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Stellar kinematics in the IC 348 cluster

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Abstract

In 30 - 40s of the last century Viktor Ambartsumian has published several studies on the kinematics and dynamics of stellar systems. The scientific issues of these papers not only remain relevant up to nowadays, but also are of key importance for the construction of the generalized theory of star formation. The launch of the Gaia spacecraft on December 19, 2013, opens up new horizons in the study of young stellar systems origin and evolution. The accuracy of astrometric measurements (the typical uncertainty is about 0.04 - 0.7 mas for the positions and parallaxes, and about 0.05 - 1.2 $mas\ yr^{-1}$ for the proper motions), undoubtedly, will allow lifting the possibilities of study the kinematics and dynamics of star-forming regions to a new level. We focus our present research on the young ($\sim\ 2-3Myr$) stellar cluster IC 348. It has a complex structure, which includes the older compact core and the younger subgroup in the vicinity of HH 211 outflow. Based on the Gaia DR2 data, we considered the kinematic properties of both the cluster as a whole and its subgroups. We found that special velocity dispersion significantly exceeds the virial velocity dispersion and, therefore, the IC 348 stellar cluster is a supervirial or gravitationally unbound system.

1. Introduction

In 1936 academician Ambartsumyan published a work *"On the Deviation of the Frequency Function of Space velocities"* of the Stars from the Observed Radial Velocities, in which he provided an elegant mathematical solution to the problem posed earlier by Eddington (Eddington, 1915) of determining the distribution of the spatial velocities of stars from the distribution of their radial velocities, obtained for various regions of the sky. The equations, provided in Ambarzumian (1936) were of fundamental importance for study the kinematics and dynamics of stellar systems. Moreover, this work was the second one among Ambartsumian's series of papers on the solution of

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the inverse problems. It had an essential significance also for another series of papers devoted to the problems of cosmogony and formed part of the discussions of the 1930s between advocates of the *long* (10^{13} years) and *short* (10^{10} years) scales for galactic evolution (Ambartsumyan 1937a, 1937b, 1938). The scientific arguments presented in these papers put the final point in the debate about the ages of our galaxy in favour to the *short* scale. Furthermore, because of their profundity, Ambartsumyans papers had more than a momentary significance and have had an influence on research in stellar kinematics and dynamics that is perceptible even now. In particular, the Eq. (1) in Ambarzumian (1936) made the possibility to determine the spatial velocities of stars for a given set of coordinates and radial velocities of these stars, but without invoking their proper motions.

$$f(V, \alpha)dV = n(\alpha) \int_{(S)} \phi(\xi, \eta) d\eta, \tag{1}$$

where $f(V, \alpha)dV$ is the number of the observed stars with azimuths between α and $\alpha + d\alpha$ and with radial velocities between V and $V + dV$. The graph, which is explaining the notation in the Eq. (1), is borrowed from Ambarzumian (1936) and represented on Fig. 1.

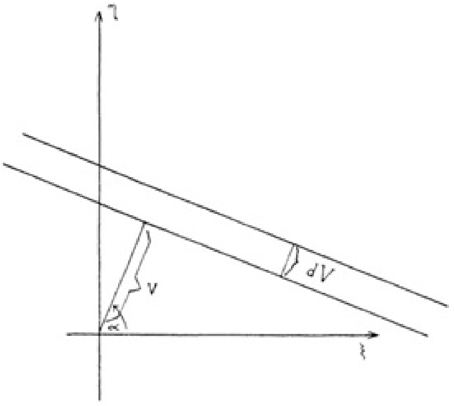

Figure 1. The graph explaining the notation in the Eq. (1).

Further, this mathematical solution was the subject of active research. (Ossipkov 2012 and ref. therein). It should be emphasized that the solution of Eq. (1) is of great importance not only for solving problems related to the kinematics of stellar systems, but also goes far beyond astronomy, in particular, computerized tomography (Cormack 1985). Looking back, it can be said that mentioned above Ambartsumian's several papers contributed significantly to the formation and development of such a fundamental direction of modern astrophysics as the study of kinematics and dynamics of stellar systems.

2. New era. Gaia satellite

The launch of Gaia satellite in 2013 opened a new era for a number of fields of modern astrophysical research. In particular, the phenomenal astrometric resolution, has opened up new possibilities for the study of stellar systems structure. Currently, Gaia Data Release 2 (Gaia DR2) contains results for 1693 million sources in the magnitude range 3 to 21. The median uncertainty in parallax are 0.04 mas for bright ($G < 14$ mag) sources, 0.1 mas at $G = 17$ mag, and 0.7 mas at $G = 20$ mag. The median uncertainties in proper motion are 0.05, 0.2, and 1.2 mas yr^{-1}, respectively (Lindegren et al. 2018). Observational data with such parameters provide great opportunities for more detailed studies of a number of issues.

