221. Open clusters: kinematics

OPEN CLUSTERS were formed from the collapse of giant molecular clouds, and they travel on roughly circular orbits through the Galactic disk. They are progressively disrupted over time as a result of internal dynamical processes, and gravitational encounters with other molecular clouds and the wider Galactic potential. It was the dearth of clusters older than 500 Myr that led Spitzer (1958) to suggest that clusters are 'dissolved' by the very clouds from which they formed.

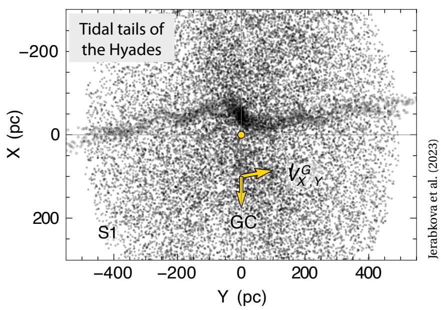
Gaia's distances and proper motions are allowing the identification of many more clusters (essay 219), along with rigorous members and age estimation (essay 220). The motions of *individual* stars allows measurement of their Galactic orbits (e.g. Soubiran et al., 2018), as well as details of their dissolution, bulk rotation, and internal dynamics (Cantat-Gaudin & Casamiquela, 2024).

AS A RESULT of two- or three-body encounters within the cluster, stars can reach the escape velocity, slowly diffusing into the field population. Preferential escape through the cluster's Lagrange points leads to the creation of 'tidal tails' in both the leading and trailing directions along their orbit (Fukushige & Heggie, 2000; Gieles & Baumgardt, 2008; Portegies Zwart et al., 2010).

Tidal tails were first discovered around *globular* clusters (Grillmair et al., 1995), and prominent examples include Pal 5 (Odenkirchen et al., 2001, essay 109) and NGC 5466 (Belokurov et al., 2006). The low-density tidal tails of *open* clusters only became evident with Gaia.

Elongation of the Hyades was found in Gaia DR1 by Reino et al. (2018). The tidal tails were later revealed in detail with DR2 (Lodieu et al., 2019; Röser et al., 2019; Meingast & Alves, 2019; Oh & Evans, 2020; essay 20).

Studies with EDR3 extended these tails to ±400 pc (Jerabkova et al., 2021). Their models shows that their orientation relative to the cluster's bulk motion constrain its initial rotation. Interestingly, they also identified spatial concentrations in both tails consistent with epicyclic overdensities (Just et al., 2009; Küpper et al., 2010; 2012). These, in turn, provide constraints on both the cluster properties, and also on the Galactic potential.



There is a growing literature on the numbers of clusters with known tidal tails as a result of the improved Gaia astrometry and photometry, along with their numerical modelling, and the interpretation of properties such as their asymmetries and mass-loss rates.

Such clusters include Praesepe/NGC 2632 (Röser & Schilbach, 2019; Alfonso & García-Varela, 2023); the Pleiades (Alfonso & García-Varela, 2023); the rapidly dissolving Ruprecht 147 (Yeh et al., 2019); the disk-shocked M 67 (Carrera et al., 2019); Coma Ber (Tang et al., 2019); NGC 752 (Bhattacharya et al., 2021; Boffin et al., 2022); UBC 274 (Casamiquela et al., 2022); and the Gaia discovery COIN–Gaia 13 (Bai et al., 2022).

In the case of Blanco 1 (Zhang et al., 2020; Alfonso & García-Varela, 2023) association of the tails with the cluster has also been confirmed via their TESS-based gyrochronological ages (Sha et al., 2024).

More than a hundred other nearby open clusters now have either known tidal tails, or an elongated morphology consistent with their tidal disruption (e.g. Hu et al., 2021a; 2021b; Meingast et al., 2021; Bhattacharya et al., 2022; Coronado et al., 2022; Moranta et al., 2022; Tarricq et al., 2022; Fürnkranz et al., 2024; Kos, 2024; Noormohammadi et al., 2024).

Various studies have been specifically targeted at a better understanding of their tidal-arm asymmetries (Pflamm-Altenburg et al., 2023; Kroupa et al., 2024); with some considering the asymmetric structures in the framework of MOdified Newtonian Dynamics (MOND; Thomas et al., 2018; Kroupa et al., 2022).

SOME OPEN CLUSTERS are also expected to experience bulk rotation, whether inherited from their parent molecular cloud, provided by impulsive interactions with massive structures, or resulting from the long-term action of tidal forces, each likely to result in distinct patterns, perhaps with a dependency on cluster age.

Indeed an open question in star formation concerns the amount of angular momentum that newly formed clusters possess after emerging from their parent cloud. For example, Corsaro et al. (2017) found an alignment of stellar spins and binary orbital spins in star clusters. While this would support a scenario in which clusters are born with net angular momentum, propagating down to stellar scales, and with the imprint surviving over several Gyr, other studies suggest that turbulent scrambling dominates (e.g. Healy et al., 2023).

