Stellar mergers as the origin of the blue main-sequence band in young star clusters

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Recent high-quality Hubble Space Telescope photometry shows that the main-sequence stars of young star clusters form two discrete components in the colour–magnitude diagram. On the basis of their distribution in the colour–magnitude diagram, we show that stars of the blue main-sequence component can be understood as slow rotators originating from stellar mergers. We derive the masses of the blue main-sequence stars, and find that they follow a nearly flat mass function, which supports their unusual formation path. Our results imply that the cluster stars gain their mass in two different ways: by disk accretion leading to rapid rotation, contributing to the red main sequence, or by binary merger leading to slow rotation, populating the blue main sequence. We also derive the approximate merger time of the individual stars of the blue main-sequence component, and find a strong early peak in the merger rate, with a lower-level merger activity prevailing for tens of millions of years. This supports recent binary-formation models, and explains new velocity dispersion measurements for members of young star clusters. Our findings shed new light on the origin of the bimodal mass, spin and magnetic-field distributions of main-sequence stars.

The main sequence (MS) of star clusters is a cornerstone of stellar formation and evolution. In the past decade, the simple picture of star clusters as an ensemble of coeval stars born with identical initial conditions has been challenged. Old and very massive globular clusters host multiple stellar populations, with differences in chemical compositions. Recent Hubble Space Telescope observations have also revealed that the MSs of young open star clusters (with ages between ~15 Myr and ~600 Myr) are composed of several discrete components, but with identical chemical compositions. In the colour–magnitude diagram (CMD), this is characterized by a split MS from the vicinity of the turn-off all the way to a faint magnitude, with the red MS component containing more stars than the blue MS (for example NGC 1755 in Fig. 1). The emergence of a subpopulation of blue MS stars is ubiquitous in Magellanic Cloud clusters younger than ~600 Myr. There is well founded observational evidence that supports rotation being responsible for the split MS, with blue MS stars rotating notably more slowly than other cluster stars (designated here as red MS stars). In particular, the spectroscopically measured average projected rotation velocity of the red MS stars in NGC 1818 was found to be $202 \pm 23 \, \text{km s}^{-1}$, while it was only $71 \pm 10 \, \text{km s}^{-1}$ for the blue MS stars in this cluster. While previous studies suggest that extremely rapid rotation (~90% of initial critical rotation) of the red MS stars may be required to account for the colour difference between blue and red MSs, our stellar models show that adopting ~65% of initial critical rotation for the red MS stars and ~35% for the blue MS stars indeed provides a good fit to the observed red MS and to the best discernible part of the blue MS (Fig. 1b and Supplementary Section B; see Supplementary Section A on how we identify blue MS stars). This also agrees with the currently available, although sparse, spectroscopic rotational velocity measurements, and, notably, with the bimodal distribution of the rotation rates of B- and A-type field MS stars, in which the average projected rotational velocities of the slow and fast components are ~20–100 km s$^{-1}$ and 180–250 km s$^{-1}$, respectively.

Other scenarios for the origin of blue MS stars have been proposed. Suggestions that the blue MS stars formed in a second burst of star formation after the formation of the majority of the cluster stars are in conflict with the persisting colour difference between blue and red MS even far below the turn-off, since the faintest stars are essentially unevolved. Similarly, the trend that the apparent cluster age spread measured from the MS widths near the turn-off increases for older Magellanic Cloud and Galactic star clusters cannot be explained by a second star burst, and is related to effects of rotation.

It has further been proposed that the blue MS stars were born with rotational velocities similar to those of the red MS stars, but that their rotation has slowed subsequently due to tidal braking. Whereas tidal braking of close binaries provides a viable spin-down mechanism, it does not produce enough blue MS stars, since

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**Fig. 1** CMD of NGC 1755 and the isochrone fits. **a**, CMD of the stars (black dots) in the MS region of the LMC open star cluster NGC 1755 based on high-quality Hubble Space Telescope photometry. Typical 1σ errors at different magnitudes are shown with red error bars on the right. **b**, Isochrone fit for the red (major) MS of NGC 1755, signified by the densest stellar concentration, using stellar models with a rotation parameter of $W_\text{Rot} = 0.65$ (red solid line), and identification of the blue MS stars (blue circles; compare Supplementary Section A). The solid blue line represents the corresponding isochrone of single-star models with $W_\text{Rot} = 0.35$. Here, $W_\text{Rot} = v_\text{rot}/v_\text{crit,i}$ is the ratio between rotational velocity and break-up velocity at the zero-age MS (ZAMS). The red dashed line shows the positions of the equal-mass binaries in which both components have $W_\text{Rot} = 0.65$. The grey dashed line indicates the ZAMS line of non-rotating stars. The adopted age, distance modulus $(m - M)_0$ and reddening $E(B - V)$ are indicated. The stars between the two thin horizontal dotted lines are used in our mass-function analysis (Supplementary Section D). The right-hand $y$ axis shows the stellar mass according to the mass-magnitude of the fast-rotating stellar models.

