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Advances in Binary Star Clusters and Cluster Groups in the Milky Way: Postprint

Authors: Shan Xingmei, Liu Guimei, Zhong Jing, Lin Qing

Date: 2024-07-03T00:00:00+00:00

Abstract

Open clusters are ideal laboratories for studying the theory of star formation and evolution; however, the formation mode of star clusters remains a fundamental yet unresolved problem. To deeply investigate the formation and evolution modes of star clusters, it is first necessary to observationally identify binary cluster or cluster group systems with physical associations. Research on the properties of binary clusters and cluster groups can provide important clues for a deeper understanding of hierarchical star formation modes; furthermore, binary clusters and cluster groups provide an excellent opportunity to study the formation and evolution modes of star clusters within the same molecular cloud, and help to understand the connection between clusters and their parent molecular clouds in terms of morphological and kinematic properties. Starting from sample selection and formation mechanisms of binary clusters and cluster groups, we briefly introduce the research history of binary clusters and cluster groups in the Milky Way, with emphasis on discussing the recent status of the field in the Gaia era.

Full Text

Preamble

Progress in Astronomy, Vol. 42, No. 2, June 2024

doi: 10.3969/j.issn.1000-8349.2024.02.01

Recent Advances in the Study of Binary Star Clusters and Star Cluster Groups in the Milky Way

SHAN Xing-mei¹, LIU Gui-mei^{2,3}, ZHONG Jing², LIN Qing¹

¹ Shanghai Astronomy Museum (Branch of Shanghai Science and Technology Museum), Shanghai 201306, China

² Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai

200030, China

³ University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

Open clusters are ideal laboratories for studying star formation and evolution theory, yet the formation mode of star clusters remains a fundamental and unresolved question. To investigate the formation and evolution patterns of star clusters, it is first necessary to observationally identify binary or multiple cluster systems with physical connections. Studying the properties of binary clusters and cluster groups provides crucial clues for understanding hierarchical star formation patterns. Moreover, binary clusters and cluster groups offer exceptional opportunities to examine the formation and evolution of star clusters born within the same molecular cloud, and to understand the connections between clusters and their parental clouds in terms of morphology and kinematics. This review begins with sample selection and formation mechanisms, briefly introduces the research history of binary clusters and cluster groups in the Milky Way, and focuses on recent developments in this field during the Gaia era.

Keywords: open cluster; binary cluster; Milky Way

1 Introduction

Open clusters in the Milky Way are gravitationally bound stellar systems typically containing dozens to thousands of member stars. With relatively weak gravitational binding, they are more loosely structured than globular clusters and have ages ranging from several million to hundreds of millions of years. Member stars of open clusters form nearly simultaneously within the same molecular cloud, sharing similar ages, distances, chemical compositions, and reddening values. Although open clusters in the Milky Way are clearly concentrated near the Galactic plane, and thousands have been discovered with likely many more remaining to be found, our understanding of their formation and evolution patterns remains limited.

During the collapse of giant molecular clouds, stars form in groups, but do star clusters also tend to form in pairs (binary clusters) or groups (multiple clusters or cluster groups)? If so, what physical factors are associated with this tendency? Previous studies of open clusters suggest that at least some form in binary or multiple systems, creating so-called primordial binary clusters or cluster groups. For example, Chupina and Vereshchagin [?] studied the star-forming region near the Orion Nebula in 2000 and found that the clusters Trapezium, NGC 1997, and NGC 1980, along with other neighboring clusters, share consistent proper motions, possibly constituting a related cluster group. Long-lived stable binary clusters or cluster groups are rare, with observed binary cluster ages seldom exceeding 100 Ma. Primordial binary clusters or cluster groups disperse into the Galactic disk within a short timescale [?, ?]. Research on binary clusters and cluster groups can help us better understand star cluster formation

and evolution processes, providing new insights into star and cluster formation models, dynamical evolution of clusters, and Galactic structure.

