Kinematic Properties of Open Star Clusters with Data from the Gaia DR2 Catalogue

V.V. Bobylev and A.T. Bajkova

Pulkovo Astronomical Observatory, Russian Academy of Sciences, Pulkovskoe sh. 65, St. Petersburg, 196140 Russia

Abstract—We consider open star clusters (OSCs) with the proper motions, parallaxes, and line-of-sight velocities calculated by various authors from Gaia DR2 data. The distance scale factor has been found by analyzing the separate solutions of the basic kinematic equations to be $p = 1.00 \pm 0.04$. It shows that the distances calculated using the parallaxes from the Gaia DR2 catalogue do not need any correction factor. We have investigated the solutions obtained from various OSC samples differing in both age and accuracy of their parallax and line-of-sight velocity measurements. The solution obtained from a sample of 930 OSCs satisfying the constraints on the age $\log t < 9$ and the relative trigonometric parallax error <30% is recognized to be the best one, with 384 OSCs in this sample having the mean line-of-sight velocities calculated from at least three probable members of the corresponding clusters. As a result of the simultaneous solution of all the basic kinematic equations, we have found the following kinematic parameters from this sample: $(U, V, W)_\odot = (8.53, 11.22, 7.83) \pm (0.38, 0.46, 0.32)$ km s$^{-1}$, $\Omega_0 = 28.71 \pm 0.22$ km s$^{-1}$ kpc$^{-1}$, $\Omega'_0 = -4.100 \pm 0.058$ km s$^{-1}$ kpc$^{-2}$, and $\Omega''_0 = 0.736 \pm 0.033$ km s$^{-1}$ kpc$^{-3}$. The linear rotation velocity at the adopted solar distance $R_0 = 8 \pm 0.15$ kpc is $V_0 = 229.7 \pm 4.6$ km s$^{-1}$. An analysis of the proper motions for these 930 OSCs has shown that, apart from the rotation around the Galactic $z$ axis, there is rotation of the entire sample around the $x$ axis with an angular velocity of $0.48 \pm 0.15$ km s$^{-1}$ kpc$^{-1}$ differing significantly from zero.

INTRODUCTION

Open star clusters (OSCs) play an important role in studying the Galaxy and its subsystems, because they have a high accuracy of the mean values of a number of kinematic and photometric parameters. The accuracy of the distances, proper motions, and line-of-sight velocities of OSCs is of great importance here.

The Gaia DR2 catalogue containing the trigonometric parallaxes and proper motions of $\sim 1.3$ billion stars was published in 2018 (Brown et al. 2018; Lindegren et al. 2018). The mean parallax errors lie in the range 0.02–0.04 milliarcseconds (mas) for bright ($G < 15^m$) stars and reach 0.7 mas for faint ($G = 20^m$) stars. For more than 7 million stars of spectral types F–G–K the line-of-sight velocities were measured with a mean error of $\sim 1$ km s$^{-1}$.

Using these up-to-date data is of great importance for studying the kinematics of stars and clusters. Based on them, the structural and kinematic parameters of a large number of OSCs have been refined (Babusiaux et al. 2018; Kuhn et al. 2018; Cantat-Gaudin et al. 1

\[1\] e-mail: vbobylev@gaoran.ru
2018), the properties of a number of young stellar associations (Zari et al. 2018; Franciosini et al. 2018; Roccatagliata et al. 2018; Kounkel et al. 2018) and OSCs (Soubiran et al. 2018; Dias et al. 2018) close to the Sun have been analyzed, and new OSCs have been detected (Beccari et al. 2018). It is also interesting to note a recent review by Krumholz et al. (2018), where the current status of research on the long-term evolution of clusters is reflected.

The kinematics of OSCs with the proper motions and trigonometric parallaxes calculated from Gaia DR2 data was analyzed in Bobylev and Bajkova (2019), where the mean line-of-sight velocities of clusters were taken mostly from the MWSC (Milky Way Star Clusters) catalogue (Kharchenko et al. 2013). A catalogue by Soubiran et al. (2018), where new mean values of the line-of-sight velocities were calculated exclusively from the Gaia DR2 catalogue, has recently been published. Using these data to determine the Galactic rotation parameters and to solve other stellar-astronomy problems is of great interest.

This paper is a continuation of the study by Bobylev and Bajkova (2019) based on new mean values of the line-of-sight velocities for OSCs, with great attention being given to studying the quality of the new line-of-sight velocities for OSCs, the quality of the distance scale, and the systematics of the Gaia DR2 catalogue.

