MODERN ASTRONOMY: FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

Study of clusters in the star forming region G174+2.5

T. Permyakova[1], G. Carraro[2], M. Kirsanova[3], D. Ladeyschikov[1], and A. Seleznev[1]

[1] Ural Federal University, 51 Lenin Str., Ekaterinburg, 620000 Russia
[2] Dipartimento di Fisica e Astronomia, Universitá di Padova, Vicolo Osservatorio 3, Padova, I-35122 Italy
[3] Institute of Astronomy, Russian Academy of Sciences, 48 Pyatnitskaya Str., Moscow, 119017 Russia

Abstract. We study the structure, photometric diagrams and kinematics of four embedded clusters (S235North-West, S235A-B-C, S235Central and S235East1+East2) in the star-forming region associated with the giant molecular cloud G174+2.5. This research uses photometric data from the GPS UKIDSS catalog and astrometric data from the Gaia DR3 catalog. We determine the center positions, radii, and interstellar extinction for clusters in the region. An extinction was determined in two ways — using the NICEST algorithm and the Q-method. The latter method gives a smaller scatter of the color indices on the extinction-corrected photometric diagrams. The membership probability of stars in the clusters, their masses and distances to clusters are also estimated. Additionally, we determine the average proper motions and study the kinematics of the clusters using data from the Gaia DR3 catalog. In all four regions, we estimate the mass of the gas component and the efficiency of star formation. Then, we apply the data obtained to evaluate the total energy of both the stellar and gas systems. It allows us to ascertain whether the clusters are gravitationally bound or not. The boundness of the systems depends on the size of the region where we estimate the mass of gas. If we take the mass of the entire cloud, all four cluster-gas systems appear to be gravitationally bound.

Keywords: open clusters and associations: general; dust, extinction; stars: formation, kinematics and dynamics

DOI: 10.26119/VAK2024.081

1 Introduction

The study of embedded star clusters allows us to improve our understanding of star formation process and of the early evolution of open star clusters after their formation. One of the closest star-forming regions is located in the giant molecular cloud G174+2.5 in the Perseus spiral arm; the distance to it, according to various estimates, ranges from 1.4 to 2.5 kpc. This work includes a study of the structure, photometric diagrams, kinematics and dynamics of four star clusters (S235North-West, S235A-B-C, S235Central and S235East1+East2). For these purposes, we use data from the UKIDSS GPS DR10PLUS (Lucas et al. 2008) and Gaia DR3 (Gaia Collaboration et al. 2023) catalogs and supply them with reddening values determined using the NICEST method (Lombardi 2009).

2 Study of clusters

We study the structure of clusters by the surface density maps and the radial density profiles built with the kernel density estimator method (KDE). Maps were plotted for different limiting magnitudes and kernel half-widths (see Fig. 1 as an example). The cluster centers were determined as the coordinates of local density maxima (2th and 3th columns of Table 1). The cluster radii (4th column of Table 1) were determined from the radial density profiles with the method proposed by Seleznev (2016).

Membership of stars in clusters was determined using the UPMASK package (Krone-Martins & Moitinho 2014) based on stellar magnitudes, color indices, and equatorial coordinates. Below, by clusters we will mean collections of stars with the membership probability greater than or equal to 0.7 (5th column of Table 1).

Table 1. Parameters of the studied clusters.

Name	RA (J2000.0) deg	Dec (J2000.0) deg	R arcmin	N $K \leq 15^m$	D kpc	$M_{\rm ph}$ $M_\odot$	$M_{\rm Kr}$ $M_\odot$	SFE
1	2	3	4	5	6	7	8	9
S235North-West	85.18981	35.91901	2.4	67	1.7	113	209	0.14
S235A-B-C	85.21402	35.68557	5.5	326	1.9	530	873	0.17
S235Central	85.27761	35.82445	1.3	35	2.2	56	91	0.04
S235East1+East2	85.37212	35.81896	3.2	75	1.7	95	156	0.07

Absorption in clusters was determined in two ways. The first one is the NICEST method. That one blurs greatly the sequences in the photometric diagrams. So, we cannot use such diagrams to determine distances to clusters. The second method is the Q-method. The Q value is a combination of the star's color indices and color