most close binaries will appear redder than non-rotating single stars regardless of the rotation rate of their components, due to the presence of two stars in the observed point source. Only very low-mass-ratio binaries containing slow rotators are expected to contribute to the blue MS stars. The blue MS has also been suggested to originate from a combination of MS stars with He-star companions and stellar mergers, where the MS split is explained by a bimodal distribution of post-merger masses. Bimodal disk locking during the star formation process has also been suggested to explain the observed MS dichotomy. In this model, the blue MS stars are slow rotators due to a longer disk-locking time during their pre-MS accretion phase compared with the red MS stars. While this may reproduce the rotation dichotomy, it cannot explain that closer MS stars are slow rotators due to a longer disk-locking time during their

Binary mergers offer a natural way to create the blue MS population. A binary merger creates a star that is more massive than either of its progenitor stars, with a core hydrogen content that is higher than that of an equally old single star of the same mass. Thus, merger products may have the same age as all other cluster stars, but appear younger in the CMD, signified by their bluer colour. Previous studies have shown that tight binary stars which merged as a consequence of the expansion of their component stars during hydrogen-burning evolution form the blue stragglers that are brighter and bluer than the turn-off stars in star clusters. The continuity in the CMD between the blue stragglers and the fainter MS stars displayed in several clusters (NGC 1866, NGC 1856, NGC 294, KRON 34, with ages between 200 Myr and 500 Myr, ref. 8) provides us a further clue for the merger origin of the latter.

Further evidence for a merger origin of the blue MS stars is provided by analysing their mass functions. We fit the CMD positions of blue and red MS stars, that is, the magnitude of the individual stars along the constructed isochrones, with single-star models of the appropriate spin and age to obtain a measurement of the stellar mass (Supplementary Section D). We then fit the mass distributions of both groups of stars with power laws. For the red MS stars, the derived power-law exponent of $\gamma = -2.35 \pm 0.15$ is close to that of a Salpeter law ($\gamma = -2.35$) in the mass range of 5.5–2.5 $M_\odot$. In the same range, the mass function of the blue MS stars is found to follow a power law with $\gamma = -1.03 \pm 0.32$, representing a much shallower mass distribution (Fig. 2). Similar results are obtained for the other clusters investigated (Supplementary Section D). This indicates that the blue MS stars more massive than 2.5 $M_\odot$ are not formed by the same mechanism as the red MS stars just at a later time, but that the two groups emerge from different formation mechanisms. The shallow slope of the mass function of the blue MS stars is in fact consistent with that of a population of blue stragglers.
with their merger origin, as it may be the result of the observed decreasing close binary fraction with decreasing stellar mass. This is also expected according to recent binary-formation models. A merger origin of the blue MS stars may also hold a clue to their slow rotation. While initially a stellar binary merger contains a large angular-momentum surplus due to the orbital angular momentum, recent hydrodynamic binary-merger calculations show that the merger product loses most of this in a puffed-up stage directly after the merger, such that it settles as a slow rotator on the MS after a Kelvin–Helmholtz timescale. These simulations suggest that a further spin-down due to magnetic wind braking may occur subsequently.

Unlike previously discussed scenarios, the merger origin of the blue MS stars provides a coherent explanation of the dichotomies in colour, rotation and mass-function slope, and of the peculiarly wider blueward extension of the blue MS for brighter magnitudes. It leads us to the exciting conclusion that stars come to accumulate their mass in two fundamentally different ways. On the one hand, the majority of stars form by accretion of gas via accretion disks, leading to a well populated red MS with a rotation rate slightly larger than half the critical rotation. On the other hand, a fair fraction of the thus created stars merge with similar-mass companions and produce blue MS stars, rotating notably more slowly and obeying a different initial mass function (IMF) than do the red MS stars. This bimodality in the star formation process may therefore be at the root of the observed bimodalities in stellar spins, magnetic fields and mass functions, and of course location in the CMD. In the following, we shall discuss these aspects in more detail.