**METHOD**

We know three stellar velocity components from observations: the line-of-sight velocity \( V_\varpi \), and the two tangential velocity components \( V_l = 4.74r \mu_1 \cos b \) and \( V_b = 4.74r \mu_b \) along the Galactic longitude \( l \) and latitude \( b \), respectively, expressed in \( \text{km s}^{-1} \). 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, and \( r \) is the stellar heliocentric distance in kpc. The proper motion components \( \mu_l \cos b \) and \( \mu_b \) are expressed in mas yr\(^{-1} \). To determine the parameters of the Galactic rotation curve, we use the equations derived from Bottlinger’s formulas, in which the angular velocity \( \Omega \) is expanded into a series to terms of the second order of smallness in \( r/R_0 \):

\[
V_\varpi = -U_\odot \cos b \cos l - V_\odot \cos b \sin l - \omega_\odot \sin b + R_0(R - R_0) \sin l \cos b \varpi_0' + 0.5R_0(R - R_0)^2 \sin l \cos b \varpi_0'',
\]

\[
V_l = U_\odot \sin l - V_\odot \cos l - r \omega_0 \cos b \\
+ (R - R_0)(R_0 \cos l - r \cos b) \varpi_0' + 0.5(R - R_0)^2(R_0 \cos l - r \cos b) \varpi_0'' \\
- r \cos l \sin b \omega_1 - r \sin l \sin b \omega_2,
\]

\[
V_b = U_\odot \cos l \sin b + V_\odot \sin l \sin b - \omega_\odot \cos b \\
- R_0(R - R_0) \sin l \sin b \varpi_0' - 0.5R_0(R - R_0)^2 \sin l \sin b \varpi_0'' \\
+ r \sin l \omega_1 - r \cos l \omega_2,
\]

where \( R \) is the distance from the star to the Galactic rotation axis:

\[
R^2 = r^2 \cos^2 b - 2R_0r \cos b \cos l + R_0^2.
\]

The quantity \( \Omega_0 \) is the angular velocity of Galactic rotation at the solar distance \( R_0 \), the parameters \( \varpi_0' \) and \( \varpi_0'' \) are the corresponding derivatives of this angular velocity, and the linear rotation velocity of the Galaxy is \( V_0 = |R_0 \Omega_0| \).

A periodicity with a wavelength of 2–3 kpc, which is attributable to the influence of the Galactic spiral density wave, is known to be observed (see, e.g., Rastorguev et al. 2017) on
the Galactic rotation curve whose parameters are determined from sufficiently young disk objects. Therefore, in the first step it is convenient to have a smooth Galactic rotation curve (which is provided by expanding the angular velocity of rotation to the second order) and then to study the influence of perturbations from the spiral density wave separately. This approach was applied in Bobylev and Bajkova (2018b, 2019).

Apart from the rotation around the Galactic $z$ axis (described by the parameter $\Omega$), here we also consider the angular velocities of rotation around the $x$ and $y$ axes described by the parameters $\omega_1$ and $\omega_2$, respectively. Note that the parameters $\omega_1$ and $\omega_2$ can be found only from Eqs. (2) and (3). Young thin disk OSCs with small values of $\sin b$ constitute the bulk of objects in our list. The application of Eq. (3) is inefficient in searching for $\Omega'_0$ and $\Omega''_0$ based on young objects. However, Eq. (3) is of great interest in searching for the parameters $\omega_1$ and $\omega_2$, because here there is no factor $\sin b$ at these two unknowns.

We know a number of present-day studies devoted to determining the mean distance from the Sun to the Galactic center using its individual determinations in the last decade by independent methods. For example, $R_0 = 8 \pm 0.2$ kpc (Vallée 2017), $R_0 = 8.4 \pm 0.4$ kpc (de Grijs and Bono 2017), or $R_0 = 8.0 \pm 0.15$ kpc (Camarillo et al. 2018). Based on these reviews, here we adopted $R_0 = 8 \pm 0.15$ kpc.