Among these issues, it should be noted the identification of new stellar clusters and checking of the membership of already known, including brown dwarfs that is very important for construction the luminosity or mass function for stellar formation at different stages of evolution. Among the most interesting results obtained in this area can be mentioned the several papers. Beccari et al. (2018) using Gaia DR2 data on positions, proper motions, and parallax in Vela OB2 region six new clusters or associations have discovered. Analysis of the colour-magnitude diagram for these clusters shows that four of them formed coevally in the same molecular clouds 10 Myr ago, while NGC 2547 formed together with a newly discovered cluster 30 Myr ago. In the nearest (100 pc) 27 associations 898 new high-likelihood candidate members with spectral types from B9 to L2 were discovered (Gagné & Faherty 2018). Wilkinson et al (2018), using Gaia DR1 data, identified 167 member candidates of Upper Scorpius, of which 78 are new. The newly discovered stellar objects are distributed within a 10 arcmin radius from core of star-forming region. These member candidates have a mean distance of 145.6 ± 7.5 pc and a mean proper motion of pm(RA) = -11.4 ± 0.7 mas yr^{-1} and pm(Dec) = -23.5 ± 0.4 mas yr^{-1}. These values are consistent with measured distances and proper motions of previously identified *bona fide* members of the Upper Scorpius association. Earlier, in the same star-forming region Cook et al. (2017) identified about 100 brown dwarfs with masses $M < 0.05 M_\odot$. They showed that the mass function of stellar objects with $0.01 < M < 0.1 M_\odot$ masses is consistent with the Kroupa Initial Mass Function and proposed that some proper motion outliers among the brown dwarfs have undergone a dynamical ejection early in their evolution.

The Gaia DR2 data provide great opportunities for studying the structural, as well as kinematic and dynamical properties of the stellar formation on a different evolutionary stages. For instance, the study of proper motions in Upper Scorpius association showed that the morphology of the association defined by brightest and faintest members are different (Galli et al 2018). The brightest (and most massive) stellar objects are distributed in a prolate ellipsoid with dimensions of 74 × 38 × 32 pc^3, while the faintest cluster members define a more elongated structure with dimensions of 98 × 24 × 18 pc^3.

The examination of the proper motions of star in the several young stellar cluster showed that they are gravitationally unbound systems and have non-isotropic velocity dispersions that undoubtedly requires the revision of some of the main tenets of the general theory of star formation. Among these works, we note the following papers. On the basis of the value of the virial velocity dispersion σ_{vir} in Bravi et al. (2018) it was found that four open stellar clusters IC 2602, IC 2391, IC 4665, and NGC 2547 are supervirial. It was shown that three subgroups of Scorpius-Centaurus OB association are gravitationally unbound and have non-isotropic velocity dispersions (Wright Mamajek 2018). The authors find the evidence that the subgroups were not formed by the disruption of individual star clusters. They conclude that Sco-Cen was likely to have been born highly substructured, with multiple small-scale star formation events contributing to the overall OB association, and not as single, monolithic burst of clustered star formation. A dynamical analysis shows that the stellar surface population of L1688 has a velocity dispersion $\sigma \sim 1.14 \pm 0.35$ km s^{-1} that is consistent with being in virial equilibrium only with a $\sim 80\%$ probability (Rigliaco et al., 2016). The study the dynamical ages of the Young Local Associations showed that in these star-forming region there were two episodes of star formation: one $\sim 40 Myr$ (Chamaeleontis, TW Hydrae, and β Pictoris) and another $5 - 15$ Myr ago (Tucana-Horologium, Columba, and Carina) (Miret-Roig et al. 2018).