The narrowness of the red MS (Fig. 1a) implies that potentially accretion-induced star formation may result in a rather narrow distribution of MS rotational velocities in the considered mass range, with a peak near 65% of critical rotation, which is in agreement with considerations of gravitational torques between stars and disks, and also in agreement with the spectroscopic velocity measurements of both the red MS stars in young star clusters and the B- and A-type field stars. Furthermore, there is evidence for stars in binaries being born with spins very similar to those of single stars. Whereas the information about the initial spins of the stars which merged to become blue MS stars is wiped out in the merger process, these stars appear to rotate so slowly that their colour is largely unaffected by rotation (Supplementary Fig. 6). While we see a substantial number of MS stars with extreme rotation, most notably the Be stars, which are probably evolved MS stars that are spun up either by mass transfer from a binary companion or as single stars by their contracting cores, it is thus conceivable that upper-MS stars are formed rotating either slowly, or about half critically.

In Fig. 3, we show the distribution of our detailed binary-evolution models (Supplementary Section C) at 30 Myr in the CMD. The two star components have SMC-like metallicity and are assumed to rotate...
This. Tidal forces imposed by the circumbinary matter from which the order of 20% all along the MS can only be produced by decay—cannot account for the large number of observed blue MS stars, particularly in the vicinity of this isochrone unambiguously implies an early peak in the merger rate, after which it dropped considerably. However, on a reduced but substantial level, the merging activity prevailed for several tens of millions of years. Since by adopting equal-mass binary mergers we only obtain lower limits to the merger time of each star, the true merger times might be somewhat larger than implied by Fig. 4. However, varying the mass ratio of the pre-merger binaries only has a limited effect (Supplementary Section E). In fact, it is the relative distance between each blue MS star and the blue MS isochrone that determines its merger time. That the star density is the highest in the vicinity of this isochrone unambiguously implies an early peak in the merger rate. In addition, we find a moderate positive correlation between merger time and stellar magnitude (Supplementary Section E), which yields representative uncertainties of the merger times. For stars fainter than ~19 mag, we cannot constrain the merger times any more.

Fig. 3 | Binary evolution models at 30 Myr in the CMD. Each open symbol indicates a binary model (or a binary merger product), showing the combined magnitude and colour of the two stars (or the magnitude and colour of the binary merger product). Circles indicate detached binary models containing two MS stars, while squares correspond to semidetached binary models containing two MS stars. Diamonds designate MS merger products. Crosses correspond to binary models containing a MS star and a stripped helium-burning star, while pentagons denote models of MS stars whose companions have evolved to compact objects and may have left them as a consequence of supernova kick. The semidetached systems are marked in grey, while the colour for other open symbols shows the current rotational velocity either of the visually brighter component in a binary model or of a binary merger product. The observed MS stars and Hx emitters are overplotted with small black and purple dots, respectively. Distance modulus and reddening are assumed as in Supplementary Section C and Supplementary Fig. 8.

The derived merger activity on a timescale at least ten times longer than binaries with lower masses37. We repeated the analysis for the three other clusters (Supplementary Section E) and found very similar results.

The strong peaks at early time in our derived merger histories appear consistent with the observed rapid rise of the velocity dispersions in star clusters during their first few million years of evolution34. Notably, this timescale corresponds to the duration of the pre-MS phase of stars in the considered mass range, during which time they are bloated and thus more prone to tidal effects.

The derived merger activity on a timescale at least ten times longer is more difficult to understand. The similarity of this timescale to the timescale of violent relaxation of star clusters, on which they revitalize after expelling the gas remaining after star formation has ended, suggests that dynamical processes may play a role. While stellar encounters can lead to binary hardening, the stellar density in the investigated clusters is too small to render this process efficient41. It appears more likely that triple and higher-order multiple systems can foster the merging of their inner binary components, for example via Lidov–Kozai cycles42,43 or by passing stars44 that can cause a high eccentricity of the inner binaries and trigger the
In our analysis, we consider clusters younger than 100 Myr. However, our conclusion that orbit decay and binary mergers account for the slow rotators may apply to much older clusters. Effects of rotation are found in clusters of up to 2 Gyr (refs. 58, 10), below which the information on the stellar birth spin and on large-scale B fields is erased by the star’s convective envelopes, which produce their own magnetic activity and lead to magnetic spin-down.

