On the Nature of Rotation in the Praesepe Cluster

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Abstract

Although a large number of Galactic open clusters (OCs) have been identified, the internal kinematic properties (e.g., rotation) of almost all the known OCs are still far from clear. With the high-precision astrometric data of Gaia EDR3, we have developed a methodology to unveil the rotational properties of the Praesepe cluster. Statistics of the three-dimensional residual motions of the member stars reveal the presence of Praesepe’s rotation and determine its spatial rotation axis. The mean rotation velocity of the Praesepe cluster within its tidal radius is estimated to be $0.2 \pm 0.05$ km s$^{-1}$, and the corresponding rotation axis is tilted in relation to the Galactic plane with an angle of $41^\circ \pm 12^\circ$. We also analyzed the rms rotational velocity of the member stars around the rotation axis, and found that the rotation of the stars within the tidal radius of Praesepe probably follows Newton’s classical theorems.

Unified Astronomy Thesaurus concepts: Open star clusters (1160); Stellar kinematics (1608)

Supporting material: machine-readable table

1. Introduction

The open star clusters in the Galaxy are gravitationally bound systems, and present a wide range of ages from a few million years to several billion years. An open cluster (OC) typically contains tens to thousands of member stars, which formed almost simultaneously in the same molecular cloud (e.g., Lada & Lada 2003). OCs serve as excellent astronomical laboratories for studying stellar structure and evolution (e.g., Barnes 2007; Bertelli Motta et al. 2017; Marino et al. 2018), and are good tracers for unveiling the structure and evolution of our Galaxy (Castro-Ginard et al. 2021; Hao et al. 2021; Hou 2021; Poggio et al. 2021). Although thousands of OCs have been identified in the Milky Way (Dias et al. 2002; Kharchenko et al. 2013; Cantat-Gaudin et al. 2020; Castro-Ginard et al. 2020, 2022; Hao et al. 2022), little is known about their internal kinematics, such as rotation and whether they are expanding or contracting. These kinematic properties are strongly related to the formation and evolution of OCs.

In the early days, there were some efforts focused on investigating the effect of cluster rotation on the proper motion vector geometry of its member stars (e.g., Wayman 1967; Hanson 1975; Gunn et al. 1988; Perryman et al. 1998). Later, based on the data set provided by Hipparcos and WEBDA, Vereshchagin & Chupina (2013) and Vereschchagin et al. (2013) attempted to explore the potential rotation in the Hyades and Praesepe clusters. They found a correlation between the tangential velocities and the parallaxes of cluster members, which implies possible rotation in the two OCs. Recently, by taking advantage of the released data set of Gaia (Gaia Collaboration et al. 2016), some works studied the relationship between tangential or radial velocities (RVs) and the angular radii of the member stars of some OCs (e.g., Kamann et al. 2019; Healy et al. 2021). The signals of rotation were found in the Praesepe and NGC 6791 clusters, but not for the Pleiades and NGC 6819 clusters. In brief, kinematic properties have only been simply explored for several OCs, which remain as major omission in the studies of Galactic OCs.

In this study, we focus on the Praesepe cluster, also known as the Beehive Cluster, located at a distance of 170–190 pc from the Sun (e.g., Pinsonneault et al. 1998; Dias et al. 2002; Kharchenko et al. 2013; Gaia Collaboration et al. 2018a; Cantat-Gaudin et al. 2018; Gao 2019). It is an intermediate-age cluster with an estimated age of 590–660 Myr (e.g., Mermilliod 1981; Vandenberg & Bridges 1984; Delorme et al. 2011; Brandt & Huang 2015; Gossage et al. 2018). The tidal radius of the Praesepe cluster is estimated to be in the range of [10, 12] pc (e.g., Adams et al. 2002; Khalaj & Baumgardt 2013; Gao 2019; Lodieu et al. 2019; Roser & Schilbach 2019; Loktin & Popov 2020). The member stars within the tidal radius of a cluster are generally gravitationally bound. As a rich OC, Praesepe contains red giants and white dwarfs representing the late stages of stellar evolution, as well as main-sequence stars and a significant number of low-mass stars (e.g., Dobbie et al. 2004, 2006; Kraus & Hillenbrand 2007; Wang et al. 2014; Gaia Collaboration et al. 2018a). Klein Wassink (1924, 1927) first studied this cluster. The low-mass members, binarity, luminosity and mass functions of the Praesepe cluster were then investigated by subsequent works (see Lodieu et al. 2019 and references within). Recently, with Gaia data, Roser & Schilbach (2019) found a clear indication for the existence of tidal tails in Praesepe, even stretching to about 165 pc from the cluster center.

