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Abstract

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Full Text

Preamble

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How Common can the Origin of Clusters Cha I, Cha II, ε Cha and Cha be?

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Abstract

The trajectories of the groupings δ Cha, δ Cha and Cha I, Cha II, constructed backward in time, have been studied. We concluded that the hypothesis about the joint formation of all four of these clusters from one molecular cloud cannot be completely excluded. However, 10–15 Myr ago, all these four clusters were located at approximately the same height above the plane of the Galaxy. Thus, the gas-dust clouds from which all these four clusters were formed were located on one broad front. It is possible that the appearance of the Cha I, Cha II, δ Cha and δ Cha clusters may be associated with the impact on such a front of shock waves formed after supernova explosions in the Scorpius–Centaurus association. New estimates of the kinematic ages of the clusters Cha I and Cha II are obtained as 0.12 ± 0.19 and 0.05 ± 0.15 Myr, respectively. It is shown that the minimum size of the Cha I-north and Cha I-south clusters corresponded to the time of 0.55 ± 0.24 Myr and 0.04 ± 0.18 Myr ago, respectively, and approximately 1.5 Myr ago the distance between the trajectories of these two groupings was minimal.

Key words: stars: distances – stars: kinematics and dynamics – galaxies: star formation

1. Introduction

Close to the Sun (at a distance of about 100–250 pc), the fourth galactic quadrant is occupied by the Scorpius–Centaurus (Sco–Cen) OB association (Blaauw 1946, 1964). It has three main structural components: Lower Centaurus Crux (LCC), Upper Centaurus Lupus (UCL) and Upper Scorpius (US). A large number of publications have been devoted to the study of the stellar composition and kinematics of the Sco–Cen OB association (de Geus et al. 1989; de Geus 1992; de Bruijne 1999; de Zeeuw et al. 1999; Sartori et al. 2003; Fernández et al. 2008; Pöppel et al. 2010; Rizzuto et al. 2011; Pecaut et al. 2012; Pecaut & Mamajek 2016; Bobylev & Bajkova 2020, 2023). The association has a complex morphology and evolutionary history—some of its components (LCC, UCL, etc.) have an age of 10–25 Myr, in which the star formation process has already completed. There are also structures (for example, US with an age of ~ 5 Myr), where star formation is still occurring.

The star formation process in the Sco–Cen OB association generally fits well with the sequential star formation model (Preibish & Zinnecker 1999). This model is based on the assumption that shock waves from explosions of massive stars in one part of the association lead to compression of hydrogen clouds, thus triggering the process of star formation in another part.

The velocity field in the Sco–Cen association is very heterogeneous. The study of spatial and kinematic features showed that a whole complex of very young

moving stellar groups, small associations and open star clusters is associated with the Sco–Cen OB association, for example, Oph/L1688, Sco, B59, Cha or δ Cha. A detailed summary of more than 30 groupings of various ages, indicating the relationship with the main structural components (LCC, UCL and US), can be found in Ratzenböck et al. (2023).

It should be noted that the use of data from the Hipparcos project (The HIPPARCOS and Tycho Catalogues 1997) made it possible to study in detail the features of the Sco–Cen OB association based on bright stars (de Zeeuw et al. 1999; Sartori et al 2003; Fuchs et al. 2006; Bobylev & Bajkova 2007). The implementation of the Gaia project (Gaia Collaboration et al. 2016) enabled analyzing en masse the faint stars of the Sco–Cen association, which are mostly T Tauri type stars.

In Galli et al. (2021), the spatial velocities of groupings Cha, δ Cha and Cha I, Cha II were compared using data from the Gaia Data Release 2 (DR2) catalog (Gaia Collaboration et al. 2018). These authors concluded that the spatial motion of Cha, δ Cha is consistent with the spatial motion of stars in the molecular clouds Cha I and Cha II within 3σ of the stated uncertainties in their velocities. Therefore, these clusters may have been formed from the same parent cloud, but further research is needed to confirm this hypothesis. This conclusion of Galli et al. (2021) served as the main impetus for carrying out this study.

