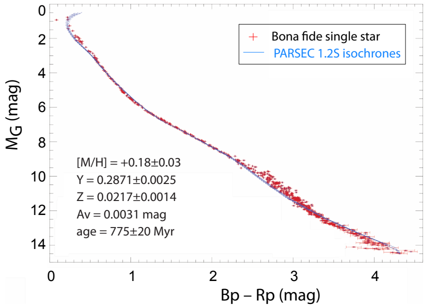
222. Open clusters: chemistry & models

The scientific importance of open clusters is underpinned by the *assumption* that their stars started life at the same time, formed from the same giant molecular cloud, so are of similar age, and with similar initial composition. These two boundary conditions provide strong constraints on models of stellar structure and evolution. Gaia's rigorous membership lists, and accurate distances and photometry, allow for the construction of clean and accurate colour–magnitude diagrams for main-sequence fitting, the identification and characterisation of stars in specific evolutionary phases, and deviations from existing state-of-the-art models.

The nearest open cluster, the Hyades, has revealed remarkable tidal tails extending more than 100° across the sky. But of specific interest here is the Gaia DR3-based colour–magnitude diagram by Brandner et al. (2023), which I have considered in some detail in essay 151. Shown below is their colour–magnitude diagram for 600 single stars, and their best-fitting PARSEC isochrones (Nguyen et al., 2022). While this gave an improved fit compared with MESA 1.2 (Jermyn et al., 2023), they found that, over the colour range $B_P - R_P = 2.4-3.2$ mag ($0.22-0.40 M_\odot$), stars are still systematically brighter (or redder) than the isochrone predictions.

Even for this nearby cluster, a wide range of ages is still found. As examples, their PARSEC isochrones gave an age 775 ± 20 Myr. My own work using the Hipparcos data gave 625 ± 50 Myr (Perryman et al., 1998), while from the cooling ages of the 9 known Hyades white dwarfs, Lodieu et al. (2019) derived 640^{+67}_{-49} Myr.



Brandner et al. (2023)

Discrepancies between stellar models and observations for sub-solar mass stars were partly attributed, by Castellani et al. (2001), to limitations in the description of superadiabatic convection in the outer layers of partially convective stars. Improvements in the definition of the Hyades main sequence, as the nearest open cluster, have led to improvements in stellar models, for example in the incorporation of updated input physics, including opacities (Kopytova et al., 2016).

Recently, Wang et al. (2024) derived empirical colour corrections based on the latest MIST and PARSEC models, and the Gaia $B_P - R_P$ and $G - R_P$ colours of the Hyades, Pleiades, and Praesepe. Applying these empirical corrections to 31 other clusters and three moving groups gave significantly better agreement between the isochrones and observed colour–magnitude diagrams, and isochrone ages consistent with the 'lithium depletion boundary' method (essay 220).

Clearly, some physics is missing. What we will see advanced in the coming years are the different estimates of the cluster's mean metallicity, and the problem of the degeneracy between metallicity ([Fe/H]), the He-to-metal enrichment ($\Delta Y/\Delta Z$), and the convective mixing length parameter (α_{ML}), with the latter also dependent on the part of the main sequence being modelled. For example, using the PISA evolution models, and estimates of $[Fe/H] = 0.14–0.18$, and the Gaia DR2 photometry and parallaxes, Tognelli et al. (2021) obtained mean values of $\alpha_{ML} = 2.01 \pm 0.05$ and $\Delta Y/\Delta Z = 2.03 \pm 0.33$.

I have gone into more details of convection in essay 150: why it is important (and uncertain), how it is modelled, and where Gaia is contributing; e.g. in understanding the so-called 'kissing instability' (van Saders & Pinsonneault, 2012). But we will also see progress in understanding the effects of rotation, more secure estimates of the He abundance (where the primordial abundance is imprinted in the lowest mass stars), eliminating still unidentified (more extreme) brightness- and mass-ratio binary systems, the effects of stellar activity and variability, and the possibility of 'radius inflation' identified in some of the Hyades stars (Jaehnig et al., 2019).

THE 'TURNOFF' region of the Hertzsprung–Russell diagram, the region where stars begin to leave the main sequence and evolve into giants, presents various puzzles, all being advanced by Gaia. One is the 'extended main sequence turnoff' (eMSTO), a broadening of the turnoff seen in many clusters (e.g. Cordoni et al., 2018). Once tentatively attributed to an age spread, Gaia studies have shown that the redder stars often corresponds to fast rotators, whereas bluer stars rotate more slowly (Bastian et al., 2018; Cordoni et al., 2018; Marino et al., 2018; Lim et al., 2019; He et al., 2022; Griggio et al., 2023). For the Galactic cluster Stock 2, the effect is attributed to differential reddening (Alonso-Santiago et al., 2021).

