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How *Gaia* sheds light on the Milky Way star cluster population

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ABSTRACT

Star clusters are among the first celestial objects catalogued by early astronomers. As simple and coeval populations, their study has been instrumental in charting the properties of the Milky Way and providing insight into stellar evolution through the 20th century. Clusters were traditionally spotted as local stellar overdensities in the plane of the sky. In recent decades, for a limited number of nearby clusters, it became possible to identify cluster members through their clustering in proper motion space. With its astrometric data of unprecedented precision, the *Gaia* mission has completely revolutionised our ability to discover and characterise Milky Way star clusters, to map their large-scale distribution, and to investigate their internal structure. In this review we focus on the population of open clusters, residing in the Galactic disc. We summarise the current state of the *Gaia*-updated cluster census and studies of young clusters and associations. We discuss recent developments in techniques for cluster detection and age estimation. We also review results enabled by *Gaia* data concerning the dynamical evolution of gravitationally bound clusters and their stellar inventory.

1. Introduction

Historically, stellar clusters have been identified as local overdensities of stars in a given region of the sky. It has long been recognised that young stars tend to be found near other young stars (Bok, 1934; Blaauw, 1952, 1964), which led to the common (and perhaps over-simplified) assumption that all stars were, at least in their infancy, aggregated with siblings who formed from the collapse of the same parent molecular cloud (Lada and Lada, 1991, 2003; Kruijssen et al., 2011; Pfalzner et al., 2012; Parmentier and Pfalzner, 2013; Kamdar et al., 2019). When these groups are formed sufficiently dense (∼1% to 70% of the clusters in spiral galaxies depending on the local gas density, according to Kruijssen, 2012) they can remain gravitationally bound for hundreds of millions of years. In the Milky Way, it is estimated that ∼4% to 14% of the total stellar mass comes from once-gravitationally-bound clusters (Goddard et al., 2010), and 30%–35% in the entire Universe (Kruijssen, 2012).

Star clusters sit at a crossroads of scales, and are relevant to many aspects of astronomy and astrophysics. As coeval and chemically homogeneous groups, they are routinely used as tracers of Galactic structure and evolution, and as calibrators for the distance scale and for developing stellar evolution models. In this review we focus on objects traditionally referred to as open clusters. They are less dense and less massive than globular clusters (a few 100 to a few 1000 solar masses), younger (a few Myr to several Gyr), and follow Galactic orbits typical of the α-poor, metal-rich disc from which they originate.

The ESA *Gaia* space mission (Perryman et al., 2001; Gaia Collaboration, 2016b) and its first (Gaia Collaboration, 2016a), second (DR2; Gaia Collaboration, 2018) and third (Brown et al., 2021; Vallenari et al., 2023) data releases have had a huge impact on our knowledge of the cluster population in the Milky Way. The *Gaia* catalogues have enabled the detection and discovery of a large number of new objects, and allowed us to characterise them with unprecedented precision.

In this article we review the major advances brought by *Gaia* in our understanding of Milky Way star clusters, and how they in turn impact our understanding of the structure and evolution of our Galaxy. Since 2018, over a hundred scientific papers exploiting *Gaia* data have been published every month. This deluge of results makes it unfeasible for a such a review to be exhaustive, even restricting its scope to the topic of Galactic star clusters. We refer the reader interested in adjacent topics to the reviews of Wright (2020) and Wright et al. (2023) on OB associations, Cantat-Gaudin (2022) summarising *Gaia* and star clusters until 2021, and the recent publication of Zucker et al. (2023) about the Solar neighbourhood in the *Gaia* era.

This review discusses updates to the cluster census in Section 2. Section 3 is dedicated to young clusters and associations. Section 4 presents various methods used to estimate the age of clusters. In

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Section 5 we review recent publications concerning the dynamical evolution of clusters. Finally, Section 6 discusses stellar evolution and chemical abundances through the lens of cluster studies.

2. The cluster census

2.1. Identifying clusters and their members

About a third of the open clusters known before *Gaia* were catalogued by Charles Messier (Messier, 1781), William Herschel (Herschel, 1786, 1789, 1802) and John Herschel (Herschel, 1864), before being compiled into the *New General Catalogue* (NGC; Dreyer, 1888). New observational techniques such as the advent of photographic plates did not have a major impact on the star cluster census, but serendipitous discoveries were added to cluster catalogues through the 20$^{\text{th}}$ century (e.g. Trumpler, 1930; Collinder, 1931; Alter et al., 1958, 1970; Lyngå, 1982, 1985). More recently, it became possible to discover new clusters as co-moving groups of stars in proper-motion catalogues (e.g. Alessi et al., 2003; Kharchenko et al., 2005; Froebrich et al., 2007). Before the second *Gaia* data release (in April 2018), the two most widely used catalogues of open clusters were Dias et al. (2002) listing about 2000 objects, and Kharchenko et al. (2013) listing over 3000, although significant fraction were stellar overdensities awaiting confirmation from more precise astrometric surveys.

The first *Gaia* data release and its 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 (Høg et al., 2000). This astrometric data set was however limited to magnitude ∼12, and the precision of its proper motions was only greater than the ground-based proper motion catalogue UCAC4 (Zacharias et al., 2013) in some regions of the sky privileged by the *Gaia* scanning law, only allowing for the astrometric characterisation of a hundred clusters within 1 kpc (Cantat-Gaudin et al., 2018b), and a detailed study of the Hyades (46 pc from us; Reino et al., 2018a)

The second *Gaia* data release Gaia Collaboration (2018) was an immediate game changer in virtually all aspects of Milky Way studies, providing proper motions better than existing catalogues by a factor of 100, and a full astrometric solution for over 1 billion stars down to magnitude ∼20. Attempting to identify all ∼3000 known clusters in the Milky Way disc, Cantat-Gaudin et al. (2018a) were only able to detect 1169 of them, indicating that a large number of clusters listed in the literature are putative groupings with no physical reality. The existence of many of them had in fact already been questioned (by e.g. Sulentic and Tifft, 1973, when building the Revised New General Catalogue) and sometimes even convincingly refuted (e.g. four NGC objects by Kos et al., 2018a, on the basis of incoherent radial velocities). Cantat-Gaudin and Anders (2020) have shown that many of these asterisms are created by extinction patterns in the inner regions of the Milky Way, leading to a fictitious population of old, inner-disc, high-altitude clusters in the Galactic disc. The presence of this old, inner-disc population had been difficult to explain theoretically (Martinez-Medina et al., 2016) and made the Milky Way appear too rich in old clusters compared to other spiral Galaxies. Based on the *Gaia*-updated cluster census, Anders et al. (2021) have shown that the cluster-age function of the Milky Way is in fact in line with empirical expectations.