The kinematic parameters are determined by solving the conditional equations (1)–(3) by the least-squares method (LSM). We use weights of the form $w_r = S_0/\sqrt{S_0^2 + \sigma_{Vr}^2}$, where $S_0$ is the “cosmic” dispersion, $\sigma_{Vr}$ and $\sigma_{Vl}$ are the dispersions of the corresponding observed velocities. $S_0$ is comparable to the root-mean-square residual $\sigma_0$ (the error per unit weight) that is calculated when solving the conditional equations (1)–(3). $S_0$ depends strongly on the age of objects; in this paper we assign it to be close to the value corresponding to the error per unit weight $\sigma_0$ found in advance. The LSM solutions were sought in two iterations with the elimination of the residuals according to the $3\sigma$ criterion.

**DATA**

**Proper Motions and Line-of-Sight Velocities of OSCs**

The main source of the mean proper motions and parallaxes calculated from Gaia DR2 data for us was the paper by Cantat-Gaudin et al. (2018), where these quantities were determined for 1229 OSCs. The parameters of several more OSCs were taken from Babusiaux et al. (2018), where they were calculated only from Gaia DR2 data based on a large number of most probable cluster members.

We took the mean heliocentric line-of-sight velocities of 953 OSCs from the MWSC (Milky Way Star Clusters) catalogue (Kharchenko et al. 2013) and, in several cases, from Kuhn et al. (2018), Babusiaux et al. (2018), Casamiquela et al. (2016), Conrad et al. (2014), and Mermilliod et al. (2008). In addition, we used the line-of-sight velocities of 861 OSCs calculated by Soubiran et al. (2018) exclusively from Gaia DR2 data.

Quite a few OSCs with measured line-of-sight velocities are common to MWSC and Soubiran et al. (2018). As the comparison of these and other catalogues made by Soubiran et al. (2018) showed, the quality of the line-of-sight velocities for OSCs calculated from Gaia DR2 data depends very strongly on the number of stars in each cluster used for averaging. There is significant disagreement with other measurements. For example, in some cases, the line-of-sight velocity differences $|\Delta V_r|$ can exceed 50 km s$^{-1}$ (Fig. 5 in Soubiran et al.
Nevertheless, Soubiran et al. (2018) identified ∼400 OSCs with a high quality of the line-of-sight velocities (their mean error is 0.5 km s$^{-1}$) calculated, on average, from seven stars.

Bobylev and Bajkova (2019) determined the Galactic rotation and spiral density wave parameters based on a sample of young OSCs from the catalogue by Cantat-Gaudin et al. (2018), where the line-of-sight velocities exclusively from the MWSC catalogue was used. In this paper we give preference to the line-of-sight velocities from Soubiran et al. (2018). Thus, only if there is no line-of-sight velocity in the list by Soubiran et al. (2018) do we take its value from the MWSC catalogue.

The age estimates for the overwhelming majority of OSCs were taken from the MWSC catalogue (Kharchenko et al. 2013). In isolated cases, we invoked the estimates from the WEBDA electronic database (https://www.univie.ac.at/webda/). Less than 100 OSCs have no age estimates, 60 of them are recently discovered Gulliver clusters (Cantat-Gaudin et al. 2018).

In this paper, in total, we consider OSCs with relative parallax errors $\sigma_\pi/\pi < 30\%$, where the dispersions $\sigma_\pi$ were taken from column 109 in the catalogue by Cantat-Gaudin et al. (2018). There are a total of 1052 such OSCs of various ages with measured proper motions and parallaxes and 863 of them also have line-of-sight velocity estimates.

**Correction to the Gaia DR2 Parallaxes**

The presence of a systematic offset $\Delta \pi = -0.029$ mas in the Gaia DR2 parallaxes with respect to an inertial reference frame was first pointed out by Lindegren et al. (2018). Here the minus means that the correction should be added to the Gaia DR2 stellar parallaxes to reduce them to the standard. Arenou et al. (2018) compared the Gaia DR2 parallaxes with 29 independent distance scales that confirm the presence of an offset in the Gaia DR2 parallaxes $\Delta \pi \sim -0.03$ mas.

Stassun and Torres (2018) found the correction $\Delta \pi = -0.082 \pm 0.033$ mas by comparing the parallaxes of 89 detached eclipsing binaries with their trigonometric parallaxes from the Gaia DR2 catalogue.

By comparing the Gaia DR2 trigonometric parallaxes and photometric parallaxes of 94 OSCs, Yalyalieva et al. (2018) found the correction $\Delta \pi = -0.045 \pm 0.009$ mas. The high accuracy of this estimate is attributable to the high accuracy of the photometric distance estimates for OSCs obtained by invoking first-class infrared photometric surveys, such as IPHAS, 2MASS, WISE, and Pan-STARRS.