The purpose of this work is to analyze the trajectories constructed backward in time of the stars in the groupings Cha, δ Cha and Cha I, Cha II in order to find out which of them could have formed from a common molecular cloud. Moreover, the analysis of the trajectories of clusters Cha and δ Cha has already been performed by us earlier in Bobylev & Bajkova (2024) using data from the Gaia Data Release 3 (DR3) catalog (Gaia Collaboration et al. 2022).

In this work, the main attention is paid to the clusters Cha I and Cha II. We also provided the values of parallaxes and proper motions from the Gaia DR3 catalog for candidate stars from the list of Galli et al. (2021) in these clusters. Of particular interest is also the study of the evolutionary relationship between the Cha I and Cha II clusters.

2. Method

We use a rectangular coordinate system centered on the Sun, where the x-axis is directed toward the galactic center, the y-axis toward galactic rotation and the z-axis to the north pole of the Galaxy. Then

$$x = r \cos l \cos b,$$

$$y = r \sin l \cos b,$$

$$z = r \sin b,$$

where $r = 1/\pi$ is the heliocentric distance of the star in kpc, which we calculate through the parallax of the star π in mas (milliseconds of arc). From observations, the radial velocity V_r and two tangential velocity projections $V_l = 4.74r\mu_l$ and $V_b = 4.74r\mu_b$ are known, directed along the galactic longitude l and latitude b , respectively, expressed in km s^{-1} . Here, the coefficient 4.74 is the ratio of the number of kilometers in an astronomical unit to the number of seconds in a tropical year. The components of proper motion μ_l and μ_b are expressed in mas yr^{-1} .

Through the components V_r, V_l, V_b , the velocities U, V, W are calculated, where the velocity U is directed from the Sun to the center of the Galaxy, V in the direction of rotation of the Galaxy and W to the north galactic pole:

$$\begin{aligned} U &= V_r \cos l \cos b - V_l \sin l - V_b \cos l \sin b, \\ V &= V_r \sin l \cos b + V_l \cos l - V_b \sin l \sin b, \\ W &= V_r \sin b + V_b \cos b. \end{aligned}$$

Thus, the velocities U, V, W are directed along the corresponding coordinate axes x, y, z .

To plot the orbits of stars in the coordinate system rotating around the center of the Galaxy, we use the epicyclic approximation (Lindblad 1927):

$$\begin{aligned} x(t) &= x_0 + \frac{U_0}{\kappa} \sin(\kappa t) + \frac{V_0}{2\Omega_0} [1 - \cos(\kappa t)], \\ y(t) &= y_0 - \frac{U_0}{2\Omega_0} [1 - \cos(\kappa t)] + \frac{V_0}{\kappa} \sin(\kappa t) - \frac{U_0}{2\Omega_0} \kappa t, \\ z(t) &= z_0 \cos(\nu t) + \frac{W_0}{\nu} \sin(\nu t), \end{aligned}$$

where time t is in million years (based on the ratio $\text{pc/Myr} = 0.978 \text{ km s}^{-1}$), κ is epicyclic frequency, Ω_0 is angular velocity of galactic rotation of the local standard of rest, $\Omega_0 = A - B$, A and B are Oort constants, ν is frequency of vertical oscillations, where G is the gravitational constant, and ρ_0 is stellar density in the near-solar neighborhood.