For binary clusters in the Milky Way, Subramaniam et al. [?] began searching for binary clusters as early as 1995. Based on Lynga's cluster catalog [?], they found that approximately 8% of open clusters might be binary clusters, similar to the fraction observed in the Magellanic Clouds. De la Fuente Marcos et al. [?] analyzed the WEBDA [?] and NCOVOCC [?] catalogs in 2009 to identify binary cluster candidates, concluding that at least 12% of open clusters in the solar vicinity are currently merging with other clusters through gravitational interactions. The release of Gaia data, providing vast amounts of astrometric data (positions, parallaxes, and proper motions) and multi-band photometry [?], has sparked widespread research interest in Milky Way open clusters. Zhong et al. [?] used Gaia DR2 data in 2019 to study the classic example of coeval binary clusters η and θ Persei (NGC 869 and NGC 884). This pair is located at a distance of approximately 2.2 ± 0.2 kpc, with an inter-cluster separation of 21 pc. The similar morphology of the two clusters in color-magnitude diagrams indicates they are at the same stellar evolutionary stage. The study also revealed an extended halo structure and an elongated filamentary substructure, suggesting that cluster formation patterns and histories may be more complex than previously expected. High-precision astrometric data facilitate the discovery of new clusters, while high-precision kinematic data enable deeper investigation of dynamical connections between binary and multiple clusters. Based on Gaia data, we anticipate finding more binary clusters and cluster groups in the Milky Way, which will enhance our understanding of cluster formation and evolution and deepen our knowledge of the structure and evolution of the Galactic disk. This review summarizes research progress on binary clusters and cluster groups in the Milky Way, with Section 2 discussing sample selection and origin of binary clusters, Section 3 introducing cluster group selection and related discussions, and Section 4 providing a summary and outlook.

2.1 Sample Selection

Prior to the Gaia data release, research on binary clusters and cluster groups in the Milky Way was limited, primarily due to the lack of high-precision astrometric data for in-depth investigation. De la Fuente Marcos et al. [?] first systematically proposed possible formation modes for binary clusters and provided a catalog of candidate binary clusters in the Milky Way in 2009. Inspired by extragalactic binary cluster studies, they set a distance criterion of less than 30 pc between clusters and identified 34 and 27 binary cluster pairs using WEBDA and NCOVOCC data, respectively. Following the work of de la Fuente Marcos et al. [?, ?], research on binary clusters and cluster groups in the Milky Way has continued to emerge. These studies often searched for binary clusters based on projected spatial information, but clusters with small angular separations are not necessarily physically associated. In most cases, they simply happen to lie along the same line of sight and can only be considered "optical cluster pairs."

Optical pairs are not physical binary clusters; although they share the same line-of-sight position, they lack common kinematic properties. Statistically, without three-dimensional velocity information for clusters, the probability of misidentifying optical pairs as genuine binary clusters is high.

Conrad et al. [?] first used six-dimensional phase-space information (positions, proper motions, parallaxes, and radial velocities) in 2017 to determine whether open clusters in the Milky Way exhibit pairing or grouping phenomena. Searching for binary clusters among 432 open clusters with complete 6D data, Figure 1 [Figure 1: see original paper] shows the distribution of separations and velocity differences between clusters. Panel (a) reveals two prominent peaks near 50 pc and 100 pc, which Conrad et al. interpreted as characteristic values for binary cluster formation, thus adopting a separation criterion of less than 100 pc. Based on typical internal velocity dispersions of open clusters of 3–5 km s⁻¹ [?, ?] and peak uncertainties in UVW data of 3–4 km s⁻¹ (with a maximum of 20 km s⁻¹), combined with panel (b), Conrad et al. argued that physically associated binary clusters should have velocity differences of less than 10 km s⁻¹. This selection yielded 14 binary cluster pairs, four cluster groups containing 3–5 member clusters, and one larger group structure with 15 member clusters. Although this work identified numerous binary clusters and cluster groups, the completeness and reliability of the member star samples used were still insufficient, and the lack of distance and kinematic information for many open clusters hindered accurate investigation of their physical properties.

