Galaxy Rotation Parameters from OB2 Stars with Proper Motions and Parallaxes from the Gaia EDR3 Catalog

V.V. Bobylev and A.T. Bajkova

Central (Pulkovo) Astronomical Observatory, Russian Academy of Sciences, Pulkovskoe shosse 65, St. Petersburg, 196140 Russia

Abstract—We have analyzed the kinematics of OB2 stars with proper motions and parallaxes selected by Xu et al. from the Gaia EDR3 catalog. The relative parallax errors for all the stars in this sample do not exceed 10%. Based on a sample of 9750 stars, the group velocity components $(U, V, W)_{\odot} = (7.21, 7.46, 8.52) \pm (0.13, 0.20, 0.10)$ km/s were obtained and the parameters of the angular velocity of rotation of the Galaxy: $\Omega_0 = 29.712 \pm 0.062$ km/s/kpc, $\Omega'_0 = -4.014 \pm 0.018$ km/s/kpc² and $\Omega''_0 = 0.674 \pm 0.009$ km/s/kpc³. The circular velocity of rotation of the solar neighborhood around the center of the Galaxy is $V_0 = 240.7 \pm 3.0$ km/s for the assumed distance of the Sun to the galactic center $R_0 = 8.1 \pm 0.1$ kpc. It is shown that the influence of the systematic correction to the trigonometric parallaxes of the Gaia EDR3 catalog with the value $\Delta \pi = -0.040$ mas does not exceed the $\sim 1\sigma$ level of the errors of the sought-for kinematic parameters of the model. Based on the proper motions of OB stars, the following variances of the residual velocities were found: $(\sigma_1, \sigma_2, \sigma_3) = (11.79, 9.66, 7.21) \pm (0.06, 0.05, 0.04)$ km/s. It is shown that the first axis of this ellipsoid slightly deviates from the direction to the center of the Galaxy $L_1 = 12.4 \pm 0.1^\circ$, and the third axis is oriented almost exactly to the north pole of the Galaxy, $B_3 = 87.7 \pm 0.1^\circ$.

DOI: 10.1134/S1063772922040011

1 INTRODUCTION

Stars of spectral classes O and early B are very young (few million years) massive (more than $10M_{\odot}$) stars of high luminosity. Due to these properties, they hold great significance for the studies of the structure and kinematics of the Galaxy at various scales.

OB stars are used to study the structure and kinematics of the solar neighborhood, which harbors young open clusters [1], OB associations [2–4], the Gould Belt [5, 6], and the Local Arm [7].

There is a large number of known so-called runaway stars. These are mainly OB stars that left their parent cluster or association at high velocities [8–11].

Due to their high luminosity, OB stars are visible from very far distances from the Sun. Spectrophotometric distances are estimated from OB stars with relative errors of 15–25% [12–14]; until recently, those served as the main source of distances to these stars. Many O stars are surrounded by compact shells of ionized hydrogen, or the so-called HII zones. The HII zones and OB stars trace the large-scale structure of the Galaxy well. For example, they are used to study the curvature of the thin disk [15, 16] or the galactic spiral pattern [7, 14, 16–19].

OB stars are used to determine the parameters of galactic rotation [3, 20–31]. Often, since the radial velocities of single OB stars are measured with large errors, only their proper motions are analyzed.

As part of the Gaia space experiment [33], a version of the Gaia EDR3 catalog (Gaia Early Data Release 3 [34]) was published, in which the values of trigonometric parallaxes and proper motions for about 1.5 billion stars were refined by approximately 30% as compared with the previous version, Gaia DR2 [35]. Trigonometric parallaxes for about 500 million stars were measured with errors less than 0.2 mas ¹. For stars with magnitudes $G < 15^m$, random errors in the measurement of proper motions lie in the range of 0.02–0.04 mas/year, and they greatly increase for fainter stars. In general, the proper motions of about half of the stars in the catalog were measured with a relative error of less than 10%. There are no new radial velocity measurements in the Gaia EDR3 catalog.

Xu et al. [19] presented a catalog of 5772 stars of spectral classes O–B2, in which the proper motions and trigonometric parallaxes of the stars were taken from the Gaia DR2 catalog. The kinematic analysis of these OB stars was performed by Bobylev and Bajkova [32]. In [7], Xu et al. compiled a new, larger sample of OB stars with the proper motions and trigonometric parallaxes from the Gaia EDR3 catalog. The aim of the present study is to redefine the parameters of the rotation of the Galaxy using the latest data on stars of spectral classes O and B from [7].

2 METHODS

2.1 Galaxy Rotation Parameters

From observations, we know three components of a star's velocity: radial velocity V_r and two tangential velocity projections $V_l = 4.74r\mu_l \cos b$ and $V_b = 4.74r\mu_b$ oriented along the galactic longitude l and latitude b, respectively, and expressed in km/s. The factor 4.74 is the dimension coefficient, and is the heliocentric distance of the star r in kpc, which is calculated via parallax as π as $r = 1/\pi$. The proper motion components and are expressed in mas/year.

