Galactic Kinematics from OB3 Stars with Distances Determined from Interstellar Ca II Lines

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Abstract—Based on data for 102 OB3 stars with known proper motions and radial velocities, we have tested the distances derived by Megier et al. from interstellar Ca II spectral lines. The internal reconciliation of the distance scales using the first derivative of the angular velocity of Galactic rotation $\Omega'_0$ and the external reconciliation with Humphreys’s distance scale for OB associations refined by Mel’nik and Dambis show that the initial distances should be reduced by $\approx$20%. Given this correction, the heliocentric distances of these stars lie within the range 0.6–2.6 kpc. A kinematic analysis of these stars at a fixed Galactocentric distance of the Sun, $R_0 = 8$ kpc, has allowed the following parameters to be determined: (1) the solar peculiar velocity components $(U_\odot, V_\odot, W_\odot) = (8.9, 10.3, 6.8) \pm (0.6, 1.0, 0.4)$ km s$^{-1}$; (2) the Galactic rotation parameters $\Omega_0 = -31.5 \pm 0.9$ km s$^{-1}$ kpc$^{-1}$, $\Omega'_0 = +4.49 \pm 0.12$ km s$^{-1}$ kpc$^{-2}$, $\Omega''_0 = -1.05 \pm 0.38$ km s$^{-1}$ kpc$^{-3}$ (the corresponding Oort constants are $A = 17.9 \pm 0.5$ km s$^{-1}$ kpc$^{-1}$, $B = -13.6 \pm 1.0$ km s$^{-1}$ kpc$^{-1}$ and the circular rotation velocity of the solar neighborhood is $|V_\odot| = 252 \pm 14$ km s$^{-1}$); (3) the spiral density wave parameters, namely: the perturbation amplitudes for the radial and azimuthal velocity components, respectively, $f_R = -12.5 \pm 1.1$ km s$^{-1}$ and $f_\theta = 2.0 \pm 1.6$ km s$^{-1}$; the pitch angle for the two-armed spiral pattern $i = -5.3^\circ \pm 0.3^\circ$, with the wavelength of the spiral density wave at the solar distance being $\lambda = 2.3 \pm 0.2$ kpc; the Sun’s phase in the spiral wave $\chi_\odot = -91^\circ \pm 4^\circ$.

INTRODUCTION

Data on various objects are used to determine the Galaxy’s kinematic parameters. These include the radial velocities of neutral and ionized hydrogen with the distances derived by the tangential point method (Burton 1971; Clemens 1985; Fich et al. 1989), Cepheids with the distance scale based on the period–luminosity relation, open star clusters and OB associations with photometric distances (Mishurov and Zenina 1999; Rastorguev et al. 1999; Dambis et al. 2001; Zabolotskikh et al. 2002; Bobylev et al. 2008; Mel’nik and Dambis 2009), and maser sources with trigonometric parallaxes (Reid et al. 2009; McMillan and Binney 2010; Bobylev and Bajkova 2010).
Young massive luminous stars with large heliocentric distances are important for the solution of our problem. However, among, for example, the O-type stars from the Hipparcos (1997) catalog, only 12 have parallaxes differing significantly from zero and the most distant of them, 10 Lac, is at a distance of only \( \approx 540 \text{ pc} \) from the Sun (Maiz-Apellániz et al. 2008). The distances to a large number of OB stars determined spectroscopically from the broadening of interstellar CaII, NaI, or KI absorption lines are of indubitable interest. The method for determining such distances has long been known (for a review, see Megier et al. 2005). However, only recently did Megier et al. (2005) and Megier et al. (2009) tie the “calcium” scale, respectively, to the Hipparcos (1997) trigonometric parallaxes. Megier et al. (2009) estimated the accuracy of an individual distance to OB stars to be \( \approx 15\% \). For many of them, such highly accurate distance estimates have been obtained for the first time, given that their Hipparcos trigonometric parallaxes are not significant. The method is based on the assumption about a uniform distribution of ionized atoms in the Galactic plane. As these authors point out, the derived distances are applicable only at low elevations of stars above the Galactic plane (\( |z| < 0.8 \text{ kpc} \)). They also point to possible local inhomogeneities in Galactic longitude, especially in the region of the cluster Tr 16.