The successive Gaia data releases have provided the foundation for discovering new clusters and verifying binary clusters. Based on the vast amount of high-precision astrometric and multi-band photometric data, researchers can thoroughly investigate the global properties and correlations of binary clusters in the Milky Way, particularly their kinematic relationships, thereby improving our understanding of star formation patterns. Gaia DR2 [?] provides precise astrometric data (positions, parallaxes, and proper motions) for approximately 1.3 billion stars and high-precision photometry in three bands, offering an extremely important data foundation for studying open clusters in the Milky Way. Gaia EDR3 [?] increased the data volume, releasing astrometric data for about 1.5 billion stars and providing quality indicators such as the Renormalized Unit Weight Error (RUWE) to filter out relatively imprecise data. Gaia DR3 [?] provides astrometric and multi-band photometric information for approximately 1.8 billion stars across the sky, with precision comparable to Gaia EDR3. For Gaia DR3, typical proper motion uncertainties range from 0.07 mas yr⁻¹ for $G \leq 17$ mag to 0.5 mas yr⁻¹ for $G = 20$ mag, while parallax uncertainties are 0.07 mas at $G \leq 17$ mag and 0.5 mas at $G = 20$ mag. Additionally, Gaia DR3 increased the number of targets with radial velocities measured by the Radial Velocity Spectrometer (RVS) from about 7 million in DR2 to over 33 million [?], and provided atmospheric parameters (Teff, log g, and [M/H]) for 470 million sources [?]. The median radial velocity precision is 1.3 km s⁻¹ at GRVS = 12 mag and 6.4 km s⁻¹ at GRVS = 14 mag [?]. Compared to Gaia DR2, the substantial increase in radial velocity measurements in DR3 is extremely helpful

for studying the dynamical evolution of open clusters in the Milky Way.

In 2019, Soubiran et al. [?] used Gaia DR2 data to obtain a sample of 406 high-quality open clusters and identified binary clusters based on inter-cluster distances and three-dimensional velocity differences. The distance distribution peaked at 150 pc, while the velocity difference peaked at 3 km s^{-1} . The low velocity difference peak occurs because the sample is dominated by young open cluster groups with very similar velocities. The separation between binary clusters should be related to and significantly smaller than the typical spacing between group members. Therefore, this work adopted selection criteria of inter-cluster distance differences less than 100 pc and velocity differences less than 5 km s^{-1} , yielding 21 binary cluster pairs. Casado [?] searched for binary clusters and cluster groups in the Galactic longitude range 240° – 271° using Gaia EDR3 data and the latest compiled open cluster catalogs [?, ?] in 2021. By restricting the quality indicator $\text{RUWE} < 1.4$ to select reliable sources [?], Casado identified 11 binary cluster pairs and 13 cluster groups through constraints on inter-cluster distances and velocity differences. Compared to previous studies, this work significantly increased the binary cluster sample, though the incompleteness of the analyzed sample remains insufficient to reliably determine the fraction of binary clusters and cluster groups in the Milky Way. Song et al. [?] identified 14 binary cluster pairs based on inter-cluster distances using Gaia DR2 data in 2022. In the most recent work, Qin et al. [?] systematically searched and studied 324 open clusters within 500 pc of the Sun using Gaia DR3 data in 2023, discovering 101 new open clusters. From this solar neighborhood sample, they reliably confirmed 15 binary cluster pairs and three cluster groups based on inter-cluster distances, velocity differences, and age differences, with 12 of the binary cluster pairs being reported for the first time.

As data precision has improved along with larger open cluster samples, the selection criteria for binary clusters have varied slightly. We have compiled and summarized the selection conditions and results from the aforementioned studies, presented in Table 1 .

