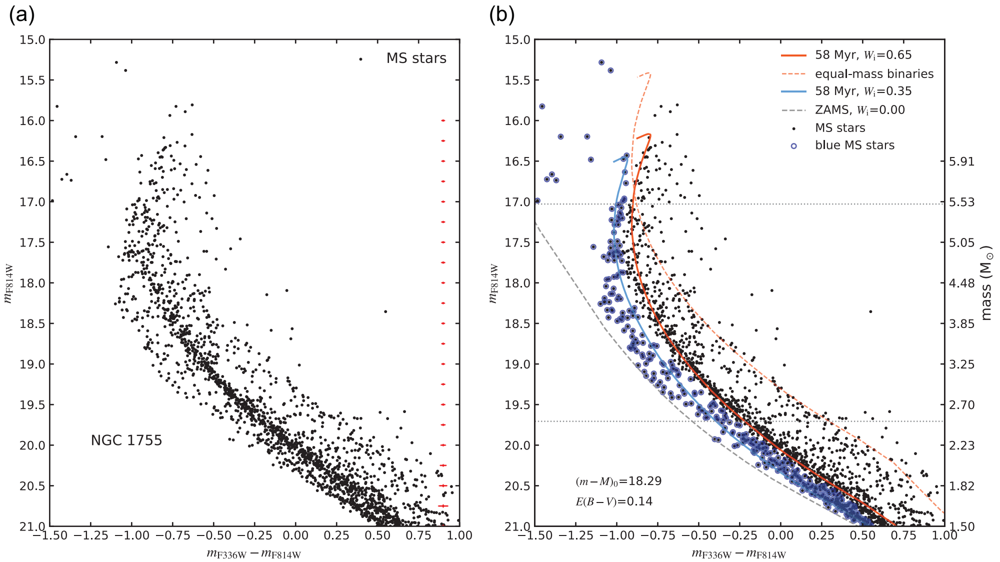

Figure 2. **a**: HST color-magnitude diagram of NGC 1755 (black dots). Red error bars indicate typical errors at corresponding magnitudes. **b**: Isochrone fit for the red and blue MSs in NGC 1755. The red and blue solid lines show the isochrones of 60 Myr single star models whose initial velocities are 65% and 35% of critical rotation. The red dashed line shows the positions of the equal-mass binaries in which both components have 65% of critical rotation initially. The grey dashed line indicates the zero-age MS line of non-rotating stars. The stars between the two horizontal dotted lines are used in our mass function analysis. The right y-axis shows the stellar mass according to the mass-magnitude relation of the fast rotating star models. (Colors can only be seen in the online version.)

Different mass functions may indicate different origin mechanisms of the red and blue MS stars.

We propose that blue MS stars stem from binary mergers. Unlike the blue stragglers that can be explained by binary evolutionary-induced mergers, the progenitors of the blue MS stars below the cluster turn-off do not have time to encounter mass transfer. These blue MS stars may originate from the binary mergers triggered by dynamical processes, e.g. the interaction between the binary systems and their surroundings, including circumbinary disks, ambient gas or a distant tertiary star. This means that binaries are born with large separations, then the two stellar components migrate towards each other due to the above-mentioned interaction. Some binaries merge during this migration phase. The derived flat mass function for the blue MS stars agrees with their merger origin, as it is shown that binary fraction increases with stellar mass (Schneider et al. 2015), and more massive binaries are probably easier to merge (Korntreff et al. 2012). Given the hypothesis of the merger origin of the blue MS stars, we derive an early merger rate peak. This can be seen by the fact that the star density is the highest in the vicinity of the blue isochrone in the right panel of Fig. 2.

There are pieces of observational evidence supporting binary migration. Firstly, a dearth of short period massive binaries is found in young star-forming regions (Sana et al. 2017), meaning that migration within the first several Myrs of the cluster lifetime is required to explain the observed high fraction of close massive binary systems (Sana et al. 2012). Secondly, the observed velocity dispersion of the cluster stars increases with cluster age during their first few million years of evolution (Ramírez-Tannus et al. 2021),

