220. Open clusters: ages

This is the second in a series of four essays on Gaia's ongoing advances in the studies of open clusters. In essay 219 I looked at the *number* of clusters that have been confirmed or discovered with Gaia, and at their Galactic distribution. Here, I will go further into the subject of age determination, again drawing on the recent review by Cantat-Gaudin & Casamiquela (2024).

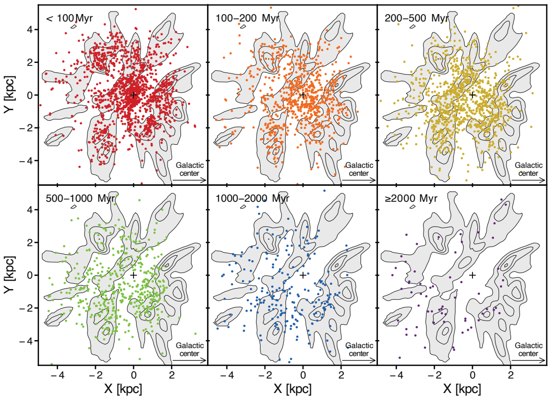
Cluster ages are most straightforwardly obtained by comparing colour–magnitude diagrams to theoretical isochrones. Accurate ages nonetheless require knowledge of the cluster's metallicity and extinction, as well as sufficient members in key evolutionary phases.

In some of the first Gaia studies, using DR2 astrometry and photometry, Bayesian analysis (von Hippel et al., 2006) was used to derive their ages, distances, and reddenings. This technique was applied to 269 clusters by Bossini et al. (2019), to 45 clusters by Monteiro et al. (2020), to 150 clusters by Monteiro & Dias (2019), and to 1743 clusters by Dias et al. (2021).

Studies using EDR3/DR3 aimed to better account for unresolved binaries, field stars, differential reddening, stellar rotation, and even the presence of blue stragglers.

In this spirit, Li & Shao (2022) treated an open cluster as a mix of single and binary stars, with some field stars. Applied to 10 clusters using EDR3, they found binary fractions of 30–50%, and best-fit isochrones generally consistent with previous measurements, but with more precise ages. The inferred slope of the mass function is in the range −2.7 to −1.6 for clusters younger than 2 Gyr, while older clusters are significantly flatter.

Machine-learning (see reviews by Baron, 2019; Fluke & Jacobs, 2020) has led to more robust estimates of ages (and other parameters): for 1900 clusters and co-moving groups (comprising 300 000 sources) within 1 kpc by Kounkel & Covey (2019), for about 2000 clusters by Cantat-Gaudin et al. (2020), for some 4000 by Hunt & Reffert (2023), and some 5400 by Cavallo et al. (2024). The latter authors, for example, argue that their algorithm effectively traces sequences in colour–magnitude diagrams despite photometric errors and outliers.



Cavallo et al. (2024)

The results provide greater details of the local Galactic structure, but also inform about cloud collapse and star formation on larger scales. Kounkel & Covey (2019) found filamentary structures, oriented parallel to the Galactic plane, and some hundreds of parsecs in length. Most lack a central cluster, indicating that the filamentary structure is primordial. Their velocity dispersion increases with age, suggesting a timescale for dynamical heating and disruption of 300 Myr, leaving only individual clusters to be identified at the oldest ages.

The figure shows the results from Cavallo et al. (2024) in Galactic XY coordinates, divided into age groups, and with an over-density map shown in grey. Their results reproduce the Galactic metallicity gradient found in high-resolution spectroscopic surveys, while finding systematically older ages compared to previous analyses.

Let me turn to other methods used for estimating cluster ages, all being advanced by Gaia.

For ages in the range 20–200 Myr, the 'lithium depletion boundary' provides an independent spectroscopic age estimate. Since stars burn lithium in their cores but not in their outermost layers, ages can be inferred from equivalent width of the Li I 670.8 nm absorption line in low-mass stars, since its strength depends both on mass (and hence on the importance of convection) and age (e.g. Rebolo et al., 1992; Burke et al., 2004).

Gaia is providing the opportunity to re-assess the consistency between ages determined from the lithium depletion test, based on improved cluster membership, bolometric luminosities, and effective temperatures (e.g. Lodieu et al., 2019; Miret-Roig et al., 2024).