To determine the parameters of the galactic rotation curve, we use the equations obtained from the Bottlinger formulas, in which the angular velocity Ω is expanded in series up to terms of the second order of smallness r/R_0 :

$$V_r = -U_{\odot} \cos b \cos l - V_{\odot} \cos b \sin l - W_{\odot} \sin b + R_0 (R - R_0) \sin l \cos b \Omega'_0 + 0.5 R_0 (R - R_0)^2 \sin l \cos b \Omega''_0,$$
(1)

$$V_{l} = U_{\odot} \sin l - V_{\odot} \cos l - r\Omega_{0} \cos b + (R - R_{0})(R_{0} \cos l - r \cos b)\Omega_{0}' + 0.5(R - R_{0})^{2}(R_{0} \cos l - r \cos b)\Omega_{0}'',$$
(2)

$$V_{b} = U_{\odot} \cos l \sin b + V_{\odot} \sin l \sin b - W_{\odot} \cos b -R_{0}(R - R_{0}) \sin l \sin b\Omega_{0}' - 0.5R_{0}(R - R_{0})^{2} \sin l \sin b\Omega_{0}'',$$
(3)

where R is the distance from the star to the rotation axis of the Galaxy, $R^2 = r^2 \cos^2 b - 2R_0 r \cos b \cos l + R_0^2$. Velocities $(U, V, W)_{\odot}$ are the average group velocity of the sample; they are taken with the opposite sign and reflect the peculiar motion of the Sun. Ω_0 is the

¹mas is milliarcsecond

angular velocity of rotation of the Galaxy at solar distance R_0 ; parameters Ω'_0 and Ω''_0 are the corresponding derivatives of the angular velocity.

Knowing the Ω_0 and R_0 values, we can calculate the linear velocity of rotation of the Galaxy at a near solar distance, $V_0 = R_0\Omega_0$. In this study, the value R_0 is taken equal to 8.1 ± 0.1 kpc according to the review by Bobylev and Bajkova [36], in which it was derived as a weighted average from a large number of modern individual estimates.

2.2 Residual Velocity Ellipsoid

The variance of the residual velocities of the stars is estimated using the following known method [32]. We consider six moments of the second order a, b, c, f, e, d:

$$a = \langle U^2 \rangle - \langle U_{\odot}^2 \rangle, \qquad b = \langle V^2 \rangle - \langle V_{\odot}^2 \rangle, \qquad c = \langle W^2 \rangle - \langle W_{\odot}^2 \rangle, \qquad (4)$$
$$f = \langle VW \rangle - \langle V_{\odot}W_{\odot} \rangle, \qquad e = \langle WU \rangle - \langle W_{\odot}U_{\odot} \rangle, \qquad d = \langle UV \rangle - \langle U_{\odot}V_{\odot} \rangle,$$

which are the coefficients of the surface equation

$$ax^{2} + by^{2} + cz^{2} + 2fyz + 2ezx + 2dxy = 1,$$
(5)

as well as the components of the symmetric tensor of moments of residual velocities

$$\begin{pmatrix} a & d & e \\ d & b & f \\ e & f & c \end{pmatrix}.$$
 (6)

In this paper, the attention is focused on the analysis of the proper motions of OB stars; there are few radial velocities in this sample, so to determine the elements of the residual velocity tensor, we use the following three equations:

$$V_l^2 = a\sin^2 l + b\cos^2 l\sin^2 l - 2d\sin l\cos l,$$
(7)

$$V_b^2 = a \sin^2 b \cos^2 l + b \sin^2 b \sin^2 l + c \cos^2 b -2 f \cos b \sin b \sin l - 2e \cos b \sin b \cos l + 2d \sin l \cos l \sin^2 b.$$
(8)

$$V_l V_b = a \sin l \cos l \sin b + b \sin l \cos l \sin b + f \cos l \cos b - e \sin l \cos b + d(\sin^2 l \sin b - \cos^2 \sin b),$$
(9)

which are solved by the least-squares method (LSM) with respect to six unknowns a, b, c, f, e, d. The eigenvalues of tensor (6) $\lambda_{1,2,3}$ are then found from the solution of the secular equation

$$\begin{vmatrix} a - \lambda & d & e \\ d & b - \lambda & f \\ e & f & c - \lambda \end{vmatrix} = 0.$$
 (10)

The eigenvalues of this equation are equal to the reciprocals of the square semiaxes of the velocity moment ellipsoid and, at the same time, the square semiaxes of the residual velocity ellipsoid:

$$\lambda_1 = \sigma_1^2, \lambda_2 = \sigma_2^2, \lambda_3 = \sigma_3^2, \qquad \lambda_1 > \lambda_2 > \lambda_3.$$
(11)

Directions of the principal axes $L_{1,2,3}$ and $B_{1,2,3}$ of tensor (10) are found from the relations

$$\tan L_{1,2,3} = \frac{ef - (c - \lambda)d}{(b - \lambda)(c - \lambda) - f^2},\tag{12}$$

$$\tan B_{1,2,3} = \frac{(b-\lambda)e - df}{f^2 - (b-\lambda)(c-\lambda)} \cos L_{1,2,3}.$$
(13)



Figure 1: Distribution of OB stars with relative parallax errors less than 7% in projection onto the galactic plane XY; the position of the Sun is marked with a yellow circle, a four-armed spiral pattern with a twist angle $i = -13^{\circ}$ is shown according to [45].

