219. Open clusters: numbers

I HAVE CONSIDERED the substantial topic of open clusters with Gaia in two previous essays, detailing some of the early results from EDR3 (essay 74), and the numbers of open clusters identified in DR3 (essay 144).

In these next four essays, I will give an update of some of Gaia's latest advances, drawing on a recent review by Cantat-Gaudin & Casamiquela (2024). Here, in the first of these, I will look at their overall properties and Galactic distribution.

AROUND A THIRD of the open clusters known before Gaia were catalogued by Charles Messier, and William and John Herschel, and subsequently compiled into the New General Catalogue (NGC; Dreyer, 1888).

Clusters found in photographic surveys were added in the 20th century, with more recent discoveries from proper-motion surveys. Before Gaia DR2, in April 2018, the two largest catalogues were by Dias et al. (2002), with about 2000 objects, and by Kharchenko et al. (2013) listing over 3000. But a significant fraction of these were apparent 'overdensities', while the compilations were also highly incomplete (Cantat-Gaudin et al., 2019b, §1).

THE EARLY Tycho–Gaia Astrometric Solution (TGAS; Michalik et al., 2015) provided improved proper motions and, for the first time, parallaxes, for the two million stars of the Tycho-2 catalogue. This allowed the astrometric characterisation of a hundred clusters within 1 kpc (Cantat-Gaudin et al., 2018b).

Gaia DR2 provided proper motions improved by a factor of 100, and a full astrometric solution for over one billion stars to ~20 mag. Attempting to identify all ~3000 known clusters in the Milky Way disk, Cantat-Gaudin et al. (2018a) confirmed just 1169, implying that a large number in the literature were *apparent* groupings with no physical reality, many created by extinction patterns in the inner Milky Way (Cantat-Gaudin & Anders, 2020).

The presence of this fictitious old, inner-disk population had been difficult to explain (Martinez-Medina et al., 2016). Based on the Gaia revisions, Anders et al. (2021) showed that the cluster-age function of the Milky Way is indeed in line with empirical expectations.

AT LEAST 30 STUDIES have since identified some 25 000 open clusters out to 15 kpc, exploiting the DR3 parallaxes and proper motions, and using clustering algorithms such as DBSCAN (Castro-Ginard et al., 2022), HDBSCAN (Hunt & Reffert, 2023), and various others. The *Unified Cluster Catalogue* of Perren et al. (2023), online at https://ucc.ar, has compiled these into a list of almost 14 000 unique Milky Way clusters, with more than a million probable members in total (essay 144).

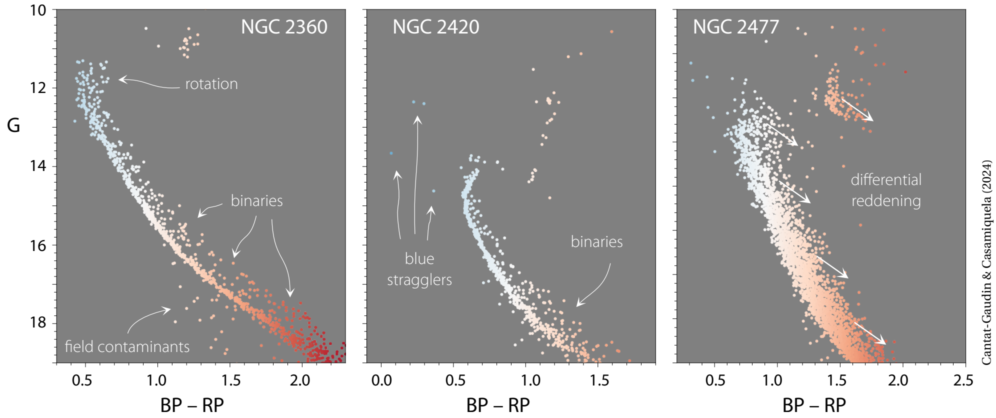
Typical clusters have around 50 members, but many of the most populated have several hundred up to several thousand. Most have half-number radii in the range 2–6 pc, somewhat independent of numerical size (Tarricq et al., 2022; Zhong et al., 2022; Hunt & Reffert, 2023).

These advances allow better studies of membership, Galactic distribution, age, chemistry, and dynamics.

CLUSTER AGES are most commonly obtained by comparing colour–magnitude diagrams to theoretical isochrones. Bayesian analysis (von Hippel et al., 2006) using Gaia photometry to derive ages, distances, and reddening, was applied to 269 clusters by Bossini et al. (2019), and to 1743 clusters by Dias et al. (2021).