The unprecedented precision of the *Gaia* data have allowed for serendipitous discoveries of new clusters (Cantat-Gaudin et al., 2018a; Ferreira et al., 2019; Jaehnig et al., 2021; Negueruela et al., 2021) or discoveries through visual inspection of proper-motion diagrams (Sim et al., 2019). Since star clusters are expected to be compact[1] on the sky (α, δ), in proper motion ($\mu_{\alpha*}, \mu_{\delta}$) and in parallax ($\varpi$), many off-the-shelf clustering algorithms that were not initially designed for astronomical data can be applied directly to the *Gaia* catalogue. Some examples include Density-Based Spatial Clustering of Applications with Noise (DBSCAN; Ester et al., 1996), Hierarchical-DBSCAN Campello et al. (2013), or Ordering Points To Identify the Clustering Structure (OPTICS; Ankerst et al., 1999). The most successful searches were however performed with carefully chosen data mining schemes and algorithms to pick up clusters in the large 5D *Gaia* catalogue, based for instance on DBSCAN (e.g. Hunt and Reffert, 2021; Castro-Ginard et al., 2018, 2019, 2020, 2022), Gaussian Mixture Models (Cantat-Gaudin et al., 2019b), or HDBSCAN (Hunt and Reffert, 2023). Over 4000 objects with high probability of being true clusters (according to their astrometric and photometric properties) are currently listed in the catalogue of Hunt and Reffert (2023). Several thousand more potential clusters have been identified in dozens of studies,[2] and might be confirmed as true clusters by the improved astrometry of the fourth *Gaia* data release.

The nominal precision of the *Gaia* proper motions can vary from ∼0.01 mas yr^{-1} for bright and well-behaved sources to over 0.5 mas yr^{-1}. Clusters can be found at distances ranging from a few parsecs to 15 kpc from us, and exhibit a variety of sizes, densities, and surrounding environment. Different approaches can be viable depending on the required sensitivity or runtime requirements. While some methods have been shown to efficiently recover large numbers of clusters and their members over the entire sky (in particular HDBSCAN, which according to Hunt and Reffert, 2021, scales better than OPTICS for large datasets), many studies focusing on specific objects use various hybrid methods to assign cluster members to known clusters. The Unsupervised Photometric Membership Assignment in Stellar Clusters (UPMASK Krone-Martins and Moitinho, 2014) is built on a k-means clustering inner loop, while its Python implementation pyUPMASK (Pera et al., 2021) supports several clustering methods. Many studies base membership assignment on Gaussian Mixture Models (e.g. Agarwal et al., 2021; Deb et al., 2022; Noormohammadi et al., 2023). Other successful approaches include extreme deconvolution (Bovy et al., 2011) used by Jaehnig et al. (2021), wavelet decompositions (e.g. Meingast et al., 2019; Fürnkranz et al., 2019), support vector machines (e.g. Ratzenböck et al., 2020; Grasser et al., 2021), self-organising maps (e.g. StarGO Yuan et al., 2018, 2022; Tang et al., 2019; Pang et al., 2020, 2021), significance mode analysis (SigMA; Ratzenböck et al., 2023b), or deep neural networks (van Groeningen et al., 2023). When dealing with very small numbers of clusters, tailored modelling can be even more effective at separating cluster stars from the field populations, as shown in e.g. Griggio and Bedin (2022) for M 37.

2.2. Estimating cluster parameters

In the past decades, cluster ages and interstellar extinction have traditionally been obtained via comparisons of observational colour–magnitude diagrams (CMDs) to theoretical isochrones, often performed by hand. In an era where clusters are routinely discovered by batches of several hundreds, automated methods are the key to providing homogeneous parameters for the known cluster population. Bossini et al. (2019) applied the Bayesian code BASE-9 (von Hippel et al., 2006) to *Gaia* photometry (supplemented with the mean parallax of the cluster) in order to obtain ages, distances, and reddening for 269 clusters. Isochrone fitting was also employed by Dias et al. (2021) for 1743 objects. Li and Shao (2022) proposed a mixture model that is able to reproduce the presence of unresolved binaries and field star contamination, but have so far only applied their approach to a small number of clusters.

[1] In Section 5 we mention techniques used to recover structures when they are coherent but not compact.

[2] We refer the reader to Table 3 of Hunt and Reffert (2023) and Table 1 of Perren et al. (2023) for lists of papers reporting cluster candidates.

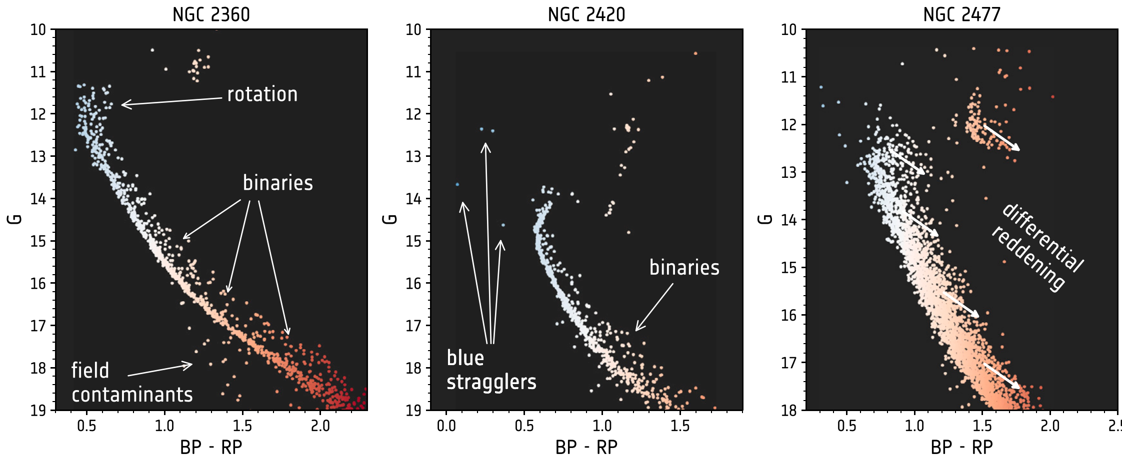

Fig. 1. Colour–magnitude diagrams of three clusters with members taken from Hunt and Reffert (2023). Stellar isochrones predict that stars of the same age and chemical composition are aligned on a single line, but observed CMDs often feature deviations from this simple approximation, which must be accounted for when estimating cluster parameters.

Automating isochrone fitting procedures is surprisingly not straightforward. The single sequence of a theoretical isochrone is not always a good approximation for the overall distribution of stars in an observed CMD (Fig. 1). The presence of unresolved binaries creates a second line parallel to the single-star sequence. Stellar rotation and possible age scatters can introduce a colour spread near the main-sequence turnoff. Inhomogeneous extinction across the field of view (also called differential reddening) can blur and broaden the entire CMD. In old clusters, blue straggler stars can remain brighter and bluer than the location of the turnoff. At the faint end, photometric errors affect the aspect of the CMD. Machine learning procedures have been increasingly successful at quickly retrieving cluster parameters from their photometry, with procedures trained on synthetic data (Kounkel and Covey, 2019; Hunt and Reffert, 2023; Cavallo et al., 2024) or real clusters (Cantat-Gaudin et al., 2020).

The median number of members in the latest open cluster catalogues is around 50, but a few hundred of the most populated clusters have 500 to several thousands of known members. Tarricq et al. (2022), Zhong et al. (2022), and Hunt and Reffert (2023) all report that 90% of the clusters have half-number radii (the radius containing half the identified members) between 2 and 6 pc, without any obvious relation to the total number of stars. This indicates that clusters exhibit significantly different spatial densities, and dynamical states (see Section 5).

2.3. Clusters as tracers of the Milky Way structure

Open clusters are distributed along the Galactic plane, with the majority of the youngest objects being located less than 100 pc from the plane, while the oldest objects can be found at altitudes larger than 1 kpc (top panels of Fig. 2). This was known before *Gaia* , and is intuitively understood as the consequence of star formation taking place close to the Galactic plane (where the cold gas densities are sufficiently high) and stars subsequently dispersing as they travel through the Milky Way, gaining hotter orbits and reaching higher altitudes (Soubiran et al., 2018; Tarricq et al., 2021).