3 DATA

In this paper, we used a sample of OB stars from the compilation by Xu et al. [7], for which the proper motions and trigonometric parallaxes were taken from the Gaia EDR3 catalog. For this purpose, 9750 stars of spectral classes O to B2, spectroscopically confirmed by Skiff [37], were identified in [7] with the Gaia EDR3 catalog. The authors of [7] selected stars with relative errors of trigonometric parallaxes less than 10%, while stars with pc were excluded from the sample.

The parallaxes of the Gaia EDR3 catalog apparently retained a small systematic shift with respect to the inertial coordinate system [38–43]. This shift was first revealed in the Gaia DR2 parallaxes with a value $\Delta \pi = -0.029$ mas [44], and later it was confirmed from the analysis of various highly accurate data. This correction should be added to the measured parallaxes, so the true distances to the stars should be smaller. The $\Delta \pi$ correction to the parallaxes of the Gaia EDR3 catalog ranges from -0.015 [41] to -0.039 mas [40]. The value of the correction greatly depends on the stellar magnitude, and it cannot be completely eliminated by simple methods.

Xu et al. [7] studied the effect of the correction $\Delta \pi = -0.017$ mas on the characteristics of the spiral pattern. The authors concluded that this systematic correction does not significantly affect the character of the spatial distribution of the OB stars under study.

Parameters	$\sigma_{\pi}/\pi < 5\%$	$\sigma_{\pi}/\pi < 7\%$	$\sigma_{\pi}/\pi < 10\%$
N_{\star}	6861	8766	9750
N_{eq}	6764	8640	9610
\overline{z} , pc	-14.5 ± 1.0	-18.7 ± 0.9	-19.3 ± 0.9
\overline{r} , kpc	1.89	2.12	2.27
$U_{\odot},{ m km/s}$	6.80 ± 0.19	6.92 ± 0.17	7.17 ± 0.16
$V_{\odot},{ m km/s}$	6.76 ± 0.37	7.43 ± 0.29	7.37 ± 0.24
$\Omega_0, {\rm km/s/kpc}$	29.633 ± 0.084	29.696 ± 0.076	29.700 ± 0.076
$\Omega_0^{\prime},{ m km/s/kpc^2}$	-4.013 ± 0.023	-4.007 ± 0.022	-4.008 ± 0.022
$\Omega_0^{''},{ m km/s/kpc^3}$	0.655 ± 0.018	0.670 ± 0.011	0.671 ± 0.011
$\sigma_0,{ m km/s}$	11.3	11.6	11.8
$A, \mathrm{km/s/kpc}$	16.37 ± 0.23	16.25 ± 0.22	16.23 ± 0.22
$B, \mathrm{km/s/kpc}$	-13.29 ± 0.25	-13.38 ± 0.24	-13.47 ± 0.23
$V_0, \mathrm{km/s}$	240.3 ± 3.1	240.0 ± 3.0	240.6 ± 3.0

Table 1: Galaxy rotation parameters found from OB stars on the basis of equation (2) only, N_{\star} is the total number of the stars in the sample, N_{eq} is the number of the equations.x

In this paper, we aim to verify the influence of the correction on the sought-for kinematic parameters of OB stars.

Figure 1 shows the distribution of OB stars with relative parallax errors below 7% in projection onto the galactic plane XY. The X axis of the coordinate system is oriented from the center of the Galaxy to the Sun, and the direction of the Y axis coincides with the direction of rotation of the Galaxy. A four-arm spiral pattern with a twist angle $i = -13^{\circ}$ [45] is constructed for kpc; the following segments of the spiral arms are numbered with Roman numerals: I—Scutum, II—Carina–Sagittarius, III—Perseus, and IV—Outer Arm.

4 RESULTS

The system of conditional equations of the form (1)–(3) is solved by the least-squares method with weights $w_{r,l,b} = S_0/\sqrt{S_0^2 + \sigma_{V_{r,l,b}}^2}$, where S_0 is the "cosmic" variance, and $\sigma_{V_r}, \sigma_{V_l}, \sigma_{V_b}$ are the error variances of the corresponding observed velocities. The value S_0 is comparable to the root-mean-square residual σ_0 (unit weight error) when solving conditional equations of the form (1)–(3). We adopted $S_0 = 10$ km/s. The system of equations was solved in several iterations using the 3σ criterion to exclude open clusters with large residuals.

The first way is to find a solution using a single conditional equation (2). The galactic rotation parameters found for three samples of OB stars with different levels of parallax errors are listed in Table 1. The average value of the \overline{z} coordinate is given for each sample (it reflects the "elevation effect", i.e., the altitude of the Sun above the galactic plane). The obtained estimates of \overline{z} are in very good agreement, for example, with the value $\overline{z} = -23 \pm 3$ pc found from the analysis of open clusters with the data from the Gaia DR2 catalog in [46].

