# Observational evidence of instability phenomena related to open star clusters based on Gaia data

D. A. Kovaleva *

Institute of Astronomy, Russian Acad. Sci., Moscow, 48 Pyatnitskaya st., Russia

**Abstract**

The vast amount of high-quality astrometric and photometric data from Gaia space mission opened new prospects in the investigation of the population of galactic star clusters. In particular, a number of observational evidence have emerged in relation to the phenomena of instability that previously were mainly predicted by dynamical simulations. These are signs of former violent relaxation, ongoing tidal disruption, interaction between the clusters and results of disruption of the clusters. We discuss methods of discovery of such evidence along with some interesting examples.

***Keywords:*** *open star clusters, Gaia, tidal tails, disruption of star clusters*

## 1. Introduction

The importance of process of disruption of stellar systems in the evolution of Galaxy was stressed by V. A. Ambartsumyan in his pioneering analytical works on dynamical evolution of stellar systems / statistical mechanics (Ambartsumian, 1955, 1985). In these papers, starting from at least 1938, he suggested reliable estimates for the lifetime of open star clusters and a description of the process of their disruption.

Afterwards, especially with raise of N-body modelling, different aspects of dynamical evolution of open star clusters have been explored since 1970s (e.g., Aarseth et al., 1974, Tutukov, 1978). Let us provide a few examples to illustrate the problems explored. In the paper by Moyano Loyola & Hurley (2013) authors quantitatively analyze the mechanisms that produced the cluster escapers, such as evaporation through weak two-body encounters, energetic close encounters, or stellar evolution events. Chumak & Rastorguev (2006) have numerically simulated the formation, structure, and dynamical evolution of the population of stars that escaped from open clusters via tidal tails. Shukirgaliyev et al. (2017, 2019) explored the open cluster survivability after instantaneous gas expulsion, in the process of violent relaxation.

However, though basically the scheme of "Birth, Evolution and Death" (Kroupa, 2001) of star clusters seemed to be understood by the beginning of this century, lack of observational information prevented numerous models to lean on well defined boundary conditions. Only the approach based on broad statistics could provide some very general quantitative clues for the evolution of open clusters (Just et al., 2023, Piskunov et al., 2018). As for the fine details, in the era before Gaia the situation was as follows. Although models predicted open clusters to have extended low surface density features like tidal tails (Chumak et al., 2010, Ernst et al., 2011, Küpper et al., 2010), or halo (Danilov et al., 2014) which may serve as evidence of cluster dynamical evolution, observational signs were very modest (Röser et al., 2011) or nonexistent. The true extent and scale of these features could have not been assessed. The known massive stellar streams were mainly products of evolution of globular clusters (see, e.g., Koposov et al., 2010).

After the start of the Gaia space mission Gaia Collaboration et al. (2016), its data releases, especially DR2 (Gaia Collaboration et al., 2018) and EDR3 (Gaia Collaboration et al., 2021) became table-turners in many aspects of star cluster investigation. This involved drastic improvement in the selection of cluster membership, as well as development of methods involving the use of clustering algorithms to search for new clusters and related aggregates (see a review in Hunt & Reffert, 2021). These data also provided numerous chances to obtain and interpret signatures of processes of instability during the cluster evolution. For them, however, the methods of search and discovery should be specifically adjusted.

*dana@inasan.ru


doi: https://doi.org/10.52526/25792776-23.70.2-277

In this paper, we provide a review of the methods and some results (including ours) of search and discovery of low-surface-density extended stellar groups signifying evidence of processes of instability. We follow the natural course of events. Section 2 is dedicated to the remnants of the star formation process. Section 3 deals with search of the expended features in the vicinity of known clusters. Section 4 describes the approach of automatic blind search in the multiparameter space for the search of moving groups and low-mass stellar streams originating from disrupted open clusters. Section 5 summarizes the main ideas of this review.