Gaia has shown that the inner disc hosts relatively few old clusters. The median age of known clusters at Galactocentric distances R_{GC} <6.5 kpc is 120 Myr, compared to 800 Myr at R_{GC} >12 kpc (Cantat-Gaudin et al., 2020). The relative lack of old clusters in the inner disc is commonly attributed to the denser environment leading to higher disruption rates. Due to large amounts of extinction, our knowledge of stellar populations in the inner disc is a lot less complete than for the Solar neighbourhood (see Minniti, 2024, discussing the Galactic Extinction Horizon). Progress in this area is expected during this decade owing to LSST (Usher et al., 2023) and the JAXA mission JASMINE (Kawata et al., 2024). In the long term, the proposed astrometric mission GaiaNIR (Hobbs et al., 2021) will shed light on the dense inner regions of the Milky Way.

The lack of young clusters in the outer disc is less straightforward to explain, because these regions are not devoid of young stars (for instance, Skowron et al., 2019; Chen et al., 2019; Lemasle et al., 2022, have investigated the spatial distribution of Cepheids in the outer disc). One possible reason for the lack of known clusters could be that star formation at large galactocentric distances happens at densities that are too low to form gravitationally bound clusters. A similar idea was explored by Pflamm-Altenburg and Kroupa (2008) and Krumholz and McKee (2008) to explain why the extension of the discs of external spiral galaxies exhibits a sharp Hα cut off but a smoother UV profile, concluding that the outer disc does not form massive stars beyond a certain radius. In this scenario, all the old clusters beyond a cut-off radius of $R_{GC} \sim 12$ kpc formed in the inner Milky Way before migrating outward.

A second explanation to the lack of young outer-disc clusters could simply be the incompleteness of our catalogues. It is reasonable to believe that cluster catalogues are biased in favour of objects with high Galactic altitude, which are projected against sparser backgrounds. Cluster searches in the 5D astrometric space provided by the *Gaia* can also be biased in favour of objects whose proper motion is significantly different from the surrounding field stars. Since hot orbits and large excursions from the Galactic plane are typical characteristics of old stars (and old clusters, see Soubiran et al., 2018; Tarricq et al., 2021), the cut-off radius could be explained, at least in part, by a more incomplete census of the young cluster population. There has been so far no quantitative study of the cluster selection function.

Old clusters are survivors, while field stars are the outcome of cluster disruption. It is currently unclear to what extent the old cluster population is representative of the orbital properties of the general field population. Viscasillas Vázquez et al. (2023) have shown recently that the orbits of clusters older than 3 Gyr have larger eccentricities and inclinations than field stars of the same age, suggesting that clusters are more likely to survive if their orbits allow them to spend most of their lives outside the Galactic plane. Simulations by Jørgensen and Church (2020) also show that clusters on hot orbits have lower fractions of escapers, allowing them to survive on longer time scales.

At the far edge of the disc, distant clusters tend to be found under the Galactic plane (Vázquez et al., 2008; Cantat-Gaudin et al., 2020), following the known warp of the disc. He (2023) show that the variation of the line of node of the tilt with radius, as traced by clusters, is identical to the relation obtained from Cepheids. Probing the

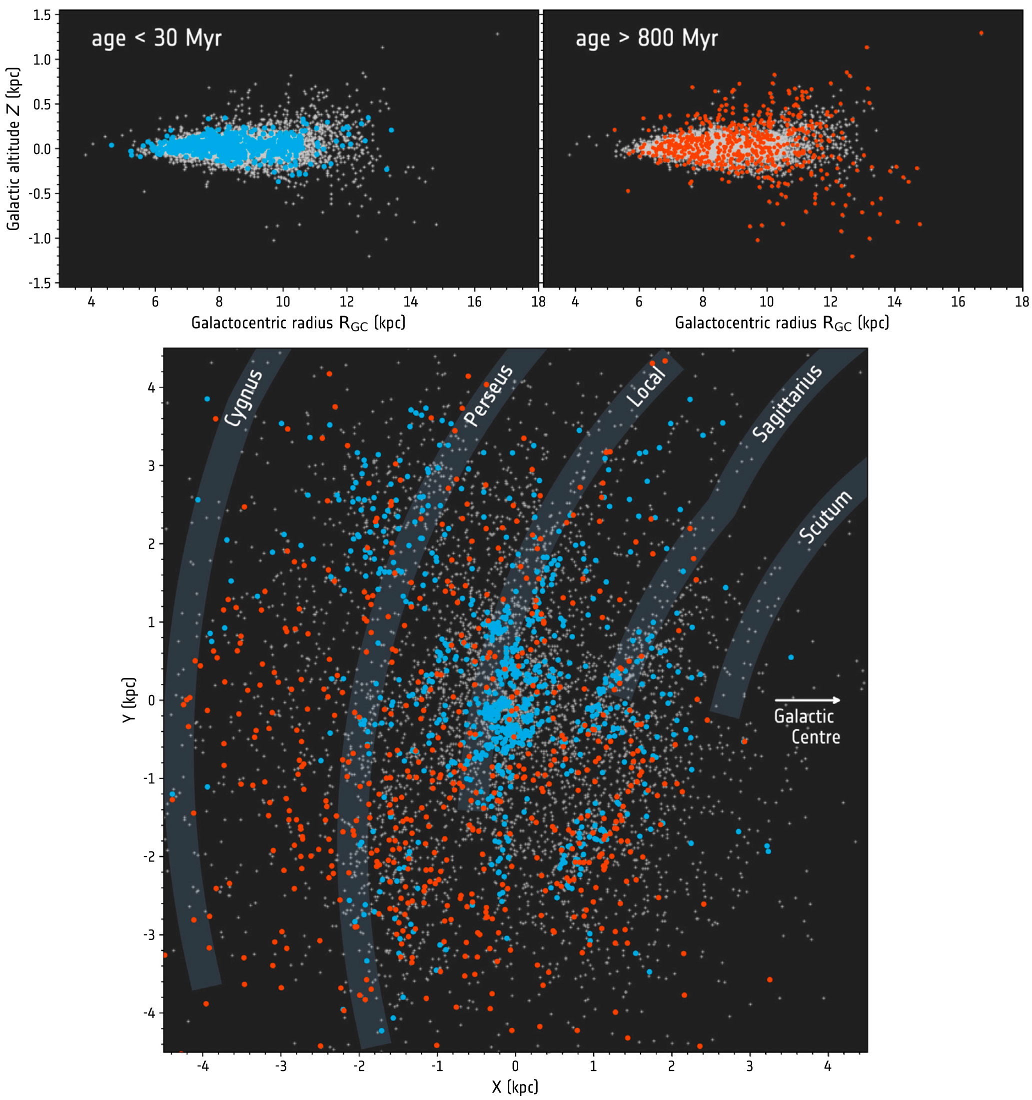

Fig. 2. Spatial distribution of high-certainty clusters from Hunt and Reffert (2023), with ages from Cavallo et al. (2024). The Sun is located at R_{GC} = 8.2 kpc and (X, Y) = (0, 0). The spiral arm model is from Reid et al. (2019).

vertical structure of the outer disc with clusters is however a difficult endeavour, due to the small number of young clusters, and the large vertical scale height of the old ones.

