# 262. Main sequence splits in clusters

THE THEORY of stellar structure and evolution applies to topics almost as wide-ranging as astronomy itself. Gaia is allowing a much deeper analysis, and many refinements, of its many areas of application.

Specifically, Gaia's astrometric measurements are providing reliable luminosities for enormous numbers of stars. Combined with high-accuracy multicolour photometry, this yields powerful constraints on the colour–magnitude and Hertzsprung–Russell diagrams. Additionally, for the sorts of open cluster studies discussed here, it greatly assists in defining membership.

I have considered some of these refinements in previous essays, amongst them some new insights into convection and convective overshooting (essay 150), and the related Jao gap (essay 152), recalibration of the low-mass end of the main sequence (essay 151), the white dwarf main sequence splitting due to convective dredge-up (essay 178), and the observational effects of core crystallisation in white dwarfs (essays 42 and 108).

HERE I will look at an (as yet) unresolved problem in interpreting two related features in the colour–magnitude diagram of many open clusters, viz. a main-sequence bifurcation, and an extended main-sequence turn-off (eMSTO). This is distinct from the phenomenon of multiple populations found in *globular* clusters (essay 235; see also D'Antona et al. (2015), §4.3).

These open cluster features were first seen, pre-Gaia, in intermediate-age (0.6–2 Gyr) clusters in the Magellanic Clouds some 20 years ago, and later confirmed in much younger *Galactic* open clusters with Gaia DR2.

While the current consensus is that the main-sequence bifurcation reflects a bimodal distribution of stellar *rotation*, there is no definitive understanding as to how this widespread phenomenon arises.

In their review, Li et al. (2025) state: *'Research on stellar rotation and its connection to eMSs has opened up a myriad of fascinating avenues, such as investigations of the magnetic braking mechanism in stars, searches for tidally locked binary systems in star clusters, and whether binary mergers can give rise to massive magnetars.'*

FIRST REPORTS of a bifurcation in the main-sequence turnoff in intermediate-age open clusters were for the LMC clusters NGC 1846 (Mackey & Broby Nielsen, 2007), and NGC 1783 and NGC 1806 (Mackey et al., 2008). These authors ruled out binarity as an explanation, instead attributing the split to a bimodal age distribution, perhaps resulting from the tidal merger of two clusters formed separately in a single molecular cloud.

In NGC 1846, for example, the double main-sequence turn-off is strikingly evident in their Figure 2. Their Padova and BaSTI isochrones (their Figures 7–8) both provide a good fit to a bimodal age model, resulting in an inferred age difference of $\Delta\tau \sim 300$ Myr. However, it is noteworthy that the two sets of absolute ages, of order 2 Gyr, nonetheless differ by 700 Myr!

A bimodal age distribution could also result from an *extended* period of star formation. Finding that all the analysed clusters have escape velocities, $v_{\rm esc} > 17\,{\rm km\,s^{-1}}$, and that intermediate-mass AGB stars and massive binaries have winds $12–15\,{\rm km\,s^{-1}}$, Goudfrooij et al. (2014) and Correnti et al. (2014) suggested that such an eMSTO can (only) occur in clusters whose escape velocities are higher than the winds of first-generation stars from which the second generations formed.

SIMILAR FEATURES were, however, subsequently observed in much *younger* clusters with HST, where extended star formation is more tightly constrained. They were instead attributed to the effects of stellar *rotation*, which can mimic an age spread (Milone et al., 2015; Milone et al., 2016). Evolutionary models show that the spread near the turn-off can be attributed to a combination of the effects of stellar rotation on the structure (oblateness) of the star, and the inclination angle of the star relative to the observer. Both effects change the star's observed effective temperature, and hence its colour and estimated flux (Bastian & de Mink, 2009).

Rotation also affects chemical mixing, and therefore a star's main-sequence lifetime. Models ignoring rotation can therefore give systematically erroneous ages and evolutionary properties (e.g. Nguyen et al., 2025).

THIS FIELD OF STUDY has expanded, in part, with the Gaia data. Gaia DR3, in particular, contains extensive variability information, as well as millions of rotational velocities derived from both line-broadening as well as rotational modulation of surface structure.

As first reported with Gaia DR2 by Marino et al. (2018), and further based on the colour–magnitude diagrams of 12 Galactic open clusters by Cordoni et al. (2018), these structured main sequences previously observed in the Magellanic Cloud clusters are also seen in nearby open clusters. These early results suggested that a split or broadened main sequence is observed in clusters younger than ~700 Myr, while older objects display only an extended main-sequence turnoff, again supporting the idea that rotation is responsible.