The values of the Oort constants $A = 0.5\Omega'_0R_0$ and $B = A - \Omega_0$, calculated from the obtained Ω_0 and Ω'_0 values are given at the bottom of the table. The linear velocity of rotation of the Galaxy at a near-solar distance, $V_0 = R_0\Omega_0$, is also given for the adopted

Parameters	$\sigma_{\pi}/\pi < 5\%$	$\sigma_{\pi}/\pi < 7\%$	$\sigma_{\pi}/\pi < 10\%$
N_{\star}	6861	8766	9750
N_{eq}	13513	17263	19202
-			
$U_{\odot},{ m km/s}$	6.90 ± 0.15	7.00 ± 0.14	7.21 ± 0.13
$V_{\odot}, \mathrm{km/s}$	7.00 ± 0.30	7.57 ± 0.24	7.46 ± 0.20
$W_{\odot}, \mathrm{km/s}$	8.27 ± 0.11	8.53 ± 0.10	8.52 ± 0.10
$\Omega_0, \mathrm{km/s/kpc}$	29.650 ± 0.069	29.704 ± 0.062	29.712 ± 0.062
$\Omega'_0, {\rm km/s/kpc^2}$	-4.022 ± 0.019	-4.013 ± 0.018	-4.014 ± 0.018
$\Omega_0'',{ m km/s/kpc^3}$	0.666 ± 0.015	0.674 ± 0.009	0.674 ± 0.009
$\sigma_0, \mathrm{km/s}$	9.2	9.4	9.6
$A, \mathrm{km/s/kpc}$	16.39 ± 0.23	16.29 ± 0.22	16.26 ± 0.21
$B, \mathrm{km/s/kpc}$	-13.22 ± 0.24	-13.36 ± 0.23	-13.45 ± 0.22
$V_0, \mathrm{km/s}$	239.9 ± 3.0	240.2 ± 3.0	240.7 ± 3.0

Table 2: Galaxy rotation parameters found from OB stars using two equations of the form (2), (3), N_{\star} is the total number of the stars in the sample, N_{eq} is the number of the equations.

value $R_0 = 8.1 \pm 0.1$ kpc.

To verify the influence of the systematic correction to the parallaxes of the Gaia EDR3 catalog stars on the kinematic parameters of OB stars, we use two values, 0.020 and 0.040 mas. Using this method, for the entire sample of 9750 stars with corrected parallaxes $\pi = \pi + 0.020$ mas, the velocity components $(U, V)_{\odot} = (6.96, 7.74) \pm (0.16, 0.24)$ km/s and the following parameters of the angular velocity of the galactic rotation are found:

$$\Omega_0 = 29.469 \pm 0.076 \text{ km/s/kpc},$$

$$\Omega'_0 = -3.965 \pm 0.021 \text{ km/s/kpc}^2,$$

$$\Omega''_0 = 0.663 \pm 0.013 \text{ km/s/kpc}^3.$$
(14)

In this solution, the unit weight error $\sigma_0 = 11.2$ km/s. The linear velocity of rotation of the Galaxy at a near-solar distance $V_0 = 238.7 \pm 3.0$ km/s, and the Oort constants $A = 16.06 \pm 0.22$ km/s/kpc and $B = -13.41 \pm 0.23$ km/s/kpc.

Repeating solution (14) with new parallax values $\pi = \pi + 0.040$ mas gives $(U, V)_{\odot} = (6.79, 7.99) \pm (0.15, 0.24)$ km/s and the parameters of the angular velocity of the galactic rotation:

$$\Omega_0 = 29.305 \pm 0.077 \text{ km/s/kpc},$$

$$\Omega'_0 = -3.933 \pm 0.021 \text{ km/s/kpc}^2,$$

$$\Omega''_0 = 0.653 \pm 0.015 \text{ km/s/kpc}^3.$$
(15)

In this solution, the unit weight error $\sigma_0 = 10.7$ km/s. The linear velocity of rotation of the Galaxy at a near-solar distance $V_0 = 237.4 \pm 3.0$ km/s, and the Oort constants $A = 15.93 \pm 0.21$ km/s/kpc and $B = -13.38 \pm 0.23$ km/s/kpc. The values of parameters (14) and (15) should first be compared with the values from the last column of Table 1, since they were found using the same stars.

The second way is to jointly solve the system of conditional equations of the form (2)-(3). The Galactic rotation parameters found by this method for three samples of OB stars are given in Table 2. Using this method, for the entire sample of OB stars with experimental parallax correction $\pi = \pi + 0.020$ mas, the following parameters were found: $(U, V, W)_{\odot} = (6.98, 7.81, 8.14) \pm (0.13, 0.20, 0.09)$ km/s and

$$\Omega_0 = 29.461 \pm 0.062 \text{ km/s/kpc},$$

$$\Omega'_0 = -3.969 \pm 0.018 \text{ km/s/kpc}^2,$$

$$\Omega''_0 = 0.665 \pm 0.011 \text{ km/s/kpc}^3.$$
(16)

In this solution, the unit weight error $\sigma_0 = 9.1$ km/s. The linear velocity of rotation of the Galaxy at a near-solar distance $V_0 = 238.6 \pm 3.0$ km/s, and the Oort constants $A = 16.07 \pm 0.21$ km/s/kpc and $B = -13.39 \pm 0.22$ km/s/kpc. Values (16) should be compared with those given in the last column of Table 2.

The tables show the N_{eq} value, which indicates the actual number of stars in the search for a solution after filtering by the 3σ criterion. In Table 1, the number of stars rejected by this criterion is indicated by a simple difference $N_{\star} - N_{eg}$. The number of discarded stars here is very small (less than 1%). In the second case, the number of discarded stars is indicated by the difference $2N_{\star} - N_{eq}$, and this number is larger, but also not critical.

Xu et al. [7] formed a sample of 5772 O-B2 stars with kinematic parameters from the Gaia DR2 catalog. The radial velocities for more than 2500 of the stars were taken from the SIMBAD electronic database ².