2.4. The spiral arms of the Milky Way

It has long been noted that the distribution of young clusters is not uniform, and roughly follows the expected trace of the spiral arms. Until *Gaia*, the uncertainties on the distances of young clusters were too large to allow for an accurate characterisation of the spiral structure in the Solar neighbourhood. The expansion of the cluster census, combined with better distance estimates owing to the parallaxes and deep photometry provide by *Gaia*, have brought significant insight on the spiral arms within 2 kpc. Rather than continuous and well-defined structures, all studies of the distribution of young clusters (e.g. Cantat-Gaudin et al., 2018a, 2020; Hunt and Reffert, 2023; Cavallo et al., 2024) report a fragmented pattern, challenging the classical picture of a grand-design Milky Way (see Fig. 2). Cantat-Gaudin et al. (2019b) focused on a ∼ 1 kpc gap in the Perseus arm, showing that the lack of known clusters was not due to interstellar extinction, but to a true physical under-density of objects. The arms traced by clusters also exhibit some high-pitch structures, following those reported in the distribution of young stars such as the Cepheus spur (Pantaleoni González et al., 2021), the spur-like structures of the second Galactic quadrant (Molina Lera et al., 2019), or the chevrons of the inner disc (Kuhn et al., 2021). Studies of the large-scale distribution of OB stars also paint a fragmented spiral (Poggio et al., 2021; Xu et al., 2023), suggesting that the Milky Way is likely to be a flocculent spiral.

The question of whether the Milky Way spiral perturbations are global and stationary (Lin and Shu, 1964) or local and transient (Toomre, 1964) has been a matter of debate for decades (see reviews by Dobbs and Baba, 2014; Shu, 2016; Xu et al., 2018; Shen and Zheng, 2020). Using young clusters (<30 Myr) with precise 3D positions and velocities, Castro-Ginard et al. (2021) have shown that the four classical spiral arms have independent pattern speeds, all of them close to the corotation of the disc. These findings support the idea that they are short-lived structures, rather than perennial Galaxy-scale density waves. Interestingly, their result is at odds with Dias et al. (2019) who included slightly older clusters (up to 50 Myr) and report no significant difference in pattern speed between the arms.

Recent studies mapping the chemical distribution of field stars by Poggio et al. (2022) and Hawkins (2023) have observed that giants associated with the spiral arms exhibit higher metallicities than those located in the interarm regions. It is currently not possible to confirm this result using young clusters, due to the lack of available metallicities for these objects.

3. Young clusters, associations, moving groups

The *Gaia* parallaxes have enabled detailed studies of the 3D distribution of young stars in the Solar neighbourhood, revealing a wide range of sizes and densities within 150 pc (Gagné et al., 2018b, 2019, using DR1 data), several hundreds of parsecs (Zari et al., 2018; Kounkel and Covey, 2019; Kerr et al., 2021, with DR2), and beyond a kiloparsec with DR3 data (Zari et al., 2021; McBride et al., 2021; Prisinzano et al., 2022; Pang et al., 2022; Kerr et al., 2023).

In this section we discuss some key ideas that *Gaia* has introduced or solidified in the recent years concerning the structure and origin of young stellar aggregates.

3.1. Loose associations are (usually) not expanding clusters

During the early phases of star formation, radiation pressure from hot stars and supernovae can rapidly strip a proto-cluster from its gas, causing the cluster to become supervirial and its stars to quickly disperse. While this scenario can happen in the Milky Way (e.g. λ Orionis, Kounkel et al., 2018), it was reported even before *Gaia* that some associations are not rapidly expanding (Wright et al., 2016; Wright, 2017b,a) a result allowed by theoretical models (e.g. Kruijssen, 2012; Kruijssen et al., 2012). The *Gaia* data indicates that not just some, but the majority of loose stellar aggregates in the Solar neighbourhood are in fact expanding slowly (Kuhn et al., 2019; Ward and Kruijssen, 2018; Melnik and Dambis, 2020; Ward et al., 2020).

As associations are barely supervirial, they retain some of their initial structure and provide clues on the conditions of star formation. Perhaps the best example is provided by the Scorpius-Centaurus association (Sco-Cen), the most nearby and the most studied major association. While Hipparcos studies of Sco-Cen were able to identify a few hundred members (de Zeeuw et al., 1999a), the *Gaia* data has allowed the detection of low-mass stars bringing the census to 15,000 members (Damiani, 2018; Gagné et al., 2018b; Wright and Mamajek, 2018; Damiani et al., 2019; Röser et al., 2018; Goldman et al., 2018; Luhman et al., 2018; Luhman and Esplin, 2020; Squicciarini et al., 2021; Luhman, 2022; Žerjal et al., 2023a; Briceño-Morales and Chanamé, 2023; Ratzenböck et al., 2023a,b). The recent study by Ratzenböck et al. (2023b) reports the identification of 37 distinct and coeval clusters within the association, reaching densities as low as 0.01 sources pc^{-3}, and with relative velocities of 0.5 $km\,s^{-1}$. The authors also show a continuous age gradient through the entire structure, hinting at sustained star formation across ∼15 Myr. Briceño-Morales and Chanamé (2023) investigated the space-kinematics-age structure of Sco-Cen, and propose that four massive stars have shaped the present structure of the association through stellar winds and supernovae.

Despite being gravitationally unbound, stellar groupings can remain spatially coherent over hundreds of Myr (e.g. Meingast et al., 2019; Kounkel and Covey, 2019; Gagné et al., 2021, 2023). Systems that are neither dense nor young are often referred to as moving groups. As a complete overview of studies of stellar associations performed with *Gaia* data would be impractical, we refer the reader to Section 3 of Cantat-Gaudin (2022) for an almost exhaustive review of association studies up to December 2021, and to Krumholz et al. (2019) (Sect. 3.4.2 and 3.5.2) and Wright (2020) (Sect. 5.3) for a discussion of the origin of these structures.

3.2. Single events of star formation can span hundreds of parsecs

The ability to identify low-mass members of associations and young clusters has revealed that some coeval and co-moving superstructures can be traced over hundreds of parsecs. Investigations of the Vela OB2 association with *Gaia* have increased its number of known members from ∼200 (de Zeeuw et al., 1999a) to over 14,000 (Franciosini et al., 2018; Armstrong et al., 2018; Beccari et al., 2018; Cantat-Gaudin et al., 2019c,a; Beccari et al., 2020; Pang et al., 2021) and revealed a high degree of spatial and kinematic substructure. Cantat-Gaudin et al. (2019a) have shown that the clusters NGC 2547, NGC 2451B, Collinder 140, Collinder 135, and UBC 7 are part of a continuous, co-moving alignment of coeval (∼35 Myr) stars spreading over 200 pc. Beccari et al. (2020) discovered another cluster associated with this structure, showing that this kinematically cold family currently spans at least 260 pc. The young age and the small velocity dispersion within the group indicate that this morphology cannot be due to tidal disruption, and therefore reflects the filamentary structure of the parent molecular cloud, which rapidly collapsed into a coeval population.

