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Review

Milky Way Star Clusters and *Gaia*: A Review of the Ongoing Revolution

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Abstract: The unprecedented quality of the astrometric measurements obtained with the ESA *Gaia* spacecraft have initiated a revolution in Milky Way astronomy. Studies of star clusters in particular have been transformed by the precise proper motions and parallaxes measured by *Gaia* over the entire sky as well as *Gaia*'s deep all-sky photometry. This paper presents an overview of the many topics of cluster science that have been impacted by the *Gaia* DR1, DR2, and EDR3 catalogues from their release to the end of the year 2021. These topics include the identification of known clusters and the discovery of new objects, the formation of young clusters and associations, and the long-term evolution of clusters and their stellar content. In addition to the abundance of scientific results, *Gaia* is changing the way astronomers work with high-volume and high-dimensionality datasets and is teaching us precious lessons to deal with its upcoming data releases and with the large-scale astronomical surveys of the future.

Keywords: star clusters; open clusters; milky way; astrometry; data mining; stellar evolution

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1. Introduction

1.1. The Gaia Mission

The ESA *Gaia* space mission [1,2] is one of the most successful projects in the history of astronomy. The spacecraft was launched in December 2013 and has since been performing repeated measurements of the positions of stars in the sky with unprecedented precision. These measurements allow not only for the production of the deepest and most detailed two-dimensional map of the celestial sphere ever made but also for repeated observations that enable the measurement of the apparent motions of stars (proper motions) and their annual parallaxes (which can, in turn, be used to estimate their distances). In addition to this five-dimensional dataset, *Gaia* measures the apparent luminosity of every source as well as its colour. This all-sky dataset is the finest astrometric catalogue ever produced, and its impact and success are made even greater by the fact that the catalogues are completely public and freely available to anyone in the world with internet access[1].

The first *Gaia* data release (DR1) took place in September 2016 [3]. Its catalogue contained positions and *G*-band magnitudes for over a billion sources but only listed a full astrometric solution (proper motion and parallax) for two million stars that were in common with the Tycho-2 dataset [4]. Two years later, the second data release (DR2; [5]) had an immediate and transformative impact on Galactic astronomy due to the unprecedented precision of its astrometry (up to a hundred times better than previous proper motion catalogues) and to the depth and quality of its photometry (reaching $G \sim 20.5$) available for 1.7 billion sources. Over five thousand papers referring to *Gaia* DR2 are listed on NASA's Astrophysics Data System, and the number of new papers is still steadily increasing (see Figure 1). The third data release has been split into two steps, with Early Data Release 3 (EDR3, [6]) in December 2020 and a full DR3 planned for 2022. The EDR3 catalogue most notably contains improved astrometric solutions for 1.8 billion sources.

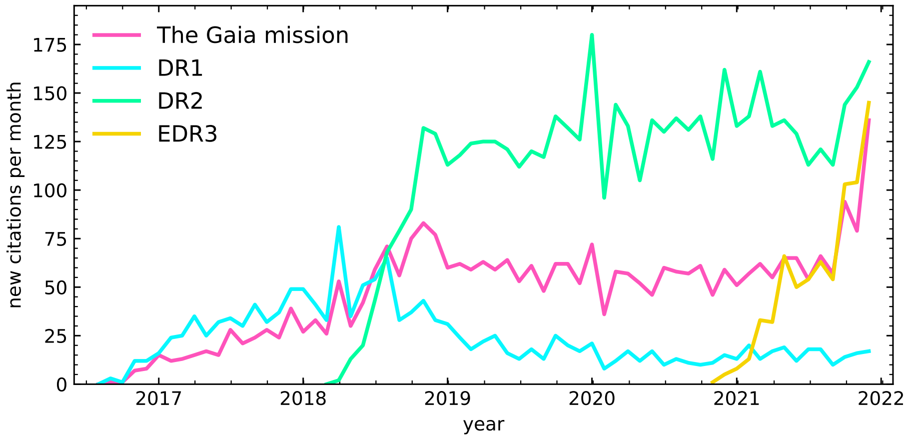

Figure 1. Citations per month for the *Gaia* mission paper [2] and the papers corresponding to DR1 [3], DR2 [5], and EDR3 [6], up to December 2021.

The availability of this enormous amount of all-sky data has not only enabled a deluge of scientific results but also changed the working habits of many astronomers to the point that, according to Brown [7], *Gaia* has *"quickly become an indispensable part of the astronomical ecosystem"*. From the *Gaia* archive, one can now, in a few minutes, retrieve deep photometric measurements for any field of view of any arbitrary size, where just a few years ago the same data would have required several nights of ground-based observations (and often months of planning proposal writing).

Brown [7] gives a historical overview of astrometry up to *Gaia*'s microarcsecond precision as well as selected science highlights showing *Gaia*'s contribution to astronomy, from Solar System and exoplanet science to the distant universe.

1.2. Star Clusters

Since the majority of young stars are observed to be located near other young stars [8–10], it has long been assumed that stars are born in groups [11–16]. These groups subsequently disperse, and most stars in the Milky Way follow lonely orbits, unrelated to their temporary neighbours, in what is commonly referred to as the Galactic field. In some cases, stars might remain gravitationally bound to their siblings, forming what is currently referred to as a star cluster. For historical reasons, the very old, dense, and almost spherical clusters orbiting the halo of our Galaxy are called globular clusters, while the sparser and significantly younger groups found in the disc of the Milky Way are called open clusters, or Galactic clusters. From ancient times to the 20th century, these clusters were identified as stellar over-densities: wherever a group of stars appeared tightly distributed in the sky, it was assumed they formed a physical cluster. Modern datasets also allow us to verify that these stars are indeed travelling together through the Milky Way (they share a common proper motion and radial velocity) and are physically close enough to each other to be considered physically related (their parallaxes indicate they are all the same distance away from us). The clean colour–magnitude diagrams resulting from this astrometric selection can quickly provide a visual confirmation that a group of stars is a true cluster. The power of this all-*Gaia* characterisation is shown in Figure 2. The dense cluster NGC 2509 was discovered in the 18th century [17,18] but was poorly characterised until recently. The cluster LP 589 is much sparser and was only discovered due to DR2 data (by [19]) as a clear group in proper motion space.

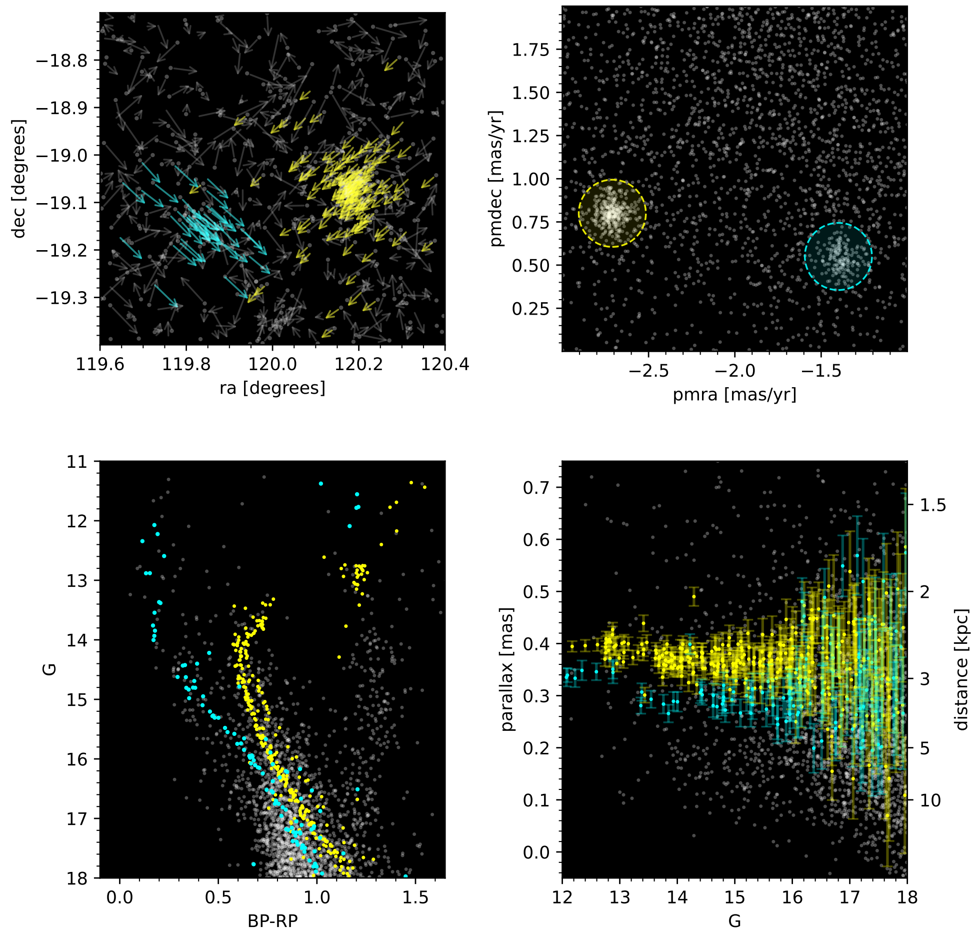

Figure 2. Example of two clusters (LP 589 in cyan and NGC 2509 in yellow) characterised with *Gaia* EDR3. The **top-left** panel shows the sky distribution of the stars and their vector proper motion. The **top-right** panel shows the distribution in proper motion space. The **bottom-left** panel shows the colour–magnitude diagram of the cluster stars, selected based on their proper motions, and the noncluster stars (white). The **bottom-right** panel shows the parallax distribution of the stars, which can be used to estimate distance to the cluster.