We identified the samples of OB stars from [7, 19] and found 1812 stars with radial velocities in the new sample. The radial velocities of OB stars in the catalog of Xu et al. [7] are given relative to the local standard of rest, so we convert them back to heliocentric velocities with the known parameters of the standard motion of the Sun $(U, V, W)_{\odot} = (10.3, 15.3, 7.7)$ km/s.

The interest in these stars is associated primarily with the fact that they can be used to plot the rotation curve of the Galaxy. To do this, we calculate the spatial velocities U, V, W, and then another two velocities: V_R , directed radially from the galactic center, and the velocity orthogonal to it V_{circ} in the direction of rotation of the Galaxy based on the following relations:

$$V_{circ} = U \sin \theta + (V_0 + V) \cos \theta,$$

$$V_R = -U \cos \theta + (V_0 + V) \sin \theta,$$
(17)

where the position angle θ satisfies the relation $\tan \theta = y/(R_0 - x)$, and x, y, z are the rectangular heliocentric coordinates of the star (velocities U, V, W are oriented along the corresponding axes x, y, z).

It should be noted that in a sample of 1812 OB stars with radial velocities, the errors in determining the radial velocities are not given for more than half of the stars; for a significant part of the stars, the errors in determining the radial velocities exceed 10 km/s.

The availability of radial velocities allows us to search for a joint solution of a system of three conditional equations of the form (1)–(3). The following parameters were found using this method for OB stars with radial velocities and proper motions: $(U, V, W)_{\odot} = (7.17, 10.03, 8.15) \pm (0.30, 0.35, 0.29)$ km/s and

$$\begin{aligned} \Omega_0 &= 29.22 \pm 0.19 \text{ km/s/kpc}, \\ \Omega_0' &= -3.885 \pm 0.042 \text{ km/s/kpc}^2, \\ \Omega_0'' &= 0.685 \pm 0.031 \text{ km/s/kpc}^3, \end{aligned} \tag{18}$$

²http://simbad.u-strasbg.fr/simbad/



Figure 2: Top panel (a): circular velocities of rotation of OB stars V_{circ} as a function of distance R; the rotation curve with the boundaries of the confidence region corresponding to the 1σ level is given. Central panel (b): radial velocities V_R . Bottom panel (c): vertical velocities of OB stars W as a function of distance R; the vertical line marks the position of the Sun.

where the unit weight error $\sigma_0 = 12.2$ km/s, and the linear rotation velocity of the Galaxy at a near-solar distance $V_0 = 236.7 \pm 3.3$ km/s. After discarding stars with large radial velocity errors (more than 20 km/s), as well as using the 3σ criterion, 1726 OB stars remained, for which solution (18) was found and Fig. 2 was plotted.

Figure 2 shows circular velocities of rotation V_{circ} , radial velocities V_R , and vertical velocities W of 1726 OB stars depending on the distance R. The rotation curve that we consider to be the best was found from proper motions only (the last column of Table 2). As can be seen from Fig. 2a, the rotation curve has a very narrow confidence region.

Both in Fig. 2a and 2b, one can easily trace the wave-like behavior of the velocities, which is associated with the influence of the galactic spiral density wave. Bobylev and Bajkova [32] performed a kinematic Fourier analysis of more than 2000 OB stars from the list [7], where Fig. 4 with periodic curves describing the effect of the spiral density wave was plotted. Bobylev and Bajkova [32] found that the amplitudes of the tangential and radial

perturbation velocities are $f_{\theta} = 4.4 \pm 1.4$ km/s and $f_R = 5.1 \pm 1.2$ km/s, respectively.

Based on the proper motions of 9720 OB2 stars, as a result of the LSM solution of the system of conditional equations of the form (7)-(9), the following variances of the residual velocities were found:

$$\sigma_{1} = 11.79 \pm 0.06 \text{ km/s}, \sigma_{2} = 9.66 \pm 0.05 \text{ km/s}, \sigma_{3} = 7.21 \pm 0.04 \text{ km/s},$$
(19)

as well as the orientation parameters of this ellipsoid:

$$L_{1} = 12.4 \pm 0.1^{\circ}, \quad B_{1} = +0.5 \pm 0.1^{\circ}, L_{2} = 102.4 \pm 0.1^{\circ}, \quad B_{2} = +2.3 \pm 0.1^{\circ}, L_{3} = 271.2 \pm 0.1^{\circ}, \quad B_{3} = 87.7 \pm 0.1^{\circ}.$$
(20)

We can conclude that these are indeed very young stars, which are characterized by a small variance of residual velocities. It should be noted that the average value $(\sigma_1 + \sigma_2 + \sigma_3)/3 = 9.55 \text{ km/s}$, which characterizes the variance of the average spatial velocity, is close to the unit weight error values σ_0 , which are listed in Table 2, and to our chosen value of the "cosmic" variance $S_0 = 10 \text{ km/s}$.