Based on the trigonometric parallaxes, proper motions, and RVs in Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2018b), Loktin & Popov (2020) reported a possible rotation at the periphery of Praesepe with a velocity of 0.4 km s$^{-1}$. As the improved data quality of the Gaia Early Data Release 3 (EDR3; Gaia Collaboration et al. 2021), the detailed kinematic properties are expected to unveil the nature of Praesepe further. In contrast to previous studies only using projection methods,
this study aims to investigate the global and particularly the internal kinematics of Praesepe in three dimensions (3D) simultaneously, according to the high-precision astrometric parameters of Gaia EDR3.

In this work, we will first extract the member stars of Praesepe from Gaia EDR3, all of which have six-parameter solutions and RVs. Subsequently, we develop a methodology used to study the kinematic properties of a Galactic OC, including calculating and analyzing the 3D residual velocities of the member stars, determining the rotation axis if the cluster rotates, and deriving the rotational velocities of the member stars. This methodology is applied to the Praesepe cluster to characterize its kinematics.

2. Sample of Member Stars

The member stars of Praesepe are relatively easy to identify, as the Praesepe cluster is close to the Sun and presents large proper motions (e.g., Pinsonneault et al. 1998; Dias et al. 2002; Kharchenko et al. 2013; Gaia Collaboration et al. 2018a; Cantat-Gaudin et al. 2018). To identify possible members, we adopt a selection method similar to that of Loktin & Popov (2020), but based on the Gaia EDR3. First, stars falling within a radius of 10° around the coordinates of R.A. = 08h40m24s and decl. = +19°40′00″ (J2000) are selected as the initial data set. Field stars are then eliminated according to a diagram of trigonometric parallax (ϖ) and apparent magnitude (G). The selection boundary for the trigonometric parallax is set to [4.6, 6.1] mas, which represents three-times the mean parallax uncertainty for the faint stars (G = 20) in Gaia EDR3. A similar procedure is applied to diagrams of proper motions (μ_α, μ_δ) and apparent magnitude, where the selection boundaries are set to [−41, −31] mas yr\(^{-1}\) and [−16, −10] mas yr\(^{-1}\), respectively, by referencing the mean and three-times standard deviation of μ_α* and μ_δ reported by Loktin & Popov (2020). Similar to Loktin & Popov (2020) (see their Figure 3), the stars below and far away from the main sequence are identified by eye and excluded according to a color–magnitude diagram, as indicated by the green dots in Figure 1(d), except for a group of white dwarfs already known to belong to Praesepe (e.g., Dobbie et al. 2004, 2006; Gaia Collaboration et al. 2018a). In addition, we notice that all the excluded objects are faint stars and do not possess RV measurements in Gaia EDR3. After eliminating stars with uncertainties of trigonometric parallax or proper motions larger than 10%, we obtain a catalog containing 1135 member stars. Figure 1 shows the distributions of the observed parameters (i.e., R.A., Decl., ϖ, μ_α*, and μ_δ) of the member stars, which are approximated by a multidimensional normal distribution. Objects that deviate from the three-times standard deviation of the mean values are possible field stars. We found that only about 5.8% of the member stars deviate in some of the five-dimensional space. The influence of contaminating field stars on the following results is believed to be small.

Because the aim of this study is to inspect the 3D kinematic properties of the Praesepe cluster, only stars with RV measurements are extracted from the catalog. Here, we adopt only the RVs provided by Gaia to ensure homogeneity of the sample and avoid potentially significant systematic errors. Stars with uncertainties of RVs larger than 2 km s\(^{-1}\) are eliminated, in order to ensure accurate measurements of the RVs. Twenty
outliers are further rejected after checking the member stars one by one, as they possess RV values that significantly diverge from the three-times standard deviation of the reported mean RV of Praesepe (35.1 ± 1.6 km s\(^{-1}\); Loktin & Popov 2020). In total, a sample of 172 member stars of the Praesepe cluster is selected, as listed in Table 3 in the Appendix. If some of the member stars are in binary systems with spurious astrometric solutions, they might affect the kinematics of an OC derived from the astrometric measurements and RVs of the member stars. For close binary stars, the reliability of the astrometry and RVs provided by Gaia EDR3 has been improved in comparison with Gaia DR2 (Seabroke et al. 2021). As discussed by Gaia Collaboration et al. (2021), a value of the parameter ipd\_gof\_harmonic\_amplitude above 0.1 in combination with ruwe being larger than 1.4 are indicators of a source that is non-single and not correctly handled in the astrometric solution. We do not find such sources in our selected member stars of Praesepe after inspecting these two parameters. For the member stars in the sample, the median uncertainties of the parallaxes, proper motions \(\mu_x^*\) and \(\mu_y\) are 0.02 mas, 0.02 mas yr\(^{-1}\), and 0.015 mas yr\(^{-1}\), respectively. The median uncertainty for the RV measurements is 0.9 km s\(^{-1}\).