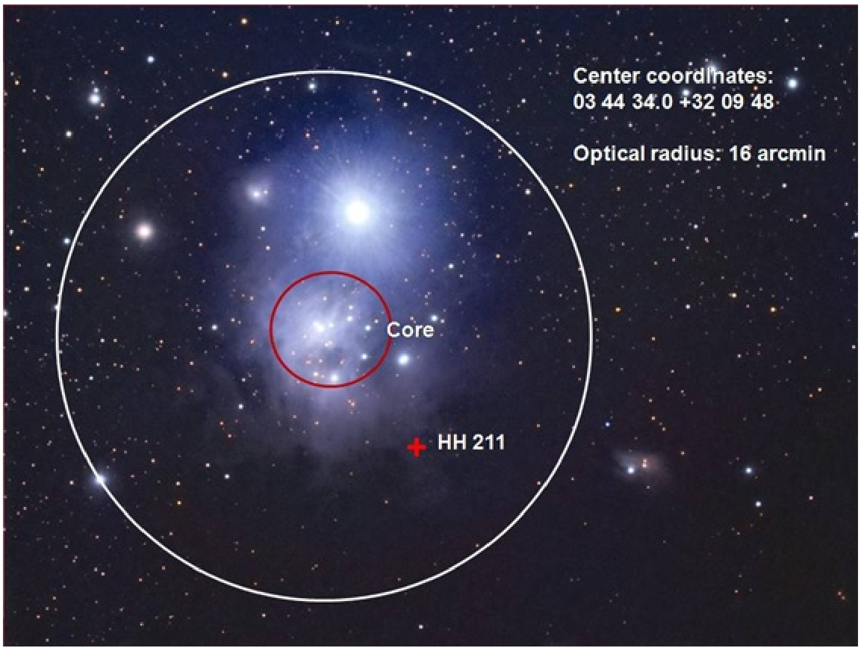

Figure 2. DSS2 R image of the IC 348 cluster and its structural features

3. Kinematics in the IC 348 cluster

3.1. IC 348 stellar cluster.

For our study we have chosen a relatively well-studied compact young star cluster IC 348 ($\sim$ 2 - 3 Myr, Stelzer et al. 2012) which is associated with the Perseus molecular cloud complex and is located at distance $\sim$ 300 pc from the Sun. The pioneering studies of Herbig (1954, 1988) discovered about 100 stars with H_α emission in this cluster. Later, the number of known H_α emitters was doubled (Luhman et al. 2003). In Nikoghosyan et al. (2015), it was shown that among the cluster members with $13.0 <$ R mag < 19.0 the percentage of emission stellar objects reaches 80%. IC 348 was also extensively studied in near- and mid-infrared wavelengths (Lada et al. 2006, Muench et al. 2007, Currie Kenyon 2009). Using measurements of infrared excess between 3.6 and 8.0 μm, Lada et al. (2006) find that the total frequency of disk bearing stars in the cluster is $\sim$ 50% and only $\sim$ 30% of the cluster members are surrounded by optically thick, primordial disks. IC 348 is also well studied in the X-ray regime. It was detected about 200 X-ray sources, which are associated with known cluster members (Preibisch Zinnecker 2002, Stelzer et al. 2012, and ref. herein). As it was concluded in Stelzer et al. (2012), the evolutionary stage of IC 348 cluster corresponds to the time where the structure of the disks of most young stellar objects changes from primordial, rather massive accretion disks to transitional and debris disks. Therefore, the cluster population represents the outcome of a recent star-formation event. However, on the southwestern direction on a distance about 1 pc molecular hydrogen jet HH 211 is located. The dynamical age of this jet is about 1000 yr, that suggesting that this is the region of a later wave of star formation. On the other hand, in the central region of the cluster more massive stellar objects with low H_α activity and a small infrared excess, i.e. the members of the cluster at a later stage of evolution, are concentrated. The age of these objects is about $7{\cdot}10^6$ years, which exceeds the average age of the cluster's members (Nikoghosyan et al. 2015). These objects form a core with surveys stellar density, which is almost 20 times higher than the average one in the cluster. Figure 2 shows an image of the IC 348 cluster and its structural features.

3.2. Cluster's membership

In previous works, according to the data of spectral and photometric observations, 377 star objects were identified as the members of the IC 348 cluster. The most complete list is given in Flaherty et al. (2013). The optical radius of the cluster is $\sim$ 16 arcmin from the centre with coordinates RA (2000) $03^h\ 44^m\ 34.0^s$ and Dec (2000) $+32^\circ$ 09' 48" (Wu et al. 2006).

A histogram of parallaxes on the left panel, clearly defines a maximum in the range of 2.5 to 3.5 mas, which corresponds to the cluster distance.