The parameters x_0, y_0, z_0 and U_0, V_0, W_0 in the system of Equations (2) denote the current positions and velocities of the stars, respectively. The elevation of the Sun above the galactic plane is assumed to be 16 pc according to Bobylev & Bajkova (2016). The velocities U, V, W are calculated relative to the local standard of rest using the values $(U_\odot, V_\odot, W_\odot) = (11.1, 12.2, 7.3) \text{ km s}^{-1}$ obtained by Schönrich et al. (2010). We took $\rho_0 = 0.1 M_\odot \text{ pc}^{-3}$ (Holmberg & Flinn 2004), which gives $\nu = 74 \text{ km s}^{-1} \text{ kpc}^{-1}$. We apply the following values of the Oort constants: $A = 16.9 \text{ km s}^{-1} \text{ kpc}^{-1}$ and $B = -13.5 \text{ km s}^{-1} \text{ kpc}^{-1}$, close to modern estimates. An overview of such estimates can be found, for example, in Krivanova et al. (2020) or Donlon et al. (2024).

3. Data

In this work, the analysis uses the list of probable members of the Cha I and Cha II clusters from Galli et al. (2021). Moreover, only stars with radial velocity measurements were taken. The selected stars were provided with parallax and proper motion values from the Gaia DR3 catalog.

The radial velocity values from the Gaia DR3 catalog, available for a number of stars, were not used in this work. The fact is that the ground-based radial velocities of the stars in both clusters Cha I and Cha II, collected in the work of Galli et al. (2021), have values close to 15 km s^{-1} with low dispersion. However, the radial velocities of the stars in these clusters in the Gaia DR3 catalog, in many cases have negative values and large measurement errors.

4. Results and Discussion

4.1. Cha, δ Cha and Cha I, Cha II

Figure 1 [Figure 1: see original paper] shows the distribution of stars of four clusters δ Cha, Cha, Cha I and Cha II in projection onto the xy plane and their trajectories integrated backward in time over an interval of 30 Myr. Their distribution and trajectories in the vertical direction are also given.

To set the trajectory of the kinematic center of the Cha I cluster, the average positions and velocities were calculated for 76 stars: $x_0 = -1.2 \text{ pc}$, $U_0 = -10.6 \text{ km s}^{-1}$, $y_0 = -165.2 \text{ pc}$, $V_0 = -19.3 \text{ km s}^{-1}$, $z_0 = -49.1 \text{ pc}$, and $W_0 = -11.7 \text{ km s}^{-1}$. The average distance to the cluster was obtained as $r_0 = 183.6 \text{ pc}$. Using the found values of the average coordinates and velocities, the trajectory of the kinematic center was constructed. Based on the coordinate differences between the star and the kinematic center Δx , Δy , Δz at each moment of integration for each star, we calculate the value of parameter q in the following form:

$$q = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2},$$

which characterizes the deviation of the star from the trajectory of the kinematic center. Note that the trajectories of the stars are calculated taking into account the elevation of the Sun above the galactic plane. Thus, in all our figures, the coordinate z reflects the position of the stars relative to the plane of the Galaxy.

In Galli et al. (2021) for the Cha I cluster using 78 stars with Gaia DR2 parallaxes, the following average velocities were calculated: $U_0 = -10.6 \text{ km s}^{-1}$, $V_0 = -19.3 \text{ km s}^{-1}$, $W_0 = -11.7 \text{ km s}^{-1}$. The average distance to the cluster Cha I, $r_0 = 191.5 \text{ pc}$, was obtained by these authors from 160 stars (Table 3 of their work). For the Cha II cluster of 19 stars, we found the following values: $x_0 = -0.6 \text{ pc}$, $U_0 = -11.5 \text{ km s}^{-1}$, $y_0 = -161.8 \text{ pc}$, $V_0 = -19.5 \text{ km s}^{-1}$, $z_0 = -51.4 \text{ pc}$, $W_0 = -11.3 \text{ km s}^{-1}$, and $r_0 = 197.1 \text{ pc}$ as well. In Galli et al. (2021), the following average velocities were calculated for the Cha II cluster

of 19 stars using Gaia DR2 parallaxes: $U_0 = -11.5 \text{ km s}^{-1}$, $V_0 = -19.5 \text{ km s}^{-1}$, $W_0 = -11.3 \text{ km s}^{-1}$ and average distance $r_0 = 197.1 \text{ pc}$ calculated from 31 stars (Table 3 of their work). Thus, we have a good agreement between us and Galli et al. (2021) in estimating the average distances and velocities of clusters Cha I and Cha II.