Figure 1 shows the distributions of the astrometric parameters (R.A., Decl., \(\varpi\), \(\mu_x^*\), \(\mu_y\), and RVs) of the member stars, including a color–magnitude diagram. It is shown that the observed parameters of the cluster member stars are approximated by a multidimensional normal distribution.

### 3. Methods

With the celestial positions, parallaxes, proper motions, and RVs given by Gaia EDR3, we can determine the 3D spatial coordinates \((x_g, y_g, z_g)\) and the 3D velocity components \((v_{xg}, v_{yg}, v_{zg})\) of the cluster members (Xu et al. 2013; Reid et al. 2019). The calculations are in the Galactic Cartesian coordinate system \((O_g–X_g, Y_g, Z_g)\). The origin of coordinates \(O_g\) is in the Galactic center. In this step, the distances of sources are derived by inverting the trigonometric parallaxes. The position and velocity uncertainties are estimated with a Monte Carlo method by taking into account the observation errors of astrometric parameters but without considering the covariances between the parallaxes and proper motions. At the location of the Sun, the \(X_g\)-axis points to the Galactic center, the \(Y_g\)-axis toward the direction of the Galactic rotation, and the \(Z_g\)-axis toward the north Galactic pole. The circular rotation speed at the Sun’s position is adopted as 236 ± 7 km s\(^{-1}\), and the Sun is at a distance of 8.15 ± 0.15 kpc to the Galactic center (Reid et al. 2019). The three velocity components of the solar motion, i.e., toward the Galactic center \((U_\odot, V_\odot, W_\odot)\), in the direction of Galactic rotation \((V_\odot)\), toward the north Galactic North Pole \((W_\odot)\), are adopted as \((U_\odot, V_\odot, W_\odot) = (10.6 ± 1.2, 10.7 ± 6.0, 7.6 ± 0.7)\) km s\(^{-1}\) (Reid et al. 2019).

By defining the OC center as the origin of coordinates, a new Cartesian coordinate system \((O_c–X_c, Y_c, Z_c)\) can be established. The OC center and its uncertainty in the Galactic coordinate system come from the means and standard deviations of the astrometric parameters of the selected member stars by performing Monte Carlo simulations. The 3D spatial coordinates \((x_c, y_c, z_c)\) and the 3D velocity components \((v_{xc}, v_{yc}, v_{zc})\) of a member star in this coordinate system can be calculated as:

\[
\begin{align*}
(x_g, y_g, z_g) &= (X_g, Y_g, Z_g) - (x_c, y_c, z_c), \\
(v_{xg}, v_{yg}, v_{zg}) &= (v_{xc}, v_{yc}, v_{zc}).
\end{align*}
\]

where \((x_{gc}, y_{gc}, z_{gc})\) are the coordinates of the cluster center and \((v_{xgc}, v_{yc}, v_{zgc})\) represent the 3D systemic velocities of the cluster in the Galactic Cartesian coordinate system. The vectors \((v_{xc}, v_{yc}, v_{zc})\) are therefore the 3D residual velocities of a member star.