The best-studied inhomogeneities are those in the immediate solar neighborhood associated with the Local Bubble. Here, the variations in the number density of CaII ions reach one order of magnitude (at a mean number density \( n_{\text{CaII}} \sim 10^{-9} \text{ cm}^{-3} \)) and the spatial sizes of the inhomogeneities are \( \approx 60 \text{ pc} \) (Welsh et al. 2010).

Our goal is to test the distance scale derived from interstellar CaII spectral lines and, subsequently, to use it to investigate the kinematics of OB stars, in particular, to construct the Galactic rotation curve and to determine the spiral density wave parameters. To refine the “calcium” scale, we apply the method for internal reconciliation of the distance scales using the first derivative of the angular velocity of Galactic rotation \( \Omega'_0 \) (Zabolotskikh et al. 2002) and the method for external reconciliation with Humphreys’s (1978) distance scale for OB associations refined by Mel’nik and Dambis (2009).

**DATA**

We used data on 290 young OB3 stars whose distances were determined by Megier et al. (2009) from the equivalent widths of CaII K and CaII H lines by tying them to the trigonometric parallaxes of a revised version of the Hipparcos catalog (van Leeuwen 2007). We supplemented the sample with data from the CRVAD-2 compilation (Kharchenko et al. 2007), with contains the radial velocities, proper motions, and photometric characteristics for \( \approx 55000 \) stars.

For spectroscopic binaries, we checked them against the SB9 database (Pourbaix et al. 2004) in order to refine their systemic radial velocities \( V_\gamma \). For a number of stars, we made significant changes to the CRVAD-2 radial velocities. There are also the most recent \( V_\gamma \) determinations, for instance, for such stars of our sample as HIP 31978 (Cvetković et al. 2010), HIP 32067 (Mahy et al. 2010), or HIP 78401 (Tango et al. 2009).

As a result, we obtained a working sample of 258 Hipparcos OB3 stars with the distances from Megier et al. (2009), proper motions (van Leeuwen 2007), and radial
velocities. These stars have various luminosity classes. Note that ≈ 20% of the sample are either known runaway stars (Tetzlaff et al. 2011) or candidates for runaway stars due to their large (> 40 km s\(^{-1}\)) residual space velocities.

**THE METHOD**

The method used here to determine the kinematic parameters consists in minimizing a quadratic functional \( F \):

\[
\text{min } F = \sum_{j=1}^{N} w_j^2 (V_r^j - \hat{V}_r^j)^2 + \sum_{j=1}^{N} w_i^2 (V_i^j - \hat{V}_i^j)^2 + \sum_{j=1}^{N} w_b^2 (V_b^j - \hat{V}_b^j)^2
\]

where \( N \) is the number of stars used; \( j \) is the current star number; \( V_r \) is the radial velocity; \( V_i = 4.74 r \mu_i \cos b \) and \( V_b = 4.74 r \mu_b \) are the proper motion velocity components in the \( l \) and \( b \) directions, respectively, with the coefficient 4.74 being the quotient of the number of kilometers in an astronomical unit and the number of seconds in a tropical year; \( \hat{V}_r^j, \hat{V}_i^j, \hat{V}_b^j \) are the measured components of the velocity field (data); \( w_j, w_i, w_b \) are the weight factors, provided that the following constraints derived from Bottlinger’s formulas (Ogorodnikov 1965) with an expansion of the angular velocity of Galactic rotation \( \Omega \) into a series to terms of the second order of smallness with respect of \( r/R_0 \) and with allowance made for the influence of the spiral density wave hold:

\[
V_r = -u_\odot \cos b \cos(l - l_0) - v_\odot \cos b \sin(l - l_0) - w_\odot \sin b - R_0 (R - R_0) \sin(l - l_0) \cos b \Omega' \sin l_0 + 0.5R_0 (R - R_0)^2 \sin(l - l_0) \cos b \Omega'' + 0.5 \cos(l - l_0 + \theta) \cos b - \tilde{v}_R \cos(l - l_0 + \theta) \cos b,
\]

\[
V_i = u_\odot \sin(l - l_0) - v_\odot \cos(l - l_0) - (R - R_0) (R_0 \cos(l - l_0) - r \cos b) \Omega' - (R - R_0)^2 (R_0 \cos(l - l_0) - r \cos b) 0.5 \Omega'' + r \Omega_0 \cos b + \tilde{v}_b \cos(l - l_0 + \theta) + \tilde{v}_R \sin(l - l_0 + \theta),
\]