Let us note some interesting points. First, in Figure 1(a) the elongation along the line of sight of the stars in the Cha I and Cha II clusters is clearly visible. The effect is clearly related to the variance of errors in estimates of distances to stars. For example, the size of Cha I in the transverse direction is about 5 pc, and along the line of sight its size is about 15 pc. Assuming that all these stars belong to one spherically symmetric cluster, we obtain an independent estimate of the error in the distance to the cluster, 5%.

Second, as can be seen from Figure 1(a), in the xy plane in the past, the trajectories of only two clusters— δ Cha and Cha intersect about 8 Myr ago. In this plane, the trajectories of Cha I and Cha II run parallel to each other. There is no convergence between the trajectories of the groupings Cha I, Cha II and δ Cha, Cha. Thus, for the joint formation of clusters Cha I, Cha II, δ Cha and

Cha from one parent gas-dust cloud, it is required that it be a Giant Molecular Cloud (GMC) larger than 100 pc. Such a scenario cannot be completely excluded. For example, according to Meingast et al. (2021), many young open clusters in the solar vicinity have extensive coronae (with a radius of up to 100 pc) formed together with the cluster core. This suggests that the star formation region may be quite extensive.

An overview of the problems with the origin and evolution of molecular clouds, and GMCs in particular, can be found in the work of Williams et al. (2000). An analysis of the sizes of young stellar associations and associated molecular clouds in the solar neighborhood with a radius of less than 3.5 kpc is given in Zhou et al. (2024), from which it is clear that the diameter value of 200 pc for such structures lies at the very edge of the distribution, and the maximum (typical size) is less than 50 pc.

4.2. Cha I and Cha II

Figure 2 [Figure 2: see original paper] shows the distribution of 76 Cha I stars projected onto the xy plane and their trajectories integrated backward in time over an interval of 8 Myr; in the middle panel of the figure is displayed the distribution of Cha I stars and their trajectories in the vertical direction. Figure 2(c) shows the dependence of the parameter q (deviation from the trajectory of the kinematic center) for each star in time. Note that here there are two identical values of the mean and variance for the moments $t = 0$ and $t = -0.5$ Myr. These suggest less than 0.5 million years ago the size of the Cha I cluster reached its minimum value. That is, the kinematic age of Cha I is less than 0.5 Myr.

Figure 2(c) shows discrete averages. Based on more detailed analysis, we esti-

minated the point in time at which the size of the star system in the past was minimal: $t = -0.12 \pm 0.19$ Myr.

Figure 3 [Figure 3: see original paper] depicts the distribution of 19 Cha II stars projected onto the xy plane and their trajectories integrated backward in time over an interval of 8 Myr; the distribution of Cha II stars and their trajectories in the vertical direction are given, as well as the dependence of the parameter q for each star in time. In Figure 3(c) the minimum value of the parameter q and the variance is present only at the moment $t = 0$ Myr. Based on more detailed calculations for Cha II stars, an estimate was obtained for the moment in time at which the size of the stellar system in the past was minimal: $t = -0.05 \pm 0.15$ Myr.

The error of the moment t in the results (4) and (5) was found as a result of statistical Monte Carlo simulations. It was assumed that the orbits of the stars were constructed with errors of 10%, distributed according to the normal law.

Thus, we can conclude that there is good agreement between our estimates of the kinematic age of the Cha I and Cha II clusters with isochronous estimates of their age, 1–2 Myr, obtained in Galli et al. (2021). Moreover, the Cha I cluster is slightly older than Cha II.