**Method**

**Single-star models.** We use the detailed one-dimensional stellar evolution code MESA50–53. Most of the physical assumptions are identical to those utilized in ref. 64. The exception is that we use a mass-dependent overshooting parameter \( \alpha_{ov} \) (that is, the number of pressure scale heights by which the hydrogen-burning core is extended). For an initial mass of 20 \( M_\odot \) we use \( \alpha_{ov} = 0.3 \) (ref. 66). Below this, \( \alpha_{ov} \) decreases linearly such that it reaches a value of \( \alpha_{ov} = 0.1 \) at 1.66 \( M_\odot \) (ref. 66). Below 1.66 \( M_\odot \), \( \alpha_{ov} \) has an even steeper linear decrease such that it is equal to zero at 1.3 \( M_\odot \) (where the convective core disappears). This mass dependence accounts for the trend that the width of the distribution of field MS stars in the CMD increases with mass66–68. The \( \alpha_{ov} \) values adopted in this work are similar to the findings in ref. 64. We emphasize here that, although overshooting still remains poorly constrained, and it can affect the location of the turn-off stars in the CMD, the uncertainty of overshooting does not play a role in explaining the observed double MS68. We include differential rotation, rotationally induced internal mixing, magnetic angular momentum transport, stellar wind mass loss and non-equilibrium carbon-cycle nucleosynthesis. We use the standard mixing-length theory to model convective mixing with a mixing-length parameter \( \alpha_{MLT} = 1.5 \). The Ledoux criterion is used to determine the boundaries of convective zones. In the superadiabatic layers that are stable according to the Ledoux criterion but unstable according to the Schwarzschild criterion, we assume that semiconvection occurs with a mixing parameter of \( \alpha_{ov} = 10 \) (ref. 60). We model rotational mixing as a diffusive process49, taking into account the effects of dynamical and secular shear instabilities, the Goldreich–Schubert–Fricke instability60,62 and the Eddington–Sweet circulations61. The efficiency parameter of rotational mixing is \( f = 1/30 \) as proposed in ref. 64. We include the Tayler–Spruit dynamo for the transport of angular momentum60,66.

We follow the mass-loss recipe used in ref. 64; for hydrogen-rich stars with surface hydrogen mass fraction \( X \geq 0.7 \) the wind prescription of ref. 64 is used, while for hydrogen-poor stars with \( X \leq 0.4 \) the Wolf–Rayet mass-loss prescription of ref. 64 is used. For intermediate surface hydrogen abundances \( 0.4 < X < 0.7 \), we linearly interpolate the value of \( \log M \) between the two prescriptions. The metallicity-dependent stellar winds scale as \( M \propto Z^{0.85} \) (ref. 64).

We consider both LMC and SMC metallicity, with \( Z_{MLC} = 0.00484 \) and \( Z_{SMC} = 0.00218 \) (ref. 64). We compute single-star models in a mass range of 1.05 \( M_\odot \) and 20 \( M_\odot \) in a dense grid with \( \Delta \log m/0.02 \), from the zero-age MS, which is defined at the position where 3% of hydrogen is burnt to avoid the initial model relaxation, until well beyond core hydrogen exhaustion. We define a stellar model’s initial fractional critical rotation as \( \chi \). We follow the MESA definition of the critical velocity \( v_{crit} = \sqrt{Gm/R_m} \), where \( m \) and \( R_m \) are the mass and equatorial radius of the stellar model, respectively. Then for each mass we compute model sequences for \( \chi \) ranging from 0.15 to 0.75, in intervals of 0.1, as well as non-rotating models. We did not go higher than this because we encounter numerical problems when computing stellar models with \( \chi > 0.75 \).

To construct the stellar distribution in the CMD, we first calculate the absolute magnitude of a star in a given filter F as \( M_F = M_{bol,F} - BC_F \), where \( M_{bol} = M_{bol,0} - 2.5 \log(L/L_\odot) \) is the bolometric magnitude of a star, \( BC_F \) its bolometric correction for the adopted filter and \( M_{bol,0} = 4.74 \) mag (ref. 64). The bolometric correction is obtained by subsequent tidal friction. Indeed, we show in Supplementary Section E and Supplementary Fig. 20 that even today, after most of the mergers may have occurred, the CMDs of the young star clusters bear evidence for a current fraction of triple and higher-order multiple systems of several per cent, which may imply that the corresponding merger activity is still ongoing.