\[
V_b = u_\odot \cos(l - l_0) \sin b + v_\odot \sin(l - l_0) \sin b - w_\odot \cos b + R_0 (R - R_0) \sin(l - l_0) \sin b \Omega' \sin l_0 + 0.5R_0 (R - R_0)^2 \sin(l - l_0) \sin b \Omega'' - \tilde{v}_b \sin(l - l_0 + \theta) \sin b + \tilde{v}_R \cos(l - l_0 + \theta) \sin b,
\]

where \( r \) is the stars heliocentric distance; the stars proper motion components \( \mu_i \cos b \) and \( \mu_b \) are in mas yr\(^{-1}\) and the radial velocity \( V_r \) is, in km s\(^{-1}\); \( u_\odot, v_\odot, w_\odot \) are the stellar group velocity components relative to the Sun taken with the opposite sign (the velocity \( u \) is directed toward the Galactic center; \( v \) is in the direction of Galactic rotation; and \( w \) is directed to the north Galactic pole); \( R_0 \) is the galactocentric distance of the Sun; \( R \) is the galactocentric distance of the star; \( l_0 \) is the direction to the kinematic center (to the Galactic center) — we included it as an unknown to reveal possible peculiarities of the “calcium” stellar distance scale. \( \Omega_0 \) is the angular velocity of rotation at the distance \( R_0 \);
the parameters $\Omega'_0$ and $\Omega''_0$ are, respectively, the first and second derivatives of the angular velocity; the distance $R$ is calculated from the expression

$$R^2 = (r \cos b)^2 - 2R_0r \cos b \cos (l - l_0) + R_0^2.$$  

To take into account the influence of the spiral density wave, we used the simplest kinematic model based on the linear theory of density waves by Lin et al. (1969), in which the potential perturbation is in the form of a traveling wave. Then,

$$\tilde{v}_R = f_R \cos \chi,$$

$$\tilde{v}_\theta = f_\theta \sin \chi,$$

$$\chi = m [\cot(i) \ln(R/R_0) - \theta] + \chi_\odot,$$

where $f_R$ and $f_\theta$ are the perturbation amplitudes for the radial (directed toward the Galactic center in the arm) and azimuthal (directed along the Galactic rotation) velocities; $i$ is the spiral pitch angle ($i < 0$ for winding spirals); $m$ is the number of arms, with $m = 2$ taken here; $\theta$ is the position angle of the star (measured in the direction of Galactic rotation); $\chi_\odot$ is the phase angle of the Sun, measured here from the center of the Carina–Sagittarius spiral arm ($R \approx 7$ kpc), as was done by Rohlfs (1977). The parameter $\lambda$ is the distance (in the Galactocentric radial direction) between adjacent segments of spiral arms in the solar neighborhood (the wavelength of the spiral wave)—it is calculated from the relation

$$\tan(i) = \frac{\lambda m}{2 \pi R_0}.$$  

The described method of allowance for the influence of the spiral density wave was applied by Mishurov and Zenina (1999) and Fernández et al. (2001), where its detailed description can be found, and by Zabolotskikh et al. (2002).

The weight factors in functional (1) are assigned according to the following expressions (for simplification, we omit the index $j$):

$$w_r = S_0 / \sqrt{S_0^2 + \sigma_{V_r}^2},$$

$$w_l = \beta^2 S_0 / \sqrt{S_0^2 + \sigma_{V_l}^2},$$

$$w_b = \gamma^2 S_0 / \sqrt{S_0^2 + \sigma_{V_b}^2},$$

where $S_0$ denotes the dispersion averaged over all observations, which has the meaning of a “cosmic” dispersion taken to be 8 km s$^{-1}$; $\beta = \sigma_{V_l}/\sigma_{V_l}$ and $\gamma = \sigma_{V_b}/\sigma_{V_b}$ are the scale factors that we determined using data on open star clusters (Bobylev et al. 2007), $\beta = 1$ and $\gamma = 2$. The errors of the velocities $V_l$ and $V_b$ are calculated from the formula

$$\sigma_{(V_l, V_b)} = 4.74 r \mu_{l,b} \left( \frac{\sigma_r}{r} \right)^2 + \sigma_{\mu_{l,b}}^2.$$  