As shown in Figure 2, if a cluster does rotate, the rotation axis \(\vec{l}\) of the cluster in the \((O_c–X_c, Y_c, Z_c)\) system can be determined from the three position angles (PAs), \(\alpha\), \(\beta\), and \(\gamma\). Here, the vector \(\vec{l}\) across the origin \(O_c\) has a positive direction above the \(X_c–Y_c\) plane. Based on the observational data, these angles can be fitted by a residual velocity method adopted in many previous studies (e.g., Bellazzini et al. 2012; Lanzoni et al. 2013; Ferraro et al. 2018; Lanzoni et al. 2018; Loktin & Popov 2020; Leanza et al. 2022). In the following, we describe the procedure to determine the angle \(\alpha\):

1. The projection of the rotation axis \(\vec{l}\) on the \(Y_c–Z_c\) plane, \(l_{yz}\), will divide the cluster members into two subsamples (Figure 2). If the cluster does rotate, the mean residual velocities \(v_{z}\) of the member stars of the two different subsamples should present opposite signs.
2. Staring from the \(Y_c\)-axis \((\alpha = 0^\circ)\), the projection of the rotation axis on the \(Y_c–Z_c\) plane, \(l_{yz}\), rotates counterclockwise with an increase of \(\alpha\). A series of the mean residual velocities \(v_{z}\) for the member stars of the two
Those of the Rotational Cartesian Coordinate System

As shown in Figure 2, the Astrophysical Journal, construct a rotational Cartesian coordinate system

\[ \mathbf{O}_{r}-X_{r}, Y_{r}, Z_{r} \] for the cluster, where the origin of coordinates \( \mathbf{O}_{r} \) is located at the cluster center. The \( Z_{r} \)-axis is in accordance with the rotation axis \( \hat{I} \). The projection of the \( X_{r} \)-axis in the \( X_{r}-Y_{r} \) plane is set to be consistent with the projection \( l_{Y} \) of \( \hat{I} \) (Figure 2). Therefore, the vectors of \( X_{r} \)-axis, \( Y_{r} \)-axis, and \( Z_{r} \)-axis in the Cartesian coordinate system \((O_{r}-X_{r}, Y_{r}, Z_{r})\) can be determined by the angles of \( \alpha \), \( \beta \), and \( \gamma \), i.e.:

\[
\begin{align*}
\mathbf{O}_{r}X_{r} &= (1, \tan \gamma, -\frac{1 + \tan^2 \gamma}{\tan \beta}), \\
\mathbf{O}_{r}Y_{r} &= (-\tan \gamma, 1, 0), \\
\mathbf{O}_{r}Z_{r} &= (1, \frac{1}{\tan \beta}, \frac{1}{\tan \alpha}, 1).
\end{align*}
\]

The 3D coordinates and 3D velocity components in the \((O_{r}-X_{r}, Y_{r}, Z_{r})\) system are related to those in the \((O_{r}-X_{r}, Y_{r}, Z_{r})\) system by:

\[
\begin{align*}
ox &= \cos \alpha_{1} \cos \beta_{1} \cos \gamma_{1} x_{r} + \cos \alpha_{2} \cos \beta_{2} \cos \gamma_{2} y_{r} + \cos \alpha_{3} \cos \beta_{3} \cos \gamma_{3} z_{r}, \\
y &= \cos \alpha_{1} \cos \beta_{1} \sin \gamma_{1} x_{r} + \cos \alpha_{2} \cos \beta_{2} \sin \gamma_{2} y_{r} + \cos \alpha_{3} \cos \beta_{3} \sin \gamma_{3} z_{r}, \\
z &= \sin \alpha_{1} \sin \beta_{1} x_{r} + \sin \alpha_{2} \sin \beta_{2} y_{r} + \sin \alpha_{3} \sin \beta_{3} z_{r}, \\
v_{x} &= \cos \alpha_{1} \cos \beta_{1} \cos \gamma_{1} v_{x_{r}} + \cos \alpha_{2} \cos \beta_{2} \cos \gamma_{2} v_{y_{r}} + \cos \alpha_{3} \cos \beta_{3} \cos \gamma_{3} v_{z_{r}}, \\
v_{y} &= \cos \alpha_{1} \cos \beta_{1} \sin \gamma_{1} v_{x_{r}} + \cos \alpha_{2} \cos \beta_{2} \sin \gamma_{2} v_{y_{r}} + \cos \alpha_{3} \cos \beta_{3} \sin \gamma_{3} v_{z_{r}}, \\
v_{z} &= \sin \alpha_{1} \sin \beta_{1} v_{x_{r}} + \sin \alpha_{2} \sin \beta_{2} v_{y_{r}} + \sin \alpha_{3} \sin \beta_{3} v_{z_{r}}.
\end{align*}
\]

\[ \begin{array}{c}
x_{r} = \cos \alpha \cos \beta \cos \gamma \\
y_{r} = \cos \alpha \cos \beta \sin \gamma \\
z_{r} = \sin \alpha \sin \beta \\
v_{x_{r}} = \cos \alpha \cos \beta \cos \gamma v_{x} \\
v_{y_{r}} = \cos \alpha \cos \beta \sin \gamma v_{y} \\
v_{z_{r}} = \sin \alpha \sin \beta v_{z}
\end{array} \]

Here, \( \alpha \), \( \beta \), and \( \gamma \) are the included angles listed in Table 1.