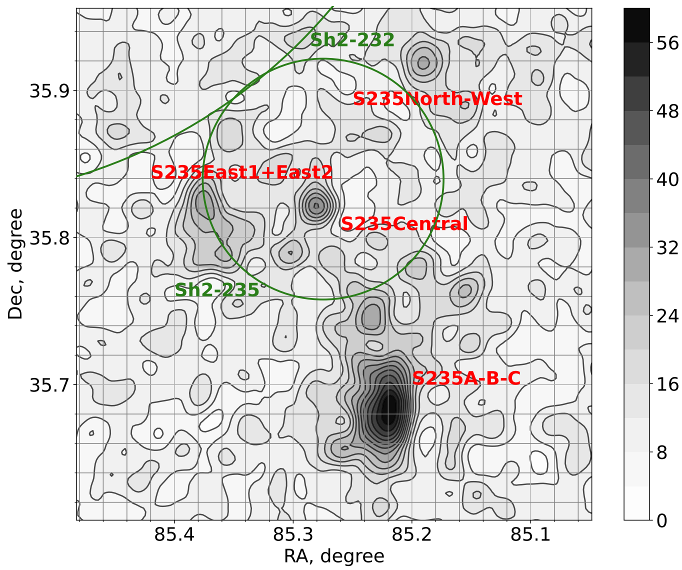

Fig. 1. Stellar density maps of the region based on UKIDSS data. Kernel half-width 1 arcmin, limiting magnitude $K = 15^m$. Clusters are indicated in red. HII regions are indicated in green.

excesses. In this work, we use the equation: $Q = (J - H) - k_R(H - K)$, $k_R = E(J-H)/E(H-K)$. This parameter is considered to be free from the influence of extinction. Thus, using the diagram "color index – Q", we can define the color excess as the difference between the color index value of the star and of the non-reddened sequence.

The main problem of the method is the difficulty to choose which segment of the non-reddened sequence the star belongs to without knowing its spectral class. We solve this problem by comparing the luminosity functions (LFs) of the studied cluster and the non-reddened "reference" cluster (Pleiades, sample of Lodieu et al. 2019). In the LF of the Pleiades, the stars of the left and right segments intersect only in a small range of values. Within this range, we select a certain limit value at which the number of stars in the left segment still significantly exceeds the number of stars in the right segment. We combine the LFs of the "reference" and studied clusters. Next, we assume that all stars with a magnitude less than the limit belong to the left segment, and all stars with a greater magnitude belong to the right one. As a result, Q method gives clearer photometric sequences.

The distances to the clusters were determined by combining extinction-corrected photometric diagrams with isochrones. The obtained estimates of the distances of 1.7–2.2 kpc (6th column of Table 1) are consistent with the data from the literature.

We determined the cluster masses (7th column of Table 1) by the photometric method. We count the number of stars between two adjacent evolutionary tracks plotted in the (H-K; K) plane and multiply this value by the average mass of the stars for which the tracks are built. This method may underestimate the mass, since not all stars are visible and not all visible stars have photometry in three bands.

Further, we plot the mass functions (MFs) of clusters in $\log(M) - \log(dN/d(lg(M)))$ plane. The MFs show a strong decrease in the region of low masses due to the fact that most low-mass stars are not visible because of the incompleteness of the catalog. The slope of the MFs for $\log M \geq -0.2$ for all clusters is close to the initial MF (IMF) of Kroupa (2001).

Suggesting the masses of the cluster stars are distributed with the IMF of Kroupa, we estimated the cluster total masses (8th column of Table 1). The total masses and number of stars are almost 2 and 3 times, respectively, higher than the values derived from visible stars.

To assess the star formation efficiency (SFE) in the region of each cluster, we first estimate the mass of the gas in the regions. To do this, we use observational data on emission in the ^{12}CO(1-0) and ^{13}CO(1-0) lines (Brunt 2004). Integrated radiation temperature maps were converted to the mass-per-pixel maps using the method described in Ladeyschikov et al. (2021). Next, the total mass of pixels in the cluster areas was calculated.

Assuming that most of the parent gas remains in the cluster region or is in the line of sight, we determine the star forming efficiency in the regions under consideration using the equation: $SFE = M_{\rm cl}/(M_{\rm g} + M_{\rm cl})$, where $M_{\rm g}$ is the mass of the gas in the region, $M_{\rm cl}$ is the mass of the star cluster found from the IMF of Kroupa. Our values (9th column of Table 1) range from 0.04 to 0.17, which is consistent with the observed SFE in the Milky Way.

To study the kinematics of clusters, we used data on the proper motions of stars from the Gaia DR3 catalog. With them, we determined the average proper motions of the clusters and plotted the dependencies of the radial and tangential velocity components on the distance from the cluster center and on the position angle relative to the right ascension axis. At the base of these plots we concluded that stars of clusters S235North-West and S235A-B-C have a rather clear translational movement, but the cluster S235East1+East2 may contain some density waves or isolated kinematic groups of stars.