The optimization problem (1)–(4) is solved for eleven unknown parameters $u_0, v_0, w_0, \Omega_0, \Omega'_0, \Omega''_0, l_0, f_R, f_\theta, i$, and $\chi_\odot$ by the coordinate-wise descent method (the sought-for parameters are taken as the coordinates).
Table 1: A summary of $\Omega_0$ and $\lambda/R_0$ determinations

| Reference                      | Method          | Data                | $\Omega_0(R_0 = 8 \text{ kpc})$, km s$^{-1}$ kpc$^{-2}$ | $\lambda/R_0$ |
|-------------------------------|-----------------|---------------------|--------------------------------------------------------|---------------|
| Clemens (1985)                | $\Delta V_{\theta}$ | CO+HI              | -                                                      | 0.22          |
| Mel’nik et al. (2001)         | $V(\mu) + V_r$  | OB associations    | -4.3 ± 0.2 (*)                                          | 0.28 ± 0.03   |
| Zabolotskikh et al. (2002)    | $V(\mu) + V_r$  | Cepheids+OSC       | -4.3 ± 0.2 (*)                                          | 0.33 ± 0.04   |
| Zabolotskikh et al. (2002)    | $V(\mu) + V_r$  | Supergiants        | -4.4 ± 0.2 (*)                                          | 0.36 ± 0.05   |
| Bobylev et al. (2008)         | $\Delta V_{\theta}$ | HI+HII+OSC        | -4.3 ± 0.2 (*)                                          | 0.33 ± 0.04   |
| Bobylev et al. (2008)         | $V_R$           | OSC                | -4.4 ± 0.2                                              | 0.36 ± 0.05   |
| Mel’nik and Dambis (2009)     | $V(\mu) + V_r$  | OB associations    | -4.4 ± 0.2                                              | 0.33 ± 0.04   |
| Bobylev and Bajkova (2010)    | $V_R$           | Masers             | -4.5 ± 0.2                                              | 0.36 ± 0.05   |

* : The mean of the values obtained at $R_0 = 7.5$ kpc and $R_0 = 8.5$ kpc; we calculated $\lambda/R_0$ us from the pitch angle $i$ (for the two-armed model) based on Eq. (5).

We estimated the errors of the sought-for parameters through Monte Carlo simulations. The errors were estimated by performing 100 cycles of computations. For this number of cycles, the mean values of the solutions virtually coincide with the solutions obtained from the input data without any addition of measurement errors. Measurements errors were added to such input data as the radial velocities, proper motions, and distances.

Here, we take a fixed value of $R_0$. Reid (1993) found a weighted mean from the measurements published over a 20-year period, $R_0 = 8.0 \pm 0.5$ kpc. Taking into account the main types of errors and correlations associated with the classes of measurements, Nikiforov (2003) derived the “best value”, $R_0 = 7.9 \pm 0.2$ kpc. A similar result was obtained by Avedissova (2005), $R_0 = 7.8 \pm 0.3$ kpc. Note several most recent $R_0$ determinations. These include the direct distance measurements based on the orbits of stars moving around a massive black hole at the Galactic center, which give $R_0 = 8.4 \pm 0.4$ kpc (Ghez et al. 2008) or $R_0 = 8.33 \pm 0.35$ kpc (Gillessen et al. 2009). A summary of the latest determinations can be found in Foster and Cooper (2010), where the weighted mean is $R_0 = 8.0 \pm 0.4$ kpc. Given all uncertainties, we consider $R_0 = 8.0 \pm 0.4$ kpc to be the most probable value.

RESULTS

When solving the system of equations (2), 38 of 258 stars are rejected according to the 3$\sigma$ criterion already at the first step. Seventeen of these stars are identified with the catalog of candidate runaway stars (Tetzlaff et al. 2011); most of the remaining ones are either new candidates for runaway stars or have measurements of the radial velocities or proper motions that are too unreliable.

Since the Gould Belt has a significant influence in the region $r < 0.8$ kpc, we do not consider any stars from this region when studying the parameters of the Galactic rotation curve.