The cylindrical coordinate system \((r, \varphi, z)\) is more convenient to study the rotational properties of stellar clusters (e.g., Lanzoni et al. 2018), which is adopted in the following analysis. The transformation equations from Cartesian coordinates to cylindrical coordinates are:

\[
\begin{align*}
r &= \sqrt{x_{r}^{2} + y_{r}^{2}}, \\
\varphi &= \tan^{-1} \frac{y_{r}}{x_{r}}, \\
z &= z_{r}, \\
v_{r} &= \cos \varphi v_{x} + \sin \varphi v_{y}, \\
v_{\varphi} &= -\sin \varphi v_{x} + \cos \varphi v_{y}, \\
v_{z} &= v_{z}.
\end{align*}
\]

4. Results

4.1. Rotation in Praesepe

According to the astrometric parameters of the 172 member stars (see Section 2), the means and standard deviations of the fundamental parameters of Praesepe are determined as \((R.A.,\) decl.) = \((129^2 85^1 251, 19^2 52^1 1749), \) \(\varpi = 5.41 \pm 0.20\) mas, proper motions \((\mu_{\alpha}, \mu_{\delta}) = (35.82 \pm 1.54, -12.79 \pm 1.09)\) mas yr\(^{-1}\), and \(RV = 35.1 \pm 1.4 \) km s\(^{-1}\), which are in good agreement with previous determinations (e.g., Gaia Collaboration et al. 2018a; Gao 2019; Lodieu et al. 2019; Roser & Schilbach 2019; Loktin & Popov 2020). Here, these parameters do not take into account the measurement errors as weights. After applying a Monte Carlo simulation to the means and standard deviations of the parameters from the selected member stars with 3D kinematic measurements, we obtain the center, systemic motion, and the corresponding uncertainties of Praesepe in the Galactic coordinate system. For each of the member stars, we first calculate its 3D coordinates, 3D velocities, as well as the uncertainties in the Galactic Cartesian coordinate system, then transform them to the \((O_{r}-X_{r}, Y_{r}, Z_{r})\) system according to Equations (1) and (2).

To investigate the rotation and estimate the rotation axis as well as velocity of the Praesepe cluster, we calculate the mean residual velocity of the member stars as a function of the PA following the method described in Section 3. A Monte Carlo method is used to estimate the uncertainties. A step length of 5° for the PA is adopted in the calculation. The mean residual velocities for the first half of the member stars correspond to PAs from 5° to 180°, and that of the second half correspond to PAs from 180° to 360°. Figures 3(a), (b), and (c) present the mean residual velocity of all the member stars as a function of the PA for \(v_{x_{r}}, v_{y_{r}}, \) and \(v_{z_{r}}\), respectively. The results for those member stars within the tidal radius are shown in Figures 3(d), (e), and (f) for comparison. They all present sinusoidal behaviors, which indicate the rotation of the Praesepe system.

Here the adopted tidal radius of Praesepe is 10 pc. The best-fitting PAs \(\alpha, \beta, \gamma\) with all the member stars in the sample are \(\alpha = 139^2 9 \pm 2^2 9, \beta = 152^2 2 \pm 6^2 4, \) and \(\gamma = 210^2 2 \pm 1^2 5\), respectively. In comparison, the obtained PAs based on the member stars within the tidal radius are \(\alpha = 120^2 8 \pm 4^2 5, \beta = 118^2 1 \pm 16^2 5, \) and \(\gamma = 211^2 2 \pm 7^2 8\), respectively. These fitted PAs satisfy the relation of tan \(\alpha \times \tan \gamma = \tan \beta\) considering the uncertainties.