5 DISCUSSION

At present, it is believed that the most reliable components of the peculiar velocity of the Sun relative to the local standard of rest, $(U, V, W)_{\odot} = (11.1, 12.2, 7.3) \pm (0.7, 0.5, 0.4)$ km/s, are determined by Schönrich et al. [47]. The U_{\odot} and V_{\odot} velocity values found in this paper for various samples of OB stars differ greatly from those found in [47]. As shown in [48], there is an influence of the galactic spiral density wave, and the U_{\odot} and V_{\odot} velocities greatly depend on the phase of the Sun in the density wave. As can be seen from Fig. 1, OB stars are strongly concentrated toward segments of the spiral arms, so the kinematics of these stars has to be influenced by the spiral density wave. Although we do not attach much importance to solution (18) in terms of estimating the rotation parameters, the V_{\odot} velocity value here is closer to the one found by Schönrich et al. [47].

An important parameter is the value of the linear velocity V_0 . It is known that such objects of the thin disk of the Galaxy as hydrogen clouds, maser sources in active starformation regions, OB stars, young open clusters, the youngest Cepheids, etc., rotate the fastest.

In [31], the estimate $V_0 = 231 \pm 5$ km/s for the adopted value $R_0 = 8.0 \pm 0.15$ kpc was obtained from the analysis of 495 OB stars from the Gaia DR2 catalog. Mróz et al. [49] obtained the estimate $V_0 = 233.6 \pm 2.8$ km/s for adopted $R_0 = 8.122 \pm 0.031$ kpc from the analysis of about 770 classical Cepheids. In [50], the velocity $V_0 = 232.5 \pm 0.9$ km/s for adopted $R_0 = 8.122 \pm 0.031$ kpc was found with very high accuracy based on the sample of about 3500 classical Cepheids. In [51], $V_0 = 240 \pm 3$ km/s was found for the calculated value $R_0 = 8.27 \pm 0.10$ kpc from the analysis of 800 Cepheids.

Rastorguev et al. [52] used data on 130 galactic masers with measured trigonometric parallaxes to find the components of the solar velocity $(U_{\odot}, V_{\odot}) = (11.40, 17.23) \pm (1.33, 1.09)$ km/s and the following values of the parameters of the rotation curve of the Galaxy: $\Omega_0 = 28.93 \pm 0.53$ km/s/kpc, $\Omega'_0 = -3.96 \pm 0.07$ km/s/kpc² and $\Omega''_0 = 0.87 \pm 0.03$ km/s/kpc³, $V_0 = 243 \pm 10$ km/s for the found value $R_0 = 8.40 \pm 0.12$ kpc.

Reid et al. [53], using a sample of 147 masers, found the following values of the two most important kinematic parameters: $R_0 = 8.15 \pm 0.15$ kpc and $\Omega_{\odot} = 30.32 \pm 0.27$ km/s/kpc, where $\Omega_{\odot} = \Omega_0 + V_{\odot}/R$. The velocity value $V_{\odot} = 12.2$ km/s was taken from [47]. These authors used a method based on the series expansion of the linear velocity of rotation of the Galaxy.

Based on the proper motions of approximately 6000 OB stars from the list [19] with proper motions and parallaxes from the Gaia DR2 catalog, the authors of [32] found $(U_{\odot}, V_{\odot}) =$ $(6.53, 7.27) \pm (0.24, 0.31)$ km/s, $\Omega_0 = 29.70 \pm 0.11$ km/s/kpc, $\Omega'_0 = -4.035 \pm 0.031$ km/s/kpc² and $\Omega''_0 = 0.620 \pm 0.014$ km/s/kpc³, where $V_0 = 238 \pm 5$ km/s for the adopted $R_0 =$ 8.0 ± 0.15 kpc. It should be noted that these values must be compared with parameters (16), which are obtained on the basis of a completely identical approach. This comparison shows that the errors in determining the kinematic parameters (16) are approximately 1.5 times smaller.

From 788 Cepheids from the list of Mróz et al. [49] with proper motions and radial velocities from the Gaia DR2 catalog, the authors of [51] found $(U_{\odot}, V_{\odot}, W_{\odot}) = (10.1, 13.6, 7.0) \pm (0.5, 0.6, 0.4) \text{ km/s}$, as well as $\Omega_0 = 29.05 \pm 0.15 \text{ km/s/kpc}$, $\Omega'_0 = -3.789 \pm 0.045 \text{ km/s/kpc}^2$, $\Omega''_0 = 0.722 \pm 0.027 \text{ km/s/kpc}^3$, at calculated $R_0 = 8.27 \pm 0.10 \text{ kpc}$.

Thus, we can conclude that the parameters of the angular velocity of rotation of the Galaxy Ω_0 , Ω'_0 and Ω''_0 found in this paper for OB stars are in good agreement with the estimates of other authors and are determined with high accuracy in our case.

There is interest [54–57] in the values of the Oort constants A and B. These constants characterize the shape of the Galactic rotation curve in a small neighborhood of the Sun. According to our definitions, the sum $A + B = -\partial V_{circ}/\partial R$ indicates that the linear velocity of the galactic rotation V_{circ} decreases in the solar neighborhood (a slight deflection of the rotation curve in the region $R = R_0$ in Fig. 2a), which is in agreement with modern estimates of the character of the rotation of the Galaxy.

For example, Bovy [56], from the analysis of the proper motions and parallaxes of a local sample of 304267 main sequence stars in the Gaia DR1 catalog [58], found $A = 15.3 \pm 0.5 \text{ km/s/kpc}$ and $B = -11.9 \pm 0.4 \text{ km/s/kpc}$, on the basis of which he obtained an estimate of the angular velocity of the rotation of the Galaxy $\Omega_0 = 27.1 \pm 0.5 \text{ km/s/kpc}$ and velocity $V_0 = 219 \pm 4 \text{ km/s}$.