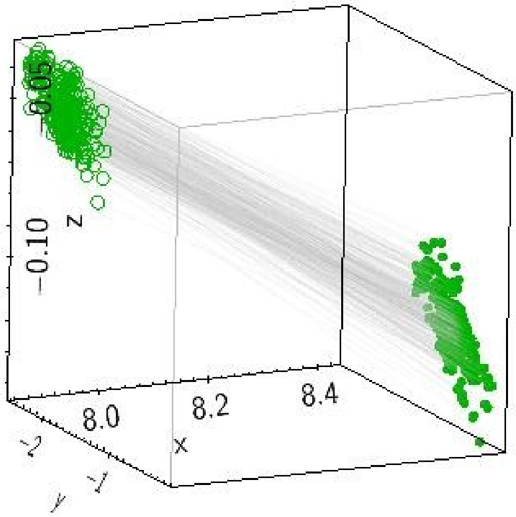


Figure 1. The location of the probable members of Group V in heliocentric carthesian galactic coordinates: present day – filled circles, 16 Myr backwards – empty circles. Thin grey lines connect positions of the same stars.

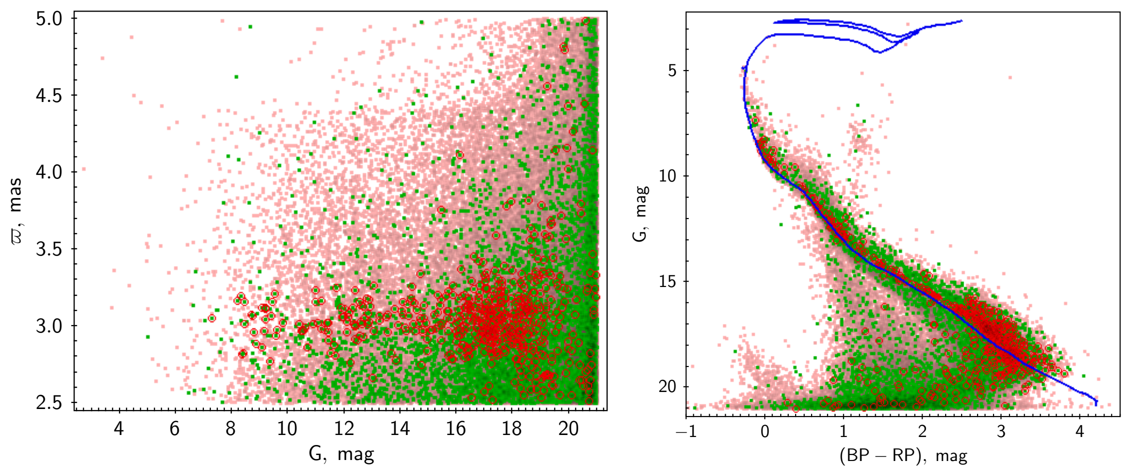


Figure 2. Probable members of [BBJ2018] 6 over parallax vs Gaia G magnitude (left panel) and in the color-magnitude diagram. Rose dots – background stars, green dots — probable stars of spatial vicinity of the group, open red circles – probable members of the stream. On the right panel, blue isochrone from Padova webserver CMD3.3 http://stev.oapd.inaf.it/cmd is for age of 50 Myr, similarly to age defined for Cr 135 and UBC 7 (Kovaleva et al., 2020).

## 2. Star formation remnants

A consensus converges to star formation taking place within molecular clouds containing embedded star clusters, filaments, fibers (e.g. André, 2017, André et al., 2010, Lada & Lada, 2003, Portegies Zwart et al.,