Recent age determinations (e.g. Li & Shao, 2022) aim to better account for unresolved binaries, field stars, and reddening (see figures over). Stellar rotation, and the presence of blue stragglers, are further complications (e.g. Kounkel & Covey, 2019; Cantat-Gaudin et al., 2020; Hunt & Reffert, 2023; Cavallo et al., 2024). I say more on this topic in essay 220.

OPEN CLUSTERS ARE found to be concentrated in the Galactic plane, confirming the pre-Gaia picture but with much greater precision and clarity. The youngest are typically located less than 100 pc from the mid-plane, where the cold gas densities are highest, while the oldest have reached heights of more than 1 kpc (Soubiran et al., 2018; Tarricq et al., 2021). The inner disk hosts relatively few old clusters, the denser environment presumably leading to higher disruption rates, although the inner population remains poorly constrained as a result of extinction and reddening (Minniti, 2024).



SOME ASPECTS of their Galactic distribution remain uncertain. For example, the dearth of young clusters in the outer disk may be a result of star formation, which is clearly still ongoing at large distances, but which occurs at densities too low to form gravitationally bound clusters (Pflamm-Altenburg & Kroupa, 2008).

Old clusters beyond ~12 kpc may have formed in the inner Milky Way before migrating outwards. And the fact that the orbits of clusters older than 3 Gyr have larger eccentricities and inclinations than field stars of the same age, suggests that clusters are more likely to survive if their orbits take them beyond the plane for most of the time (Viscasillas Vázquez et al., 2023). In the outermost regions of the disk, distant clusters tend to be found *below* the Galactic plane (Cantat-Gaudin et al., 2020), following the disk's known warp (e.g. He, 2023).

THE DISTRIBUTION OF young clusters has long been considered to broadly follow the expected trace of the spiral arms, although pre-Gaia, distances uncertainties were too large to allow for an accurate characterisation of the spiral structure in the solar neighbourhood. The greatly enlarged Gaia census, along with improved distances and photometry, has brought significant insights into their distribution within 2 kpc.

But challenging the picture of a grand-design Milky Way with continuous and well-defined structures, these studies find a fragmented pattern (Cantat-Gaudin et al., 2018a; 2019b; Molina Lera et al., 2019; Cantat-Gaudin et al., 2020; Kuhn et al., 2021; Pantaleoni González et al., 2021; Hunt & Reffert, 2023).

Their distribution and dynamics is also contributing to the long-standing question of whether the spiral perturbations are global and stationary, or local and transient (e.g. Shen & Zheng, 2020). Using young clusters, Castro-Ginard et al. (2021) showed that the Galaxy's four classical spiral arms have distinct pattern speeds, all of them close to the corotation of the disk. This supports the idea that they are short-lived structures, rather than long-standing Galaxy-scale density waves.

IN A FUTURE ESSAY, essay 223, I will go further into the connection between open clusters and the more loosely bound 'stellar associations' and 'moving groups'. Let me only mention here that some young coeval and co-moving superstructures can now be traced with Gaia over hundreds of parsecs.

The Vela OB2 association, for example, has grown from 200 Hipparcos members to more than 14 000 today (Armstrong et al., 2018; Franciosini et al., 2018; Beccari et al., 2018; 2020; Cantat-Gaudin et al., 2019c; Pang et al., 2021). And the clusters NGC 2547, NGC 2451B, Collinder 140, Collinder 135, and UBC 7 are now known, from Gaia, to be part of a continuous co-moving alignment of coeval (~35 Myr) stars extending over 200 pc (Cantat-Gaudin et al., 2019a; Beccari et al., 2020).

Nor will I say more here on the very massive star clusters ($> 10^4\,M_\odot$) found in the inner regions of the Galaxy. These are expected to form from hierarchical merging of smaller clusters, and include systems such as Westerlund 1 (essay 106) and Westerlund 2.

BUT I WILL CONCLUDE with a mention of 'binary clusters'. Rozhavskii et al. (1976) was perhaps the first to comment that open clusters are sometimes found in pairs. More recent simulations and observations indeed suggest that such pairs may form together, orbiting each other before gradual mass loss leads to them eventually separating and evolving as two independent clusters (Camargo et al., 2016; Casado, 2021).

Such discoveries and detailed kinematic studies with Gaia include three open clusters near the Aquila Rift cloud: UPK 39, UPK 41, and PHOC 39. Here, Ye et al. (2022) used Gaia DR3 to conclude that UPK 39 and UPK 41 are a primordial open cluster binary pair, which are likely to have been formed at the same time, with PHOC 39 possibly capturing both in the future.

Ishchenko et al. (2024) showed that Collinder 135 and UBC 7 perhaps formed together 50 Myr ago. And Qin et al. (2024) used Gaia DR3 proper motions to discover that NGC 2323 is, in reality, a compact binary.