2.2 Origin Discussion

Stars are generally believed to form in groups within molecular clouds [?, ?], and researchers have shown considerable interest in whether open cluster formation exhibits a similar tendency toward grouped formation. Although open clusters were initially studied primarily as isolated stellar systems, de la Fuente Marcos et al. [?] first systematically proposed possible formation modes for binary clusters and provided a catalog of candidate binary clusters in the Milky Way in 2009. De la Fuente Marcos et al. selected binary clusters for study through distance constraints. Notably, among these selected binary clusters, three pairs formed almost simultaneously, and the vast majority of clusters were younger than 25 Ma. In 2010, de la Fuente Marcos et al. [?] combined N-body simulation results to propose several possible formation modes for binary clusters and cluster groups: (1) **Coeval formation mode**: Binary clusters formed

within the same molecular cloud share very similar ages, chemical abundances, and common motion, representing primordial binary clusters. (2) **Sequential formation mode:** Supernova explosions from one forming cluster can cause neighboring molecular clouds to collapse, triggering the formation of companion clusters [?, ?]. This may result in relatively small age differences between the two clusters observationally, while metal pollution from supernova explosions may produce different metallicities. (3) **Capture formation mode:** Binary clusters formed through dynamical interactions after individual cluster formation. Tidally captured binary clusters must share common spatial velocities, but their ages and chemical compositions may differ substantially, meaning the two clusters have no common origin.

Subsequent analysis of discovered binary cluster candidates suggests that binary clusters are more likely to have formed simultaneously or sequentially. De la Fuente Marcos et al. [?] argued that binary clusters are highly unstable systems. N-body numerical simulations by Arnold et al. [?] in 2017 also demonstrated that primordial binary clusters are difficult to sustain, with dynamical disruption or merger timescales of several tens of millions of years. Furthermore, binary cluster formation during molecular cloud collapse is closely related to supervirial regions in the primordial structure of molecular clouds.

To better determine cluster membership and measure the physical properties of open clusters, Kovaleva et al. [?] identified Collinder 135 and UBC 7 as a binary cluster pair based on Gaia DR2 data in 2020. UBC 7 is located approximately 300 pc from the Sun [?, ?], near the well-known open cluster Collinder 135. Before the Gaia data release, stars belonging to UBC 7 were considered part of Collinder 135. Estimates of field star contamination probability reveal dozens of possible member stars distributed in surrounding extended structures, which may constitute a common extended halo of the two clusters or form filamentary features similar to those discovered by Beccari et al. [?] in 2020. Since it is difficult to define whether these surrounding stars are members or field stars, only central members belonging to the two clusters were selected to determine their kinematics. Based on color-magnitude diagrams, Kovaleva et al. concluded that Collinder 135 and UBC 7 have the same age and reddening, approximately 40 Ma, with a separation between centers of 24.2 ± 2.1 pc and a proper motion difference of 0.6 ± 0.1 mas yr⁻¹ (corresponding to a relative tangential velocity of 1.42 ± 0.15 km s⁻¹). Due to their similar positions, distances, ages, and kinematic information, Collinder 135 and UBC 7 are considered a binary cluster born from the same molecular cloud.

Many studies suggest that genuine primordial binary clusters should exhibit similar or overlapping distributions in color-magnitude diagrams and share common motion, similar to Collinder 135 and UBC 7. Another scenario involves non-primordial binary clusters, where two independent open clusters may coincidentally encounter each other in their orbital paths, with partially overlapping spatial distributions of member stars but different properties such as age. A typical example of this situation is the first “colliding” binary cluster system IC

4665 and Collinder 350 discovered in the Milky Way by Piatti and Malhan [?] in 2020.

IC 4665 and Collinder 350 are both located about 100 pc above the Galactic plane, approximately 330 pc from the Sun, with an age difference greater than 500 Ma and a velocity difference of about 5 km s^{-1} . The two clusters are separated by only about 36 pc in space, smaller than the sum of their individual radii [?]. Figure 2 [Figure 2: see original paper] shows a 3D view of IC 4665 and Collinder 350, revealing that both clusters have elongated shapes. The spatial velocity vectors indicate that IC 4665 and Collinder 350 are moving toward each other, suggesting these clusters may be in the process of capture and merger. The velocities (blue and red arrows) are calculated relative to the barycenter of the two clusters. Figure 2 illustrates the internal motions of the two open clusters, showing that stars on opposite sides of the clusters move in opposite directions. Although the number of stars considered is small, these trends may indicate that the clusters are in the process of disruption.