There is only one star in the region $r > 3.2$ kpc, HIP 85020 ($r = 4.5$ kpc). It has a low residual velocity, but we do not consider this star, because it is too far from the common
We obtained the following solution from 102 stars in the range of distances 0.8–3.2 kpc: $(u_\odot, v_\odot, w_\odot) = (9.3, 10.2, 8.4) \pm (0.7, 1.3, 0.4) \text{ km s}^{-1}$ and

$$\begin{align*}
\Omega_0 &= -28.6 \pm 0.8 \text{ km s}^{-1}, \\
\Omega'_0 &= +3.91 \pm 0.10 \text{ km s}^{-2}, \\
\Omega''_0 &= -0.81 \pm 0.35 \text{ km s}^{-3}, \\
f_R &= -11.9 \pm 1.3 \text{ km s}^{-1}, \quad f_\theta = 2 \pm 2 \text{ km s}^{-1}, \\
l_0 &= -1^\circ \pm 2^\circ, \quad i = -68^\circ \pm 0.5^\circ, \quad \chi_\odot = -94^\circ \pm 5^\circ,
\end{align*}$$

the error per unit weight is $\sigma_0 = 11.2 \text{ km s}^{-1}$. The almost zero value of $l_0$ shows that there are no significant global longitudinal peculiarities.

Based on the pitch angle $i$ found in solution (6) and Eq. (5), we find $\lambda/R_0 = 0.37 \pm 0.03$ and then $\lambda = 3.0 \pm 0.2$ kpc. This value of $\lambda$ is too large compared to the determinations of this parameter by other authors using various independent data. This suggests that the “calcium” distance scale is stretched. To determine how much it is stretched, we use several kinematic methods for comparing the distance scales.

### Table 2: Kinematic parameters found using the refined distance scale ($p_{\text{scale}} = 0.8$)

| Parameters | No 1       | No 2       | No 3       | No 4       | No 5       |
|------------|------------|------------|------------|------------|------------|
| $u_\odot$, km s$^{-1}$ | $8.9 \pm 0.6$ | $8.9 \pm 0.7$ | $9.3 \pm 0.7$ | $9.0 \pm 0.5$ | $9.2 \pm 0.6$ |
| $v_\odot$, km s$^{-1}$ | $10.3 \pm 1.0$ | $10.3 \pm 0.9$ | $10.1 \pm 1.0$ | $10.4 \pm 1.1$ | $10.2 \pm 1.0$ |
| $w_\odot$, km s$^{-1}$ | $6.8 \pm 0.4$ | $-$           | $-$           | $6.5 \pm 0.2$ | $6.8 \pm 0.4$ |
| $\Omega_0$, km s$^{-1}$ kpc$^{-1}$ | $-31.5 \pm 0.9$ | $-31.5 \pm 0.8$ | $-31.8 \pm 1.0$ | $-29.8 \pm 1.3$ | $-31.2 \pm 0.9$ |
| $\Omega'_0$, km s$^{-1}$ kpc$^{-2}$ | $4.49 \pm 0.12$ | $4.49 \pm 0.11$ | $4.53 \pm 0.13$ | $4.14 \pm 0.16$ | $4.46 \pm 0.12$ |
| $\Omega''_0$, km s$^{-1}$ kpc$^{-3}$ | $-1.05 \pm 0.38$ | $-1.05 \pm 0.36$ | $-1.15 \pm 0.42$ | $-0.93 \pm 0.34$ | $-1.12 \pm 0.40$ |
| $f_R$, km s$^{-1}$ | $-12.5 \pm 1.1$ | $-12.5 \pm 0.9$ | $-13.4 \pm 0.9$ | $-9.4 \pm 4.4$ | $-12.7 \pm 1.1$ |
| $f_\theta$, km s$^{-1}$ | $2.0 \pm 1.6$ | $2.1 \pm 1.5$ | $0.7 \pm 1.7$ | $2.5 \pm 1.7$ | $1.8 \pm 1.6$ |
| $l_0$, deg. | $-1.5 \pm 1.3$ | $-1.5 \pm 1.2$ | $-1.1 \pm 1.3$ | $-2.3 \pm 1.2$ | $-$           |
| $i$, deg. | $-5.3 \pm 0.3$ | $-5.3 \pm 0.3$ | $-5.4 \pm 0.3$ | $-5.3 \pm 0.4$ | $-5.4 \pm 0.3$ |
| $\chi_\odot$, deg. | $-91 \pm 4$ | $-91 \pm 4$ | $-89 \pm 3$ | $-87 \pm 47$ | $-91 \pm 4$ |
| $\lambda$, kpc | $2.3 \pm 0.2$ | $2.3 \pm 0.2$ | $2.4 \pm 0.2$ | $2.3$ | $2.4 \pm 0.2$ |
| $\sigma_0$, km s$^{-1}$ | $9.5$ | $9.5$ | $10.6$ | $8.3$ | $9.6$ |
| $N_*$ | $102$ | $102$ | $102$ | $219$ | $102$ |

As a result, our working sample consists of 102 stars.