As groups of coeval stars (born at the same time) sharing the same initial chemical composition (born from the same molecular cloud), they constitute ideal laboratories to test stellar evolution models. Since estimating the age of and distance to a cluster is easier than for individual field stars, clusters have long been used as tracers of the structure and evolution of the Milky Way (e.g., [20–26]) and its metallicity gradient (e.g., [27–35]). The questions of how clusters (and stars) form, and how clusters are disrupted by the tidal forces of the Milky Way and by encounters with giant molecular clouds are also central to several aspects of Galaxy evolution. The overall mass function of the Galactic field has been shown to be steeper than in individual clusters (with relatively fewer high-mass stars [36,37]), as it depends on both the stellar mass function within clusters and the mass functions of clusters themselves [38–40]. Detailed study of the stellar content of clusters and of possible variations in their initial mass functions [41,42] is therefore important for our understanding of the Galaxy as a whole.

Clusters are also frequently used as reference objects to assess the quality of the *Gaia* data [43–46] and value-added catalogues such as StarHorse [47]. This review aims at presenting the variety of observational studies pertaining to Milky Way star clusters that rely on *Gaia* data or on synergies with *Gaia* and documenting the immense impact *Gaia*'s DR1, DR2, and EDR3 have had on the field, both in terms of results and methods. Excellent reviews on overlapping topics exist in the literature. In [48], the authors covered young massive star clusters in the Milky Way and in external galaxies, both from an observational and a theoretical perspective. Krumholz et al. [49] provided a recent review of the literature on cluster formation, evolution, and disruption. Krause et al. [50] presented an overview of different approaches to simulating the physics of star cluster formation. In the same series, Adamo et al. [51] reviewed observational results, mostly focusing on external galaxies but also discussing new developments in Milky Way clusters. An excellent summary of our knowledge and understanding of OB associations in the Milky Way, with historical perspective and emphasis on new results, was given by [52].

This manuscript is organised as follows: Section 2 covers the contribution of *Gaia* to the Milky Way cluster census. Section 3 presents results obtained for young clusters and associations. Section 4 discusses studies of older clusters and their dynamical and stellar evolution. Section 5 presents important results obtained with combinations of *Gaia* data and other space- and ground-based observations. Section 6 mentions methods and tools of particular interest to modern studies of star clusters, and Section 7 closes with a summary and concluding remarks.

2. The Cluster Census and the Galactic Structure

The first important contribution of *Gaia* to Milky Way cluster studies concerns the cluster census itself: where are the clusters located in the sky, what are their main properties, and which stars are members of these clusters? The most cited pre-*Gaia* catalogues of cluster parameters are the works of Dias et al. [53] and Kharchenko et al. [54][2].

A study by Cantat-Gaudin et al. [56] relied on *Gaia* DR1 and its Tycho-*Gaia* Astrometric Solution (TGAS), supplemented with proper motions from the UCAC4 catalogue [57], which, in some regions of the sky, were still more precise than TGAS. That study applied the unsupervised UPMASK method [58] to identify the members of clusters in a 5D astrometric space. Since DR1 did not provide colours for its sources, the 2MASS photometry [59] of the identified members was used and analysed with the automated isochrone fitting tool BASE-9 [60]. Their work was, however, limited to 128 nearby and prominent clusters, mostly located within 1 kpc of the Sun.

Relying on DR2 data, Cantat-Gaudin et al. [61] intended to characterise all the known clusters listed in Dias et al. [53] and Kharchenko et al. [54]. They were only able to identify 1229 objects out of over 3000 listed in the literature. A large number of objects listed in catalogues with expected nearby locations and low extinctions have remained undetected in the *Gaia* data despite the many searches conducted by various teams (see Section 2.1). The explanation, also proposed by Kos et al. [62] and extensively investigated by Cantat-Gaudin and Anders [55], is therefore that many apparent stellar over-densities are not made of related stars and despite being located on the same region of the sky, *Gaia* shows that they do not share a common motion through the Milky Way. The nonexistence of these once proposed objects has implications for our understanding of the Milky Way. The majority of these asterisms were located towards the Galactic bulge, where strong extinction patterns create local over-densities of redder stars. They were therefore suspected to be old inner-disc clusters and even possibly associated with the Galactic thick disc. Anders et al. [63] showed that removing these asterisms from cluster catalogues leads to an observed cluster age function in much better agreement with theoretical models of cluster formation and destruction rates.

Soubiran et al. [64] used the radial velocities provided in *Gaia* DR2 to obtain line-of-sight velocities for 861 clusters and study their 6D phase–space distribution. They show with unprecedented precision that young clusters (under 100 Myr) have low vertical velocities (with a dispersion smaller than 5 km s^{-1}) and are, on average, closer than 100 pc of the Galactic plane. Despite their larger scale height, clusters older than 1 Gyr exhibit a vertical velocity dispersion of 14 km s^{-1}, typical of the Milky Way thin disc. These radial velocities can be supplemented with ground-based spectroscopy (see [65] for a cross-match of *Gaia* with GALAH and APOGEE). Building upon those samples, Tarricq et al. [66] integrated Galactic orbits for 1382 clusters. They showed that all clusters younger than

30 Myr follow very circular orbits and that the clusters with large excursions above the Galactic plane are all older than 1 Gyr. Although these results are in perfect agreement with our understanding of Galactic evolution, where stars (and clusters) are formed on circular orbits near the Galactic midplane, obtaining such a clear observational picture of this mechanism would not be possible without *Gaia*.

Star clusters have the convenient property of hosting coeval stars of different masses, which makes it relatively easy to estimate their ages from a colour–magnitude diagram (CMD). This can be accomplished by comparing the distribution of stars in a CMD with a theoretical model. In practice, automatically fitting such a theoretical isochrone to photometric data is not straightforward, and for studies of individual clusters this step is often performed by hand (through visual inspection). Such an approach is impractical when dealing with samples of hundreds or thousands of clusters, in addition to leading to subjective and nonreproducible results. A rigorous analysis of the CMDs of 269 clusters was performed by Bossini et al. [67], applying the Bayesian code BASE-9 to *Gaia* DR2 photometry and adding constraints from the *Gaia* parallaxes used as distances prior. The exquisite photometry and the ability to effeciently remove nonmember stars from the analysis allow for extremely good statistical precision on the estimated parameters, and in most cases the uncertainty on the absolute age of clusters is now dominated by uncertainties on stellar evolution models themselves.

A growing number of studies combine different types of data into a single analysis. Perren et al. [68] applied the Automated Stellar Cluster Analysis pipeline (ASteCA, [69]) to simultaneously estimate distance, reddening, total mass, age, and metallicity for sixteen clusters. A batch analysis of clusters was also performed by Monteiro and Dias [70], providing ages for 150 objects via isochrone fitting, and Dias et al. [71] extended the same approach to 1743 known clusters. A different approach was chosen by Cantat-Gaudin et al. [72], who trained an artificial neural network (ANN) to estimate age, reddening, and distance for clusters with *Gaia* photometry and parallaxes. The ANN processes the CMD as a 2D histogram and does not offer the same degree of statistical precision as a Bayesian tool such as BASE-9, but using real clusters as a training set allows the machine to account for the many effects that can hamper an isochrone-fitting procedure, such as the presence of unresolved binaries, blue stragglers, differential reddening, etc. They published an unprecedented catalogue of 1867 clusters with associated parameters. The same ANN was later applied to 664 clusters reported by Castro-Ginard et al. [73], producing a homogeneous catalogue of 2531 clusters. The machine-learning approach was also chosen by Kounkel et al. [74], who built the Auriga neural network [75] and provided ages and cluster parameters for the cluster sample of Cantat-Gaudin et al. [61] using *Gaia* and 2MASS photometry.

The youngest clusters from the Cantat-Gaudin et al. [72] sample were used by Castro-Ginard et al. [76] to investigate the spiral pattern of the Galactic disc. They determined that the different spiral arms exhibit different pattern speeds, favouring the idea that the arms are transient features rather than long-lived structures[3].

