OB Stars and Cepheids From the Gaia TGAS Catalogue: Test of their Distances and Proper Motions

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Abstract: We consider young distant stars from the Gaia TGAS catalog. These are 250 classical Cepheids and 244 OB stars located at distances up to 4 kpc from the Sun. These stars are used to determine the Galactic rotation parameters using both trigonometric parallaxes and proper motions of the TGAS stars. In this case the considered stars have relative parallax errors less than 200%. Following the well-known statistical approach, we assume that the kinematic parameters found from the line-of-sight velocities \( V_r \) are less dependent on errors of distances than the found from the velocity components \( V_l \). From values of the first derivative of the Galactic rotation angular velocity \( \Omega'_0 \), found from the analysis of velocities \( V_r \) and \( V_l \) separately, the scale factor of distances is determined. We found that from the sample of Cepheids the scale of distances of the TGAS should be reduced by 3%, and from the sample of OB stars, on the contrary, the scale should be increased by 9%.

Keywords: Galaxy: rotation parameters, distance scale

1 Introduction

The Gaia TGAS (the Tycho-Gaia astrometric solution, Prusti et al. 2016; Lindegren et al. 2016) catalogue was produced from a combination of data in the first year of Gaia observations with Hipparcos/Tycho (1997) stellar positions. The mean parallax errors are \( \sim \) 0.3 mas. This means that a solar neighborhood with a radius of \( \sim \) 300 pc can be covered with distance errors of about 10%. Therefore, when studying the structure and kinematics of the Galaxy at great heliocentric distances (3 kpc or more), the approach using the photometric or other distance scales is currently topical. For most TGAS stars the mean proper motion error is \( \sim \) 1 mas yr\(^{-1} \), but for quite a few Hipparcos stars this error is an order of magnitude smaller, \( \sim \) 0.06 mas yr\(^{-1} \) (Brown et al. 2016). Therefore, analyzing their space velocities using highly accurate proper motions is of great interest.

Comparison of distances to Cepheids and RR Lyra variables from the TGAS catalog with the distances obtained by other methods, showed very good agreement up to distances 2 kpc (Casertano et al. 2017; Benedict et al. 2017; Clementini et al. 2017; Bobylev and Bajkova 2017). But there are some reports about a zero-point offset of parallaxes of the TGAS stars. In particular, Stassun and Torres (2016) discovered the offset equal to \( -0.25 \pm 0.05 \) mas with respect to 158 calibration eclipsing binary stars. From the analysis of the nearest stars to the Sun (<25 pc) Jao et al. (2017) found that, on average, the parallaxes of the Gaia TGAS stars are less by \( 0.24 \pm 0.02 \) mas than trigonometric parallaxes of these stars measured by ground-based telescopes.

Since the properties of the distance scale of the TGAS catalog are not yet studied completely, the analysis of it with the use of independent approaches is actual. The purpose of this paper is to determine the Galactic rotation parameters using high-precision proper motions of the TGAS stars, a joint and separate solution of the main kinematic equations, both in terms of proper motions and line-of-sight velocities in order to investigate the distance scale of the TGAS catalog.

2 Method

From observations we know three components of the star velocity: the line-of-sight velocity \( V_r \) and the two projec-
tions of the tangential velocity \( V_t = 4.74r\mu_0 \cos b \) and \( V_b = 4.74r\mu_b \), directed along the Galactic longitude \( l \) and latitude \( b \) respectively and expressed in km s\(^{-1}\). Here, the coefficient \( 4.74 \) is the ratio of the number of kilometers in an astronomical unit to the number of seconds in a tropical year, and \( r \) is the heliocentric distance of the star in kpc. The components of a proper motion of \( \mu_l \cos b \) and \( \mu_b \) are expressed in the mass 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 \( \Omega \) was expanded in a series to terms of the second order of smallness in \( r/R_0 \):

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

\[
V_l = U_\odot \sin l - V_\odot \cos l - r\Omega_0 \cos b + (R - R_0) (R_0 \cos l - r \cos b) \Omega'_0 + 0.5 (R - R_0)^2 (R_0 \cos l - r \cos b) \Omega''_0,
\]