### The Initial “Calcium” Distance Scale

We know a method (Dambis et al. 2001; Zabolotskikh et al. 2002) where the distance scale coefficient $(p_{\text{scale}})$ is included as an additional unknown in the initial kinematic equations.
Figure 1: (a) Stellar distances $0.8 \times r_{\text{Humphreys}}$ versus distances $r_{\text{CaII}}$; (b) stellar distances $0.8 \times r_{\text{Humphreys}}$ versus distances $0.8 \times r_{\text{CaII}}$; the dotted lines mark the outer boundaries of the sample of stars used to determine the kinematic parameters.

(e.g., (2)). In this case, it can be determined by simultaneously solving the system of equations or can be found by minimizing the residuals according to the $\chi^2$ test.

Unfortunately, this method did not give a reliable result in our case. The minimum of $\chi^2$ is reached at $p_{\text{scale}} \approx 0.3 - 0.4$. The new distances are calculated as $r_{\text{NEW}} = p_{\text{scale}} \times r$. However, for such a radical reduction of the initial “calcium” scale, the remaining model parameters lose any physical meaning. We assume that this is determined by the “calcium” scale calibration method — the nonlinear (hyperbolic) relation between the equivalent widths of CaII spectral lines and trigonometric parallaxes (Megier et al. 2009). Thus, different values of the linear coefficient $p_{\text{scale}}$ should be applied for different ranges of distances. Other distance scale reconciliation methods are also known.

Reconciliation of the derivative $\Omega'_0$.

The method for internal reconciliation of the distance scales using the first derivative of the angular velocity of Galactic rotation $\Omega'_0$ (Zabolotskikh et al. 2002) consists in comparing the values obtained by separately solving the system of equations (2). For this purpose, we solved a simplified system of equations with the unknowns $u_\odot, v_\odot, w_\odot$ and $\Omega_0, \Omega'_0, \Omega''_0$; when using the radial velocities, we fixed the parameters $w_\odot$ and $\Omega_0$ found from the proper motions. We found $\Omega'_0 (V_r) = 3.87 \pm 0.35$ km s$^{-1}$ kpc$^{-2}$ only from the radial velocities and $\Omega'_0 (V_\mu) = 3.29 \pm 0.26$ km s$^{-1}$ kpc$^{-2}$ only from the proper motions. Then, $p_{\text{scale}} = 3.29/3.87 = 0.85$.

At present, there are quite satisfactory estimates of $\Omega'_0$ and $\lambda$ for external scale calibration. A number of such results are presented in Table 1; they were obtained in different distance scales: the tangential point method (Clemens 1985), the Cepheid scale, the pho-
tometric scale (open star clusters — OSCs) reconciled with the Hipparcos trigonometric parallaxes, and the trigonometric parallaxes (masers). By comparing $\Omega'_0 = 3.9 \, \text{km s}^{-1} \, \text{kpc}^{-2}$ found in solution (6) with the mean from Table 2, we obtain $p_{\text{scale}} = 3.9/4.4 = 0.89$.

**Reconciliation of the wavelength $\lambda$.**

By comparing the mean from Table 1, $\lambda/R_0 = 0.29$, with the result of solution (6), $\lambda/R_0 = 0.37$, we find $p_{\text{scale}} = 0.29/0.37 = 0.78$. Having separately considered the Galactocentric radial velocities of our OB3 stars, we found $\lambda/R_0 = 0.36 \pm 0.03$ ($\lambda = 2.9 \pm 0.2$ kpc). For this purpose, we applied the method of Fourier analysis described in detail previously (Bobylev and Bajkova 2010). In this case, $p_{\text{scale}} = 0.29/0.36 = 0.80$. Thus, this method gives $p_{\text{scale}}$ close to 0.8.