To assess the dynamic state of the clusters, we use the approach of Danilov (2024). If we determine the sign of the total energy, we can deduce whether the cluster-gas system is gravitationally bound or not. The total energy is calculated on the assumption that the system consists of two components – stars and gas. For the cluster star mass, we use the mass obtained using the MF of Kroupa.

We find the velocity dispersion for the equation of the kinetic energy from the dispersion of the stars' proper motions. Assuming that the radial velocity distribution is the same as the velocity distribution in one tangential direction, the velocity dispersion is: $\sigma^2 = 1.5(\sigma^2_{\rm pmRA} + \sigma^2_{\rm pmDec})$. We take into account the contribution of the proper motion errors, considering the observed velocity distribution, the intrinsic velocity distribution, and the errors distribution to be Gaussian ones. Also, we consider the broadening of the observed velocity distribution by the KDE (a more detailed description of the method is given in Kulesh et al. 2024).

We note that the boundness of the systems depends on the size of the region for which the gas mass is estimated. So, when taking into account the gas located only in the areas of clusters, the total energy of the gas plus stars systems is negative only for the clusters S235Central and S235East1+East2. When the mass of the entire cloud is taken into account, all clusters have a negative total energy and appear to be gravitationally bound.

3 Summary

The work involved a study of four clusters in the star formation region G174+2.5 using data from the UKIDSS and Gaia catalogs.

1. The general parameters of clusters are determined - centers, radii, number of stars, extinction, distance and probabilities of star membership in clusters.
2. The masses of the cluster stars, the masses of gas in the regions under consideration, and the efficiency of star formation are estimated.
3. The average values of the proper motions of stars in clusters are estimated. The kinematics of the clusters have been studied: the clusters S235North-West and S235A-B-C appear to move as a single units, and the cluster S235East1+East2 may contain the isolated kinematic groups of stars.
4. We estimated the total energy of the stars+gas systems in the cluster regions. When the mass of the entire cloud is taken into account, all clusters considered as a stars+gas systems appear to be gravitationally bound.

It should be noted that the star counts and an analysis of the dynamical state of the clusters in our paper are based on the assumption of a spherical symmetry. However, the real structure and formation path differ from one cluster to another. Star formation in the clusters S235 North-West, S235 Central, S235 East1+East2 was rather induced by an expanding HII region Sh2-235 (Kirsanova et al. 2008, 2014). Consequently, these clusters have rather a flattened form. Star formation in the cluster S235 A-B-C was rather spontaneous. Nevertheless, this cluster has a non-uniform structure and consists of some subclusters. Formation of some clusters in the envelope complicates the determination of the gas mass. A remarkable part of the gas there is ionised and is not visible in the molecular lines. Thus, our investigation can be considered as an attempt to use simple models for the real complex star formation region.

Acknowledgements. Authors are very grateful to Dr. A. M.Sobolev for his constant attention and useful comments. 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. This work uses data from the UKIDSS GPS catalog (version DR10PLUS) (Lucas et al. 2008).

Funding

These work was supported by the Ministry of science and higher education of the Russian Federation by an agreement FEUZ-2023-0019.

References

Brunt C., 2004, ASP Conf. Ser., 317, p. 79

Danilov V., 2024, Astrophysical Bulletin, 79, p. 71

Gaia Collaboration, Vallenari A., Brown A., et al., 2023, Astronomy and Astrophysics, 674, id. A1

Kirsanova M., Sobolev A., Thomasson M., et al., 2008, Monthly Notices of the Royal Astronomical Society, 388, p. 729

Kirsanova M., Wiebe D., Sobolev A., et al., 2014, Monthly Notices of the Royal Astronomical Society, 437, p. 1593

Krone-Martins A. and Moitinho A., 2014, Astronomy and Astrophysics, 561, id. A57

Kroupa P., 2001, Monthly Notices of the Royal Astronomical Society, 322, p. 231

Kulesh M., Samirkhanova A., Carraro G., et al., 2024, Astronomical Journal, 167, p. 212

Ladeyschikov D., Kirsanova M., Sobolev A., et al., 2021, Monthly Notices of the Royal Astronomical Society, 506, p. 4447

Lodieu N., Pérez-Garrido A., Smart R., et al., 2019, Astronomy and Astrophysics, 628, id. A66

Lombardi M., 2009, Astronomy and Astrophysics, 493, p. 735

Lucas P., Hoare M., Longmore A., et al., 2008, Monthly Notices of the Royal Astronomical Society, 391, p. 136

Seleznev A., 2016, Monthly Notices of the Royal Astronomical Society, 456, p. 3757