doi: https://doi.org/10.52526/25792776-23.70.2-277

2010). On the way from protocluster to open cluster, it should survive the violent relaxation (dynamical response to the expulsion of the residual star-forming gas). It is known that young star clusters tend to form groups, especially in the regions where star formation is going on (Casado, 2022, Conrad et al., 2017, Vaher et al., 2023). However, it was a newly discovered fact that one may detect a groupings of stars of extent up to hundreds of parsec, following past complex gaseous filamentary structures between the protoclusters and remaining after the gas expulsion from the region. The imprints of such structures have been discovered in star forming regions in Vela (Beccari et al., 2020) and in Orion (Jerabkova et al., 2019). We have independently identified similar group named Group V of extent of 60 to 70 pc hosting 150 to 300 members in Orion A (Vereshchagin et al., 2023) which most probably refers to the structure previously investigated by Jerabkova et al. (2019) and by Getman et al. (2019). In all described cases, the relict structures were noticed in the course of investigation kinematical and spatial structure of stellar population of a certain region, and probable members of these structures selected using statistical methods. The procedures used by Vereshchagin et al. (2023) involve a combination of approaches using suggestions on distribution of spatial velocities of probable members and a clustering algorithm DBSCAN applied to specially prepared dataset of probable pairs (for further details, see Sapozhnikov & Kovaleva, 2021). The backward integration of the orbits of the elements of the group in the gravitational potential of the Galaxy with *galpy* (Bovy, 2015) demonstrates its slow spread in the course of past 16 to 17 Myr which is the approximate age of the group (see Fig. 1). The calculation demonstrated at the figure lays on the dispersion of tangential velocities and neglects dispersion of radial velocities. The calculation for the groupings of members based on their mean 3D spacial velocities and their dispersion indicates that its extension approximately doubled during past 16 Myr.

## 3. Search in the vicinity of known clusters: tidal tails, halo

In the clusters that have survived violent relaxation, the period of two-body relaxation starts which tends to form their structure consisting of approximately spherical core and outskirts. These outskirts are primarily subjected to disintegration processes such as tidal disruption, disk crossing, differential rotation, providing runaway population. It may form tidal tails and an extended halo (also known as a corona) around the cluster. Such structures are sometimes discovered simply by selection of probable members of a cluster and making an analysis of their spatial and kinematical distribution. However, to discover their full extent, which, with Gaia data, happened to be much larger than we could expect, one may need to use a dynamic model of a structure, as it was done by Jerabkova et al. (2021). In this work, the tidal tails of Hyades were followed up to 800 pc, and their internal structural characteristics were revealed. Such a detailed investigations promises new fundamental results concerning testing of the theory of gravitation (Kroupa et al., 2022), dynamical evolution (Pflamm-Altenburg et al., 2023) and ages of clusters (Dinnbier et al., 2022).

Methods of recovery of expected but missing structures intrinsically related to the known clusters may use a search with clustering algorithms using known characteristics of the clusters. To discover the tidal tails of Coma Ber, Tang et al. (2019) applied cuts in proper motion to decrease the number of sources, and then used a method based on the self-organizing map to identify relevant structures. Using two methods, Clusterix and UPMASK, Carrera et al. (2019) discover an extended halo of NGC 2628 which radius, 50 pc, exceeds preliminary estimates more than twice. On the other hand, we discovered an extended halo of the binary cluster Cr 135 and UBC 7 (Kovaleva et al., 2020) by selection of cluster's members based on kinematical and photometrical probabilities.

## 4. Stellar streams and moving groups. Methods of discovery

The dissolution of star clusters may occur at different stages of their evolution. As a result of gas expulsion, the cluster may be destroyed and one or several moving groups may remain, in addition to runaway stars. Otherwise, the open cluster may be destroyed by the Galaxy disk passage, encounters giant molecular clouds, or just dissolved via the tidal tails to become a stellar stream (see, e.g., Tutukov et al., 2020). Unlike star clusters, the detection and classification of extended groups and streams where stars are not concentrated in space but just keep similar movement, in large surveys such as Gaia may be challenging. Usually it is successful for the main streams (Alvey et al., 2023, Ibata et al., 2023), or in dedicated searches in a limited multi-parameter region.


doi: https://doi.org/10.52526/25792776-23.70.2-277

So, a search in the Solar vicinity led to the discovery of a massive stellar stream originating, supposedly, from the destruction of an open cluster very similar to Pleiades independently by the two groups of authors (Ratzenböck et al., 2020, Röser & Schilbach, 2020). Fürnkranz et al. (2019) at first discovered overdensities in velocity space with wavelet decomposition method, applied filters, and then used DBSCAN to a primary selection of the data. They independently discovered the tidal tails of Coma Ber and a moving group, previously unknown and unrelated to Coma Ber. We used a DBSCAN applied to the preliminarily prepared catalog of stellar pairs to discover the full extent of these stellar structures (Sapozhnikov & Kovaleva, 2021).