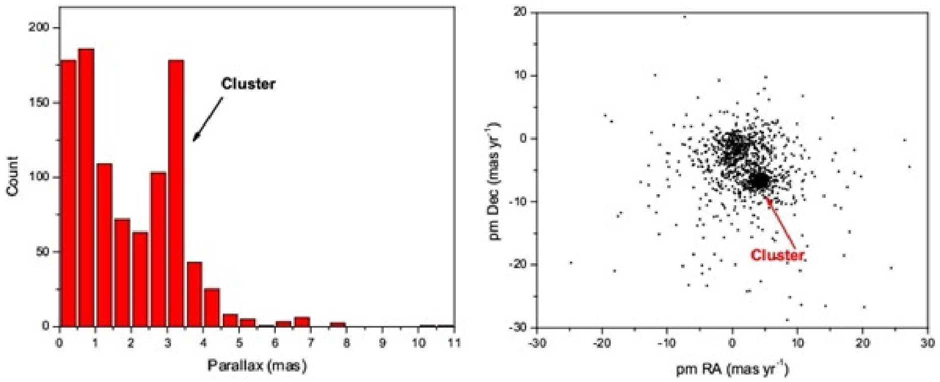

Figure 3. Distribution of the parallaxes (left panel) and proper motions (right panel) of the objects located in the region of the IC 348 cluster.

The distribution of proper motions also reflects the existence of a cluster. On right panel of Fig. 3 besides the concentration around zero values, which corresponds to the field objects, one more concentration of objects around the pm(RA) ≈ 4.5 mas yr^{-1} and pm(Dec) ≈ -7 mas yr^{-1} is clearly distinguished.

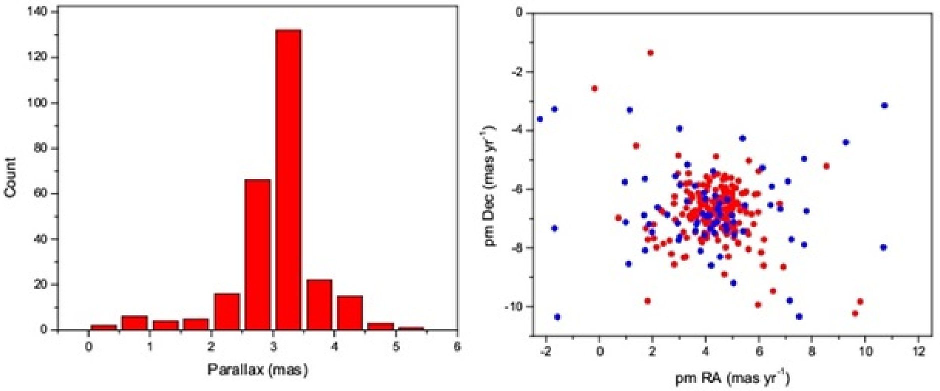

Figure 4. Distribution of the parallaxes (left panel) and proper motions (right panel) of the objects identified as cluster members. On the right panel the objects with parallaxes in the range from 2.5 to 3.5 mas are marked by red and other objects by blue.

In the Gaia DR2 database we were able to identify only 300 objects among the 377 members of the cluster. Among them the parallaxes and proper motions were determined only for 272 stellar objects.The distributions of these parameters are shown in Fig. 4. By the histogram on the left panel it is clearly seen that the parallaxes of a vast majority of objects, namely 199, are in the range from 2.5 to 3.5mas. If we assume that the cluster has a spherical shape, then at a radius of 16 arcmin and a distance of approximately 300 pc, within the errors (~ 0.37 mas), the parallaxes of the cluster's members should fall precisely into this range. The median value of the parallaxes of these 199 stellar objects is 3.069 ± 0.23 mas, which corresponds to a distance of 326 pc. This value of a distance is in good agreement with the results of previous studies. The parallaxes of the remaining 73 star objects, which were previously identified as members of the cluster, have a significant shift from the median value and do not fall within the range from 2.5 to 3.5 mas. The right panel of Fig. 4 shows the distribution of the proper motions of all cluster's members identified in the Gaia DR2 database. Notice that the stellar objects with parallaxes in the range from 2.5 to 3.5 mas are marked by red circles, the other stars are marked by blue ones. According to the graph, it is noticeable that in the first case, the values of the proper motions, especially in the direction of a right ascension, have a smaller variation relative to the average values, which are pm(RA) = 4.31 ± 1.26 mas yr^{-1} and pm(Dec) = -6.78 ± 1.02 mas yr^{-1}. The standard deviations in this case are 1.23 and 1.03 mas for pm(RA) and pm(Dec), respectively. For other objects the standard deviations are higher: 3.21 and 1.66 mas for pm RA and pm Dec, respectively.Taking into account the fact that parallax is a reliable parameter for determining the distance, we used only 199 stellar objects with parallaxes in the range from 2.5 to 3.5 mas to study the kinematics of the cluster.