Another point revealed by the spatial distribution of young clusters is that the spiral arms appear fragmented (see Figure 3). The most prominent gap is seen in the Perseus arm. As demonstrated by Cantat-Gaudin et al. [83] and Castro-Ginard et al. [84], the lack of young clusters in this region is not due to an incompleteness of the cluster census and truly corresponds to an under-density of young stars. The gap is visible in the spatial distribution of a variety of young tracers (see the discussion is Section 5.1 of [72]) and CO clouds [85]. Tchernyshyov et al. [86] (relying on spectra of diffuse interstellar bands) and Baba et al. [87] (with a sample of *Gaia* DR1 Cepheids) proposed that the Perseus arm is in a disrupting state, while the local arm might be in expansion. Xu et al. [88] showed that the local arm extends into the third Galactic quadrant, further than previously thought (confirmed by [89], tracing OB stars with *Gaia* EDR3) and should not be considered a secondary spiral feature. Poggio et al. [89] also reported a large pitch angle for the Perseus arm, at odds with the Reid et al. [90] model but supporting the young cluster distribution. Figure 3 also shows a hint of the Cepheus spur revealed by Pantaleoni González et al. [91] with DR2 OB stars, extending from the local arm towards Perseus, and a tentative cluster counterpart to the Sagittarius spur, revealed by Kuhn et al. [92] with EDR3 data of young stellar objects.

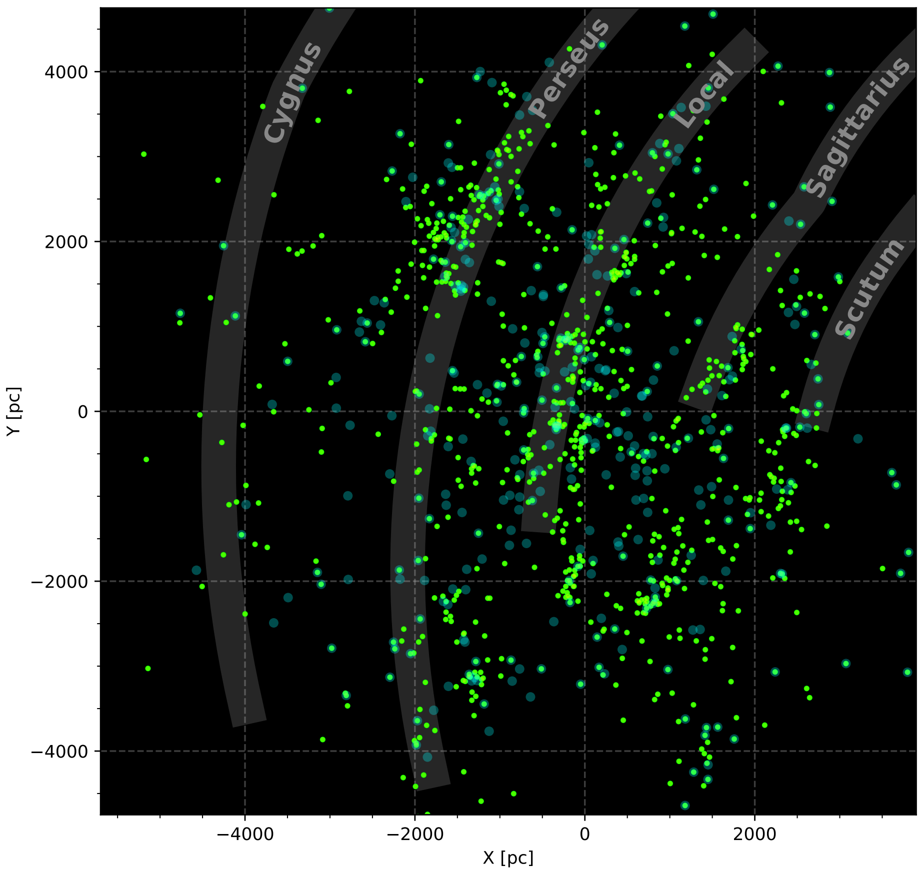

Figure 3. Distribution of all clusters from Cantat-Gaudin et al. [72] and Castro-Ginard et al. [73] younger than 60 Myr (green) and between 60 and 100 Myr (blue), projected on the Galactic plane. The trace of the spiral arms is the model of Reid et al. [90], which was obtained with VLBI trigonometric parallaxes of high-mass star-forming regions. The Sun is located at (0,0).

The distance Z of clusters with respect to the Galactic midplane is shown in Figure 4 as a function of Galactocentric distance. The correlation between age and Z is clearly visible, with older clusters reaching high Z while young objects are all found within a few hundred parsecs of the plane. This figure also shows a dearth of old clusters in the inner disc, showing that clusters are more likely to be quickly disrupted by interactions with giant molecular clouds in these dense regions. The spatial distribution of clusters also follows the known flaring of the Galactic disc, with a larger scale height in the outer disc than in the inner disc.

It is interesting to remark that few clusters are known beyond 14 kpc from the Galactic centre, and that all of them are older than 500 Myr. At the extreme edge of the disc, Berkeley 29 and Saurer 1 were once believed to have originated from outside the Milky Way. Making use of EDR3 data, Gaia Collaboration et al. [93] showed that these clusters follow circular orbits typical of disc stars. The question of how many clusters are left to be discovered between 14 and 20 kpc from the Galactic centre remains open. None of the 664 new clusters recently found by Castro-Ginard et al. [73] with EDR3 data are located in that region.

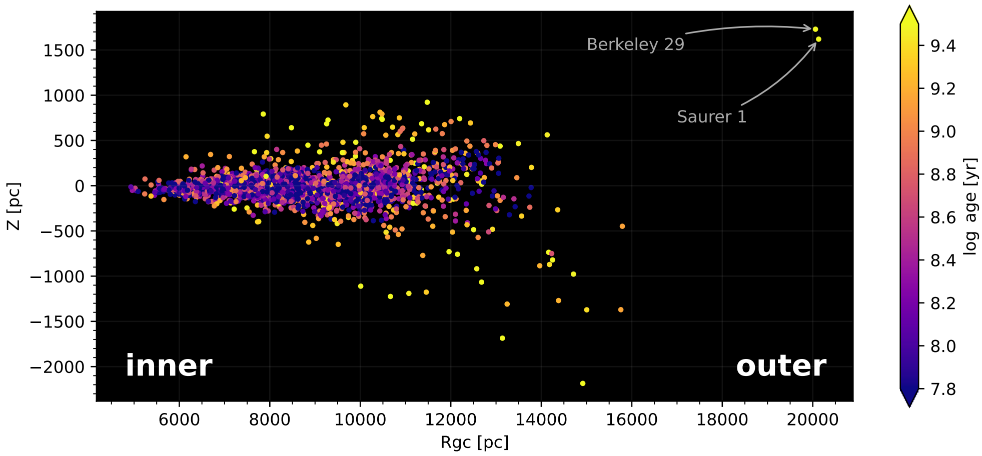

Figure 4. Distance above the Galactic plane (Z) against Galactocentric radius (Rgc) for all 2531 clusters with ages from Cantat-Gaudin et al. [72] and Castro-Ginard et al. [73], colour-coded by age. The change of scale height between the inner and outer disc is clearly visible. The two distant clusters Berkeley 29 and Saurer 1 are labelled.

2.1. *Discoveries of New Clusters*

The task of discovering new objects is somehow different from reidentifying known clusters, as one is practically looking for needles in a proverbial haystack of astrometric data. Although some authors have reported serendipitous discoveries of new clusters located in the same field of view as known objects [61,94–96], the majority of new clusters were identified through dedicated searches. In this endeavour, the main strength of the *Gaia* DR2 data is the high precision of the proper motions of *Gaia* DR2, allowing us to easily detect groups of stars that are spatially sparse, as long as they are kinematically coherent. Modern searches for star clusters largely benefit from the variety of clustering algorithms developed for data science and made available in libraries, such as the Python package `scikit-learn` [97], or density analysis, using tools such as wavelet decompositions (e.g., [98,99]). Although the majority of data mining is performed directly on the *Gaia* observables, some searches have been performed on transformed quantities such as the action-angle space (e.g., [100,101]). The many available approaches, combing schemes, and algorithms (density-based, centroid-based, etc.) make it possible to find new objects even in regions that have already been searched multiple times.

While searching the Galactic halo for faint Milky Way satellites in the *Gaia* DR1 data, Koposov et al. [102] discovered two massive clusters in the disc. Castro-Ginard et al. [103] applied the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm to the *Gaia* DR1 data, identifying 31 new objects which were confirmed with DR2 data. Cantat-Gaudin et al. [83] investigated the Perseus arm in the direction of the Galactic anticentre in order to understand whether the apparent lack of known clusters was due to an incomplete census. Identifying proper motion over-densities with a Gaussian Mixture Model, they reported 41 new identified clusters around and behind the gap, confirming that this region is effectively devoid of young clusters. An investigation of the same region by Castro-Ginard et al. [84] using DBSCAN revealed 53 more objects, again located around the gap rather than inside.