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

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

\( \Omega_0 \) is the angular velocity of Galactic rotation at the solar distance \( R_0 \), the parameters \( \Omega'_0 \) and \( \Omega''_0 \) are the corresponding derivatives of the angular velocity, and \( V_0 = |R_0 \Omega_0| \) . The Oort constants \( A \) and \( B \) can be found from the following expressions:

\[
A = -0.5 \Omega'_0 R_0, \quad B = -\Omega_0 + A,
\]

written so that the following relations are hold: \( A - B = \Omega_0 \) and \( A + B = (\Omega_0 + \Omega'_0 R_0) \). In this paper, it is customary the value of \( R_0 = 8.0 \pm 0.2 \) kpc, which Vallée (2017) in its recent survey found as the most probable. There exists also the third Bottlinger’s equation with the \( V_b \) velocity on the left-hand side. The results of the analysis of Cepheids and OB stars on the basis of a system of three conditional equations with \( V_r, V_l, V_b \) left-hand sides are described in the papers of Bobylev (2017) and Bobylev and Bajkova (2017). However, for distant young stars with the latitudes close to zero (\( b = 0^\circ \), \( \Rightarrow \sin b = 0 \)) using the equation with \( V_b \) left-hand side is ineffective. Therefore, in this paper we either solve a system of two equations (1)–(2), or separately each of them. It is known (Zabolotskikh et al. 2002), that in such an approach the velocity \( W_\odot \) can not be reliably determined only from equation (1), so we fix its value as \( W_\odot = -7 \) km s\(^{-1}\).

The values \( \Omega'_0 \), obtained with separate solutions, are of great interest for controlling the distance scale. This method is based on the fact that the errors of the line-of-sight velocities are independent of the distance errors, but the errors of the tangential components of the proper motion depend on the distance errors. This is the basis for statistical methods for analyzing the distance scale. For example, the distance scale factor \( p \) can be found from comparison of the values \( \Omega'_0 \) obtained by different methods (Zabolotskikh et al. 2002; Rastorguev et al. 2017), or from comparison of spatial velocities \( U, V, W \) or their variances \( \sigma_U, \sigma_V, \sigma_W \) (Schönrich and Aumer 2017).

### 3 Data

In the present work we use the following two samples of OB stars: 1) the sample of spectroscopic binary OB stars (Bobylev and Bajkova 2015), 2) the sample of OB stars with distances determined by the spectral lines of the interstellar CaII (Bobylev and Bajkova 2011), and 3) the sample of classical Cepheids described in Mel’ník et al. (2015). The latter consists of 290 classical Cepheids with distances, line-of-sight velocities and proper motions from the Gaia TGAS catalog.

The distributions on the Galactic plane XY of stars of three considered samples are given in figure 1. As it can be seen from this figure, all the stars are distant on no more than 5 kpc from the Sun. OB stars are very young, therefore they well trace a spiral pattern. It is also seen that among the older Cepheids, there are a sufficient number of stars well tracing the Carina-Sagittarius arm (\( R = 7 \) kpc).

### 4 Results and Discussion

#### 4.1 Cepheids

In table 1 the parameters of Galactic rotation obtained from Cepheids with the TGAS proper motions and parallaxes are given. We used the Cepheids with relative errors of trigonometric parallaxes \( \sigma_\pi/\pi < 200\% \). In the table the error of unit weight \( \sigma_0 \), obtained by solving conditional equations (1)–(2) using a well-known least squares method is given. This error is close to the dispersion of residual velocities of the analyzed sample stars averaged over all directions. The Oort constants \( A \) and \( B \) calculated using (4) are also given in the table. According to this table, we find the coefficient of the distance scale \( p = (-4.03)/(-4.16) = \ldots \)
The tangential velocities are more accurate than the line-of-sight velocities, because the distance errors, determined on the basis of the period-luminosity relation, are no more than 10–15%. In comparison with the Sun’s circular velocity of 290 km s\(^{-1}\), the Oort constants \(A = 16.53 \pm 0.50\) km s\(^{-1}\) kpc\(^{-1}\) and \(B = -13.34 \pm 0.68\) km s\(^{-1}\) kpc\(^{-1}\). In comparison with the parameters specified in the first column of the table, the parameters (7) are determined with less errors, because the distance errors, determined on the basis of the period-luminosity relation, are no more than 10–15%.