Riess et al. (2018) obtained an estimate of $\Delta \pi = -0.046 \pm 0.013$ mas based on a sample of 50 long-period Cepheids when comparing their parallaxes with those from the Gaia DR2 catalogue. The photometric parameters of these Cepheids measured from the Hubble Space Telescope were used.

By comparing the distances of ∼3000 stars from the APOKAS-2 catalogue (Pinsonneault et al. 2018) belonging to the red giant branch with the Gaia DR2 data, Zinn et al. (2018) found the correction $\Delta \pi = -0.053 \pm 0.003$ mas. These authors also obtained a close value $\Delta \pi = -0.050 \pm 0.004$ mas, by analyzing stars belonging to the red giant clump. The distances to such stars were estimated from asteroseismic data. According to these authors, the parallax errors here are approximately equal to the errors in estimating the stellar radius and are, on average, 1.5%. Such small errors in combination with the enormous number of stars allowed $\Delta \pi$ to be determined with a high accuracy.
Table 1: The Galactic rotation parameters found only from the line-of-sight velocities $V_r$ (Eq. (1)) based on OSCs of various ages with relative trigonometric parallax errors less than 15%.

| Parameters | All ages | $0 < \log t \leq 8$ | $8 < \log t \leq 9$ | $9 < \log t$ |
|------------|----------|----------------------|----------------------|----------------|
| $U_\odot$, km s$^{-1}$ | $11.4 \pm 0.8$ | $10.7 \pm 1.4$ | $11.7 \pm 1.1$ | $11.9 \pm 3.3$ |
| $V_\odot$, km s$^{-1}$ | $13.1 \pm 0.8$ | $13.4 \pm 1.5$ | $13.0 \pm 1.2$ | $13.1 \pm 3.2$ |
| $\Omega'_0$, km s$^{-1}$ kpc$^{-2}$ | $-3.97 \pm 0.10$ | $-3.85 \pm 0.19$ | $-4.05 \pm 0.14$ | $-3.85 \pm 0.38$ |
| $\Omega''_0$, km s$^{-1}$ kpc$^{-3}$ | $0.45 \pm 0.088$ | $0.49 \pm 0.23$ | $0.57 \pm 0.13$ | $0.27 \pm 0.21$ |
| $\sigma_0$, km s$^{-1}$ | $15.4$ | $14.2$ | $13.5$ | $20.4$ |
| $N_\star$ | $856$ | $273$ | $434$ | $110$ |

$N_\star$ is the number of clusters used.

The listed results lead to the conclusion that the trigonometric parallaxes of stars from the Gaia DR2 catalogue should be corrected by applying a small correction. We will be oriented to the results of Yalyalieva et al. (2018), Riess et al. (2018), and Zinn et al. (2018), which look most reliable. Thus, we apply a correction of 0.050 mas to all the original parallaxes of OSCs.

**RESULTS**

Table 1 gives the kinematic parameters derived by solving Eqs. (1) for various age groups. Note that the velocity $W_\odot$ is determined very poorly in this case of using only the line-of-sight velocities and, therefore, we eliminate it as a parameter being determined by taking it to be 7 km s$^{-1}$. OSCs with relative trigonometric parallax errors less than 15% were used here. We used all of the OSCs with a nonzero number of probable cluster members from which the mean line-of-sight velocities were calculated. In the case of nonzero line-of-sight velocities in two catalogues, MWSC and Soubiran et al. (2018), preference was given to the latter.

The error per unit weight $\sigma_0$ that we find when solving the conditional equations (1)–(3) characterizes the residual velocity dispersion for OSCs averaged over three directions. The residual velocity dispersion for hydrogen clouds in the Galactic disk is known to be $\sim 5$ km s$^{-1}$. The residual velocity dispersion for OB stars lies in the range 8–10 km s$^{-1}$. One might expect the velocity dispersion of relatively young OSCs, $0 < \log t \leq 8$, to be 8–10 km s$^{-1}$. However, for this sample of OSCs this quantity turned out to be considerably larger than the expected one, $\sigma_0 = 14.2$ km s$^{-1}$. To improve the quality of OSC samples with measured line-of-sight velocities, below we proceed as did Soubiran et al. (2018). More specifically, we use OSCs with the mean line-of-sight velocities calculated from at least three probable cluster members.