To investigate the physical origin of the two open clusters, Piatti et al. [?] calculated their orbits within the Galactic disk. By integrating their orbits backward in time using positional and velocity information, they found that the two clusters were spatially separated in the past but have approached each other today due to their respective motions. Collinder 350 was inferred to be moving about 5 km s^{-1} faster than IC 4665. Orbital analysis shows that 60 Ma ago, the distance between IC 4665 and Collinder 350 was greater than 500 pc, significantly larger than the sum of their physical radii. Therefore, IC 4665 and Collinder 350 are not a primordial binary cluster system but rather two independently born open clusters that have encountered each other through kinematic evolution. Since most primordial binary clusters originate from a common molecular cloud, their initial separation would not have been so large. The ongoing collision between IC 4665 and Collinder 350 differs from typical phenomena proposed by cluster formation theory, making these two clusters a unique laboratory for exploring various aspects of cluster formation and evolution.

As indicated above, member clusters in binary systems are typically young, with no binary clusters composed of older clusters discovered, suggesting that most binary clusters formed simultaneously within the same molecular cloud and have not yet had sufficient time to dynamically disrupt and disperse into the Galactic field star population. The three formation modes for binary clusters and cluster groups proposed by de la Fuente Marcos et al. [?] in 2009 suggest that “simultaneous formation” implies member clusters should be young with similar chemical compositions, and thus should appear very similar or overlapping in color-magnitude diagrams. For “non-simultaneous formation,” the possibility of binary cluster formation through tidal capture or resonant trapping remains uncertain. Tidally captured binary clusters should share common kinematic information but may have substantially different ages and chemical compositions and would tend to merge, resulting in significantly different color-magnitude diagrams for each cluster.

3 Star Cluster Groups

Star cluster groups consist of three or more clusters, with member clusters serving as the link between individual stars and the entire group. Therefore, cluster groups are optimal samples for studying star and cluster formation patterns, enhancing our understanding of clustered star formation and evolution in giant molecular clouds. The search criteria for cluster groups are similar to those for binary clusters, with identification based on inter-cluster distances and consistent kinematic information. Some cluster groups have been discovered during previous binary cluster searches. If cluster A and cluster B can each form a binary cluster with cluster C, then clusters A, B, and C are considered a cluster group. As data precision continues to improve, search methods for cluster groups have advanced, with increasing studies employing machine learning algorithms to find cluster groups over larger sky areas. Most studies suggest that open cluster groups form within the same giant molecular cloud, with the morphology of cluster groups reflecting the filamentary/turbulent structure of the primordial molecular cloud that formed the open clusters.

Previous binary cluster searches have reported discoveries of some cluster groups, such as the work of Conrad et al. [?], Casado [?], and Qin et al. [?] mentioned above. These studies all indicate that cluster groups likely originate from a common molecular cloud rather than through capture. Since most member clusters are relatively young with small age differences, the most probable explanation is that these clusters formed simultaneously within the same molecular cloud and have not yet had sufficient time to disrupt and disperse into the Galactic disk. Conrad et al. [?] proposed a larger cluster group containing 15 member clusters in 2017, with an age distribution ranging from 4.7–61.7 Ma, comparable to the timescale of sequential star formation events. Feedback activity from stars in initially formed clusters (such as supernova shocks) can trigger the formation of surrounding clusters. If the molecular cloud complex is sufficiently large, such triggered cluster formation events can occur sequentially over tens of millions of years. This result aligns with the formation mode proposed in [?] and is consistent with the scenario of open clusters forming in groups. In Casado's [?] 2021 sample, two cluster groups contained 8 and 9 member clusters, respectively. The large number of member clusters also suggests that most cluster groups are primordial, as the probability of gravitationally capturing more than two clusters is extremely low.