3.3. Young massive clusters: a distinct mode of star formation?

The inner regions of the Milky Way host a handful of very massive clusters ($> 10^4\,M_\odot$) that contain a dense population of massive stars, and are strongly affected by extinction and reddening. Westerlund 1 is a $5 \times 10^4\,M_\odot$ cluster (see Andersen et al., 2017, and references therein). *Gaia* DR2 studies of this cluster placed its distance between 2.5 (Aghakhanloo et al., 2020) and 4 kpc (Davies and Beasor, 2019). Recent studies support a distance of 4 kpc, albeit still with a significant uncertainty (Rocha et al., 2022; Navarete et al., 2022; Negueruela et al., 2022). Beasor et al. (2021) estimate that the pre-main sequence stars in the cluster are 7 Myr old, while the W13 eclipsing binary is 5 Myr at most. Rocha et al. (2022) propose an age of 7 Myr for the eclipsing binary W36B and OB stars, but an older age of 10, 7 Myr for the red supergiants, a result confirmed by Navarete et al. (2022). Beasor et al. (2023) also present evidence in favour of a multi-age cluster, resulting from several bursts of star formation. Ritchie et al. (2022) report that the binary fraction in Westerlund 1 is at least 40%.

Although the cores of young massive clusters cannot be easily observed directly at optical wavelengths, the *Gaia* data has been used to study their surroundings, and in particular the population of runaway massive stars expelled from these dense regions. Evidence for recent and non-isotropic ejection in Westerlund 2 (Drew et al., 2018; Zeidler et al., 2021) supports the scenario of massive clusters growing via mergers. However, Drew et al. (2019) remark that in NGC 3603 the spatial distribution of escapers could be better explained by a cluster core collapse rather than the merging of fully-formed clusters. We refer the interested reader to Longmore et al. (2014) for a (pre-*Gaia*) overview of observational and theoretical studies of young massive clusters in the Milky Way and the Magellanic Clouds, and to the study of Westerlund 1 and 2 by Guarcello et al. (2024) for a summary of the open questions regarding these objects. In Section 5 of this review, we further discuss studies of stars escaping for clusters.

While they are not expected in the Solar neighbourhood, supermassive clusters are expected to be formed in the inner regions of spiral galaxies (Ali et al., 2023), from hierarchical merging of smaller clusters (e.g. simulations by Howard et al., 2018; Rieder et al., 2022; Guszejnov et al., 2022; Dobbs et al., 2022; Ali et al., 2023; Cournoyer-Cloutier et al., 2023). The structure and kinematics of these obscured regions are difficult to probe with *Gaia* data, but represent an obvious science case for the near-infrared space-based astrometric mission GaiaNIR.

4. Estimating cluster ages

The ages of most clusters, and possible departures from a coeval star formation scenario, can be estimated by comparing the distribution of their stars in a colour–magnitude diagram with theoretical isochrones. The accuracy and precision of the resulting age depends on prior knowledge of the cluster metallicity and extinction, but also on the number of cluster members in key evolutionary phases. For clusters older than ∼100 Myr, the colour of the bluest main-sequence stars combined with the presence of red giants provide a simple constraint on the cluster age. For clusters younger than ∼40 Myr, the presence of pre-main-sequence stars can be an age indicator, provided that the cluster is not strongly obscured by extinction, and nearby enough for its low-mass population to be observable. In this section we review various indicators other than photometric isochrone fitting used by recent studies to estimate the ages of stellar clusters and associations.

4.1. The Lithium depletion boundary

Stars burn Li in their cores, but not in their outermost layers. For convective stars, the mixing of material progressively depletes Li throughout the entire star, while for stars of F and earlier types the surface Li depletion remains minimal. The Li depletion boundary (LDB) technique relies on establishing the age-dependent mass (or luminosity) at which low-mass stars have not yet depleted their Li. In practice, it requires to measure the equivalent width of the Li I 6708 Å absorption line in the stellar spectra of cluster stars, at resolution greater than 3000 (Duncan and Jones, 1983; Stauffer et al., 1998; Jeffries et al., 2009, 2013)

Ages obtained from the LDB method are sometimes discrepant from those obtained from photometric isochrone fitting (e.g. Jeffries et al., 2017; Galindo-Guil et al., 2022). Based on Li abundances collected by the *Gaia*-ESO Survey (Randich et al., 2013), Franciosini et al. (2022) propose a set of pre-main-sequence models that include radius inflation due to the presence of star spots and magnetic activity. They also point out that for the clusters younger than ∼20 Myr, their models require more spot coverage on the low-mass stars to fit the observations.

Lithium abundances have also been shown to be related to stellar rotation, with fast rotators preserving their Li reserves over longer time scales (see Jeffries et al., 2021, and references therein). Binks et al. (2022) have studied five clusters with ages ranging from 5 to 125 Myr. They show that the apparent LDB age spread of NGC 2264 is in fact a rotation rate spread. On the other hand, they found that the γ Velorum cluster exhibits no correlation between Li and rotation, hinting at a true age spread for this cluster. Sun et al. (2023) have shown that even in the 420 Myr old cluster M 48, fast-rotating G-K stars have larger Li abundances than their slowly rotating counterparts. Tsantaki et al. (2023) have shown that this relation also exists for Li-rich giants. Jeffries et al. (2023) also provide empirical models,[3] calibrated on 6200 stars in 52 open clusters with ages ranging from 2 Myr to 6 Gyr.

4.2. Gyrochronology

The study of how stellar rotation spins down with time has led to the emergence of gyrochronology, which uses rotation periods as a proxy for age (Barnes, 2003; Douglas et al., 2014, 2016; Meibom et al., 2015). A great advantage of colour–period diagrams over isochrone fitting is the possibility to obtain ages for main-sequence stars. This field has benefited from a tremendous boost enabled by *Gaia* astrometry (allowing for pure membership lists) and the data collected by the space-based missions CoRoT (Auvergne et al., 2009), Kepler (Borucki et al., 2010), K2 (Howell et al., 2014), and the Transiting Exoplanet Survey Satellite (TESS, (Ricker et al., 2015)), but gyrochronology can also be performed with ground-based observations (Godoy-Rivera et al., 2021).

A large number of recent studies have been focusing on well-known clusters in order to better understand the relation between rotation, age, and stellar type. Gyrochronological investigations have been performed for the Hyades (Douglas et al., 2019), Pleiades (Douglas et al., 2019), NGC 2516 (Fritzewski et al., 2020; Bouma et al., 2021), Ruprecht 147 (Gruner and Barnes, 2020; Curtis et al., 2020), NGC 6811 (Curtis et al., 2019a), NGC 3532 (Fritzewski et al., 2021b,?), M 67 (Gruner et al., 2023), or NGC 6709 (Cole-Kodikara et al., 2023).

Gyrochronology has also been successfully employed to constrain the ages of clusters that are either too young or too sparse to host evolved stars to use as age markers. Curtis et al. (2019b) have shown that the age of the Pisces-Eridanus stream (Meingast et al., 2019) is comparable to that of the Pleiades. Messina et al. (2022) and Newton et al. (2022) show that the moving group X is coeval with NGC 3532 (∼300 Myr) and therefore not associated with the much older Coma Berenices. Palakkatharappil and Creevey (2023) have studied rotation periods NGC 2477 (a cluster strongly affected by differential reddening) and reduced the uncertainty on its age from 0.3 to 0.1 dex. Frasca et al. (2023) have shown that the sparse cluster ASCC 123 is coeval with the Pleiades. NGC 2281 is another cluster for which uncertain age estimates range from ∼200 to 700 Myr. Fritzewski et al. (2023) estimate a gyrochronological age of 435 ± 50 Myr. Recently, Fritzewski et al. (2024) were able to constrain the age of the sparse UBC 1 from rotation periods and the identification of a single star exhibiting gravity-mode pulsations.