Table 2 gives the kinematic parameters derived by separately solving Eqs. (1) and (2) for various age groups. We used OSCs with relative trigonometric parallax errors less than 15%. When seeking a solution only from the line-of-sight velocities, we used OSCs with the mean values calculated from at least three probable cluster members. As can be seen from Table 2, with this approach the values of $\sigma_0$ determined from various types of velocities came closer together, although the values derived from the line-of-sight velocities slightly exceed those found from the proper motions.
Table 2: The Galactic rotation parameters found from OSCs of various ages with relative trigono-
metric parallax errors less than 15% 

| Parameters           | All ages    | $0 < \log t \leq 8$ | $8 < \log t \leq 9$ | $9 < \log t$  |
|----------------------|-------------|---------------------|---------------------|--------------|
| $U_\odot$, km s$^{-1}$ | $11.7 \pm 1.0$ | $9.0 \pm 1.4$       | $10.2 \pm 1.3$      | $15.1 \pm 4.3$ |
| $V_\odot$, km s$^{-1}$ | $13.1 \pm 1.0$ | $13.9 \pm 1.4$      | $13.4 \pm 1.5$      | $13.6 \pm 3.9$ |
| $\Omega_0$, km s$^{-1}$ kpc$^{-1}$ | $-3.99 \pm 0.14$ | $-4.05 \pm 0.23$    | $-4.21 \pm 0.19$    | $-3.87 \pm 0.46$ |
| $\Omega''_0$, km s$^{-1}$ kpc$^{-3}$ | $0.37 \pm 0.10$ | $1.18 \pm 0.37$     | $0.67 \pm 0.21$     | $0.21 \pm 0.23$ |
| $\sigma_0$, km s$^{-1}$ | $13.5$       | $9.4$                | $13.5$              | $20.3$       |
| $N_*$                | $456$        | $127$               | $238$               | $74$         |
| $U_\odot$, km s$^{-1}$ | $8.60 \pm 0.54$ | $7.68 \pm 0.63$     | $9.02 \pm 0.81$     | $11.7 \pm 2.4$ |
| $V_\odot$, km s$^{-1}$ | $9.36 \pm 0.70$ | $8.15 \pm 0.85$     | $10.59 \pm 1.03$    | $10.1 \pm 3.5$ |
| $\Omega_0$, km s$^{-1}$ kpc$^{-1}$ | $28.78 \pm 0.30$ | $29.70 \pm 0.36$    | $28.64 \pm 0.45$    | $29.2 \pm 1.2$ |
| $\Omega''_0$, km s$^{-1}$ kpc$^{-3}$ | $-3.988 \pm 0.081$ | $-4.061 \pm 0.036$  | $-4.107 \pm 0.123$  | $-3.67 \pm 0.34$ |
| $\sigma_0$, km s$^{-1}$ | $0.637 \pm 0.039$ | $0.677 \pm 0.032$   | $0.713 \pm 0.063$   | $0.40 \pm 0.12$ |
| $N_*$                | $1052$       | $345$               | $518$               | $122$        |
| $z_0$, pc            | $-10 \pm 5$  | $-21 \pm 4$         | $-14 \pm 5$         | $32 \pm 30$  |
| $\Omega''_0 V_* / (\Omega_0 V_*)$ | $1.00 \pm 0.04$ | $1.00 \pm 0.06$     | $1.03 \pm 0.05$     | $1.05 \pm 0.16$ |

The results obtained only from the line-of-sight velocities $V_*$ (Eq. (1)) and only from the component $V_\parallel$ (Eq. (2)) are given in the upper and lower parts, respectively, $N_*$ is the number of clusters used.

As an additional characteristic of the spatial distribution of the sample Table 2 gives the mean $z$ coordinate that is designated as $z_\odot$ and reflects the well-known fact of the Sun’s elevation above the Galactic plane. A review of its determinations can be found, for example, in Bobylev and Bajkova (2016), where $z_\odot = -16 \pm 2$ pc was found from several samples of young objects. As follows from Table 2, the values of $z_\odot$ found from OSCs with ages $\log t < 9.0$ are in good agreement with the known results. Only $z_\odot$ found from the sample of oldest OSCs agrees poorly with other determinations. Furthermore, the OSCs with a logarithm of the age more than nine have a very large error per unit weight, i.e., a large velocity dispersion; therefore, we do not use these OSCs below. An analysis of Tables 1 and 2 (mostly $\sigma_0$) also leads us to conclude that the Galactic rotation parameters are determined more accurately using only their proper motions than only their line-of-sight velocities.