The study of cluster groups is incomplete without discussing Vela OB2. In recent years, research on cluster groups in the Vela OB2 region has continuously emerged, expanding the sample of cluster groups and providing new perspectives on the scale of clustered star formation. Beccari et al. [?] used Gaia DR2 data and the DBSCAN clustering method to search for cluster groups in the Vela OB2 region in 2018, identifying six clusters through clustering in different parameter spaces. Figure 3 [Figure 3: see original paper] shows the parallax distribution and color-magnitude diagrams of the six clusters. Parallax calculations reveal that Cl 1-3 have similar distances (about 400 pc), while the other

three clusters are closer (330–360 pc). The color-magnitude diagrams show very clear main sequences for each cluster, with measured ages being very young. Cl 3 and Cl 6 have similar ages, while Cl 1, Cl 2, Cl 4, and Cl 5 share similar ages. Therefore, Cl 1, Cl 2, Cl 4, and Cl 5 may have formed simultaneously about 10 Ma ago, while Cl 3 (NGC 2547) and the newly discovered Cl 6 may have formed together 30–35 Ma ago. Further analysis of each cluster's radial velocity and proper motion data indicates that all clusters move along nearly parallel trajectories from southwest to northeast. However, based on existing data, it remains uncertain whether all members of the entire cluster group originated from the same region 10–30 Ma ago, requiring more detailed kinematic information to reconstruct the star formation history of this region.

Beccari et al. [?] revisited the Vela OB2 region using Gaia DR2 data in 2020, expanding the sky area to a radius of 40° centered on Collinder 135. This study performed three rounds of clustering using DBSCAN in different parameter spaces, revealing two components of different ages: one group of four clusters with ages around 15 Ma, and another group of ten clusters with ages around 35 Ma, as shown in Figure 4 [Figure 4: see original paper]. A new cluster was discovered and named BBJ1, located at about 347 pc with an age of approximately 30 Ma, similar to NGC 2547. BBJ1 is about 259 pc from NGC 2547 and about 158 pc from Collinder 135.

As shown in Figure 4, the relatively young group of cluster groups (see panel c) is distributed in projection space within $257^\circ < l < 270^\circ$ and $-15^\circ < b < -5^\circ$, while the other group (see panel f) shows a filamentary stellar structure about 260 pc long in projection. This structure became fully apparent only with the expansion of the study area and the discovery of BBJ1. Figure 5 [Figure 5: see original paper] shows the 3D spatial distribution of the 35 Ma cluster group, with the blue line indicating the main filamentary structure of the group, located at distances of 320–420 pc from the Sun. Since the cluster group is young overall, it cannot be explained by mechanisms involving the formation of stellar tidal tails/streams around older clusters [?, ?]. Tidal tail structures are regulated by internal cluster dynamics, with member stars escaping due to two-body relaxation [?] or external influences from the Galactic gravitational field accelerating cluster disruption [?]. Both mechanisms lead to tidal tail formation on very large timescales. However, the cluster group proposed in this work is a young structure of 35 Ma extending 260 pc, which is too short a timescale to form such a long tidal tail. This large-scale structure witnesses the instantaneous star formation in complex filamentary molecular clouds 35 Ma ago, similar to ALMA observations [?, ?]. This structure is called a relic stellar filament. This study and young stellar samples discovered in Orion both indicate that these cluster components retain their primordial filamentary distribution structure from formation, consistent with the conclusions of Cantat-Gaudin et al. [?, ?] in 2019.