Binary mergers of MS stars have also been suggested to be responsible for the generation of the large-scale B field found in about 10% of the upper MS stars69, and magnetohydrodynamic simulations of the merger process appear to support this idea45. According to our analysis, the fraction of merger stars (~20%) is larger than the observed fraction of magnetic stars47. This means that not every merger event leads to a magnetic star, or that the merger-generated B fields decay on a timescale comparable to the nuclear timescale of the stars. The fact that the topological requirement of intertwined toroidal and poloidal field components69 is not a guaranteed outcome of the turbulent merger phase provides evidence for the former scenario, while the distribution of the fractional MS ages of magnetic massive stars69 justifies the latter.

Furthermore, our results have implications for the understanding of the stellar IMF. They imply that the IMF when measured from field stars consists of two components with very different slopes. In star clusters, on the other hand, the stellar mass function is not static and equatorial radius of the stellar model, respectively. Then for.

\[ a = \alpha_{MLT} = 1.5 \]

\[ 0.4 < X < 0.7 \]

\[ M = M_{bol} - 2.5 \log(L/L_\odot) \]

\[ M_{bol,0} = 4.74 \text{ mag} \]

\[ BC_F \]

\[ M_F = M_{bol,F} - BC_F \]

\[ \chi \]

\[ v_{crit} = \sqrt{Gm/R_m} \]

\[ m \]

\[ R_m \]

\[ \alpha_{ov} \]

\[ \alpha_{MLT} \]

\[ Z_{MLC} = 0.00484 \]

\[ Z_{SMC} = 0.00218 \]

\[ \Delta \log m/0.02 \]

\[ \log M \]

\[ f = 1/30 \]

\[ \alpha_{MLT} \]

\[ \alpha_{ov} \]

\[ M \]

\[ Z \]

\[ M \]

\[ Z \]

\[ M \]

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\[ M \]

\[ Z \]
interpolating tables computed from one-dimensional atmosphere models based on ATLAS12/SYNTHETE\textsuperscript{7,12} for the Hubble Space Telescope/WFC3 F814W or F336W filters, as these correspond to observations used in this paper. The absorption coefficients are $A_{\text{B,FLC}} = 2.04E(B-V)$ and $A_{\text{J,LMB}} = 5.16E(B-V)$ (ref. 9). The apparent magnitude is then obtained from $m_i = M_i + A_i + (m-M)_0$.

**Binary-star models.** These newly computed binary models are an extension of the binary models in ref. \textsuperscript{22}, using MESA version 8845, but assuming that both binary components start with 55% of their critical rotation velocities at the zero-age MS. The physics assumptions adopted in each star model are otherwise the same as in the single-star models of this work. We use SMC-like metallicity for our binary models, because the metallicity-dependent stellar wind is weak, so any differences between binary and single-star models are mainly caused by binary interaction. We briefly describe the physics and assumptions adopted for the binary interactions in the following.

We simultaneously compute the detailed structure of both components, together with the orbital evolution. We assume the orbit to be circular. Our binary models are not synchronized initially but have 55% of their critical velocities ($W_i = 0.55$), as we have shown in the last section that single stars with this velocity are consistent with the observed red MS of young star clusters. The two stars in each binary model can exchange mass and angular momentum via Roche lobe overflow. The mass transfer rate is implicitly adjusted such that the radius of the donor star is restricted to its Roche lobe radius\textsuperscript{2}. The specific angular momentum accreted by the secondary star depends on whether the accretion is ballistic or occurs via a Keplerian disk. If the orbit of a binary system is wide enough to avoid tidal spin-down, the accretor can reach critical rotation by accreting only a few per cent of its initial mass. When this happens, we enhance the mass-loss rate of the accretor\textsuperscript{5,29} such that it remains rotating just below critical. We assume radiation to be the driving force of the enhanced wind. If the required mass loss is beyond the radiative capability of the system, we assume that the binary is engulfed in the excess material, and merges as a consequence. The merger models are computed with the method described in detail in the next section. We assume the merger products to have an initial spin of 15% of critical rotation ($W_i = 0.15$), which is consistent with the blue MS when single-star models with $W_i = 0.55$ are used to reproduce the red MS.