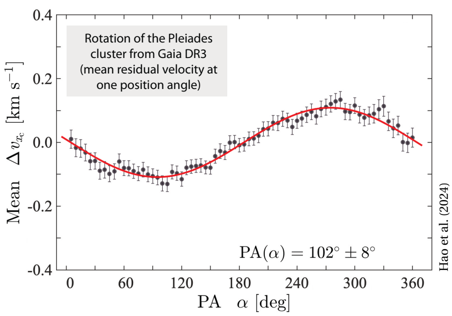
Evidence for rotation based on the proper motions from DR2 was reported for the ancient (8 Gyr) NGC 6791 by Kamann et al. (2019). Their estimate of the inclination angle was broadly consistent with the mean inclination determined for its constituent stars.

For Praesepe/NGC 2632, Loktin & Popov (2020) found a rotation velocity of 0.4 $\mathrm{km\,s^{-1}}$ at the cluster's periphery. With improved proper motions from EDR3, Hao et al. (2022) found a mean rotation velocity, within its tidal radius, of $0.2 \pm 0.05\,\mathrm{km\,s^{-1}}$, with the rotation axis tilted by $41 \pm 12°$ to the Galactic plane.

Also using EDR3, Guilherme-Garcia et al. (2023) found rotational signatures in eight open clusters (nine others displaying a possible rotation), and identified 14 expanding clusters, with contraction evident in two.

Hao et al. (2024) used the astrometry and radial velocities from Gaia DR3 to determine the mean 3D rotation velocities of the Pleiades, α Per, and Hyades clusters, within their tidal radii, of 0.24 ± 0.04, 0.43 ± 0.08, and $0.09 \pm 0.03\,\mathrm{km\,s^{-1}}$ respectively.

From a study of 1379 open clusters with Gaia DR3, Jadhav et al. (2024) identified spin signatures in 10 clusters and 16 candidates, with expansion found in 18 and contraction in three. The expansion rate was compatible with theoretical estimates based on the expulsion of residual gas, while the orientation of the spin axis is independent of the cluster's orbital angular momentum. They concluded that at least 1% of clusters are born rotating, or have undergone strong interactions since.



THE STRUCTURE of an initially spherically symmetric star system evolves through small changes of velocity during 2-body encounters ('relaxation'). And this is accompanied by 'mass segregation': high-mass stars and binaries sinking to the centre, and low-mass stars being elevated to the cluster halo where they more easily evaporate (e.g. Spitzer, 1969; Kroupa, 1995; Khalisi et al., 2007; Binney & Tremaine, 2008 §7.5).

Pre-Gaia evidence for mass segregation includes Praesepe and NGC 6231 (Raboud & Mermilliod, 1998; Khalaj & Baumgardt, 2013), and the Hyades (Röser et al., 2011), although it has not always been clear whether this is a result of relaxation, or due to the preferential formation of more massive stars towards the cluster centres.

With the Gaia data, mass segregation has been observed in Coma Ber (Tang et al., 2018), in Ruprecht 147 (Yeh et al., 2019, Fig. 10), in Czernik 3, where simulations indicate that the observed mass segregation is indeed a consequence of relaxation (Sharma et al., 2020, §4.1), in ASCC 92 (Piatti, 2023), and in several of the 15 clusters using EDR3 data by Ebrahimi et al. (2022).

In a study of 773 clusters using Gaia EDR3, Almeida et al. (2023) found '*… no significant evidence that clusters lose and segregate mass with age*'. But in a study of 60 clusters using Gaia DR3, Angelo et al. (2023) found that the core radii do appear to decrease with age. Other studies are underlining the inherent complexity of disentangling the many effects at work (Viscasillas Vázquez et al., 2023; Alvarez-Baena et al., 2024; Hu et al., 2024).

THE EVOLUTION of open clusters is also influenced by its binary population, and their own disruption by passing perturbers. Various studies have used Gaia DR3 to probe their influence. For 78 clusters, Cordoni et al. (2023) found a binary fraction ranging from 15–60%, hints of a correlation between the total fraction of binary stars and the central density, and with a radial distribution depending on cluster age. Comparable ranges of binary fractions were found for 202 clusters by Donada et al. (2023), and for 16 clusters by Long et al. (2023).

Pang et al. (2023) found a decreasing binary fraction with increasing cluster age (depending strongly on stellar density), only limited evidence for mass segregation, but clear evidence for the early disruptions of binary stars, with the binary fraction depending strongly on radial distance. Several other studies along these lines have been reported (Childs et al., 2024; Chulkov, 2024; Jiang et al., 2024; Alexander & Albrow, 2025).

FINALLY, I SHOULD mention the search for the likely presence of stellar-mass black holes in open clusters, which I considered in some detail in essay 175. I will only mention here that in their study of the Hyades, Torniamenti et al. (2023) found that their Gaia DR3 observations are best reproduced by models with 2–3 black holes still in the cluster today.