3.3. Stellar kinematics

To study the kinematics of the star population of the cluster, we transformed the proper motions into tangential velocities in the directions of right ascension and declination and determined their average values and standard deviations, which are equal to 3.07E-6 ± 1.88 km s^{-1} and 5.39E-6 ± 1.51 km s^{-1}, respectively. The histograms of the distribution of these velocities are shown in Figure 5. The distribution has a wide spread, which is also indicated by the values of the standard deviation.

In Cottaar et al. (2015) it was determined that the value of the virial equilibrium velocity dispersion for IC 348 should be of 0.44 ± 0.06 km s^{-1}. Moreover, the authors of this paper, on the basis of the values of the radial velocities of 157 cluster members, obtained the value of velocity dispersion (0.72 ± 0.07 km s^{-1} or 0.64 ± 0.08 km s^{-1}, if two Gaussians are fitted), which is almost $\sqrt{2}$ times more than the viral one and came to the conclusion that the cluster is in a superviral state. In our case, the dispersion value is significant greater, which also, suggests that in general the cluster is not in equilibrium state and gravitationally unbound. The authors of the mentioned above paper also did not found the evidence for a dependence of velocity dispersion on a distance from the cluster centre or stellar mass.

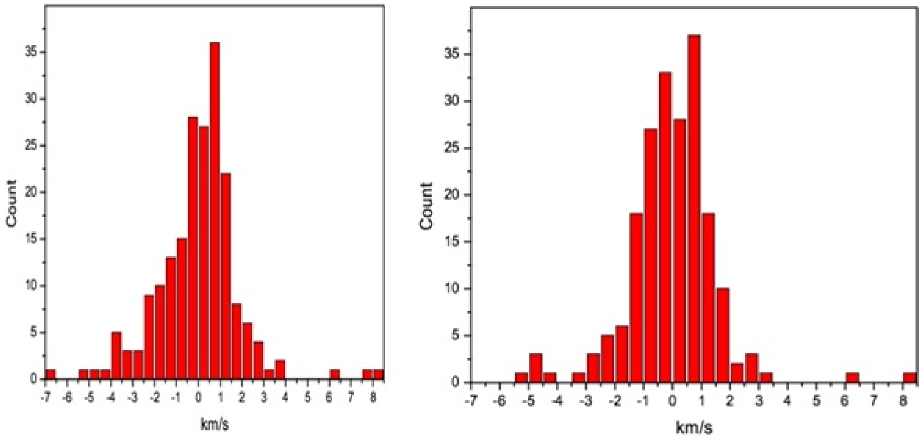

Figure 5. Distribution of the tangential velocities of the IC 348 cluster members in the direction of right ascension (left panel) and declination (right panel).

Moreover, they concluded that the stars in IC 348 are converging along the line of sight.

We also considered the averaged values of tangential velocities and standard deviations in different samples: in the quadrants and along the radius of the cluster. Fig. 6 shows the result obtained for quadrants. On this figure the red arrows represent the direction of motion of the stars in each quadrant. In general, we can say that modules of average velocities do not differ by quadrants. The direction of motion in both northern and south-eastern quadrants to some extent confirms the conclusion of Cottaar et al. (2015) that the stars in IC 348 are converging along the line of sight. The exception is the south-western quadrant, for which, in addition, the highest values of standard deviations for both directions are obtained. It should be recalled that the region of a later wave of star formation associated with HH 211 object is located in this quadrant.

The distribution of the averaged values of tangential velocities and standard deviations along cluster radius in the rings with a width of 2 arcmin is presented in Table 1. From these data, we can conclude that in the central region of the cluster, the dispersion of velocities in the direction of right ascension significantly exceeds the values of the same parameter in more external areas of the cluster. As mentioned above, in the central region of the cluster massive stellar objects at a later stage of evolution, are concentrated. As in the previous case, it can be assumed that the presence of this substructure is the cause of the greater value of the velocity dispersion.