Further analysis of the vicinity of a binary cluster Cr 135 and UBC 7 (Kovaleva et al., 2020) in Vela-Puppis region led us to the discovery of a stellar stream with kinematical properties and age very similar to those of Cr 135. This is why it reveals itself if one considers probabilities of membership to this cluster. This stream may be be connected to this structure was previously described as loosely spread cluster [BBJ2018] 6 by Beccari et al. (2018), however, its full extent is a way larger than it has been supposed initially. At Fig. 1 the probable members of the stream are compared with the background and with the stars of spatial vicinity in the Vela-Puppis region. One sees them clustering over parallax and along the same isochrone.

## 5. Conclusions

The results of Gaia mission have provided a valuable opportunity for researchers to discover and investigate observational evidence of processes of dynamical evolution of open clusters. These are remnants of processes of formation of stars, remnants of processes of their quick and slow disruption in the course of violent relaxation or two-body relaxation, encounters with the giant molecular clouds or passage through the disk of Galaxy. These structures may be discovered in dedicated systematic searches or in connection with the investigation of some clusters or other objects. Even solar vicinity revealed to be abundant with unknown previously moving groups, clusters with tidal tails, stellar streams. Many known star clusters at close investigation revealed their extended halos. The scale and extent of these stellar structures is usually much larger than was expected before. This provides us with the clues to fundamental problems of dynamical history and evolution of our Galaxy.

### Acknowledgements

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. The use of TOPCAT, an interactive graphical viewer and editor for tabular data (Taylor, 2005), is acknowledged.

## References

Aarseth S. J., Henon M., Wielen R., 1974, Astron. Astrophys. , 37, 183

Alvey J., Gerdes M., Weniger C., 2023, Mon. Not. R. Astron. Soc. , 525, 3662

Ambartsumian V. A., 1955, The Observatory, 75, 72

Ambartsumian V. A., 1985, in Goodman J., Hut P., eds, Vol. 113, Dynamics of Star Clusters. p. 521

André P., 2017, Comptes Rendus Geoscience, 349, 187

André P., et al., 2010, Astron. Astrophys. , 518, L102

Beccari G., Boffin H. M. J., Jerabkova T., Wright N. J., Kalari V. M., Carraro G., De Marchi G., de Wit W.-J., 2018, Mon. Not. R. Astron. Soc. , 481, L11

Beccari G., Boffin H. M. J., Jerabkova T., 2020, Mon. Not. R. Astron. Soc. , 491, 2205

Bovy J., 2015, Astrophys. J. Suppl. Ser. , 216, 29

Carrera R., et al., 2019, Astron. Astrophys. , 627, A119

Casado J., 2022, Universe, 8, 113

Chumak Y. O., Rastorguev A. S., 2006, Astronomy Letters, 32, 157

Chumak Y. O., Platais I., McLaughlin D. E., Rastorguev A. S., Chumak O. V., 2010, Mon. Not. R. Astron. Soc. , 402, 1841

Conrad C., et al., 2017, Astron. Astrophys. , 600, A106

Danilov V. M., Putkov S. I., Seleznev A. F., 2014, Astronomy Reports, 58, 906


doi: https://doi.org/10.52526/25792776-23.70.2-277

Dinnbier F., Kroupa P., Šubr L., Jeřábková T., 2022, Astrophys. J. , 925, 214

Ernst A., Just A., Berczik P., Olczak C., 2011, Astron. Astrophys. , 536, A64

Fürnkranz V., Meingast S., Alves J., 2019, Astron.~Astrophys, 624, L11

Gaia Collaboration et al., 2016, Astron. Astrophys. , 595, A1

Gaia Collaboration et al., 2018, Astron. Astrophys. , 616, A1

Gaia Collaboration et al., 2021, Astron. Astrophys. , 649, A1

Getman K. V., Feigelson E. D., Kuhn M. A., Garmire G. P., 2019, Mon. Not. R. Astron. Soc. , 487, 2977