The last row in Table 2 gives the ratio of the first derivative of the angular velocity found using only the line-of-sight velocities, $(\Omega''_0)_{V_*}$, to that found using only the proper motions, $(\Omega_0)_{V_*}$. This method is based on the fact that the errors in the line-of-sight velocities do not depend on the distance errors, while the errors in the tangential components depend on them. Therefore, comparing the values of $\Omega''_0$ found by various methods allows the correction factor of the distance scale $p$ to be found (Zabolotskikh et al. 2002; Rastorguev et al. 2017; Bobylev and Bajkova 2017a); in our case, $p = (\Omega''_0 V_*) / (\Omega_0 V_*)$. The error in $p$ was calculated based on the relation $\sigma_p^2 = (\sigma_{\Omega''_0 V_*} / \Omega''_0 V_*)^2 + (\sigma_{\Omega_0 V_*} \cdot \sigma_{\Omega''_0 V_*} / \Omega_0 V_*)^2$. Having analyzed more than 50 000 stars from the TGAS catalogue (Brown et al. 2016), Bobylev and Bajkova (2017a) obtained an estimate of $p = 0.97 \pm 0.04$ by this method. According to the results from Table 2, we can unambiguously conclude that the distance scale factor is equal to unity. Therefore, the distances used do not need any correction factor.
Figure 1: Radial (a), tangential (b), and vertical (c) velocities for the sample of 384 OSCs with measured space velocities versus Galactocentric distance; the vertical dotted line marks the Sun’s position.
We then selected OSCs with the constraints on the age log \( t < 9 \) and the relative parallax error \( \sigma_\pi/\pi < 30\% \). There were a total of 930 such clusters. Among them there are 384 OSCs with the mean line-of-sight velocities that were calculated using at least three probable cluster members. Based on this sample of OSCs, we found the following kinematic parameters by simultaneously solving all Eqs. (1)–(3):

\[
(U_\odot, V_\odot, W_\odot) = (8.53, 11.22, 7.83) \pm (0.38, 0.46, 0.32) \text{ km s}^{-1}, \\
\Omega_0 = 28.71 \pm 0.22 \text{ km s}^{-1} \text{ kpc}^{-1}, \\
\Omega_0' = -4.100 \pm 0.058 \text{ km s}^{-1} \text{ kpc}^{-2}, \\
\Omega_0'' = 0.736 \pm 0.033 \text{ km s}^{-1} \text{ kpc}^{-3},
\]

where the error per unit weight is \( \sigma_0 = 9.71 \text{ km s}^{-1} \), the linear rotation velocity of the Galaxy is \( V_0 = 229.7 \pm 4.6 \text{ km s}^{-1} \) at the solar distance, and the Oort constants are \( A = 16.40 \pm 0.23 \text{ km s}^{-1} \text{ kpc}^{-1} \) and \( B = -12.31 \pm 0.32 \text{ km s}^{-1} \text{ kpc}^{-1} \).

For 384 OSCs with measured space velocities (these OSCs were used in seeking the solution (5)) their Galactocentric radial, \( V_R \), tangential, \( V_{circ} \), and vertical, \( W \), velocities are plotted against the distance \( R \) in Fig. 1. We see that the greatest and smallest velocity dispersions are observed in the radial (Galactic center–anticenter) and vertical directions, respectively. The velocity dispersions calculated from this sample of OSCs are: \( (\sigma_{V_R}, \sigma_{V_{circ}}, \sigma_W) = (15.8, 11.3, 5.5) \text{ km s}^{-1} \).

This sample contains many relatively young OSCs and, therefore, low-amplitude waves with a wavelength of 2–3 kpc due to the influence of the Galactic spiral density wave are visible on all three graphs. Such periodicities in the velocities of OSCs have recently been studied in more detail by Bobylev and Bajkova (2019).

Based on the same sample of 930 OSCs with \( \log t < 9.0 \) and \( \sigma_\pi/\pi < 30\% \), we found the following kinematic parameters using only two equations, (2) and (3):

\[
(U_\odot, V_\odot, W_\odot) = (7.90, 9.61, 7.79) \pm (0.40, 0.53, 0.29) \text{ km s}^{-1}, \\
\Omega_0 = 28.88 \pm 0.22 \text{ km s}^{-1} \text{ kpc}^{-1}, \\
\Omega_0' = -4.078 \pm 0.061 \text{ km s}^{-1} \text{ kpc}^{-2}, \\
\Omega_0'' = 0.684 \pm 0.033 \text{ km s}^{-1} \text{ kpc}^{-3}, \\
\omega_1 = 0.48 \pm 0.15 \text{ km s}^{-1} \text{ kpc}^{-1}, \\
\omega_2 = 0.32 \pm 0.20 \text{ km s}^{-1} \text{ kpc}^{-1},
\]

where the error per unit weight is \( \sigma_0 = 8.5 \text{ km s}^{-1} \). Interestingly, \( \omega_1 \) here differs significantly from zero.