Boyle and Bouma (2023) have exploited rotation periods to select a sample of stars coeval with the ∼80 Mr α Per association, and recover the full extent of the complex defined as Theia 133 by Kounkel and Covey (2019). The possibility to identify young stars from their rotation periods (as young as 40 Myr; Douglas et al., 2024) opens exciting possibilities for the study of the spatial and kinematic structures of young stellar complexes.

While many studies rely on visual comparisons between period distributions, tools have been developed to simplify the use of gyrochronological data. Angus et al. (2019) propose a Python package to simultaneously derive ages from photometry and rotation periods,[4] and Bouma et al. (2023) make tools available for the computation of empirical rotation–temperature relations.[5] Finally, Van-Lane et al. (2023) have recently explored the use of normalising flows to build a data-driven probabilistic model extracting stellar ages.

4.3. Ages from internal kinematics

The possibility to resolve the 3D spatial and 3D kinematic distribution of young clusters and associations has allowed comparisons between their isochronal ages and estimates from dynamic traceback of their member stars. This approach can be especially useful for sparse objects offering little age constraints in their CMDs. For instance, Miret-Roig et al. (2020) obtained a traceback age of 18.5 ± 2 Myr for β Pictoris, a cluster for which literature estimates range from 10 to 40 Myr. The estimates are however subject to systematics. Couture et al. (2023) show that a possible, radial velocity shift of 0.6 km s^{-1} affects the traceback age of β Pictoris by ∼2 Myr, and the presence of stars with uncertain membership status by 3 Myr. Galli et al. (2023) found the dynamical age of Tucana–Horologium (∼40 Myr) to be consistent with both isochronal and Li ages.

Miret-Roig et al. (2022) remark that the dynamical age of Upper Scorpius appear younger than the age estimated from its CMD. Further investigation of this idea by Miret-Roig et al. (2023) for six young

[3] Empirical AGes from Lithium Equivalent widthS (EAGLES); https://github.com/robdjeff/eagles.

[4] https://github.com/RuthAngus/stardate

[5] https://github.com/lgbouma/gyro-interp

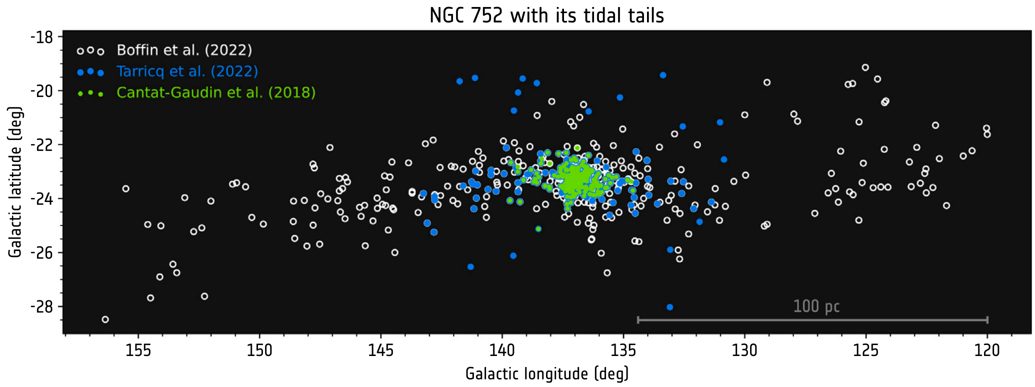

Fig. 3. Members of NGC 752 identified by Cantat-Gaudin et al. (2018a) by clustering in astrometric space (green), by Tarricq et al. (2022) modelling an elongated structure (blue), and by Boffin et al. (2022) with a convergent point method.

stellar associations shows a systematic difference of ∼5 Myr, which the authors suggest is the typical time a star remains bound to its siblings before moving away: the isochrone age of a group indicates the time its stars were born, while the dynamical traceback age indicates when it started expanding. Pelkonen et al. (2024) proposed and validated a method based on the expulsion age of individual stars, showing 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.

While the above methods are only applicable to young unbound associations, Dinnbier et al. (2022) propose an approach based on the observed tilt angle between the orbital direction and the tidal tails of dissolving clusters, which can be predicted analytically. The authors estimate that such age estimates can have a precision of 10 to 20% for clusters younger than ∼300 Myr.

5. Internal kinematics and dynamics

A gravitationally bound cluster finds itself in a situation of temporary but unstable equilibrium. While its stars orbit each other following their collective gravitational potential, they also feel the presence of the gravitational potential of the entire Milky Way. Stars that reach the cluster's escape velocity (due to stochastic 2- or 3-body encounters) may become lost to the Galactic field population. Stars preferentially escape through the Lagrange points of the cluster (Fukushige and Heggie, 2000; Gieles and Baumgardt, 2008; Portegies Zwart et al., 2010), creating a leading and a trailing tidal tail. While the tidal tails of globular clusters have been studied for decades (e.g. Odenkirchen et al., 2001; Belokurov et al., 2006), the study of open cluster tidal tails only became possible in the *Gaia* era due to the relatively low density of these objects, and the much higher background and foreground contamination.

The elongated morphology of the Hyades was first reported by Reino et al. (2018b) using *Gaia* DR1 data. Its tidal tails were later mapped in greater detail with DR2 data (Lodieu et al., 2019; Röser et al., 2019; Meingast and Alves, 2019; Oh and Evans, 2020). With DR3 astrometry, Jerabkova et al. (2021) traced the Hyades tidal tails over a distance of 800 pc. Other nearby clusters exhibit prominent tidal tails: NGC 2632 (Röser and Schilbach, 2019); Ruprecht 147 (Yeh et al., 2019); M 67 (Carrera et al., 2019); Coma Berenices (Tang et al., 2019); NGC 752 (Bhattacharya et al., 2021; Boffin et al., 2022); UBC 274 (Casamiquela et al., 2022); COIN-Gaia 13 (Bai et al., 2022). Hu et al. (2021b), Hu et al. (2021a) and Tarricq et al. (2022) report that nearly a hundred nearby clusters have an elongated morphology, with a preferential elongation parallax to the Galactic plane, consistent with the expectation of tidal disruption. Bhattacharya et al. (2022) found tidal tails in 20 clusters, and a total of 46 clusters with stars outside their tidal radius.

In Fig. 3 we show how *Gaia* has increased the known extent of the tidal tails of NGC 752, which according to Boffin et al. (2022) span up to 260 pc (over 25 degrees on the sky). Studying objects with large angular sizes requires to properly account for projection effects, both in their spatial and kinematic distribution. This can be done with convergent-point methods (e.g. Meingast et al., 2021; Boffin et al., 2022; Žerjal et al., 2023b), or by converting the observed *Gaia* astrometry into Cartesian coordinates (Gagné et al., 2018a; Moranta et al., 2022), or even performing clustering analyses on transformed quantities such as action angles (e.g. Coronado et al., 2020, 2022; Fürnkranz et al., 2024).