**Reconciliation with Humphreys’s refined distance scale.**

The membership in OB associations with the distances to them determined by Humphreys (1978) is specified in the catalog by Megier et al. (2009) for a considerable number of stars. A number of researchers of Humphreys’s scale (Dambis et al. 2001; Mel’nik and Dambis, 2009) conclude that it should be reduced by $\approx 20\%$, i.e., the refined distances should be calculated as $r_{\text{NEW}} = 0.8 \times r_{\text{Humphreys}}$. Figure 1 shows the “$0.8 \times r_{\text{Humphreys}} - r_{\text{CaII}}$” and “$0.8 \times r_{\text{Humphreys}} - 0.8 \times r_{\text{CaII}}$” relations. In fact, the distance scale by Mel’nik and Dambis (2009) is along the vertical axis. It is clearly seen from the figure that the “calcium” scale should be reduced with a coefficient close to 0.8.

As can be seen from Fig. 1b, the stars with distances greater than 3 kpc already deviate significantly from the general relation even in the corrected “calcium” scale. We did not specially determined the outer boundary indicated in the figure, because it was revealed.
Figure 3: Galactic rotation curve (solid line). The vertical line marks the position of the solar circle. The dashed lines indicate the 1σ confidence intervals.

automatically — the stars outside this boundary were either rejected according to the 3σ criterion when solving the system of equations (2) or had no velocity measurements.

**Galactic Rotation Curve**

Using several methods of analysis, we showed that the scale coefficient $p_{\text{scale}}$ lies within the range 0.7–0.9, with a mean close to 0.8. We use this mean to form the refined distances $r_{\text{NEW}} = 0.8 \times r_{\text{CaII}}$ with which all of the subsequent computations are performed.

The positions of 219 stars in the Galactic $XY$ plane computed in the refined distance scale are shown in Fig. 2.

Based on the sample of 102 relatively distant stars located in the range of distances $r_{\text{NEW}}$ from 0.6 to 2.6 kpc, we found several solutions of the system of equations (2) given in Table 2. Solution 1 was obtained in the same way as solution (6) using all tree components $V_r, V_t, V_b$. To obtain solution 2, we used the same components $V_r, V_t, V_b$ but fixed the velocity $w_\odot = 7 \, \text{km s}^{-1}$. We found solution 3 only from two components, $V_r$ and $V_t$, with the fixed velocity $w_\odot = 7 \, \text{km s}^{-1}$. Solution 4 was obtained in the same way as solution 1 using all three components $V_r, V_t, V_b$ from all 219 stars.

Solution 4 shows that the influence of nearby stars degrades considerably the accuracy of determining the spiral-structure parameters. Solutions 1 and 2 are virtually identical. Comparison of solution 3 with solutions 1 and 2 shows that using the three components $V_r, V_t, V_b$ is more preferable, i.e., the stars are not too far from the Sun for valuable information to be lost in the components $V_b$.

Solution 5 was obtained in the same way as solution 1 using all three components $V_r, V_t, V_b$, but the direction to the Galactic center was fixed at $l_0 = 0^\circ$. All of the determined parameters in solution 5 agree well with the results of solutions 1 and 2. Therefore,
Figure 4: Galactocentric radial velocities for 102 relatively distant OB3 stars (a), the sine wave with a period of 2.3 kpc and an amplitude of 12.5 km s$^{-1}$ (solid line), and the residual azimuthal velocities (b). The vertical line marks the position of the solar circle.

below we will use the result of the more general case (solution 1).

Figure 3 displays the Galactic rotation curve constructed according to solution 1 from Table 2. The dashed lines indicate the boundaries of the confidence intervals corresponding to a 1σ error level calculated by taking into account the contributions from the error in the angular velocity and the uncertainty in $R_0$.

Figure 4 presents the Galactocentric radial velocities $V_R$ (the direction away from the Galactic center is considered the positive one) for 102 relatively distant OB3 stars and the residual azimuthal velocities $\Delta V_{rot}$. The azimuthal velocities are residual, because the Galactic rotation curve found was excluded from them; both velocities $V_R$ and $\Delta V_{rot}$ were freed from the group velocity. The sine wave associated with the influence of the spiral density wave was fitted into the radial velocities (based on solution 1 from Table 2).

The Oort constants calculated using solution 1 from Table 2 are $A = 17.9 \pm 0.5$ km s$^{-1}$ kpc$^{-1}$ and $B = -13.6 \pm 1.0$ km s$^{-1}$ kpc$^{-1}$. The circular rotation velocity of the solar neighborhood is $|V_0| = 252 \pm 14$ km s$^{-1}$ (calculated by taking into account the error in $R_0$ of 0.4 kpc).