4.3. Cha I-north and Cha I-south

In Galli et al. (2021), it is indicated that there may be differences between two structures in the Cha I cluster, namely, between Cha I-north and Cha I-south. Therefore, we repeat our analysis for these two structures. The average values of the positions and velocities of Cha I-north (40 stars) and Cha I-south (36 stars) are given in Table 1. In addition, we found that the average distance to the grouping Cha I-north is $r_0 = 183.6$ pc, and that to the grouping Cha I-south is $r_0 = 183.7$ pc.

The distribution of stars in the Cha I-north and Cha I-south clusters in projection onto the xy plane and in the vertical direction is given in Figure 4 [Figure 4: see original paper]. The trajectories of the kinematic center of each cluster were calculated using data from Table 1.

As can be seen in panel (a), approximately 1.5 Myr ago the trajectories of the centers of these groups intersected, and in the vertical direction the trajectories ran almost parallel. Thus, in three-dimensional space about 1.5 Myr ago, the distance between the trajectories of these clusters was minimal.

In Figure 5 [Figure 5: see original paper] the dependence of the parameter q on time is given for the stars in the clusters Cha I-north and Cha I-south. The average interval values are also given. Based on a more detailed analysis, a time point was found at which the size of the Cha I-north star system was minimal in the past: $t = -0.55 \pm 0.24$ Myr, and for Cha I-south: $t = -0.04 \pm 0.18$ Myr.

The q parameter can also be considered as an estimate of the cluster radius. As

can be seen from Figure 5(a), the Cha I-north cluster is very compact; about 0.5 Myr ago its radius was approximately 5 pc. This is the typical size of a gravitationally bound open star cluster (Piskunov et al. 2008; Kharchenko et al. 2009). The radius of the cluster Cha I-south is currently about 8 pc. However, it seems that the compression of this complex is still ongoing.

5. Conclusion

A study of the trajectories of the Cha, δ Cha and Cha I, Cha II groupings, constructed backward in time, over a time interval of 30 million years, allows us to conclude the following.

1. In order to form all these four clusters from a common molecular cloud (the hypothesis of Galli et al. 2021), the size of such a cloud must be about 100–120 pc. According to current data, such a scenario cannot be completely excluded.
2. However, 10–15 Myr ago, all these four clusters were located approximately at the same height above the plane of the Galaxy. Thus, the gas-dust clouds from which all these four clusters were formed were on the same broad front. It is possible that the occurrence of clusters Cha I, Cha II, δ Cha and Cha may be associated with the impact of shock waves caused by supernova explosions in the Sco-Cen association on such a front from smaller parent clouds.
3. The kinematics of clusters Cha I and Cha II have been studied. For this purpose, stars with trigonometric parallaxes and proper motions from the Gaia DR3 catalog and radial velocities from the work of Galli et al. (2021) were used, where they were taken from the literature. Moreover, the radial velocities of these stars were measured as a result of ground-based observations. New estimates of the average distance $r_0 = 183.6$ pc and $r_0 = 197.1$ pc to clusters Cha I and Cha II, respectively, are obtained. It is shown that there is good agreement between our estimates of the kinematic age of t obtained for clusters Cha I and Cha II, 0.12 ± 0.19 and 0.05 ± 0.15 Myr respectively, with isochronous estimates of their age, 1–2 Myr, found in Galli et al. (2021). We concluded that it is quite possible that the clusters Cha I and Cha II may originate from the same parent cloud.
4. The kinematics of the cluster Cha I-north by 40 stars and Cha I-south by 36 stars are analyzed in detail. Based on the trigonometric parallaxes of Gaia DR3, the average distance to Cha I-north is determined, which is $r_0 = 183.6$ pc, and that to Cha I-south is $r_0 = 183.7$ pc. The time points at which the size of these clusters was minimal in the past have also been found. For Cha I-north, this moment is $t = -0.55 \pm 0.24$ Myr, and for Cha I-south $t = -0.04 \pm 0.18$ Myr. It is shown that approximately 1.5 Myr ago, the distance between the trajectories of these clusters was minimal.

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