Kroupa et al. (2022) have shown that the tidal tails of the Hyades are significantly asymmetrical, with a leading tail more populated than the trailing tail. Pflamm-Altenburg et al. (2023) suggest this is also the case in NGC 2632, Coma Berenices, and NGC 752, although the results are statistically less robust for these more distant objects. Interestingly, Thomas et al. (2018) have theorised that asymmetric tidal tails naturally arise from MOdified Newtonian Dynamics (MOND; Milgrom, 1983; Sanders and McGaugh, 2002; Merrifield, 2005; Famaey and McGaugh, 2012). While Pflamm-Altenburg et al. (2023) do consider that the observed asymmetry of the Hyades could be due to local bumps in the Milky Way potential or to external perturbations, they point out the need for investigations of the morphology of tidal tails in a larger number of clusters. Kroupa et al. (2022) point out that MOND also predicts clusters older than 200 Myr should experience a spin-up opposite to their orbital angular momentum, a prediction that the current data is not able to verify yet. The low-acceleration regime surrounding dissolving clusters in the Galactic disc provides a good opportunity to test this theory.

Detecting the signal of open cluster rotation is challenging, even in the *Gaia* era. Evidence for clear rotation was found in NGC 2632 by Loktin and Popov (2020) and Hao et al. (2022), with a significant tilt of 41 ± 12° with respect to the Galactic plane. Guilherme-Garcia et al. (2023) report a rotational signature in the plane of the sky for eight more clusters, detected from *Gaia* proper motions. By supplementing *Gaia* proper motions with ground-based spectroscopy, Kamann et al. (2019) reported evidence for rotation in NGC 6791, but not in NGC 6819 (two clusters older than 1 Gyr). The origin of rotational patterns in clusters can be multiple: it can be inherited at birth, imprinted by interactions with massive structures, or due to the long-term action of tidal forces. These different mechanisms should result in distinct patterns (for instance, strong interactions would preferentially induce solid-body rotation). Given the small number of clusters with known rotational signatures, we are currently far from being able to construct the empirical relations between cluster age and rotation.

Interpreting the observational clues about the dynamical state of clusters is made even more difficult by the mechanism of mass segregation. The equipartition of kinetic energy causes more massive stars to orbit closer to the centre of the cluster, with a lower velocity than low-mass stars (Spitzer, 1969). This phenomenon has been observed in many Galactic star clusters, and causes the low-mass members to be lost to the Galactic field at higher rates than the high-mass members. In a study of the strongly mass-segregated Hyades, Evans and Oh (2022) show that Milky Way open clusters can in fact never be near energy equipartition, due to the combined influence of the Galactic tidal field and the evaporation driven by mass segregation.

Mass segregation is common in open clusters, and Ruprecht 147 (Yeh et al., 2019), Czernik 3 (Sharma et al., 2020), and ASCC 92 (Piatti, 2023) have even been shown to be heavily depleted in low-mass members. Since cluster membership can only be established up to a certain magnitude and within a given radius, estimates of the total mass of a cluster are often based on extrapolations of the known stellar content, and therefore affected by significant uncertainties. Ebrahimi et al. (2022) determined the mass function and the dynamical parameters of 15 nearby clusters, and show a correlation between the slope α of the mass function and the quantity $\log(t_{age}/t_{rh})$, which is the ratio of the age to relaxation time. The resulting sequence is analogous to the corresponding relation obtained for globular clusters, but with a steeper mass function. The authors propose that this difference could be primordial, and that Galactic clusters are born with a steeper initial mass function than globular clusters. Almeida et al. (2023) provide mass estimates for 773 clusters (from 100 to 2000 $M_\odot$), and find no apparent dependence between mass segregation and age. However, Angelo et al. (2023) report that the core radius of clusters appear to decrease with age, and that the older clusters are those that tend to underfill their Jacobi radius. They also report that inner-disc clusters appear dynamically older and to have experienced more mass loss than in the outer disc. Comparing the dynamical properties of clusters in different Galactic environment is however difficult, especially given the uncertainty in establishing the membership of inner-disc clusters affected by extinction and projected against a dense background field population.

Understanding the dynamical evolution of star clusters requires some insight on their binary population. Donada et al. (2023) studied the binary fraction in 202 clusters, and found that high-mass stars are more likely to be in binary systems. They report a typical binary fraction of 18%, but with significant variations, ranging from ∼10 to 80% throughout the sample of clusters studied. Cordoni et al. (2023), on the other hand, found a flat relation between binary fraction and primary mass in a study of 78 clusters. The authors also report that in clusters older than several Gyr, the binaries appear more centrally concentrated than the single stars. Childs et al. (2024) present a method to account for the presence of photometric binaries in colour–magnitude diagrams, and remark that the binary fraction increases with age in their sample of six clusters. Donada et al. (2023) discuss trends of binary fraction with age appearing in their studies, and warn that they are most likely caused by selection effects in the cluster membership. They also report no apparent correlation between binary fraction and location in the Milky Way. In the near future, astrometric time series provided by *Gaia* might help provide further constraints on the binary content of star clusters.

Another relevant piece of information in describing the dynamical state of a cluster is whether it hosts stellar-mass black holes. Comparing *Gaia* observations to N-body simulations, Torniamenti et al. (2023) show that the half-mass radius of the Hyades is 50% too large for its total stellar content, and more consistent with a system retaining two or three black holes.

6. Stellar evolution and chemistry

6.1. Clusters and the stellar bestiary

The clean CMDs obtained from pure membership lists and millimag *Gaia* photometry allow for robust calibrations of stellar evolution models (e.g. Madore et al., 2022; Brandner et al., 2023c,a,b), and for the identification of stars in specific phases of their evolution.

Some clusters exhibit an extended turnoff. While it was sometimes proposed that age spreads in open clusters could cause a spread in colour near the turnoff point, recent studies have shown that the redder side of extended turnoffs often corresponds to fast rotators, whereas bluer stars are slower rotators (Marino et al., 2018; Bastian et al., 2018; Cordoni et al., 2018; Lim et al., 2019; He et al., 2022; Griggio et al., 2023). Rotation is essential but not unique in explaining broadened turnoffs. In the Magellanic Clouds, this phenomenon has also been linked to significant age spreads (e.g. Goudfrooij et al., 2014) and stellar variability (Salinas et al., 2016). We note that in Stock 2, Alonso-Santiago et al. (2021) observe no significant different in rotation rates, and attribute the extended turnoff to differential reddening.

Blue straggler stars (BSSs) are bright stars whose colour is bluer than the main sequence turnoff of old clusters. The number of known BSSs is now over 1500, in over 300 different clusters (Li et al., 2023). The main idea invoked to explain these objects is that they have recently gained mass, either via merger or mass transfer from a binary companion. Vaidya et al. (2020) and Rain et al. (2021) observed that the spatial distribution of BSSs is not more concentrated than that of other high-mass stars. Leiner and Geller (2021) investigated sixteen old open clusters and found that standard population synthesis produces too few BSSs with respect to observations, proposing updates to mass-transfer prescriptions. Ultraviolet studies by Panthi et al. (2022), Vaidya et al. (2022), Vaidya et al. (2022), and Jadhav et al. (2023), were able to confirm a large number of BSSs as post-mass-transfer binary objects. Interestingly, Rao et al. (2023) observe a double BSS sequence in Berkeley 17, which they warn might be coincidental.

Star clusters are a privileged ground for the observation of white dwarfs (WDs). Since robust estimates of the cluster age are often available, the mass of the WD progenitors can be constrained much more accurately than for field WDs (Si et al., 2018; Canton et al., 2021; Heyl et al., 2022). Multiple studies have searched for WDs associated with clusters (Gentile Fusillo et al., 2019; Prišegen et al., 2021; Richer et al., 2021). Prišegen and Faltová (2023) remark that very few WDs with progenitors more massive than 5 $M_\odot$ are known to reside in clusters, suggesting that more massive objects are subjected to strong kicks and ejected from clusters.