Member stars beyond the tidal radius are no longer simply controlled by the cluster itself, but influenced by the gravitational force of the Galaxy. Actually, most OCs cross the Galactic plane several times in one orbital period (e.g., Wu et al. 2009). Taking this into account, we adopt the best-fitting PAs from the member stars within the cluster tidal radius in the following analysis. Considering the relation tan \(\alpha \times \tan \gamma = \tan \beta\) considering the uncertainties.
β, the PAs of (α, β, γ) = (120°.8, 134°.5, 211°.2) are adopted in this study to derive the (r, ϕ, z) and (vr, vϕ, vz) of the member stars in the cylindrical coordinate system. The corresponding uncertainties are estimated by a Monte Carlo method. The angle between the rotation axis of the Praesepe cluster and the Galactic plane is estimated to be 41° ± 12°. Meanwhile, based on the rotational velocities of the member stars, the mean rotational velocity of Praesepe within its tidal radius is estimated to be 0.2 ± 0.05 km s⁻¹, which is concordant with the properties shown in Figures 3(d), (e), and (f). Here, the error bars (gray), as well as the best-fitting sine functions (red) are also shown in the plots.

Figure 3. Mean residual velocities of vx, vy, and vz as a function of the PA are shown in panels (a), (b), and (c), respectively, for all the member stars. The results given in panels (d), (e), and (f) are similar to those of the left column, but are derived from member stars within the tidal radius of Praesepe. The error bars (gray), as well as the best-fitting sine functions (red) are also shown in the plots.
bar is the uncertainty of the mean rotational velocity, obtained through a Monte Carlo simulation.

Generally, dense molecular cores are the nurseries of embedded clusters, which are the predecessors of OCs (e.g., Lada & Lada 2003). Hydrodynamical simulations show that the stellar component of the embedded cluster can inherit the rotational signature from the parent gas and the rotation is common for embedded clusters (Mapelli 2017). The rotation of Praesepe probably originates from the rotational characteristic of its progenitor embedded cluster. From the derived rotational velocities of the member stars, it is shown that not all the member stars rotate in the same direction, although this may be partially influenced by the astrometric measurement uncertainties. Such phenomenon also occurs in the rotations of global clusters (e.g., Lanzoni et al. 2018; Leanza et al. 2022). OCs are the survivors of hierarchical or substructured protoclusters that gestated in molecular clouds. Many stellar feedback mechanisms play important roles in the formation of protoclusters, such as protostellar outflows, stellar radiation pressure, stellar winds from massive stars, etc. Mutual interference during stellar cluster formation may result in that not all the member stars of Praesepe neatly rotate in the same direction.

4.2. Rotational Properties of the Stars in Praesepe

Figure 4 shows the rotational velocities \( v_\phi \) of the cluster members as a function of the distance \( r \) from the cluster center. A Monte Carlo method is used to estimate the uncertainties. The reference value of the tidal radius of Praesepe is adopted as 10 pc. Inside the tidal radius (10 pc) of the Praesepe cluster, we find that the member stars in the inner region have slightly larger rotational velocities than those in the outer region. Near or beyond the tidal radius of Praesepe, the rotational velocities of the member stars tend to present large dispersion, which may be due to these stars being partially influenced by the Galactic tidal force, rather than simply dominated by the gravitational force of the cluster itself. Inside the tidal radius, there are several stars with peculiar rotational velocities that deviate significantly from the main part, which may be “passing through” stars and not bona fide members of the Praesepe cluster.

The kinematic property of stars in an OC, e.g., whether the rotations of member stars follow Newton’s classical theorems, is an interesting question that has not been well addressed. This issue can be explored by comparing observational results with the theoretical expectations of Newton’s theorems. In the following, we primarily analyze the properties of \( v_\phi \) of the member stars within the tidal radius of Praesepe. First, assuming that the OC system follows a spherically symmetric density distribution, then the gravitational potential at the radius \( r \) is:

\[
\Phi(r) = -4\pi G \left[ \frac{1}{r} \int_0^r \rho(r') r'^2 dr' + \int_r^\infty \rho(r') r' dr' \right].
\]  

The asymmetry assumption of the data distribution is evaluated by calculating the skewness of the sample. The skewness of any perfectly symmetric distribution is zero. If the skewness is between \(-0.50 \) and \(0.50\), the data are suggested to be fairly symmetrical. The Pearson’s moment coefficients of skewness of the Galactic longitude, latitude, and parallaxes of all the member stars within the tidal radius of Praesepe are 0.01, \(-0.13\), and 0.11, respectively. The results indicate that the stars in the parent catalog described in Section 2 present a well-described spherically symmetric distribution. For the selected 172 member stars with 3D kinematic measurements, the corresponding skewness coefficients are 0.28, \(-0.35\), and 0.15, respectively, which are slightly larger than those of the parent sample but still show a good spherically symmetric distribution.