**DISCUSSION**

**Rotation around the \( z \) Axis**

Based on 130 masers with measured VLBI trigonometric parallaxes, Rastorguev et al. (2017) found the solar velocity components \( (U_\odot, V_\odot) = (11.40, 17.23) \pm (1.33, 1.09) \text{ km s}^{-1} \) and the following parameters of the Galactic rotation curve: \( \Omega_0 = 28.93 \pm 0.53 \text{ km s}^{-1} \text{ kpc}^{-1} \), \( \Omega_0' = -3.96 \pm 0.07 \text{ km s}^{-1} \text{ kpc}^{-2} \) and \( \Omega_0'' = 0.87 \pm 0.03 \text{ km s}^{-1} \text{ kpc}^{-3} \), where \( V_0 = 243 \pm 10 \text{ km s}^{-1} \) (for \( R_0 = 8.40 \pm 0.12 \text{ kpc} \) found).

Based on a sample of 495 OB stars with proper motions from the Gaia DR2 catalogue, Bobylev and Bajkova (2018b) found the following kinematic parameters: \( (U, V, W)_\odot = \)
(8.16, 11.19, 8.55) ± (0.48, 0.56, 0.48) km s\(^{-1}\), \(\Omega_0 = 28.92 \pm 0.39\) km s\(^{-1}\) kpc\(^{-1}\), \(\Omega'_0 = -4.087 \pm 0.083\) km s\(^{-1}\) kpc\(^{-2}\) and \(\Omega''_0 = 0.703 \pm 0.067\) km s\(^{-1}\) kpc\(^{-3}\), where \(V_0 = 231 \pm 5\) km s\(^{-1}\) (for the adopted \(R_0 = 8.0 \pm 0.15\) kpc).

Based on a sample of 326 young OSCs with proper motions from the Gaia DR2 catalogue and line-of-sight velocities from the MWSC catalogue, Bobylev and Bajkova (2019) found the following kinematic parameters: \((U, V, W) = (7.88, 11.17, 8.28) \pm (0.48, 0.63, 0.45)\) km s\(^{-1}\), \(\Omega_0 = 29.34 \pm 0.31\) km s\(^{-1}\) kpc\(^{-1}\), \(\Omega'_0 = -4.012 \pm 0.074\) km s\(^{-1}\) kpc\(^{-2}\) and \(\Omega''_0 = 0.779 \pm 0.062\) km s\(^{-1}\) kpc\(^{-3}\), where \(V_0 = 235 \pm 5\) km s\(^{-1}\) (\(R_0 = 8.0 \pm 0.15\) kpc).

Note that the kinematic parameters corresponding to our solutions (5) and (6) are in best agreement with these three results. Moreover, the errors in the parameters being determined are smallest in the solution (5). Thus, we conclude that the best solution for the sought-for kinematic parameters is the solution (5) obtained from the sample of 930 OSCs satisfying the constraints on the age \(\lg t < 9.0\) and the relative trigonometric parallax error < 15%, which also includes the line-of-sight velocities of 384 OSCs calculated from at least three probable members of the corresponding clusters.

**Rotation around the \(x\) and \(y\) Axes**

Liu et al. (2017) performed a kinematic analysis of \(~23\ 000\) K–M giants from the TGAS catalogue (Brown et al. 2016) based on the Ogorodnikov–Milne model and found a nonzero component \(\omega_2 = -0.38 \pm 0.15\) mas yr\(^{-1}\) (rotation around the Galactic \(y\) axis). They interpreted this as a possible residual rotation in the TGAS frame or the presence of problems in the kinematic model.

Our analysis of the kinematics of OSCs does not confirm such a rapid rotation. Indeed, the mean distance for the sample of stars used in obtaining the solution (6) is 2.0 kpc; then \(\omega_1 = 0.051 \pm 0.016\) mas yr\(^{-1}\) and \(\omega_2 = 0.034 \pm 0.021\) mas yr\(^{-1}\). We see that here \(\omega_2\) differs from the result of Liu et al. (2017) by an order of magnitude.