The extended turnoffs in the Magellanic Clouds also appear to involve stellar rotation, but combined with significant age spreads (e.g. Goudfrooij et al., 2014), and effects of stellar variability (Salinas et al., 2016).

'Isochrone clouds' have been invoked to describe a coeval population of various masses, and fractional core masses, due to different internal mixing profiles (Johnston et al., 2019b). But Johnston et al. (2019a) concluded that a *'global theoretical interpretation is still lacking'*.

BLUE STRAGGLERS are more luminous, and have a higher $T_{\rm eff}$ (hence bluer), than the cluster's main sequence turnoff. First identified in M3 by Sandage (1953), they are inconsistent with standard evolutionary theory – they should have consumed their nuclear fuel, and evolved to become white dwarfs, long ago. Rather, they are considered to result from collisions, from binary stars in the process of merging (or recently merged), or a result of mass-transfer in a binary (Mapelli et al., 2006; Boffin et al., 2015). Ahumada & Lapasset (2007) listed 1887 candidates in 427 open clusters.

Gaia is providing the improved location and fidelity of candidates in the colour–magnitude diagram. From Gaia DR2, Rain et al. (2021a) confirmed just 897 (and 77 yellow stragglers) in 408 open clusters. At the same time, also from DR2, Jadhav & Subramaniam (2021) found 868 blue stragglers in 228 clusters. And they established that their numbers *increase* with cluster age and mass. Using Gaia DR3, Li et al. (2023) found a further 138.

Their radial distribution provides an important dynamical probe for globular clusters, and Gaia has enabled similar studies for open clusters. I will simply refer here to DR2-based studies of seven such clusters by Vaidya et al. (2020), and three more by Rain et al. (2021b).

Based on sixteen old nearby ($d < 3500$ pc) open clusters, Leiner & Geller (2021) found that their fractional number increases with age. They also found that population synthesis models in which blue stragglers form by mass transfer, dramatically under-produce the numbers in old clusters, as well as overproducing high-mass relative to lower-mass stragglers. Again, additional physics seems to be required to explain these findings.

Ultraviolet observations combined with astrometry and photometry from Gaia DR2/EDR3 now accurately locates blue stragglers in various other clusters (Vaidya et al., 2022; Panthi et al., 2022; Rani et al., 2023; Jadhav et al., 2023), confirming many as post-mass-transfer binaries as inferred from their high ultraviolet flux.

An important Gaia discovery is a double blue straggler sequence in the ancient (8.5–10 Gyr) Galactic cluster Berkeley 17 (Rao et al., 2023). Parallel sequences have been seen previously in four *globular* clusters (the first of which was M30, Ferraro et al., 2009), the bluer attributed to stellar collisions, and the redder to the results of binary mass transfer. However, the lower densities of open clusters makes formation via collisions unlikely, suggesting a mass-transfer formation channel for both, but with an unexplained offest between them.

I HAVE COVERED various aspects of white dwarfs in several previous essays. Of relevant here is that those in clusters come with a known age. This helps constrain the 'initial-to-final mass relation' (IFMR) which provides a mapping (through evolutionary mass-loss models) between the zero-age main sequence mass and its end-of-life white dwarf mass (essays 134 and 178).

Various Gaia studies have searched for other white dwarfs specifically associated with clusters (e.g. Gentile Fusillo et al., 2019; Prišegen et al., 2021; Richer et al., 2021). Others have used these to study the IFMR (e.g. Si et al., 2018; Canton et al., 2021; Heyl et al., 2022). As an example, Prišegen & Faltová (2023) found 63 such 'cluster' white dwarfs, 36 of which were new, with six falling in relatively unconstrained regions of the IFMR where the relation seems to exhibit non-linear behaviour.

THE STUDY OF chemical abundances in open clusters is a huge topic, and I will give only a couple of 'pointers' most directly related to Gaia. Gaia DR3 itself included stellar parameters and chemical abundances for 5.6 million stars derived from its Radial Velocity Spectrometer (Recio-Blanco et al., 2023a), and applied to 503 open clusters by Recio-Blanco et al. (2023b).

Gaia-based memberships are assisting recent or planned large-scale spectroscopic surveys focused on Galactic chemo-dynamics, including the Gaia–ESO survey, APOGEE, GALAH, LAMOST–LEGUE, RAVE, 4MOST, and WEAVE, and several other smaller programmes.

Goals include understanding their chemical homogeneity and the relationship to 'strings' (Liu et al., 2016a; 2016b; Manea et al., 2022; Zucker et al., 2022), the idea of chemical tagging (Freeman & Bland-Hawthorn, 2002; Casamiquela et al., 2022; Bhattarai et al., 2024), and stellar nucleosynthesis processes and the radial metallicity gradient in the Galaxy (e.g. Casamiquela et al., 2019; Jofré et al., 2019; Donor et al., 2020; Spina et al., 2022; Zhang et al., 2022; Magrini et al., 2023; Palla et al., 2024).