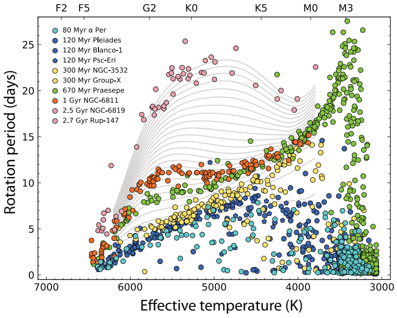
While agreement is often found, other studies (using Gaia DR2 or DR3) point to the effects of 'radius inflation', attributed to enhanced contributions of star spots and magnetic activity in the youngest stars (Galindo-Guil et al., 2022; Franciosini et al., 2022), as well as rotational dependencies, with fast rotators generally preserving Li over longer times (Jeffries et al., 2021; Binks et al., 2022; Sun et al., 2023; Tsantaki et al., 2023). Jeffries et al. (2023), for example, used Gaia DR3 to provide empirical models of the Li equivalent width, calibrated on 6200 stars in 52 open clusters with ages from 2–6 Gyr.

A second independent method of age estimation uses gyrochronology. This exploits the decrease of stellar rotation with time, due to magnetic braking, which enables the use of rotation periods as a proxy for age. One goal is to provide ages of main sequence stars, as well as clusters too young or too sparse to host the evolved stars more robustly used as age markers (e.g. Barnes, 2003; Meibom et al., 2015; Douglas et al., 2024).

The field *'… has benefited from a tremendous boost enabled by Gaia'* (Cantat-Gaudin & Casamiquela, 2024), with its astrometry providing improved membership, and its photometry already providing rotation periods for 3 million stars (Frémat et al., 2023, essay 103).

Gaia (DR2/DR3) is providing such age estimates for Hyades and Praesepe (Douglas et al., 2019), α Per (Boyle & Bouma, 2023), M 67 (Gruner et al., 2023), NGC 2281 (Fritzewski et al., 2023), NGC 2477 (Palakkatharappil & Creevey, 2023), NGC 2516 (Fritzewski et al., 2020; Bouma et al., 2021), NGC 3532 (Fritzewski et al., 2021b; 2021a), NGC 6709 (Cole-Kodikara et al., 2023), NGC 6811 (Curtis et al., 2019a), Ruprecht 147 (Gruner & Barnes, 2020; Curtis et al., 2020), ASCC 123 (Frasca et al., 2023), the Pisces–Eridanus stream (Curtis et al., 2019b), as well as the Gaia discoveries UBC 1 (Fritzewski et al., 2024), and the moving group X (Messina et al., 2022; Newton et al., 2022). Various software tools are also available (Angus et al., 2019; Bouma et al., 2023; Van-Lane et al., 2023).

While a full theoretical interpretation remains challenging, it is useful to emphasise that an important contribution of Gaia is to challenge and advance existing models of star formation and evolution. A broad conclusion offered by Bouma et al. (2023) is that *'the uncertainty floor varies still strongly with both stellar mass and age'*. Gruner & Barnes (2020) conclude that *'models describing the rotational evolution of solar metallicity cool main sequence stars need to include three distinct physical processes if they are to account for the fast, slow, and low mass rotators observed in open clusters to date'*.



Bouma et al. (2023)

Another age estimate, especially relevant for young or sparse clusters and associations, uses Gaia's high-accuracy proper motions to yield age estimates from the 'dynamic traceback' of their members. I have covered Gaia's contributions to this topic in essay 186, and will mention only a couple of key poins here.

For the β Pic cluster, where literature age estimates ranged from 10–40 Myr, Miret-Roig et al. (2020) found a traceback age of 18.5 Myr (see also Couture et al., 2023). Galli et al. (2023) found the dynamical age of Tucana–Horologium (~40 Myr) to be consistent with both isochronal and Li ages. And Miret-Roig et al. (2022) found that the dynamical age of Upper Scorpius is younger than that from its colour–magnitude diagram.

For six young associations, Miret-Roig et al. (2024) found traceback ages consistently younger than those from isochrones by 5.5 ± 1.1 Myr. They concluded that the two have different time origins: if the cluster is gravitationally bound before dispersion of the parent gas cloud, the zero-point of the expansion time scale is a few Myr after that probed by the colour–magnitude diagram.

In other words, the dynamical traceback 'clock' starts when the system begins to expand after expelling most of the gas, whereas the isochrone 'clock' starts earlier when most stars form. Pelkonen et al. (2024) showed that the oldest age (corresponding to the first star to leave the cluster) generally provides a better match to the isochronal age than the traceback method.

Finally, I should mention ages inferred from asteroseismology, although they are determined somewhat indirectly: the detection of solar-like oscillations (in Kepler, as well as in Gaia photometry) provide global seismic parameters such as the 'large separation' and the frequency of maximum oscillation power which, combined with the effective temperature, can be used to derive stellar masses through so-called 'scaling relations'. In turn, the mass can be used to provide an indirect estimate of age through evolutionary models.

Bossini et al. (2019) used this approach for red giant stars with asteroseismic parameters derived by Kepler for NGC 6791, NGC 6811, and NGC 6819, and found ages broadly compatible with their (log) isochronal ages, of 9.972, 8.94, and 9.30 Gyr respectively.