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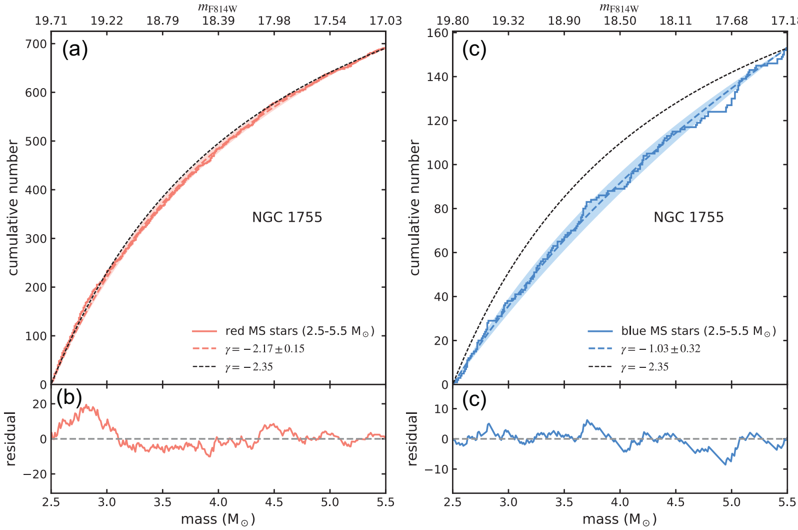

Figure 3. **a** and **c**: Cumulative number distribution of the red MS (red lines) and the blue MS stars (blue lines) in NGC 1755 as a function of their mass. Dashed lines show the best fitting power-law mass function. The shaded areas represent one sigma errors of our power-law fitting. The dashed black lines show the distribution predicted by the Salpeter IMF with a power-law index of $\gamma = -2.35$. The top x-axes show the apparent magnitudes for given masses. **b** and **d**: Residuals, i.e. difference between the colored solid and dashed lines in Panels a and c, as a function of mass. The grey dashed lines indicate zero residual. (Colors can only be seen in the online version.)

which also indicates that the close binary fraction increases with time. From the theoretical side, tidal forces imposed by the circumbinary matter are known to induce a drastic decay of the binary orbit (Korntreff et al. 2012). Recent binary formation models indeed predict ∼30% of binary B stars to merge during their pre-MS evolution or early MS evolution (Tokovinin & Moe 2020).

4. Conclusions

We find that binary interaction plays a vital role in shaping the MS morphology of young star clusters. Binary interaction can produce the slowest rotating stars by binary mergers, which will populate the blue MS. Meanwhile, binary interaction can also produce the fastest rotating stars by stable mass transfer, which will populate the red Be sequence. Our results imply that stars might be born in two fundamentally different ways. On the one hand, the majority of stars form by accretion of gas via accretion disks. These stars should have natal spins slightly larger than half of the critical rotation; they should follow the Salpeter IMF and should not be magnetic stars. On the other hand, some of the thus created stars merge and produce blue MS stars, rotating slowly and obeying a flatter mass function than the red MS stars. These stars may have strong magnetic fields. Our work shed new light on the origin of the bi-modal mass, spin, and magnetic field distributions of MS stars. Further spectroscopic observations are encouraged to thoroughly test our theory.

Acknowledgements

The research leading to these results has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement numbers 772225: MULTIPLES). CW acknowledges funding from CSC scholarship. This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research innovation programme (Grant Agreement ERC-StG 2016, No 716082 'GALFOR', PI: Milone, http://progetti.dfa.unipd.it/GALFOR). APM acknowledges support from MIUR through the FARE project R164RM93XW SEMPLICE (PI: Milone) and the PRIN program 2017Z2HSMF (PI: Bedin). HS and JB acknowledge support from the FWO Odysseus program under project G0F8H6N. NC gratefully acknowledges funding from the Deutsche Forschungsgemeinschaft (DFG) - CA 2551/1-1. PM acknowledges support from the FWO junior postdoctoral fellowship No. 12ZY520N. SdM acknowledges funding by the Netherlands Organization for Scientific Research (NWO) as part of the Vidi research program BinWaves with project number 639.042.728.

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Questions and Answers

Question: How will your findings affect cluster age estimation?

Answer: Previous studies only use single non-rotating star models to estimate cluster age, however, our findings tell us that we need to consider binary interaction and rotation. But we have not quantified how large the difference will be at this moment. Fabian Schneider suggested a difference of up to a factor of 10 merely from binary interaction.

Question: What is the fraction of the blue MS stars, and what is the fraction of the MS stars that are detected to have magnetic fields?

Answer: The fraction of the blue MS stars is around 10–30%, while the fraction of magnetic upper MS stars is around 10%. This difference may come from magnetic decay or perhaps not all binary mergers can create strong magnetic fields.