We use a Monte Carlo scheme to generate the initial parameters of 3,500 binaries, representing a cluster of $7.7 \times 10^7 M_\odot$, with a binary fraction of 1 and the lowest star mass being $0.8 M_\odot$. The initial primary mass varies from $3 M_\odot$ to $100 M_\odot$, following a Salpeter IMF with an exponent of $-2.35$, while the initial mass ratio ranges from 0.1 to 1, obeying a flat distribution. The initial period varies from a minimum value, at which the two stars would encounter Roche lobe overflow at zero-age MS, to 3,162 days, following a flat distribution in logarithmic space.

We follow the evolution of these binaries from the zero-age MS to core carbon exhaustion. If the core mass of the primary star exceeds the Chandrasekhar mass at the time of carbon depletion, we assume that a supernova explosion happens, and compute the remaining evolution of its companion as a single star. Such a system produces either a binary system containing a MS star and a compact object or a single MS star, depending on whether the system remains bound after supernova kick, which is not calculated in our work.

**Stellar merger models.** We follow the method in ref. \textsuperscript{40} to compute models of the merger product of two MS stars. There, it is assumed that the chemical structure of the merger star adjusts itself to that of an ordinary single star with the appropriate mass and age. Whereas the details of the internal mixing process during a stellar merger event are clearly more complex, the major aspect of our simplified models is confirmed by multidimensional merger simulations and detailed follow-up calculations\textsuperscript{41,42}. These studies show that the convective core mass of the merger product increases to a mass found in single-star models of the post-merger stellar mass. This increase in convective core mass brings fresh hydrogen to the centre of the star, which is responsible for the rejuvenation process.

We assume that all stars are born with moderate rotation (that is, $W_i = 0.65$; see Supplementary Section B for the reason), and use corresponding single-star models to obtain the masses $M_1$ and $M_2$ of the two stars in a binary system immediately before the merger. The mass of the merger product $M$ is expressed as

$$M = (1 - \Phi) (M_1 + M_2),$$

where $\Phi = 0.3q/(1+q)^2$ with $q = M_2/M_1$ describes the fraction of the mass lost by the binary in the merger event\textsuperscript{43}. We assume that the lost material has the same composition as the initial composition of the two stars. We then compute the average hydrogen mass fractions of the two stars $X_1$ and $X_2$ immediately before the merger. The hydrogen masses after and before the merger are connected through

$$M_X = M_1 X_1 + M_2 X_2 - (M_1 + M_2) \Phi X_0,$$

where $\bar{X}$ is the average hydrogen mass fraction of the merger product and $X_0$ is the initial hydrogen mass fraction of the stars. We use our single-star models to identify the one which has the same mass and average hydrogen mass fraction as the merger product, and treat it as the starting model of the merger product evolution. The age of this starting model denotes the apparent age $t_{app}$ of the merger product immediately after the coalescence. We then follow the evolution of the merger product until the required age (that is, the age of the cluster). This means that we evolve the merger model further for a time equal to the difference between the cluster age and the age at which the coalescence happens.

The rotation rate of the merger products, which has not been constrained well to date, plays the dominant role in affecting their positions in the CMD at a given merger time. Even though results of magnetohydrodynamic simulations have suggested mergers to be slow rotators\textsuperscript{41}, occasionally faster-rotating stars are detected among blue stragglers\textsuperscript{49}. Current available velocity measurements of the blue stragglers report $v \sin i$, where $v$ and $i$ are the equatorial velocity and inclination of the stars, respectively, to be between 20 and 270 km s$^{-1}$, notably smaller than those of most other cluster members\textsuperscript{47}. In Supplementary Fig. 6, we see that when the red MS is fitted with $W_i = 0.65$ the vast majority of the blue MS stars correspond to slow rotators with $W_i \lesssim 0.55$. On the basis of the rotational velocities considered in our single-star model grids, we build grids of merger models with birth fractional critical rotational rates of 0, and from 0.15 to 0.55, in intervals of 0.1.

**Data availability**

The observational data in this work can be found at https://doi.org/10.5281/zenodo.5770868. The MESA inlist files used to compute the single- and binary-star models in this work can be downloaded at: https://doi.org/10.5281/zenodo.5233209.

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Author contributions

C.W., A.S., B.H. and X.-T.X. performed the stellar evolution calculations, based on earlier work by P.M. and on his advice. N.L. carried out the analysis and interpretation of the results, together with C.W., A.S., B.H. and S.E.d.M. A.M., J.B., H.S., N.C., D.J.L. and A.d.K. provided an interpretation of the related observations. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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