As Lindegren et al. (2018) showed, the Gaia DR2 frame has no rotation relative to the system of quasars within 0.15 mas yr\(^{-1}\), with the greatest effect manifesting itself in the region of bright \((G < 12^n)\) stars. The mean proper motions of the OSCs under consideration seem to have been calculated from a considerable number of precisely bright stars. Thus, on the one hand, the value of \(\omega_1 = 0.051 \pm 0.016\) mas yr\(^{-1}\) found in this paper may be a consequence of a slight residual rotation of the Gaia DR2 frame relative to the extragalactic reference frame. On the other hand, the slight rotation around the Galactic \(x\) axis with an angular velocity of \(0.48 \pm 0.15\) km s\(^{-1}\) kpc\(^{-1}\) found in this paper may somehow be related to the presumed precession/rotation of the warped Galactic disk. Various authors have attempted to detect this kinematic effect in the kinematics of stars and clusters over many years. However, at present there is no agreement between the results obtained. For example, using the proper motions of O–B5 stars, Miyamoto and Zhu (1998) found rotation of this system of stars around the Galactic \(x\) axis with an angular velocity of about 4 km s\(^{-1}\) kpc\(^{-1}\) based on the simplest solid-body rotation model. Based on the proper motions of \(~80\ 000\) red giant clump stars, Bobylev (2010) found rotation of this system of stars around the \(x\) axis with an angular velocity of about \(-4\) km s\(^{-1}\) kpc\(^{-1}\), while based on a sample of classical Cepheids, Bobylev (2013) found rotation around the \(x\) axis with an angular velocity of \(-15 \pm 5\) km s\(^{-1}\) kpc\(^{-1}\).

On the whole, various observations confirm the asymmetry in the vertical velocities of stars (López-Corredoira et al. 2014; Romero-Gómez et al. 2018), but the application of a
complex disk precession model is required to describe the phenomenon. Based on a simplified approach, L´opez-Corredoira et al. (2014) obtained an estimate of the rotation around the $x$ axis with an angular velocity of $\sim -2$ km s$^{-1}$ kpc$^{-1}$. While analyzing the Gaia DR2 data, Romero-Gómez et al. (2018) showed that the observed structure of the vertical velocities is complex and depends strongly on the sample age.

**CONCLUSIONS**

Thus, based on published data, we selected a sample of more than 1000 OSCs with their proper motions and parallaxes from the Gaia DR2 catalogue and their line-of-sight velocities from the Gaia DR2 (predominantly) and MWSC catalogues. Following the latest results of an analysis of the zero point for the Gaia DR2 parallax scale, we calculated the distances to OSCs by adding the correction $\Delta \pi = 0.050$ mas to the original mean values of their parallaxes.

We studied the joint and separate solutions of the basic kinematic equations when determining the Galactic rotation parameters. We showed that the Galactic rotation parameters are determined more accurately from OSCs located within 4–5 kpc of the Sun using only their proper motions than only their line-of-sight velocities. We conclude that the distance scale factor is virtually equal to unity, $p = 1.00 \pm 0.04$. Therefore, the distances calculated using the parallaxes from the Gaia DR2 catalogue do not need any correction factor.

Nevertheless, the best (with the smallest error per unit weight and with the smallest errors of the parameters being determined) solution was obtained as a result of the simultaneous solution based on a sample of 930 OSCs selected under the constraint on the age $\log t < 9.0$ with relative trigonometric parallax errors less than 30%. In this solution we used 384 OSCs with the mean line-of-sight velocities calculated from at least three probable cluster members. The parameters found are reflected in the solution (5).

Having analyzed the proper motions of 930 OSCs, we established that, apart from the rotation around the Galactic $z$ axis (the well-known Galactic rotation), there is rotation of the entire sample around the Galactic $x$ axis with an angular velocity $\omega_1 = 0.48 \pm 0.15$ km s$^{-1}$ kpc$^{-1}$ differing significantly from zero. This quantity can also be expressed in angular units, given the mean distance of the OSC sample; then $\omega_1 = 0.051 \pm 0.016$ mas yr$^{-1}$. This rotation can be both a kinematic peculiarity of OSCs and a consequence of the slight residual rotation of the Gaia DR2 frame relative to the extragalactic reference frame. Of course, this effect should be studied and confirmed on greater statistics.

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