Hunt E. L., Reffert S., 2021, Astron. Astrophys. , 646, A104

Ibata R., et al., 2023, arXiv e-prints, p. arXiv:2311.17202

Jerabkova T., Boffin H. M. J., Beccari G., Anderson R. I., 2019, Mon. Not. R. Astron. Soc. , 489, 4418

Jerabkova T., Boffin H. M. J., Beccari G., de Marchi G., de Bruijne J. H. J., Prusti T., 2021, Astron. Astrophys. , 647, A137

Just A., Piskunov A. E., Klos J. H., Kovaleva D. A., Polyachenko E. V., 2023, Astron. Astrophys. , 672, A187

Koposov S. E., Rix H.-W., Hogg D. W., 2010, Astrophys. J. , 712, 260

Kovaleva D. A., et al., 2020, Astron. Astrophys. , 642, L4

Kroupa P., 2001, in Montmerle T., André P., eds, Astronomical Society of the Pacific Conference Series Vol. 243, From Darkness to Light: Origin and Evolution of Young Stellar Clusters. p. 387 (`arXiv:astro-ph/0010405`), doi:10.48550/arXiv.astro-ph/0010405

Kroupa P., et al., 2022, Mon. Not. R. Astron. Soc. , 517, 3613

Küpper A. H. W., Kroupa P., Baumgardt H., Heggie D. C., 2010, Mon. Not. R. Astron. Soc. , 401, 105

Lada C. J., Lada E. A., 2003, Ann. Rev. Astron. Astrophys. , 41, 57

Moyano Loyola G. R. I., Hurley J. R., 2013, Mon. Not. R. Astron. Soc. , 434, 2509

Pflamm-Altenburg J., Kroupa P., Thies I., Jerabkova T., Beccari G., Prusti T., Boffin H. M. J., 2023, Astron. Astrophys. , 671, A88

Piskunov A. E., Just A., Kharchenko N. V., Berczik P., Scholz R. D., Reffert S., Yen S. X., 2018, Astron. Astrophys. , 614, A22

Portegies Zwart S. F., McMillan S. L. W., Gieles M., 2010, Ann. Rev. Astron. Astrophys. , 48, 431

Ratzenböck S., Meingast S., Alves J., Möller T., Bomze I., 2020, Astron. Astrophys. , 639, A64

Röser S., Schilbach E., 2020, Astron. Astrophys. , 638, A9

Röser S., Schilbach E., Piskunov A. E., Kharchenko N. V., Scholz R. D., 2011, Astron. Astrophys. , 531, A92

Sapozhnikov S., Kovaleva D., 2021, Open Astronomy, 30, 191

Shukirgaliyev B., Parmentier G., Berczik P., Just A., 2017, Astron. Astrophys. , 605, A119

Shukirgaliyev B., Parmentier G., Berczik P., Just A., 2019, Mon. Not. R. Astron. Soc. , 486, 1045

Tang S.-Y., et al., 2019, Astrophys.~J., 877, 12

Taylor M. B., 2005, in Shopbell P., Britton M., Ebert R., eds, Astronomical Society of the Pacific Conference Series Vol. 347, Astronomical Data Analysis Software and Systems XIV. p. 29

Tutukov A. V., 1978, Astron. Astrophys. , 70, 57

Tutukov A. V., Sizova M. D., Vereshchagin S. V., 2020, Astronomy Reports, 64, 827

Vaher E., Hobbs D., McMillan P., Prusti T., 2023, Astron. Astrophys. , 679, A105

Vereshchagin S., Chupina N., Lyzenko K., Kalinkin A., Kondratev N., Kovaleva D., Sapozhnikov S., 2023, Galaxies, 11, 99


doi: `https://doi.org/10.52526/25792776-23.70.2-277`