Other automated searches have reported large numbers of previously unknown objects. He et al. [104] found 74 clusters with a nearest-neighbours approach. Liu and Pang [19] applied a friend-of-friend cluster finder method to propose 76 new candidates. Sim et al. [105] flagged 207 new objects, most of them closer than 1 kpc, through a visual inspection of proper motion diagrams. Ferreira et al. [106] detected 25 distant objects with a combination of spatial and photometric filters, inspecting the resulting change of contrast in proper motion space. Hunt and Reffert [107] applied DBSCAN, HDBSCAN, and Gaussian Mixture Models (GMMs) to the DR2 data and identified 41 new cluster candidates. They showed that HDBSCAN with a minimum cluster size of 10 stars is the most efficient at recovering known objects in the *Gaia* data but that it also produces the largest rate of false positives, which they mitigate by assessing the significance of each candidate cluster compared to the field density. On the other hand, GMMs are efficient at identifying members of known clusters but are an impractical approach when performing blind searches in catalogues as large as *Gaia* DR2.

The all-sky data-mining searches of Castro-Ginard et al. [108] in DR2 and Castro-Ginard et al. [73] in EDR3 respectively present 582 and 664 new objects using an implementation of DBSCAN in the parallel computation environment PyCOMPS on a supercomputer. Given the increasing volume of astronomical catalogues, it is expected that such Big-Data approaches to data processing will become increasingly common in this decade.

The sheer pace at which cluster discoveries are published nowadays sometimes makes it difficult to keep catalogues updated. Clusters presented as newly discovered might have already been reported, and cross-identification can be made difficult by the fact that not all authors share the individual list of stars they consider members of a given cluster.

At the extreme low end of what can be considered a star cluster, pairs of comoving stars have been identified in *Gaia* DR1 [109,110] and DR2 [16]. Although some of them are not conatal [111], their frequency relative to field stars is still an indication of the level of clustering and the virial state associated with star formation, as illustrated in Kamdar et al. [112], who computed the two-point correlation function in spatial and kinematic space for the DR2 stars with 6D phase space information within 1 kpc of the Sun.

2.2. Globular Clusters

Although globular clusters (GCs) are not the focus of this review, bulge GCs located at low Galactic latitudes can be detected in surveys of the Milky Way plane with the same methods as open clusters, as they represent spatial and kinematic over-densities. The inner Milky Way is a very crowded region in which clusters can be difficult to notice, but GCs present the double advantage of being very dense and having significantly different velocities from the field stars. In a systematic search of known clusters, Cantat-Gaudin et al. [61] remarked that BH 140 and FSR 1758, classified until then as open clusters, are in fact GCs. Probing the inner disc and the Galactic bulge is, however, difficult at optical wavelengths, and most recent discoveries of bulge GCs have required the use of near-infrared photometry. For instance, Ryu and Lee [113] reported two new GCs found with WISE data [114], and five new GCs were reported by Camargo [115] with a combination of 2MASS [59] and *Gaia* data. FSR 1758 was further characterised by Barbá et al. [116] using near-IR data from the DECaPS survey [117].

The VISTA Variables in the Via Lactea (VVV, [118]) survey produces deep near-IR photometry which has been used to identify a number of GC candidates. The combination of this photometry with *Gaia* proper motion has led to a number of unprecedented new discoveries since the 19th century [119–131].

3. Young Clusters and Associations

Aggregates of young stars have historically been identified as groups of luminous O- and B-type stars and are commonly referred to as OB associations. Most of them are too sparse to be gravitationally bound, and for a long time they were considered to be the expanded remnants of (once dense) clusters. This picture has, however, recently been challenged by a number of observational studies made possible by *Gaia*, which allows us to reliably identify members of associations down to low masses, trace their spatial distribution (in three dimensions for those nearby), and investigate their internal kinematics. We refer the reader to the wonderful and thorough review of Wright [52] for an exhaustive list of known OB associations and our current knowledge of their properties.

In the context of the present review, we will focus on three main results brought about by *Gaia*: (a) OB associations are born extended and highly substructured and only exhibit slow expansion patterns. They are not the expanded remnants of dense clusters. (b) Coeval structures span large distances, reflecting the original size and morphology of their parent gas filament. (c) There exists a continuous distribution of sizes and densities between the structures once called associations and those called clusters, making the distinction arbitrary.

Using *Gaia* DR2 data, Kuhn et al. [132] and Melnik and Dambis [133] showed that most associations exhibit small but measurable levels of expansion. Ward and Kruijssen [134] and Ward et al. [135], however, demonstrated that the proper motions within each association also reveal many kinematic substructures and are not compatible with a model where most of the velocities trace radial expansion. They also showed that in associations that are spatially very elongated, the velocity distributions are not highly anisotropic, which means that these elongated morphologies were imprinted at birth. These observations are in agreement with models predicting that star-forming regions of low density can produce substructures close to virial equilibrium [136,136] but so far have not been reproduced by numerical simulations taking into account a full range of physical processes, such as stellar feedback. We refer the reader to Krumholz et al. [49] (Sections 3.4.2 and 3.5.2) and Wright [52] (Section 5.3) for discussions of the theoretical knowledge on the origin of such stellar aggregates.

3.1. Orion

The Orion complex, which still hosts ongoing star formation, is perhaps the most studied nearby stellar complex. Using a combination of *Gaia* DR2 and APOGEE data [137], Kounkel et al. [138] investigated the 6D structure of the region (3D spatial and 3D velocity) and identified distinct kinematic groups. All of them exhibit further kinematic substructures, but one in particular (λ Ori) shows strong signs of radial expansion, attributed to a supernova explosion.

Subsequent DR2 studies of this complex were performed by Kos et al. [139], Großschedl et al. [140], Jerabkova et al. [141], Zari et al. [142], Swiggum et al. [143], and Kounkel et al. [144], all taking advantage of the possibility to follow the three-dimensional structures of individual stars and to map their velocities. The groups have ages ranging from 0 (in the currently star-forming Orion Nebula Cluster) to 21 Myr and are not distributed in space in age order.

3.2. Scorpius–Centaurus (Sco–Cen OB2)

This region has also been receiving considerable attention for a long time, and our understanding of its structure has been transformed by *Gaia*. This structure is the closest region of recent star formation to us and spans across several constellations in the sky due to its proximity.

The work of de Zeeuw et al. [145], based on Hipparcos data, identified 500 members separated in three components (Upper Scorpius, Upper Centaurus–Lupus, and Lower Centaurus–Crux). Due to *Gaia*'s ability to observe faint, low-mass members of associations, recent studies based on DR1 [146–148] and DR2 [149–154] now report up to 15,000 candidate members. The age of the Upper Scorpius grouping has been a topic of debate in the literature, with estimates based on high-mass stars suggesting $\sim$5 Myr, while low-mass stars suggest a smaller age of 10 Myr. Luhman and Esplin [155] performed an empirical comparison with β Pictoris (whose age was estimated using the Li depletion boundary technique) to show Upper Scorpius 10.5 to 12 Myr old and Upper Centaurus–Lupus and Lower Centaurus–Crux 18 to 21 Myr old.

Žerjal et al. [154] identified eight different kinematic subgroups in the complex. Wright and Mamajek [148] noted that the high degree of kinematic substructure indicates that *"Sco-Cen was likely born highly substructured, with multiple small-scale star formation events contributing to the overall OB association, and not as single, monolithic bursts of clustered star formation"*.

3.3. Vela–Puppis

This nearby region (300 to 500 pc) is perhaps the stellar complex for which the *Gaia* data have had the most transformative effect. The complex hosts a group of young stars

(∼10 Myr) historically known as Vela OB2. Several dense groups of slightly older stars were classified as open clusters (in particular NGC 2547, NGC 2451B, and Trumpler 10). Making use of ground-based spectroscopy, Jeffries et al. [156] have shown that the youngest stars are in fact distributed in at least two kinematic groups.

Due to *Gaia* DR2, the number of known members of this historically lesser-studied structure has increased from ∼200 [145] to over 14,000 [157–163]. Seven main coeval kinematic groups have been identified, each of them presenting a complex spatial substructure (shown in Figure 5). Similarly to the Orion complex, no age gradient is visible in the region. A subsequent EDR3 study by Wang et al. [164] proposes that the structure can be split into two main filaments and stretches over 400 pc to the Orion constellation. The coeval populations are spatially too extended (over 100 pc) to be the result of expansion.