Bastian et al. (2018) found the same phenomenon in NGC 2818, also based on DR2. The main sequence is particularly narrow, $\Delta$(GBP–GRP) ~ 0.1 mag, implying very low extinction. Ground-based (VLT–FLAMES) spectroscopy of 60 cluster members showed that stars on the red side of the eMSTO have high $V \sin i$ (>160 km s$^{-1}$), while stars on the blue side have $V \sin i$ <160 km s$^{-1}$, in agreement with evolutionary models including the effects of rotation.

For the young (14 Myr) double clusters h and $\chi$ Persei, Li et al. (2019) used Gaia DR2 to show that a simple population composed of coeval stars that span a wide range of rotation rates is unable to reproduce their colour spread. They concluded that variability and binary interactions also affect the extended main-sequence turnoff of these very young clusters.

INVESTIGATIONS have continued with Gaia DR3, now totalling some some 100 clusters, and again with somewhat different interpretations (Cordoni et al., 2024; Cordoni et al., 2025; Pancino et al., 2026). Rao & Chen (2026) reported 15 clusters that exhibit a split main sequence with fast and slow rotators populating the redder and bluer parts of the main-sequence turnoff.

Other non-Gaia studies, including HST and ground-based studies of LMC clusters (e.g. Kamann et al., 2020; Correnti et al., 2021; Kamann et al., 2021; Kamann et al., 2023), confirm the phenomena as widespread. But they have not converged on a consensus explanation.

ACCEPTING THAT these features in the main sequence turnoff of young massive open clusters can be attributed to a bimodal distribution of rotation, how could such a bimodal distribution arise?

At least three hypotheses have been put forward over the past decade. Each theory predicts specific rotation distributions in various locations of the colour–magnitude diagram, while revised stellar models using the Gaia data have also been developed to validate the effects of rotation (e.g. Nguyen et al., 2025).

THE EARLIEST hypothesis was that the slowly rotating (blue) component could be attributed to binary synchronisation as a result of tidal interactions and Roche-lobe overflow (D'Antona et al., 2015). Their model predicted that many of the resulting slow-rotators should still be part of binary systems with orbital periods 4–500 d, and that the bluer main sequence would have a much higher binary fraction than the red.

However, later observations showed that the binary fractions are very similar in both sequences (Kamann et al., 2021; He et al., 2023; Bu et al., 2024). Furthermore, the observed radial velocity variations of the slow rotators were found to be too small to support the idea of tidal interactions being responsible (He et al., 2023). N-body cluster simulations were similarly unsupportive (Wang et al., 2023).

Other studies suggested that the observations are more consistent with magnetic braking as a function of age (He et al., 2023; Bu et al., 2024; Maurya et al., 2024), although this seems also unlikely (e.g. Li, 2026).

ANOTHER HYPOTHESIS was that stellar *mergers* can result in a slow-rotating merger product, particularly during the pre-main sequence phase (Wang et al., 2022). In this case, the blue main sequence would arise as a result of two effects. Firstly, the slowly rotating stars are hotter on average for a given luminosity. Additionally, the stars are 'rejuvenated', i.e., the merger product effectively resets the start of the zero-age main sequence.

However, Bastian et al. (2025) used HST photometry and VLT–MUSE spectroscopy of three young LMC clusters to show that the brightest blue stars at the upper end of the main sequence (the blue stragglers) have rotational distributions that differ significantly from that on the blue main sequence. They concluded that stellar mergers cannot play a significant role in forming the split main sequence, or the bimodal rotational distribution. The same conclusion is drawn from N-body cluster simulations (Wang et al., 2023; Rao & Banerjee, 2026).

A FURTHER MODEL, proposed by Bastian et al. (2020), and probably the leading contender as I write, is that the rotation rate of a star is determined, within the first few Myr, by whether it has been able to retain its circumstellar disk throughout the pre-main sequence phase (transporting angular momentum away from the collapsing star, and resulting in the slow rotators), or whether the disk gets disrupted due to X-ray/UV photoionisation or dynamical encounters (resulting in the fast rotators). Applied to very young clusters, this model predicts a strong anti-correlation between the presence of a disk and the rotation rate of the stars.

Some recent results appear to confirm this trend, for example in NGC 2264 (Bu et al., 2025), in NGC 3532 (Rao & Chen, 2025), and in NGC 6067 (Maurya et al., 2025).