By Bobylev (2017) for this sample of Cepheids the following parameters were found as a result of joint solution of equations (1)–(2):

\[
(U, V) = (7.9, 11.0) \pm (0.8, 1.0)\text{ km s}^{-1},
\]

where \(\sigma_0\) is \(\Omega'_0(\alpha, \beta)\). Such an estimate from Cepheids was obtained, apparently, for the first time.

It is possible to estimate the distance at which the accuracy of the tangential \(V_t\) velocity is equal to the accuracy of the line-of-sight velocity \(V_r\). Using the upper bound of the accuracy estimate of the tangential component, from the equality

\[
\sigma_{V_t}^2 = (\sigma_{\Omega'_0}/\Omega'_0)^2 + (\sigma_{\Omega''_0}/\Omega''_0)^2,
\]

where \(\Omega'_0\) is \(\Omega'_0(\alpha, \beta)\). Such an estimate from Cepheids was obtained, apparently, for the first time.

### Table 1. Parameters of Galactic rotation, found from Cepheids with the TGAS proper motions and trigonometric parallaxes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(V_1)</th>
<th>(V_2)</th>
<th>(V_3)</th>
<th>(V_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U_0)</td>
<td>7.5 ± 1.0</td>
<td>7.3 ± 1.6</td>
<td>8.6 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>(V_0)</td>
<td>12.5 ± 1.1</td>
<td>13.6 ± 1.4</td>
<td>6.3 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>(\Omega_0)</td>
<td>29.13 ± 0.50</td>
<td>—</td>
<td>27.44 ± 0.83</td>
<td></td>
</tr>
<tr>
<td>(\Omega'_0)</td>
<td>-4.04 ± 0.15</td>
<td>-4.03 ± 0.20</td>
<td>-4.16 ± 0.19</td>
<td></td>
</tr>
<tr>
<td>(\Omega''_0)</td>
<td>0.97 ± 0.11</td>
<td>0.81 ± 0.16</td>
<td>0.74 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>(\sigma_0)</td>
<td>14.31</td>
<td>14.34</td>
<td>11.71</td>
<td></td>
</tr>
<tr>
<td>(N_\alpha)</td>
<td>220</td>
<td>216</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>(N_\beta)</td>
<td>16.17 ± 0.60</td>
<td>16.11 ± 0.78</td>
<td>16.66 ± 0.78</td>
<td></td>
</tr>
<tr>
<td>(\Omega_0)</td>
<td>-12.96 ± 0.78</td>
<td>—</td>
<td>-10.78 ± 1.14</td>
<td></td>
</tr>
</tbody>
</table>

Note: \(U_0, V_0, \sigma_0\) are in km s\(^{-1}\), \(\Omega_0, A, B\) are in km s\(^{-1}\) kpc\(^{-1}\), \(\Omega'_0\) is in km s\(^{-1}\) kpc\(^{-2}\), \(\sigma_{\Omega'_0}\) is in km s\(^{-1}\) kpc\(^{-3}\).

The error of \(p\) was calculated as follows

\[
\sigma_p^2 = (\sigma_{\Omega'_0}/\Omega'_0)^2 + (\sigma_{\Omega''_0}/\Omega''_0)^2,
\]

where \(\Omega'_0\) is \(\Omega'_0(\alpha, \beta)\). Such an estimate from Cepheids was obtained, apparently, for the first time.

It is possible to estimate the distance at which the accuracy of the tangential \(V_t\) velocity is equal to the accuracy of the line-of-sight velocity \(V_r\). Using the upper bound of the accuracy estimate of the tangential component, from the equality

\[
\sigma_{V_t} = 4.74r\sigma_{\mu_\alpha}\cos \delta + \sigma_{\mu_\beta},
\]

we find the value of the critical distance, near which the tangential velocities are more accurate than the line-of-sight ones. Based on the fact that \(\sigma_{\mu_\alpha} = 3\) km s\(^{-1}\) and \(\sigma_{\mu_\beta} = 1\) mas yr\(^{-1}\) for TGAS stars we obtain \(r = 0.45\) kpc. Therefore, it is most correct to apply our method as follows: for distances greater than the critical value, it is necessary to consider the kinematic parameters obtained from the line-of-sight velocities of the stars to be more accurate, and at distances less than the critical one, it is necessary to consider the kinematic parameters obtained from the proper motions of the stars to be more accurate.