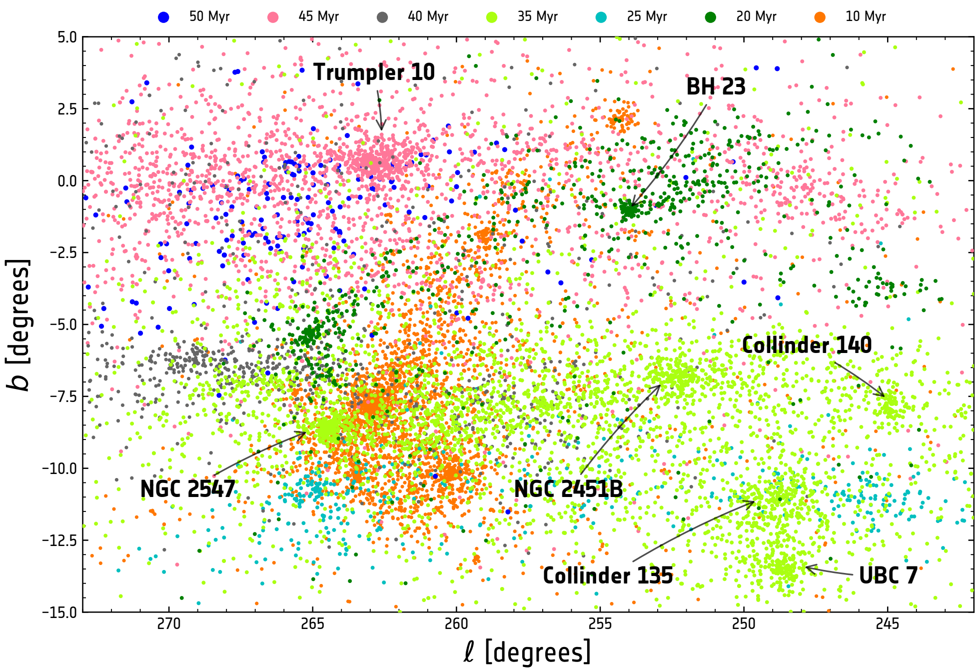

Figure 5. Distribution of young stars in the Vela–Puppis complex. The main groups known prior to *Gaia* are labelled. Adapted from Cantat-Gaudin et al. [161].

The peculiar ring-like structure of the youngest population [160] and the presence of a slightly older population at the centre of this ring led the authors of [161] to propose that the feedback from the massive stars of each generation triggered the formation of the following age group.

3.4. Other Gaia Studies of Young Aggregates

Other historically lesser-studied regions have been investigated with *Gaia* data. The Taurus region has been shown to exhibit a filamentary structure with no strong signs of expansion [165–167]. The quality of the proper motions allows us to split Chameleon 1 [168] and Cep OB3 [169] into two kinematic subgroups. Santos-Silva et al. [170] identified 28 different groups in the direction of the Canis Major OB1 association. Figure 6, reproduced from their study, illustrates the difficulty of cross-matching the increasingly complex results of clustering algorithms with existing catalogues.

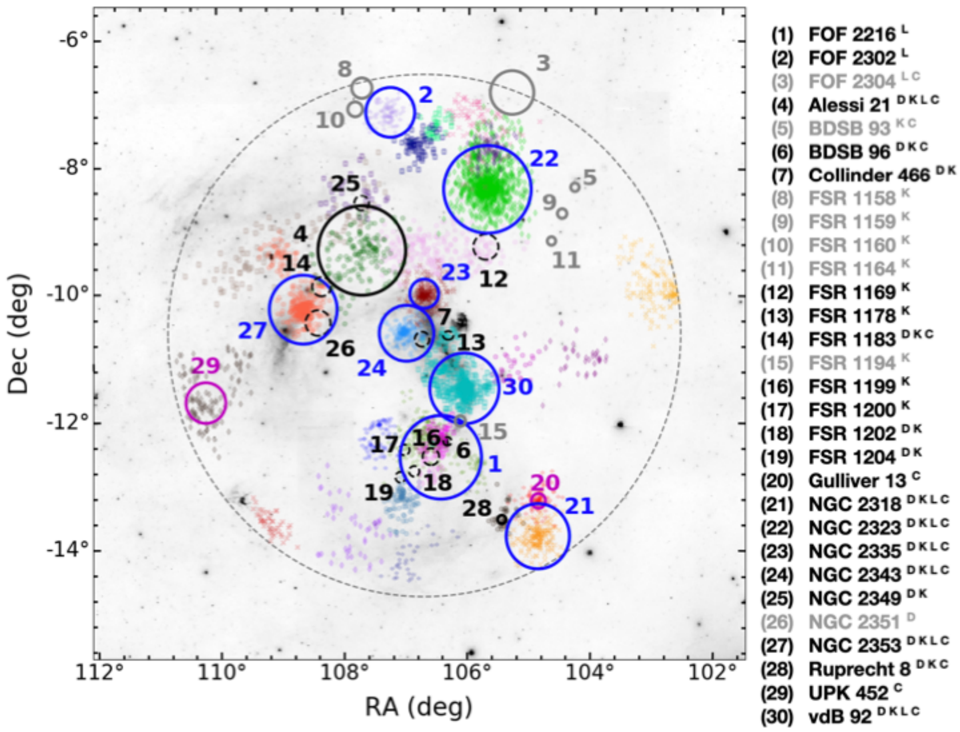

Figure 6. Stellar groups and clusters identified by Santos-Silva et al. [170] in Cep OB3. The labelled groupings are those that the authors reported to be listed in various catalogues in the literature. Reproduced from Santos-Silva et al. [170] with the permission of the authors.

A large number of studies have focused on individual objects which were poorly studied or sometimes unknown before *Gaia*, for instance, Cánovas et al. [171] and Grasser et al. [172] for ρ Oph; Manara et al. [173] and Galli et al. [174] for Lupus; Damiani et al. [175] for NGC 6530; Zuckerman [176] for the Argus association; Zhong et al. [177] for the Persei double cluster; Yalyalieva et al. [178] for Sco OB1; Berlanas et al. [179], Berlanas et al. [180], Quintana and Wright [181], and Orellana et al. [182] for Cyg OB2; Miret-Roig et al. [183] for IC 4665; Pang et al. [184] for NGC 2232 and LP 2439; Miret-Roig et al. [185] for β Pictoris; Galli et al. [186] for Chameleon 1 and 2; or Zuckerman et al. [187] and Galli et al. [188] for χ^1 Fornacis.

Some of these young objects are still surrounded by significant amounts of dust and gas, and several of the aforementioned studies combine *Gaia* with infrared photometry from Herschel [189] or WISE [114]. The *Gaia* parallaxes have been used to characterise the spatial structure of star-forming regions and molecular clouds by producing 3D maps of the dust content of the Milky Way disc (e.g., [190–193]). In particular, the 1-pc resolution dust map of the Solar neighbourhood ($\sim$400 pc) by Leike et al. [194] was used by Zucker et al. [195] to trace the three-dimensional morphologies and density profiles of nearby complexes and star-forming regions, including Chameleon, Ophiucus, Orion, Lupus, and Taurus.

Further constraints on the early conditions of star formation can be gained by investigating the population of dynamically ejected stars (called runaway stars) around star-forming regions, which can be accomplished by identifying stars with high *Gaia* proper motions originating from a particular region. Two mechanisms can expel those stars at velocities greater than 30 km s^{-1} (even reaching hundreds of km s^{-1} in [196]). In the binary-supernova scenario [197], the binary companion of a massive star that undergoes a supernova explosion can escape the cluster at a velocity close to its orbital velocity. In younger systems, dynamical ejection [198,199] can cause stars to be accelerated in the disruption of single–binary or binary–binary interactions within a dense cluster. McBride and Kounkel [200] identified 26 runaway stars around the Orion nebula. Schoettler et al. [201] showed that the number of ejected stars identified is consistent with an initially moderate amount of substructure and a subvirial dynamical state. Schoettler et al. [201] searched the region around NGC 2264. The number of runaway and walkaway stars they observed indicates a significant amount of initial substructure and densities reaching 10,000 $M_\odot$ pc^{-3}. Runaway stars have also been identified around NGC 3603, by Drew et al. [202] and Drew et al. [203], and around Westerlund 2, by Drew et al. [203] and Zeidler et al. [204] (shown in Figure 7).