Based on a large sample of Gaia DR2 stars located in the Sun's neighborhood with a radius of 500 pc, the following estimates were obtained in [57]: $A = 15.1 \pm 0.1 \text{ km/s/kpc}$, $B = -13.4 \pm 0.1 \text{ km/s/kpc}$ and $\Omega_0 = 28.5 \pm 0.1 \text{ km/s/kpc}$.

6 CONCLUSIONS

The kinematics of the Galaxy was studied using a sample of OB2 stars from the paper by Xu et al. [7] with proper motions and trigonometric parallaxes from the Gaia EDR3 catalog. These very young stars are located no higher than 300 pc above the galactic plane and no farther than 5–6 kpc from the Sun (on average, at a distance of approximately 2 kpc).

Two approaches to solving kinematic equations were tested: (a) using only the component V_l and (b) using two components, V_l and V_b . It was shown that in comparison with the first method, the second method has a slight advantage in the possibility of estimating velocity W_{\odot} , as well as in reducing the level of errors of the determined parameters.

It was shown that the influence of the systematic correction to the trigonometric par-

allaxes of the Gaia EDR3 catalog with the value $\Delta \pi = -0.040$ mas does not exceed the level (approximately 1σ) of errors of the sought-for kinematic parameters of the model. The actual effect of the correction is that the values of such parameters as Ω_0 , Ω'_0 , Ω''_0 , and V_0 and become smaller (in absolute value). The beneficial effect is a significant reduction of the unit weight error σ_0 in the search for the LSM solution of kinematic equations.

The kinematic equations were solved using three constraints on the stellar parallax errors σ_{π}/π : 10%, 7%, and 5%. We concluded that there was almost no dependence of the determined kinematic parameters on the level of parallax errors.

From the sample of 9750 OB stars, without introducing a correction to their parallaxes, we found the group velocity components $(U, V, W)_{\odot} = (7.21, 7.46, 8.52) \pm (0.13, 0.20, 0.10)$ km/s and the following parameters of the angular velocity of rotation of the Galaxy: $\Omega_0 = 29.712 \pm 0.062$ km/s/kpc, $\Omega'_0 = -4.014 \pm 0.018$ km/s/kpc² and $\Omega''_0 = 0.674 \pm 0.009$ km/s/kpc³. The circular velocity of the rotation of the solar neighborhood around the center of the Galaxy $V_0 = 240.7 \pm 3.0$ km/s for the adopted distance $R_0 = 8.1 \pm 0.1$ kpc. Based on 1726 OB stars with radial velocities and proper motions, the V_{circ} and V_R velocities were calculated, and a graph of the rotation curve was plotted with parameters found from proper motions only. This curve was shown to have a very narrow confidence region.

Based on the proper motions of 9720 OB stars, the following variances of residual velocities were determined: $(\sigma_1, \sigma_2, \sigma_3) = (11.79, 9.66, 7.21) \pm (0.06, 0.05, 0.04)$ km/s. It was shown that the first axis of this ellipsoid slightly deviates from the direction to the center of the Galaxy, $L_1 = 12.4 \pm 0.1^\circ$, and the third axis is directed almost exactly to the north pole of the Galaxy, $B_3 = 87.7 \pm 0.1^\circ$.

ACKNOWLEDGMENTS

The authors are grateful to the reviewer for the valuable comments, which helped to improve the paper.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. E. Piskunov, N. V. Kharchenko, S. Röser, E. Schilbach and R.-D. Scholz, Astron. Astrophys. 445, 545 (2006).

- 2. P. T. de Zeeuw, R. Hoogerwerf, and J. H. J. de Bruijne, Astron. J. 117, 354 (1999).
- 3. A. K. Dambis, A. M. Mel'nik, and A. S. Rastorguev, Astron. Lett. 27, 58 (2001).
- 4. M. Mel'nik and A. K. Dambis, Mon. Not. R. Astron. Soc. 472, 3887 (2017).
- 5. J. A. Frogel and R. Stothers, Astron. J. 82, 890 (1977).
- 6. J. Torra, D. Fernández, and F. Figueras, Astron. Astrophys. 359, 82 (2000).
- 7. Y. Xu, L.G. Hou, S. Bian, et al., Astron. Astrophys. 645, L8 (2021).
- 8. A. Blaauw, Bull. Astron. Inst. Netherland 15, 265 (1961).
- 9. R. Hoogerwerf, J. H. J. de Bruijne, and P. T. de Zeeuw, Astrophys. J. 544, L133 (2000).
- 10. N. Tetzlaff, R. Neuhäuser, and M. M. Hohle, Mon. Not. R. Astron. Soc. 410, 190 (2011).
- 11. V. V. Bobylev and A. T. Bajkova, Astron. Lett. 47, 224 (2021).