Tian [?] discovered a young snake-like structure (Snake) in the Vela OB2 region using Gaia DR2 data and the Friend-of-Friend (FOF) machine learning cluster-

ing method in 2020. Members of this structure were identified based on spatial proximity and overlap/continuity in velocity space, as shown in Figure 6 [Figure 6: see original paper]. The snake-like structure consists of an extended “tail” and two dissolving clusters as cores, clearly distinguishable in 6D phase space. The snake-like structure includes thousands of member stars, with an average distance of about 310 pc and a total mass greater than 2,000 M_{\odot} . Since the age of the snake-like structure is only about 30–40 Ma, it cannot be explained by classical tidal tail formation theory, similar to the conclusion of Beccari et al. [?] in 2020. The snake-like structure shares similar 5D phase-space characteristics and age with the filamentary stellar structure proposed by Beccari et al. [?]. Although the snake-like structure may be expanding, its similar 5D phase-space characteristics and age suggest it likely formed in the same environment as the filamentary stellar structure studied by Beccari et al. [?] in 2020. If the correlation is confirmed, the snake-like structure could expand the scope of cluster groups in the Vela OB2 region by about a factor of two, which is important for understanding the formation and evolution history of clusters in this region.

Wang et al. [?] further expanded the sky area in 2022 to study the snake-like structure and its relationship with surrounding structures, aiming to reveal the completeness of the snake-like structure. As shown in Figure 7 [Figure 7: see original paper], using the FOF algorithm to cluster data yielded a large structure containing nearly 1.2×10^4 member stars, including the snake-like structure studied by Tian [?] in 2020 (part 1) and the cluster group studied by Beccari et al. [?] in 2020 (part 2). By combining radial velocities and metallicities from multiple spectroscopic databases to study the comprehensive properties of this structure, the results indicate that these two parts likely originated from the same giant molecular cloud, as they are spatially contiguous, share ages of 30–40 Ma, and have consistent metallicities. This enormous structure likely originated from a primordially hierarchical distribution, born in several regions within filamentary structures inside a giant molecular cloud, with each region having its own distinct formation history.

With the release of Gaia EDR3 data, Pang et al. [?] proposed an alternative hypothesis for the formation mode of cluster groups in the Vela OB2 region in 2021, suggesting that the Vela OB2 cluster groups originated from continuous star formation processes. Using the StarGO machine learning algorithm based on neural networks [?], Pang et al. studied cluster groups in the Vela OB2 region, discovering five new open clusters (named Huluwa 1–5) and the known binary cluster Collinder 135 and UBC 7. Figure 8 [Figure 8: see original paper] shows the 2D distribution of cluster member stars overlaid on IRIS images [?]. The ages of Huluwa 1–3 are about 10–22 Ma, while Huluwa 4–5 have ages of 7–20 Ma. Huluwa 1 was found to consist of two components, Huluwa 1A and Huluwa 1B. Although Huluwa 1A and Huluwa 1B are relatively diffuse, their kinematic information suggests they may still be a coeval binary cluster. Studying the overall formation process revealed that stellar feedback from Huluwa 1–3 during their evolution triggered turbulence that induced the formation of the younger generation of clusters Huluwa 4–5 (7–20 Ma). Subsequent supernova explosions

within Vela IRAS rapidly expelled the remaining gas from the clusters, halting continued star formation in Huluwa 4-5. Based on the velocity dispersion of Vela OB2, both Vela OB2 and the Huluwa 1-5 clusters are supervirial and in a state of disruption. N-body simulations predict that Huluwa 1-5, the binary cluster Collinder 135, and UBC 7 in Vela OB2 will continue to expand and eventually disrupt within the next 100 Ma.