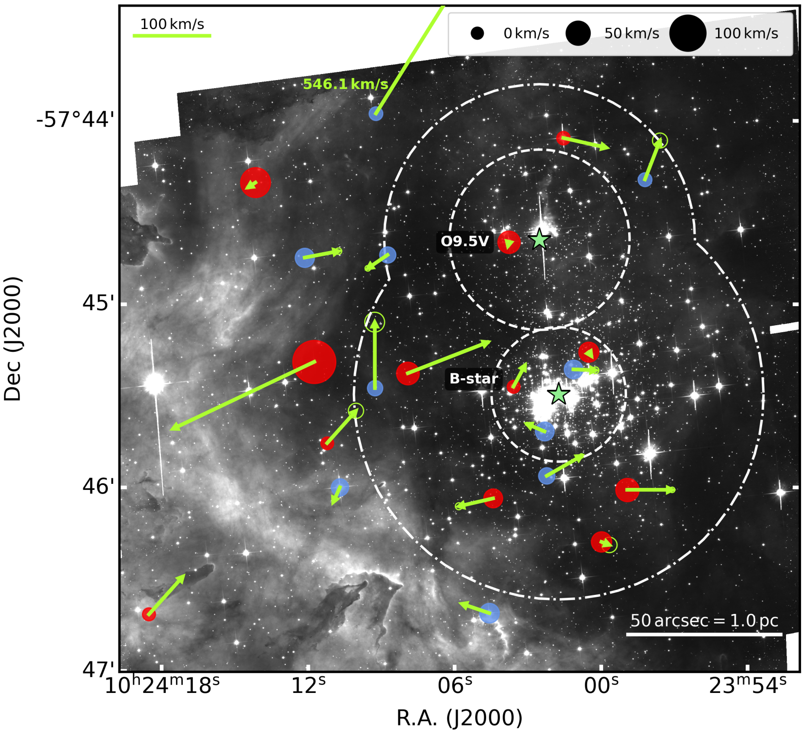

Figure 7. High-velocity stars moving away from Westerlund 2, identified from their proper motions and radial velocities. Reproduced from Zeidler et al. [204] with the permission of the authors and the AAS.

3.5. Strings, Pearls, and Other Extended Structures

Perhaps one of the most surprising results enabled by *Gaia* DR2 is that the variety of complex spatial distributions observed in young stellar aggregates persists at older ages.

Meingast et al. [98] reported a nearby kinematically cold structure spanning 400 pc and 120° across the sky. Dubbed the Pisces–Eridanus stream (or Meingast 1), this massive group [205] is 120 Myr old [206]. Kounkel and Covey [207] and Kounkel et al. [74] also reported on a large number of sparse and extended structures and further grouped those that appear coeval and show continuity in kinematic space into "strings"[4] spanning hundreds of parsecs. They show that young groups are more likely to be part of strings than older ones but that such superstructures can still be identified in stars with ages of several hundred Myrs.

Increasingly detailed maps of stellar structures in the Solar neighbourhood are being published [147,208–210]. The variety of spatial arrangements we now observe in stellar aggregates is reflected in the vocabulary used in recent publications, referring to groups as streams [98], strings [207], rings [160], snakes [164], and pearls [101], thereby blurring the traditional distinction made between clusters, associations, and moving groups.

4. Old Clusters

4.1. Dynamical Evolution

Despite being bound by gravity, star clusters slowly dissolve into the Galactic field over time scales of several hundred million years, due to two-body and three-body interactions accelerating stars to velocities higher than the cluster's escape velocity. When plunged in a Galactic potential, clusters preferentially lose stars through their Lagrange points L_1 and L_2 (e.g., [48]), which leads to the formation of two so-called tidal tails made up of stellar escapees. This mechanism is theoretically well understood (e.g., [211–214]) but has so far only been observed in globular clusters, which are denser, more massive, older, and often further from the Galactic plane than open clusters.

The spatial elongation of the Hyades cluster was first observed Reino et al. [215] using *Gaia* DR1 data. The full extent of its tidal tails was revealed by Lodieu et al. [216], Röser et al. [217], and Meingast and Alves [218] using *Gaia* DR2. Through complete dynamical modelling, Oh and Evans [219] estimated that the cluster (which is currently 680 Myr old) will become entirely unbound within the next 30 Myr. Jerabkova et al. [220], using EDR3 data, traced the Hyades tidal tails over a distance of 800 pc. Another cluster for which the tidal tails can be observed very clearly is Praesepe (NGC 2632), studied by Röser and Schilbach [221]. Figure 8 shows the extension of the tails over 200 pc.

Other studies have witnessed the ongoing dynamical disruption of older clusters, for instance, Yeh et al. [222] in Ruprecht 147, Carrera et al. [223] in M 67, Tang et al. [224] in Coma Berenices, Sharma et al. [225] in Czernik 3, Zhang et al. [226] in Blanco 1, Ye et al. [227] in IC 4756, or Bhattacharya et al. [228] in NGC 752. Piatti and Malhan [229] reported that IC 4665 and Collinder 350, with respective ages of $\sim$50 Myr and $\sim$600 Myr, are unrelated in origin but currently located within each other's tidal radii. They both present an elongated morphology, and their relative velocity is only $\sim$5 km s^{-1}, which means they could be driving each other's dynamical disruption.

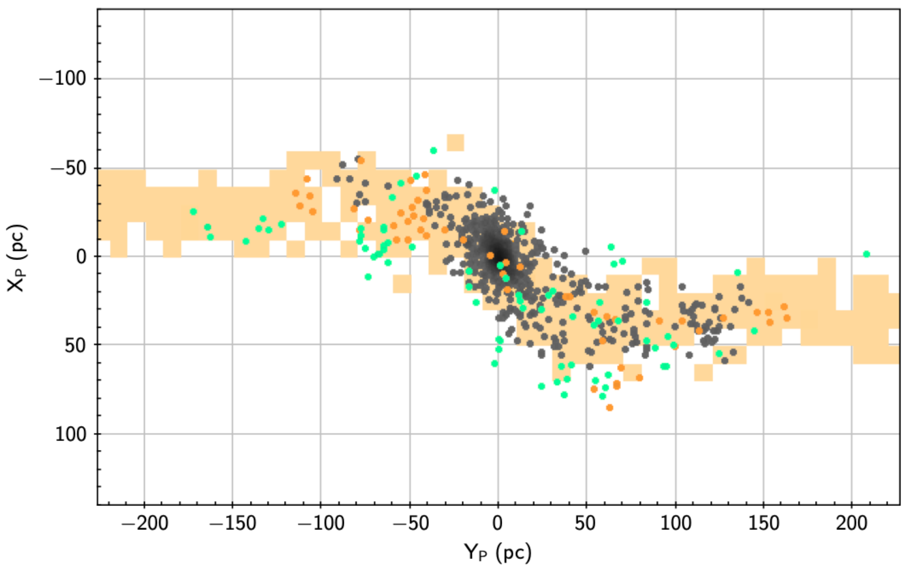

Figure 8. Members of the Praesepe cluster (NGC 2632) identified by Röser and Schilbach [221], displayed in Cartesian Galactic coordinates centred on the cluster. The grey, orange, and cyan points are secure, likely, and possible members of the cluster (respectively). The shaded background is the tidal tail model from Kharchenko et al. [230]. Credit: Röser and Schilbach [221], A&A, 627 (2019) A4, reproduced with permission © ESO.

Meingast et al. [231] investigated ten nearby clusters and showed that for most of them, more than half of the total cluster mass is located beyond the tidal radius. Comparable figures were obtained by Heyl et al. [232] for four young nearby clusters. With EDR3 data, Pang et al. [233] studied the 3D morphology of thirteen clusters within 500 pc, concluding that five of them appear as oblate spheroids, five as prolate spheroids, and three as triaxial ellipsoids. They also found that the semimajor axes tend to align with the Galactic midplane, a result confirmed by Hu et al. [234] with 265 clusters and Hu et al. [235] with 1256 clusters (both results based on DR2 membership lists). Using EDR3, Tarricq et al. [236] characterised

369 clusters older than 50 Myr and closer than 1.5 kpc, finding tidal tails in 71 of them. The ability offered by *Gaia* to reliably identify cluster members and reveal their full spatial extension opens the possibility to study them as dynamical objects interacting with their Galactic environment, rather than as isolated and idealised spheres of self-gravitating stars.

Further insight on the dynamical evolution of clusters, and possibly on the conditions of their formation as well, can be obtained by investigating the rotation of the cluster and the spin of its stars, especially if the *Gaia* data are supplemented with ground-based spectroscopy (see Section 5). For instance, isotropic (random) distributions of spin axes might indicate that the stars were formed in a turbulent environment, while aligned spin axes could be evidence that the stars inherited the angular momentum of their parent molecular cloud. Healy and McCullough [237] reported that no significant signs of an alignment are present in NGC 2516. Healy et al. [238] reached a similar conclusion for the Pleiades and Praesepe but found that their data for M 35 correspond to a moderate spin alignment. Kamann et al. [239] reported that NGC 6791 rotates, with a possible correlation with the spin axes of its stars, while NGC 6819 shows no sign of rotation.