12. M. Mohr-Smith, J. E. Drew, R. Napiwotzki, et al., Mon. Not. R. Astron. Soc. 465, 1807 (2017).

13. B.-Q. Chen, Y. Huang, L.-G. Hou, et al., Mon. Not. R. Astron. Soc. 487, 1400 (2019).

- 14. J. M. Shull and C. W. Danforth, Astrophys. J. 882, 180 (2019).
- 15. R. Drimmel, R. L. Smart, and M. G. Lattanzi, Astron. Astrophys. 354, 67 (2000).
- 16. D. Russeil, Astron. Astrophys. 397, 133 (2003).
- 17. Y. M. Georgelin and Y. P. Georgelin, Astron. Astrophys. 49, 57 (1976).
- 18. D. Fernández, F. Figueras, and J. Torra, Astron. Astrophys. 372, 833 (2001).
- 19. Y. Xu, S. B. Bian, M. J. Reid, J. J. Li, et al., Astron. Astrophys. 616, L15 (2018).
- 20. J. Byl and M. W. Ovenden, Astrophys. J. 225, 496 (1978).
- 21. M. Miyamoto and Z. Zhu, Astron. J. 115, 1483 (1998).
- 22. M. Uemura, H. Ohashi, T. Hayakawa, et al., Publ. Astron. Soc. Jpn. 52, 143 (2000).
- 23. R. L. Branham, Astrophys. J. 570, 190 (2002).
- 24. R. L. Branham, Mon. Not. R. Astron. Soc. 370, 1393 (2006).
- 25. M. V. Zabolotskikh, A. S. Rastorguev, and A. K. Dambis, Astron. Lett. 28, 454 (2002).
- 26. M. E. Popova and A. V. Loktin, Astron. Lett. 31, 663 (2005).
- 27. Z. Zhu, Chin. J. Astron. Astrophys. 6, 363 (2006).
- 28. A. M. Mel'nik and A. K. Dambis, Mon. Not. R. Astron. Soc. 400, 518 (2009).
- 29. M. Melnik and A. K. Dambis, Astrophys. Space Sci. 365, 112 (2020).
- 30. G. A. Gontcharov, Astron. Lett. 38, 694 (2012).
- 31. V. V. Bobylev and A. T. Bajkova, Astron. Lett. 44, 676 (2018).
- 32. V. V. Bobylev and A. T. Bajkova, Astron. Lett. 45, 331 (2019).
- 33. T. Prusti, J. H. J. de Bruijne, A. G. A. Brown, et al., Astron. Astrophys. 595, A1 (2016).
- 34. A.G. A. Brown, A. Vallenari, T. Prusti, et al., Astron. Astrophys. 649, A1 (2021).
- 35. G. A. Brown, A. Vallenari, T. Prusti, et al., Astron. Astrophys. 616, A1 (2018).
- 36. V. V. Bobylev and A. T. Bajkova, Astron. Rep. 65, 498 (2021).
- 37. A. Skiff, VizieR Online Data Catalog, B/mk (2014).
- 38. L. Lindegren, U. Bastian, M. Biermann, et al., Astron. Astrophys. 616, A2 (2021).
- 39. F. Ren, X. Chen, H. Zhang, et al, Astrophys. J. Lett. 911, L20 (2021).
- 40. M. A. T. Groenewegen, Astron. Astrophys. 654, A20 (2021).
- 41. J. C. Zinn, Astron. J. 161, 214 (2021).
- 42. Y. Huang, H. Yuan, T. Beers, and H. Zhang, Astrophys. J. Lett. 910, L5 (2021).
- 43. J. Maiz Apellániz; arXiv: 2110.01475 [astro-ph.IM] (2021).
- 44. L. Lindegren, J. Hernandez, A. Bombrun, et al., Astron. Astrophys. 616, A2 (2018).
- 45. V. V. Bobylev and A. T. Bajkova, Mon. Not. R. Astron. Soc. 437, 1549 (2014).
- 46. T. Cantat-Gaudin, F. Anders, A. Castro-Ginard, et al., Astron. Astrophys. 640, A1 (2020).
- 47. R. Schönrich, J. J. Binney, and W. Dehnen, Mon. Not. R. Astron. Soc. 403, 1829 (2010).
- 48. V. V. Bobylev and A. T. Bajkova, Mon. Not. R. Astron. Soc. 441, 142 (2014).
- 49. P. Mróz, A. Udalski, D. M. Skowron, J. Skowron, et al., Astrophys. J. 870, L10 (2019).
- 50. Ablimit, G. Zhao, C. Flynn, and S. A. Bird, Astrophys. J. 895, L12 (2020).

51. V. V. Bobylev, A. T. Bajkova, A. S. Rastorguev, and M. V. Zabolotskikh, Mon. Not. R. Astron. Soc. 502, 4377 (2021).

52. A. S. Rastorguev, M. V. Zabolotskikh, A. K. Dambis, et al., Astrophys. Bull. 72, 122 (2017).

53. M. J. Reid, K. M. Menten, A. Brunthaler, et al., Astrophys. J. 885, 131 (2019).

- 54. F. Mignard, Astron. Astrophys. 354, 522 (2000).
- 55. R. P. Olling and W. Dehnen, Astrophys. J. 599, 275 (2003).
- 56. Jo Bovy, Mon. Not. R. Astron. Soc. 468, L63 (2017).
- 57. Li, G. Zhao, and C. Yang, Astrophys. J. 872, 205 (2019).
- 58. A. G. A. Brown, A. Vallenari, T. Prusti, et al., Astron. Astrophys. 595, A2 (2016).