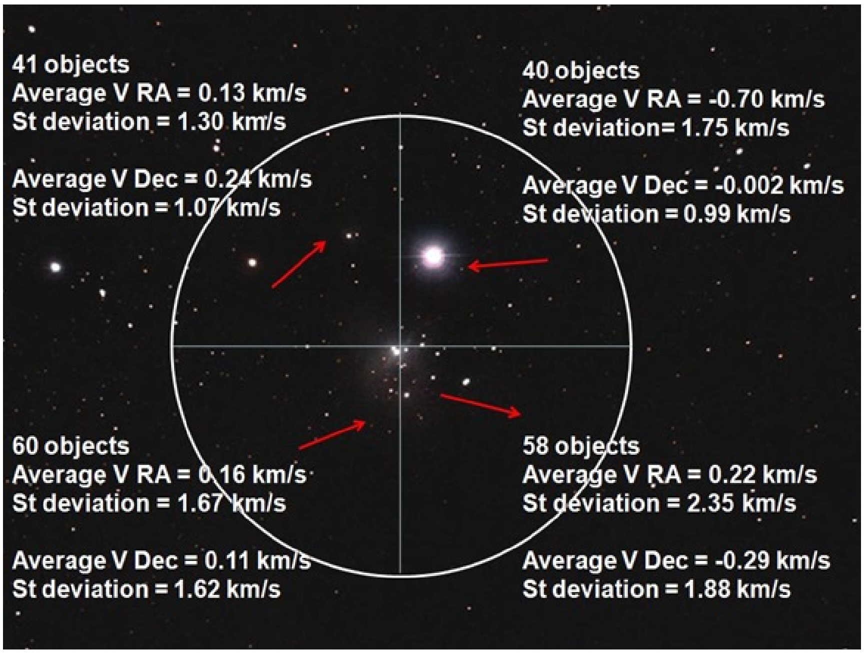

Figure 6. Average velocities and standard deviations in the quadrants. The red arrows show the direction of motion of the stars in each quadrant.

Table 1. The kinematic parameters along the radius of cluster

		Velocity in RA direction (km s^{-1})		Velocity in Dec direction (km s^{-1})	
Region (arcmin)	Number	Average	Sd. dev.	Average	Sd. dev.
0 - 2	14	0.11	2.15	-0.57	1.14
2 - 4	31	0.31	2.87	0.10	1.72
4 - 6	27	0.21	1.15	0.01	1.16
6 - 8	14	0.16	1.39	-0.25	1.41
8 - 10	18	-0.16	1.09	1.46	1.08

4. Discussion and conclusion

The early (i.e., few Myr) dynamical evolution of star clusters is still poorly constrained. The majority of stars form in clusters and associations inside giant molecular clouds. However, most clusters dissipate within 10 – 100 Myr, leaving more than 90% of the stellar population dispersed in the Galactic field (e.g., Ambartsumyan 1947, 1949, Lada Lada 2003). The scientific debate on the origin of bound and unbound clusters, along with the processes leading to their dissolution, is still open. Several authors suggest that all stars form in dense clusters (density $\geq 10^3 - 10^4$ stars pc^3), which rapidly dissipate after feedback from massive stars (i.e., supernova explosions, stellar winds, and radiation pressure) sweeps out the gas that was keeping the cluster bound (e.g., Goodwin & Bastian 2006, Baumgardt & Kroupa 2007). These models predict that clusters – after gas dispersion – should be found in a supervirial state. Recent observations and simulations question this scenario suggesting that clusters have origin in a hierarchically structured environment covering a large range of densities and that the stellar feedback and gas expulsion are irrelevant for the cluster dispersion, which is, instead, driven by two-body interactions (e.g., Parker & Dale 2013; Parker & Wright 2016).

From this perspective, the possible scenarios for explanation of observed supervirial state in IC 348 cluster include: a) the cluster is fluctuating around a new virial equilibrium after a recent disruption due to gas expulsion or a merger event, or b) the stellar population in IC 348 a is forming the subgroups which, moreover, may be the result of successive two or more star formation waves.

Undoubtedly, the presented results are only the initial stage of the study of the kinematics and dynamics of the young stellar cluster IC 348. For the study of the above issues, it is planned to conduct a more detailed study of various samples of cluster members, relation to both masses and evolutionary stages.As noted above, in previous works it was shown that in the cluster there is a stellar population with different infrared excess and activity, i.e. stellar objects at II and III evolutionary classes (Herbig 1988, Lada 2006, Falaherty et al. 2013, Nikoghosyan et al. 2015). Moreover, stellar objects with different degrees of activity form substructures, which, as already shown, can affect the kinematics. The presence of a rich database of observational data, including radial velocities, will allow us to construct 3D model of the cluster as a whole.

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