4.2. Stellar Evolution

The colour–magnitude diagrams of clusters make it possible to identify stars in different phases of stellar evolution. One particular type of star which is much harder to identify outside of clusters ar blue straggler stars (BSSs). Blue straggler stars are bluer and brighter than the main sequence turnoff traced by the rest of the cluster members. Their origin is still unclear and could be due to mass transfer between closely interacting binaries or direct dynamical mergers. *The pre-Gaia reference for BSSs in clusters was the catalogue of Ahumada and Lapasset [240], who pointed out the difficulty to identify them in CMDs contaminated by field stars*. They have been extensively investigated in globular clusters, but studies of open cluster BSSs were rare until now. The BSS populations in Berkeley 17, NGC 7789, and Collinder 261 were studied by Bhattacharya et al. [241], Nine et al. [242], and Rain et al. [243], respectively. A subsequent study by Rain et al. [244] investigated BSSs in Trumpler 5, Trumpler 20, and NGC 2477, showing that they are not spatially more concentrated than high-mass red giant branch stars. Vaidya et al. [245] studied seven clusters hosting BSSs and found that in two of them (Berkeley 39 and NGC 6819) the BSSs are not mass-segregated. Their study and a subsequent paper by the same team investigating eleven clusters with BSSs [246] found that the radial distribution of BSSs within old open clusters correlates with their dynamical age in the same way as in young globular clusters [247]. Leiner and Geller [248] investigated sixteen old open clusters and found that standard population synthesis produces too few BSSs with respect to observations, suggesting that canonical mass-transfer prescriptions must be updated using a higher critical mass ratio and considering mechanisms such as nonconservative mass transfer.

Another aspect of stellar evolution that can be more easily investigated in clusters is extended main-sequence turnoffs (eMSTOs). This phenomenon, observed mostly in Magellanic Cloud clusters and characterised with Hubble Space Telescope photometry [249–251], was also shown to be present in Milky Way clusters such as NGC 2099, NGC 2360, or NGC 2818. The main competing scenarios to explain these observations were different rotation rates and intrinsic age spreads within clusters. The quality of the *Gaia* photometry as well as the ability to securely select cluster members to be observed from the ground has shown that the redder side of the eMSTO corresponds to fast rotators ($v \sin i > 150\,\mathrm{km\,s^{-1}}$), while bluer stars are slower rotators [252–254].

Star clusters are also relevant to white dwarf (WD) studies. The study of the initial–final mass relation (IFMR), which links the final mass of a WD to the initial mass of its progenitor, is also important to stellar evolution, and additional constraints can be obtained by studying WDs in clusters (e.g., [255–257]). Prišegen et al. [258] and Richer et al. [259] have built upon the *Gaia* DR2 WD catalogue of Gentile Fusillo et al. [260]. Interestingly, they did not identify WD precursors more massive than $6\,\mathrm{M}_\odot$, which is lower than expected from observed SN II rates. A possible explanation is that WDs with precursors of higher mass could be expelled from their clusters by dynamical events.

Several studies have been devoted to finding variable stars in clusters, for instance, Michalska [261] in NGC 2244, Joshi et al. [262] in NGC 1960, or Murphy et al. [263], who reported five young Delta Scuti stars in the Pleiades. Breuval et al. [264] and Zhou and Chen [265] identified 14 and 33 Cepheids, respectively, in open clusters, to which Medina et al. [266] added 138 candidates. These objects are especially valuable because they can be used to refine the Milky Way Leavitt law (the period–luminosity relation). Using the host cluster's mean parallax rather than the parallax of the Cepheid itself provides improved distances, as their *Gaia* astrometric reduction assumes the source does not change colour (an assumption valid for most stars but not for variables). Cepheids are primary distance indicators of choice for cosmological studies, and *Gaia* offers the first opportunity to calibrate their distances without the use of geometrical parallaxes from the Hubble Space Telescope [264]. A refined distance scale will help us understand, for instance, how and why measurements of the Hubble constant in the local universe differ from the ΛCDM cosmological model (the so-called Hubble tension, e.g., [267–269]).

5. Synergies with Other Instruments

5.1. Spectroscopy and Chemical Abundances

The *Gaia* spacecraft hosts an on-board spectrograph (RVS, [270]), which was able to deliver radial velocities for 7.2 million stars in DR2 and will provide more in the upcoming data releases. The RVS spectra can also be used to estimate chemical abundances, but due to its short spectral range ($\lambda \in [845, 872]$ nm), medium resolution ($R \sim$11,000), and small exposure times (about a minute per transit due to *Gaia*'s constant spinning motion), the depth and precision of its measurements cannot rival ground-based observations such as those of the *Gaia*-ESO Survey [271,272], LAMOST [273,274], GALAH [275], APOGEE [137], or the upcoming WEAVE [276] and 4MOST [277].

A recurrent theme in Milky Way astronomy is the question of the metallicity gradient of the Galactic disc. We know that stars in the inner disc present higher abundances of all chemical elements than stars in the outskirts, with a negative gradient which seems to flatten at a distance of 12 kpc from the Galactic centre. The shape of the gradient is the consequence of various mechanisms, such as the star formation rate at different Galactic radii, how efficiently the enriched gas mixes in the disc, and how often stars migrate during their lifetimes. A vast amount of literature exists on the topic, and clusters have long been tracers of choice for studies of the metallicity gradient because their distances and ages can be estimated with greater precision than the same for other tracers. This is still true in the *Gaia* era.

Donor et al. [34], Carrera et al. [65], Donor et al. [278], and Spina et al. [35] have exploited the ability to select cluster members and estimate their distance to revise the Galactic metallicity gradient. At present, two main issues persist. The first is that too few clusters are known in the outer disc to reliably trace the gradient and its change of slope. The second issue concerns studies of the age dependence of the gradient. In cluster studies, the impact of radial migration is made more complicated by the fact that clusters appear to survive longer when they migrate outward rather than inward. This idea was proposed by Anders et al. [279] and is also discussed in Cantat-Gaudin et al. [72] and Spina et al. [35]. The bias introduced by this mechanism is difficult to account for, as migration and destruction rates are not currently known in detail.

A remarkable result by Spina et al. [35] is that the observed metallicity gradient can be made significantly tighter by using the guiding radii of the cluster orbits rather than their current Galactocentric distances. Although unsurprising, this result can only be obtained through numerical integration of cluster orbits, which requires knowledge of their 6D phase space (3D position and 3D velocity). Studies of the present-day metallicity distribution are still hampered by the effect of radial migration, which changes the guiding radius of particles and cannot be accounted for by orbit integration. Chen and Zhao [280] estimated a migration rate of 1.5 kpc Gyr^{-1}, while Netopil et al. [281] (with APOGEE data) and Zhang et al. [282] (with LAMOST) found a rate of 1 kpc Gyr^{-1} for clusters younger than 2 Gyr and 0.5 kpc Gyr^{-1} for older objects.

Jackson et al. [283] and Jackson et al. [284] combined *Gaia* data with radial velocities from the *Gaia*-ESO Survey to obtain membership probabilities in 63 open clusters. Carrera et al. [285] also provided radial velocities for clusters that, until then, lacked those measurements.

Performing high-resolution spectroscopy, Casamiquela et al. [286] provided age–abundance relations for 25 elements in red clump stars. Such a study is impossible for field stars, as estimating the age of a field red clump star is very uncertain. The Stellar Population Astrophysics (SPA) project also investigates the abundance patterns of clusters, using *Gaia* as the basis of their target selection and observing recently discovered clusters [287–291].

The large number of newly reported objects and the ability to identify member stars even in their sparse outskirts is valuable to the upcoming spectroscopic surveys WEAVE and 4MOST. This new generation of multiobject spectrographs is able to observe hundreds of targets in a single pointing and to provide chemical and kinematic characterisation of the clusters and extended structures unravelled by *Gaia*.

5.2. Light Curves and Gyrochronology

A by-product of the high-precision photometry of exoplanet-hunting missions such as CoRoT [292], Kepler [293], K2 [294], the Transiting Exoplanet Survey Satellite (TESS, [295]), or the upcoming PLATO [296] are measurements of surface rotation periods for large numbers of stars. The study of how stellar rotation spins down with time has led to the emergence of gyrochronology, which allows us to use rotation period as a proxy for age. A great advantage of colour–period diagrams over CMDs is that they provide ages for main-sequence stars, while CMD techniques, such as isochrone fitting, rely on the presence of stars in key evolutionary phases or on well-defined MSTOs. This technique was successfully used well before *Gaia* [297–300], but combined with secure membership lists established with *Gaia* data, it can be used to estimate ages for sparse clusters, especially if a sufficient number of well-characterised clusters can be used as empirical calibrators.

A spectacular application of the method by Curtis et al. [206] shows that the Pisces–Eridanus stream, once suggested to be as old as 1 Gyr, is in fact coeval with the Pleiades (120 Myr). The old estimate was driven by one bright red star with uncertain membership status. The colour–rotation diagram established from TESS data includes dozens of stars which unmistakably indicate that the stream is much younger than 1 Gyr and coeval with the Pleiades (Figure 9).

Bouma et al. [301] provided TESS light curves for stars that *Gaia* data have shown to be probable members of clusters. Recent publications combining *Gaia* and rotation periods include Douglas et al. [302] for the Hyades and Pleiades, Curtis et al. [303] for NGC 6811, Gruner and Barnes [304] and Curtis et al. [305] for Ruprecht 147, and Fritzewski et al. [306] and Bouma et al. [307] for NGC 2516. Godoy-Rivera et al. [308] also showed that rotation periods obtained from ground-based observations can be as constraining as space-based observations if the *Gaia* astrometry is used to clean the sample from nonmembers.