From Newton’s theorems, the gravitational attraction of the system at \( r \) is entirely determined by the mass interior to \( r \), i.e.:

\[
\begin{align*}
F(r) &= -\frac{d\Phi}{dr} \hat{e}_r = \frac{GM(r)}{r^2} \hat{e}_r, \\
M(r) &= 4\pi \int_0^r \rho(r') r'^2 dr'.
\end{align*}
\]  

Here, \( M(r) \) is the mass inside radius \( r \) and \( G = 4.3 \times 10^{-3} \) pc \( M_\odot^{-1} \) (km s\(^{-1}\))^2 is the gravitational constant. The circular speed \( v_c(r) \) of the system therefore can be calculated by:

\[
v_c^2(r) = r \frac{d\Phi}{dr} = r |\mathbf{F}| = \frac{GM(r)}{r}.
\]  

Here, this formula is used in an attempt to describe the rotational property of Praesepe, since its rotation has been identified. Although individual stars may not present perfectly circular motion, we can try to make an approximate comparison between the rms rotational velocity derived from cluster members and the theoretical expectation from Equation (10). Actually, many of the member stars may have residual radial motions, as discussed in the next subsection. The same as Roser & Schilbach (2019), the mass density of Praesepe adopted in this study is described by a Plummer model (Plummer 1915), which is:

\[
\rho(r) = \frac{3M}{4\pi r_{co}^3} \left[ 1 + \left( \frac{r}{r_{co}} \right)^2 \right]^{-3/2}.
\]  

Here, \( M \) is the total mass inside the tidal radius of Praesepe and \( r_{co} \) is the core radius. Then, \( M(r) \) and the corresponding circular
rms rotational velocities. Equation (13) after considering the possible ranges of the tidal mass and the core radius of Praesepe. The red line is the best-fitting curve to the observed rms rotational velocities.

$$v_c(r) = \sqrt[3]{\frac{GM_r}{r^2 + r_{co}^2}} \cdot \frac{r^2}{(r^2 + r_{co}^2)^{3/2}}$$

The tidal mass $M_t$ and the core radius $r_{co}$ of Praesepe have been determined by many research works. The estimated value of $M_t$ is in the range [483, 630] $M_{\odot}$ (e.g., Holland et al. 2000; Adams et al. 2002; Kraus & Hillenbrand 2007; Wang et al. 2014; Gao 2019; Roser & Schilbach 2019). The core radius $r_{co}$ is in the range [1.6, 3.7] pc (e.g., Roser & Schilbach 2019; Mermilliod et al. 1990; Adams et al. 2002; Gao 2019; Lodieu et al. 2019). The differences between the theoretical circular velocities derived from different tidal masses are not very significant, less than 0.1 km s$^{-1}$, and the maximum difference for the derived core radius is $\sim 0.3$ km s$^{-1}$. According to the ranges of $M_t$ and $r_{co}$, the possible theoretical circular velocity curves are calculated and shown in Figure 5.

For member stars inside the tidal radius of Praesepe, the median absolute value of their rotational velocities is $\sim 0.5$ km s$^{-1}$, and the standard deviation of $v_\varphi$ is $\sim 1.0$ km s$^{-1}$. We notice that there are eight stars with $v_\varphi$ larger than 2.0 km s$^{-1}$, which deviate from those of the vast majority of the member stars. In order to reduce the influence of stars with peculiar rotational velocities and investigate the features indicated by the vast majority of the member stars, cluster members with values of $v_\varphi$ smaller than 2.0 km s$^{-1}$ are extracted from the sample and divided into several bins. Then, we calculate the rms rotational velocity of the member stars in each bin. Monte Carlo simulations are used to estimate the uncertainties. The results are shown in Table 2 and Figure 5. The derived rms rotational velocities are in agreement with the theoretical values. By fitting the rms velocities listed in Table 2 with Equation (13), we obtain a core radius of 1.6 $\pm$ 0.5 pc and a tidal mass of 537 $\pm$ 146 $M_{\odot}$ for the Praesepe cluster. The uncertainties are estimated by the Monte Carlo method. The best-fitting rms velocity curve shown in Figure 5 also indicates that the rotation of member stars within the tidal radius of Praesepe probably follow Newton’s theorems. Besides, according to the best-fitting curve, the member stars at the periphery of the Praesepe cluster may have rotational velocities of about 0.4 km s$^{-1}$.