6.2. Chemical abundances of stellar clusters

In the past ten years, spectroscopic surveys have been collecting data enabling detailed chemical analyses of stellar populations in the Milky Way. Some of the largest observational campaigns, such as the Gaia-ESO survey (Randich et al., 2013), APOGEE (Apache Point Observatory Galactic Evolution Experiment; Majewski et al., 2017), RAVE (Radial Velocity Experiment; Steinmetz et al., 2020), LEGUE (LAMOST Experiment for Galactic Understanding and Exploration; Deng et al., 2012), or GALAH (GALactic Archaeology with HERMES; De Silva et al., 2015) have selected cluster stars among their targets. Smaller programmes dedicated to clusters are also currently ongoing, such as OCCASO (Open Cluster Chemical Abundances from Spanish Observatories) survey (Casamiquela et al., 2016; Carrera et al., 2022b; Carbajo-Hijarrubia et al., 2024), SPA (Stellar Population Astrophysics; Zhang et al., 2021), OSTTA (One Star to Tag Them All; Carrera et al., 2022a), or BOCCE (Bologna Open Clusters Chemical Evolution; Bragaglia and Tosi, 2007).

In the pre-*Gaia* era, the selection of probable members for spectroscopic follow-up was sometimes a tedious task (e.g. Bragaglia et al., 2022) and could lead to the selection of a large fraction of non-members (Kos et al., 2018b). The *Gaia* astrometry offers a more secure membership estimate down to the faint magnitude reached by the current generation of multi-object spectrographs such as WEAVE (Jin et al., 2023) and 4MOST (Dalton, 2016; Lucatello et al., 2023).

The *Gaia* spacecraft itself has limited spectroscopic capabilities, through its Radial Velocity Spectrograph (RVS; Cropper et al., 2018; Katz et al., 2019) observing in the 845–872 nm wavelength range where Fe and prominent Ca II lines are visible in stellar spectra. While this instrument was mainly designed to allow for radial velocity measurements, *Gaia* DR3 came with the publication of stellar parameters and chemical abundances for 5.6 million stars (Recio-Blanco et al., 2023a). Recio-Blanco et al. (2023b) explored the chemical properties of stars belonging to open clusters in the context of the thin disc from Gaia DR3 chemistry only. Their sample contained 503 clusters older than 100 Myr, and was limited to Galactocentric radius of 12 kpc due to the limiting magnitude of RVS. This sample, though with larger overall uncertainties than high-resolution studies, is several times larger than any previous sample and allowed to investigate the radial [M/H] and [α/H] gradient in the Galaxy, and their evolution in age bins. Mean radial [M/H] gradients seem compatible with previous literature studies from open clusters with much less statistics (e.g. Spina et al., 2021; Casamiquela et al., 2019). Interestingly, the evolution of the gradient as a function of age investigated by Recio-Blanco et al. (2023b) shows a steepening with age, the opposite of the results reported by Anders et al. (2017) and Spina et al. (2021).

High-resolution ($R > 20,000$) spectroscopic observations are essential to retrieve abundances with precision better than 0.05 dex, which is usually desired to perform Galactic archaeology studies (e.g. Jofré et al., 2019). From APOGEE data, Donor et al. (2020) studied the radial abundance gradients of 16 chemical elements, using a sample of 128 open clusters spanning a large range of Galactocentric radii ($6 < R_{GC} < 18$ kpc). A change of slope in the radial metallicity gradient in the outer disc is confirmed though the exact radius at which this happens depends on the distance catalog used. On the other hand, (Magrini et al., 2023) used Gaia-ESO survey data of 62 clusters between $6 < R_{GC} < 20$ kpc to investigate the evolution of the chemical gradients for 24 chemical elements, they find to be very limited in time, indicating a slow and stationary evolution of the thin disc. For a recent overview of studies of abundance gradients in the Milky Way using star clusters as tracers, we refer the reader to Spina et al. (2022).

In clusters, the precision of high signal-to-noise spectra (> 100) can be improved to 0.01–0.02 dex by using a cluster member as a reference to derive differential abundances for the other similar stars at the same location in the HR diagram (e.g. Casamiquela et al., 2020). At this precision it becomes possible to study internal chemical homogeneity of clusters (Liu et al., 2016b,a), which can be related to the internal mixing level of the proto-cluster cloud, or the effects of planetary formation. Manea et al. (2022) studied the chemical abundances derived from GALAH of five of the large stellar strings identified by Gaia (Kounkel and Covey, 2019), which seem to be in general chemically homogeneous. However, chemical studies with larger statistics are needed to clarify which of these filamentary structures are real physically related objects (see also Zucker et al., 2022).

Clusters are reference objects due to their large number of stars presumably sharing their age and chemical composition. Deriving abundances of cluster members from automatic pipelines, is a typical way of assessing the internal precision (from the dispersion among its members) and the systematic uncertainties using stars of different stellar parameters (Jofré et al., 2019, e.g. dwarfs vs giants;). Star clusters are also good laboratories to test methods and assumptions. A good example is the chemical tagging idea (Freeman and Bland-Hawthorn, 2002), which states that it should be possible to use chemical information to tag stars that formed within the same proto-cluster cloud, even in the cases where the cluster no longer exists. Since some clusters are known to exhibit unique abundance patterns (e.g. UBC 274 with an overabundance of neutron-capture elements Casamiquela et al., 2022), chemical tagging with high-precision abundances should be feasible in theory. Studies in the recent years have shown that this idea seems to have low chances of success in practice, in the first place due to internal chemical differences found in member stars, as we have discussed in the previous paragraphs. Additionally, it is now more and more evident that the chemical patterns of known clusters in the thin disc have a large overlap (Blanco-Cuaresma et al., 2015; Casamiquela et al., 2021), thus, making most of the clustering techniques to fail to recover members of known clusters from blind chemical searches (see also discussion in Spina et al., 2021). The only study in the literature to attempt to identify new clusters in large catalogs using chemistry only is Price-Jones et al. (2020), from APOGEE data. However, the inability of their method to recover any of the known clusters in their sample, and the fact that real cluster members show a larger abundance dispersion than the identified new groups, highlights the difficulty of the task.

7. Summary and conclusions

Gaia's microarcsecond astrometry has already revolutionised Milky Way astronomy, and perhaps the studies of Galactic clusters more than any other field. The ability to discover and confirm new clusters and to estimate their main parameters allows to map the stellar content our Galaxy with unprecedented accuracy within 4 kpc of the Sun. The possibility to establish reliable lists of cluster members down to faint magnitudes is invaluable for follow-up studies, and in particular the construction of target lists for large ground-based spectroscopic surveys.

We are now entering an era where star clusters can no longer be treated as individual data points, but as fluid objects in interaction with the Milky Way's gravitational potential. However, only a small fraction of the known clusters can be resolved kinematically, and probing their dynamical state is not straightforward. Large regions of the Milky Way remain obscured by dust and difficult to investigate by *Gaia*. While we can expect improved data from the upcoming *Gaia* data releases, it is probably safe to assume that no single instrument will have, in the near future, a transformative impact comparable to *Gaia*.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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