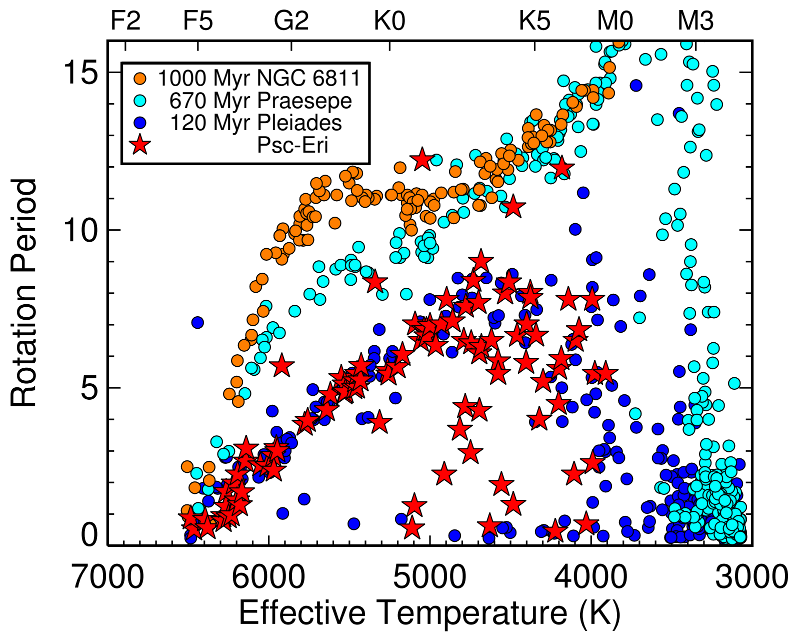

Figure 9. Relation between colour (effective temperature) and rotation period for stars in three well-studied clusters and for the Pisces–Eridanus structure. The Psc–Eri structure appears indistinguishable from the Pleiades, indicating that they are of very similar age. Reproduced from [206] with the permission of the authors and the AAS.

6. Tools and Methods

Given the large amount of data and the possibility to characterise large numbers of clusters at the same time, recent publications increasingly rely on automated procedures. A key aspect in many cluster studies is to determine which stars are members of a particular object. The unsupervised membership assignment code UPMASK [58] and its adaptation to astrometric data [56] have been used in a number of publications and were recently published as a Python package by Pera et al. [309]. The UPMASK approach was also adapted by Peña Ramírez et al. [310] to use both the *Gaia* astrometry and the VVV photometry as input. The code Clusterix [311] is an unsupervised procedure as well, comparing the proper motion distribution of the cluster to that of the field stars to identify cluster members. Yuan et al. [312] developed the unsupervised scheme StarGO, originally to reveal substructures in the Milky Way halo (see also [313]), based on self-organising maps. StarGO has since been successfully applied to a number of star clusters (e.g., [163,184,224]). Agarwal et al. [314] developed the ML-MOC tool, which also performs unsupervised membership assignment from astrometric data. Jaehnig et al. [95] applied the extreme deconvolution method of Bovy et al. [315] to determine members in 431 clusters. Gagné et al. [316] introduced the BANYAN Σ algorithm to identify members of young nearby stellar associations and clusters. Their code needs star coordinates and proper motions but can also integrate parallax and radial velocity information as well as photometric data. The task of identifying members of a given structure can also be performed with supervised learning if a preliminary list of secure members is available, as conducted, for instance, by Ratzenböck et al. [205] and Grasser et al. [172] using One-Class Support Vector Machines.

The ASteCA code [69] performs membership assignments but also estimates cluster parameters for stellar isochrones (metallicity, age, extinction, and distance) and returns uncertainties on those values. The Bayesian code BASE-9 von Hippel et al. [60] also performs automated cluster parameter estimates. Without fitting theoretical models, Cantat-Gaudin et al. [72] used machine learning to estimate cluster parameters for two thousand objects. Monteiro et al. [317] presented an isochrone fitting procedure that can also characterise thousands of clusters. Overall, papers presenting a basic characterisation of a single cluster (age, distance, morphology, etc.) are becoming increasingly rare, and recent publications either provide an analysis of a large sample of clusters or present deep studies of selected clusters. For the particular task of estimating distances to clusters, Olivares et al. [318] published the code Kalkayotl, which employs a Bayesian hierarchical model and takes into account the known small-scale correlations in the *Gaia* parallaxes (e.g., [319]).

The task of automating cluster studies would be very difficult without the tools allowing us to script queries to the *Gaia* archive. As a part of the Astropy project [320], the Astroquery tool Ginsburg et al. [321] now includes the `astroquery.gaia` package[5]. Similar queries can be made with the `pygacs` package[6]. These projects are extremely valuable to the community, as they provide efficient libraries for data query and analysis and allow reproducible science. Standardised methods enable more direct comparisons between studies. However, a diversity of methods is also desirable, as it allows for robust cross-checking of results, especially when they were obtained with black-box systems such as machine-learning procedures. Developing and maintaining a variety of methodological tools is a sign of a scientifically healthy community.

The high dimensionality of the input data can also make it difficult to present results in the traditional format of a two-column journal article. An increasing number of publications include animations as electronic material (e.g., the distribution of young Vela stars in [160])[7] or interactive visualisation, for instance, the material of Kounkel and Covey [207][8] or Zucker et al. [195][9], or the 3D, animated, interactive model of Orion by Swiggum et al. [143][10].

7. Conclusions and Future Prospects

The *Gaia* data (and especially DR2) have unlocked a deluge of new results related to many astronomical topics and transformed our ability to study star clusters and stellar structures in the Milky Way. The cluster census has been vastly improved, and dubious objects have been dusted off in the literature. Automated and homogeneous characterisations of hundreds or even thousands of clusters are increasingly common. Maps of the Galactic disc reveal groupings on a wide range of scales and densities, forcing us to revise the traditional distinctions between clusters and associations and providing important observational constraints on star formation. The nature of the *Gaia* data allows us to witness a broad variety of physical phenomena, from the internal kinematics of clusters and associations to their overall dispersion in the Milky Way disc. The *Gaia* catalogue provides a reliable target selection for follow-up studies, in particular spectroscopic observations, and will represent an anchor for many upcoming surveys in the decades to come.

Galactic astronomy is no longer a data-starved science, and this trend will continue in the upcoming decade. For instance, the ground-based Pan-STARRS DR1 catalogue [322] features 3 billion sources with photometry, a number to be increased in the upcoming Pan-STARRS DR2. The Legacy Survey of Space and Time [323], expected to begin operations in 2023, will provide astrometry and multiband photometry for 20 billion stars and a similar number of galaxies. A proposed near-infrared space-based astrometric mission [324–326] would be able to observe five times more sources than *Gaia*. Many lessons learned from handling *Gaia* data will therefore apply to future astronomical surveys.

The *Gaia* catalogue itself is still growing and improving. The DR3 data are scheduled to arrive in 2022 and will notably increase the number of stars with measured radial velocities from $\sim$7 to $\sim$20 million. *Gaia* DR4 will be based on 66 months of observations (compared to 34 in DR3, 22 in DR2, and 14 in DR1), thus providing parallaxes more precise than DR2 by a factor of about two and proper motions more precise by a factor of about five. In addition to this improved astrometry, DR4 will also contain the time series of astrometric, photometric, spectroscopic, and spectrophotometric measurements for every source. The scientific potential of such a gigantic dataset is immense, and the *Gaia* revolution is far from over.

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Conflicts of Interest: The author declares no conflicts of interest.

Notes

1 https://gea.esac.esa.int/archive/ (accessed on 15 December 2021).
2 See the introduction of Cantat-Gaudin and Anders [55] for a historical overview of cluster catalogues.
3 The question of whether the Milky Way spiral perturbations are global and stationary Lin and Shu [77] or local and transient Toomre [78] has been a matter of debate for decades (see reviews by [79–82]).
4 Some of the reported structures are so vast in coordinate and kinematic space that automated matches with other cluster catalogues fail. A number of clusters mentioned in Section 2.1 might be rediscoveries of groupings first reported by Kounkel and Covey [207] and Kounkel et al. [74] under the denomination *Theia*.
5 https://astroquery.readthedocs.io/en/latest/gaia/gaia.html (accessed on 15 December 2021).
6 https://pypi.org/project/pygacs/ (accessed on 15 December 2021).
7 https://www.aanda.org/articles/aa/olm/2019/01/aa34003-18/aa34003-18.html (accessed on 15 December 2021).
8 http://mkounkel.com/mw3d/ (accessed on 15 December 2021).
9 https://faun.rc.fas.harvard.edu/czucker/Paper_Figures/3D_Cloud_Topologies/gallery.html (accessed on 15 December 2021).
10 https://faun.rc.fas.harvard.edu/czucker/Paper_Figures/orion_movie.html (accessed on 15 December 2021).

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