It is important to note that in our sample average distance \(\bar{r} = 2\) kpc. Only 9 Cepheids are located closer than 0.45 kpc from the Sun. Their exclusion from the sample does not affect an estimate of the coefficient \(p\).

Using the distances to Cepheids, calculated on the basis of the period-luminosity relation and the proper motions of the TGAS catalog, the following kinematic parameters were obtained from joint solution of equations (1)–(2):

\[
(U, V) = (7.9, 11.0) \pm (0.8, 1.0)\text{ km s}^{-1},
\]

Here we used 250 Cepheids. The linear circular rotation velocity of the Sun around the center of the Galaxy is \(V_0 = 239 ± 7\) km s\(^{-1}\) for the accepted distance \(R_0 = 8.0 ± 0.2\) kpc, and the Oort constants \(A = 16.53 ± 0.50\) km s\(^{-1}\) kpc\(^{-1}\) and \(B = -13.34 ± 0.68\) km s\(^{-1}\) kpc\(^{-1}\). In comparison with the parameters specified in the first column of the table 1, the parameters (7) are determined with less errors, because the distance errors, determined on the basis of the period-luminosity relation, are no more than 10–15%.

By Bobylev (2017) for this sample of Cepheids the following parameters were found as a result of joint solu-
Table 2. Parameters of Galactic rotation, found from OB stars with the TGAS proper motions and trigonometric parallaxes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( V_\odot )</th>
<th>( V_\odot' )</th>
<th>( V_\odot'' )</th>
<th>( V_\odot''' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_\odot )</td>
<td>( 6.8 \pm 0.9 )</td>
<td>( 6.4 \pm 1.7 )</td>
<td>( 8.6 \pm 1.1 )</td>
<td>( 9.0 \pm 1.0 )</td>
</tr>
<tr>
<td>( V_\odot )</td>
<td>( 9.0 \pm 1.0 )</td>
<td>( 12.7 \pm 1.7 )</td>
<td>( 4.7 \pm 1.2 )</td>
<td>( 29.82 \pm 0.62 )</td>
</tr>
<tr>
<td>( \Omega_0 )</td>
<td>( -4.34 \pm 0.14 )</td>
<td>( -4.68 \pm 0.25 )</td>
<td>( -3.29 \pm 0.35 )</td>
<td>( 0.67 \pm 0.07 )</td>
</tr>
<tr>
<td>( \Omega_0' )</td>
<td>( 13.71 )</td>
<td>( 16.05 )</td>
<td>( 10.97 )</td>
<td>( 220 )</td>
</tr>
<tr>
<td>( \Omega_0'' )</td>
<td>( 223 )</td>
<td>( 223 )</td>
<td>( 225 )</td>
<td>( 17.35 \pm 0.56 )</td>
</tr>
<tr>
<td>( \Omega_0''' )</td>
<td>( 18.73 \pm 1.01 )</td>
<td>( 17.18 \pm 0.60 )</td>
<td>( -12.48 \pm 0.83 )</td>
<td>( -13.40 \pm 0.82 )</td>
</tr>
</tbody>
</table>

In this table, we have found that the distance scale factor from the TGAS catalog for these stars, the following kinematic parameters were found as a result of joint solution of equations (1)–(2):

\[
(U, V) = (7.5, 9.5) \pm (0.8, 1.1) \text{ km s}^{-1},
\]

\[
\Omega_0 = 30.82 \pm 0.59 \text{ km s}^{-1} \text{ kpc}^{-1},
\]

\[
\Omega_0' = -4.50 \pm 0.12 \text{ km s}^{-1} \text{ kpc}^{-2},
\]

\[
\Omega_0'' = 0.835 \pm 0.106 \text{ km s}^{-1} \text{ kpc}^{-3}.
\]

Here, we used 244 OB stars, \( V_0 = 247 \pm 8 \text{ km s}^{-1} (R_0 = 8.0 \pm 0.2 \text{ kpc}), \) the Oort constants \( A = 17.98 \pm 0.51 \text{ km s}^{-1} \text{ kpc}^{-1} \) and \( B = -12.83 \pm 0.78 \text{ km s}^{-1} \text{ kpc}^{-1}.\)