Pang et al. [?] continued investigating the origins of cluster groups and correlations between different cluster groups in other regions in 2022. The results showed that different cluster groups with common motion may be due to coincidental orbital alignment caused by the Galactic bar/spiral arms. Using the StarGO algorithm again, Pang et al. identified three comoving cluster groups in the Collinder 132-Gulliver 21 region: (1) a subgroup with an age of 25 Ma (ASCC 32, Collinder 132 gp1-4); (2) an intermediate-age subgroup with ages of 50-100 Ma (Collinder 132 gp5-6); and (3) the cluster Gulliver 21 with an age of 275 Ma. These clusters extend over 270 pc in 3D space, with a maximum age difference of about 250 Ma. The U-V velocity distribution of member stars is shown in Figure 9 [Figure 9: see original paper], displaying parallel diagonal patterns with similar slopes. The elongated distribution in velocity is robust, as the velocity extension (less than 30 km s^{-1}) far exceeds observational errors (see lower left corner of panel b) and radial velocity dispersion. This elongated structure in U-V space is unique compared to clusters or cluster groups near the Sun, reflecting the comoving state of different subgroups. Known classical cluster groups form a horizontal branch/arc with constant velocity in U-V space, implying angular momentum conservation along the vertical direction, which is the expected kinematic feature in resonant scenarios. However, these three cluster groups exhibit “parallel inclined” features in U-V velocity space, similar to features observed in the moving group HR 1614 [?]. Galactic bar resonances [?, ?], resonant scattering by transient spiral arms [?], and stochastic spiral waves [?] can all alter stellar motions within the Galactic plane. The young Collinder 132 subgroups were born in giant molecular clouds on spiral arms, while Gulliver 21 and the intermediate-age subgroups may be influenced by these mechanisms and may have dispersed to the location of the Collinder 132 moving group. To confirm the formation and evolution of each subgroup, Pang et al. integrated the orbital motions of the eight clusters forward and backward in time, finding that the distances between the seven younger clusters and Gulliver 21 have reached a minimum at present and will rapidly increase in the near future. This suggests that the three subgroups may have coincidentally overlapped due to resonant effects, a phase that began about 20 Ma ago and can only persist for approximately 70 Ma.

Most studies indicate that young cluster groups formed simultaneously within the same giant molecular cloud, and the primordial molecular cloud that formed the open cluster groups had a filamentary structure [?, ?, ?, ?]. Cluster groups may also include subgroups with different ages and metallicities, and may exhibit elongated substructures in velocity distributions [?]. These studies provide important observational constraints on the dynamical origins of cluster groups.

The results of cluster groups from the aforementioned studies are summarized in Table 1.

4 Summary and Outlook

To date, there is no clear definition for binary clusters and cluster groups. However, regardless of formation mechanism, close proximity between member clusters is the primary criterion. Most studies suggest that binary clusters formed together within the same molecular cloud and therefore share similar ages, chemical abundances, and consistent motion, also known as primordial binary clusters. Binary clusters identified in previous studies are mostly young, and numerical simulations indicate that the lifetimes of binary clusters range from several million to tens of millions of years. It is generally believed that only sufficiently young open clusters can form binary clusters or cluster groups, while older open clusters should be intrinsically isolated because gravitational interactions between open clusters in primordial molecular clouds are very weak, making the probability of maintaining long-term stability through gravitational binding extremely low. Primordial binary cluster systems are also very unstable, merging or disrupting and dispersing into the Galactic disk within a short time. The lifetime of a binary cluster depends on their mutual separation, tidal forces, and to a lesser extent, encounters with giant molecular clouds. The physical origin of non-primordial binary clusters is more complex, with two general modes [?]: sequential formation, where binary clusters should have small age differences and different metallicities; and capture formation, where binary clusters may have different ages and chemical compositions but typically share consistent velocities.

The origin of cluster groups is similar to that of binary clusters. Most cluster groups discovered in recent years are believed to have formed within the same giant molecular cloud, reflecting the filamentary/turbulent structure of the primordial molecular cloud that formed the open clusters. Whether primordial cluster groups or those assembled through coincidental orbital overlap, both ultimately tend to disrupt.

Although current Gaia data are unprecedentedly precise, the lack of sufficient kinematic information makes it difficult to study the kinematic structure of identified cluster groups in detail. It is worth noting that the future Gaia DR4 release will represent a major advancement over Gaia DR3. Based on 66 months of observations, Gaia DR4 will contain an unprecedented quantity, quality, and variety of astrophysical data, particularly high-precision kinematic data, including nearly five times more stellar radial velocity samples and proper motion precision improved by nearly a factor of three. Combined with spectroscopic survey data such as LAMOST, this will enable deeper investigation of the connections between binary clusters and cluster groups in the Milky Way, facilitating a better understanding of star formation patterns and the formation and evolution of the Milky Way.

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