### 4.3. Absence of Expansion or Contraction

As an OC emerges from its natal cloud, it can expand for a long period before reaching an equilibrium state (e.g., Lada & Lada 2003). The age of Praesepe is about 590–660 Myr (e.g., Mermilliod 1981; Vandenberg & Bridges 1984; Delorme et al. 2011; Brandt & Huang 2015; Gossage et al. 2018). It is not sure whether the Praesepe cluster is still expanding.

The expansion or contraction of Praesepe can be understood by a statistical analysis of the radial component $v_r$ of the member stars perpendicular to the rotation axis. Figure 6 shows the radial components of the cluster members within two times the tidal radius (10 pc) of Praesepe as a function of the distance $r$ from the cluster center, which does not present a visible indication of expansion or contraction. In addition, the mean radial component $v_r$ of the member stars within 5 pc, 10 pc, and 20 pc of the cluster center is $-0.01$ km s$^{-1}$, $0.01$ km s$^{-1}$, and $-0.02$ km s$^{-1}$, with uncertainties of 0.06 km s$^{-1}$, 0.05 km s$^{-1}$, and 0.05 km s$^{-1}$, respectively. Here, the error bars are the uncertainties on the mean, obtained through Monte Carlo
simulations. The mean radial components are close to zero, which show that there is no significant indication of expansion or contraction for the Praesepe cluster, implying that the rotation of member stars within the tidal radius of Praesepe present a closed-loop motion. Figure 6 also implies that there is a non-negligible RV acceleration and RV dispersion contribution due to the support of the cluster, although the RV dispersion is partially influenced by the astrometric measurement uncertainties. The absence of expansion or contraction of Praesepe suggests that the cluster system should possess additional mass to provide force for supporting the RV acceleration of the member stars. It is speculated that the derived dynamic mass in Section 4.2 is a lower limit for the Praesepe cluster.

5. Summary

In this work, we explored the kinematic properties of Praesepe, the only OC in the Milky Way whose rotation has been investigated exclusively. Based on the high-precision astrometric data set of Gaia EDR3, the rotation in the Praesepe cluster and its rotation axis in the Galaxy were determined by analyzing the 3D residual velocities of cluster members for the first time. Our developed methodology also derived the rotational velocity components of the member stars, suggesting that the member stars within the tidal radius of the Praesepe cluster probably also conform to the theorems of Newtonian mechanics. Additionally, the current results suggest no significant indication of expansion or contraction for Praesepe.

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Appendix

Table 3 presents the astrometric parameters and errors of examples of selected member stars with 3D kinematic measurements in this work.

| Gaia ID | α (deg) | δ (deg) | l (deg) | b (deg) | μα∗ (mas yr⁻¹) | μδ (mas yr⁻¹) | G (mag) | bp–rp (mag) | V_r (km s⁻¹) |
|--------|---------|---------|---------|---------|----------------|--------------|--------|------------|-------------|
| 660944717521395840 | 131.07 | 18.74 | 207.34 | 33.02 | 5.43 ± 0.02 | −35.98 ± 0.02 | −11.63 ± 0.02 | 12.07 | 1.06 | 33.66 ± 0.71 |
| 660954067664386944 | 131.32 | 18.89 | 207.27 | 33.30 | 5.54 ± 0.02 | −37.62 ± 0.02 | −12.54 ± 0.02 | 9.52 | 0.57 | 34.54 ± 0.54 |
| 660957980380034688 | 130.95 | 18.80 | 207.22 | 32.93 | 5.40 ± 0.02 | −36.14 ± 0.02 | −11.78 ± 0.01 | 9.98 | 0.64 | 36.67 ± 1.89 |
| 6609628675934768 | 130.98 | 18.89 | 207.12 | 32.99 | 5.42 ± 0.02 | −36.34 ± 0.02 | −12.80 ± 0.01 | 12.39 | 1.15 | 33.96 ± 0.85 |
| 660998317844267264 | 130.20 | 18.90 | 206.80 | 32.30 | 5.34 ± 0.02 | −36.69 ± 0.04 | −12.92 ± 0.03 | 11.27 | 0.89 | 35.87 ± 0.40 |

Note: The full table is available online.

(This table is available in its entirety in machine-readable form.)
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