In Bobylev and Bajkova (2017) the following kinematic parameters were found when using a smaller number of stars from this sample and solving three equations (for \( V_r, V_t, \) and \( V_b \)): \( (U, V, W) = (8.2, 9.3, 8.8) \pm (0.7, 0.9, 0.7) \text{ km s}^{-1}, \)

\[
\Omega_0 = 31.53 \pm 0.54 \text{ km s}^{-1} \text{ kpc}^{-1},
\]

\[
\Omega_0' = -4.44 \pm 0.12 \text{ km s}^{-1} \text{ kpc}^{-2},
\]

\[
\Omega_0'' = 0.706 \pm 0.100 \text{ km s}^{-1} \text{ kpc}^{-3},
\]

wherein \( V_0 = 252 \pm 8 \text{ km s}^{-1} (R_0 = 8.0 \pm 0.2 \text{ kpc}), A = -17.77 \pm 0.46 \text{ km s}^{-1} \text{ kpc}^{-1} \) and \( B = 13.76 \pm 0.71 \text{ km s}^{-1} \text{ kpc}^{-1}.\)

Note that Bobylev and Bajkova (2017) found the value \( p = 1.04 \) from kinematic analysis of OB stars with proper motions and parallaxes from the TGAS catalog.

5 Conclusions

Galactic rotation parameters are determined using three samples of young stars with different distance scales. These samples were studied previously using data from various catalogs. The first sample contains massive spectral-double OB stars with photometric distances, the second one consists of OB stars, which distances are determined along the lines of interstellar Calcium, the third sample consists of classical Cepheids, the distances to which are determined using the period-luminosity relation. In this paper, we use those stars from these samples that are included in the Gaia TGAS catalog.

In this paper, in contrast to the papers of Bobylev (2017) and Bobylev and Bajkova (2017), only two main kinematic equations with left-hand sides \( V_t \) and \( V_b \) are considered. From 250 Cepheids, the distances to which are calculated on the basis of the period–luminosity relation, and the proper motions taken from the TGAS catalog, the following kinematic parameters are found as a result of joint solution of the equations for \( V_t \) and \( V_b \): \( (U, V) = (7.9, 11.0) \pm (0.8, 1.0) \text{ km s}^{-1}, \)

\[
\Omega_0 = 29.87 \pm 0.45 \text{ km s}^{-1} \text{ kpc}^{-1},
\]

\[
\Omega_0' = -4.13 \pm 0.13 \text{ km s}^{-1} \text{ kpc}^{-2},
\]

\[
\Omega_0'' = 0.50 \pm 0.12 \text{ km s}^{-1} \text{ kpc}^{-3}.
\]

Here the circular rotation velocity of
the Sun around the center of the is $V_0 = 239 \pm 7$ km s$^{-1}$ (for the accepted distance $R_0 = 8.0 \pm 0.2$ kpc), and the Oort constants $A = 16.53 \pm 0.50$ km s$^{-1}$ kpc$^{-1}$ and $B = -13.34 \pm 0.68$ km s$^{-1}$ kpc$^{-1}$.

Based on a similar approach for 244 OB stars, the following kinematic parameters are found:

$$(U, V)_\odot = (7.5, 9.5) \pm (0.8, 1.1)$ km s$^{-1}$, $\Omega_0 = 30.82 \pm 0.59$ km s$^{-1}$ kpc$^{-1}$, $\Omega'_0 = -4.50 \pm 0.12$ km s$^{-1}$ kpc$^{-2}$, $\Omega''_0 = 0.835 \pm 0.106$ km s$^{-1}$ kpc$^{-3}$. Here $V_0 = 247 \pm 8$ km s$^{-1}$, $A = 17.98 \pm 0.51$ km s$^{-1}$ kpc$^{-1}$ and $B = -12.83 \pm 0.78$ km s$^{-1}$ kpc$^{-1}$.

According to the samples of Cepheids and OB stars, kinematic parameters were determined using also trigonometric parallaxes. In this case we used the stars with relative errors of parallaxes less than 200%. From the comparison of values $\Omega'_0$, found as a result of solutions of equations for $V_r$ and $V_l$ separately, the distance scale coefficient $p$ has been determined. Here, we start from the assumption that the kinematic parameters, found from line-of-sight velocities, are less dependent on distance errors than those found from proper motions. According to Cepheids, we found that the distance scale of the TGAS catalog should be reduced by 3% ($p = 0.97 \pm 0.07$), and for OB stars, on the contrary, it should be increased by 9% ($p = 1.09 \pm 0.07$).

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References