Table 3 lists the stars with residual space velocities $|V_{pec}| > 40$ km s$^{-1}$. We calculated the velocities $V_{pec}$ by excluding the rotation curve found and the solar peculiar velocity as
well as by excluding the wave found in the radial velocities. These stars are either already known runaway stars or suitable candidates for runaway stars.

**DISCUSSION**

(1) The phase \( \chi_\odot \) we found is almost equal to \(-\pi/2\). Its value does not depend on the distance scale. The specific values of the solar peculiar velocity relative to the local standard of rest (LSR) depend on the phase \( \chi_\odot \) (see Eqs. (19),(20) in Bobylev and Bajkova 2010). Since young stars experience perturbations from the spiral density wave, the components of their mean motion \( u_\odot \) and \( v_\odot \) can differ significantly from the velocities found from older stars (Dehnen and Binney 1998). Denote the solar peculiar velocity components unperturbed by the spiral wave by \((U_\odot, V_\odot, W_\odot)_{LSR}\). As is clearly seen from Fig. 4a, the sine wave passes through zero at \( R = 8 \) kpc. Therefore, despite its significant amplitude \( (f_R) \), the radial component of the wave causes no shift of the mean velocities (its main contribution to the velocity \( U_\odot_{LSR} \)). The amplitude of the azimuthal component of the spiral wave \( (f_\theta) \) is almost zero (its main contribution to the velocity \( V_\odot_{LSR} \)). Then, \( (U_\odot, V_\odot, W_\odot)_{LSR} = (u_\odot, v_\odot, w_\odot) = (8.9, 10.3, 6.8) \pm (0.6, 1.0, 0.4) \) km s\(^{-1}\) according to solution 1 from Table 2.

The present-day situation with the determination of this velocity by various methods but without invoking any data on young stars is as follows. Schönrich et al. (2010) took into account the stellar metallicity gradient in the Galactic disk and found the following components: \((U_\odot, V_\odot, W_\odot)_{LSR} = (11.1, 12.2, 7.3) \pm (0.7, 0.5, 0.4) \) km s\(^{-1}\). Having analyzed the eccentricities of stars in the solar neighborhood, Francis and Anderson (2009) found \((U_\odot, V_\odot, W_\odot)_{LSR} = (7.5, 13.5, 2, 6.8) \pm (1.0, 0.3, 0.1) \) km s\(^{-1}\). Based on an updated version of the Geneva–Copenhagen survey (Holmberg et al. 2007), Koval’ et al. (2009) found \((U_\odot, V_\odot, W_\odot)_{LSR} = (5.1, 7.9, 7.7) \pm (0.4, 0.5, 0.2) \) km s\(^{-1}\) from stars born at a circumsolar distance by taking into account the radial migration of stars and the metallicity gradient in the Galactic disk. Thus, the solar peculiar velocity components are \((U_\odot, V_\odot, W_\odot)_{LSR} = (10, 11, 7) \) km s\(^{-1}\). The components we found from OB3 stars are in good agreement with these values.

This is confirmed by the analysis of a sample of blue supergiants that are closest in evolutionary status to the OB3 stars of our sample: \((U_\odot, V_\odot, W_\odot)_{LSR} = (6, 11, 7) \) km s\(^{-1}\) (Zabolotskikh et al. 2002), where the phase was \( \chi_\odot = -97^\circ \) at a significant amplitude \( f_R = -6.6 \pm 2.5 \) km s\(^{-1}\). A similar result was obtained by Fernández et al. (2001) both using a sample of OB stars, \((U_\odot, V_\odot, W_\odot)_{LSR} = (8.8, 12.4, 8.4) \pm (0.7, 1.0, 0.5) \) km s\(^{-1}\), and from Cepheids, \((U_\odot, V_\odot, W_\odot)_{LSR} = (6.5, 10.4, 5.7) \pm (1.2, 1.9, 0.7) \) km s\(^{-1}\), with a phase \( \chi_\odot \approx -30^\circ \), although the spiral wave amplitudes turned out to be insignificant.

(2) The ratio of the spiral wave amplitudes we found from our sample of 102 OB3 stars, \( f_R = -13 \pm 1 \) km s\(^{-1}\) and \( f_\theta = 0 \pm 1 \) km s\(^{-1}\), is in good agreement with the analysis of blue supergiants by Zabolotskikh et al. (2002), \( f_R = -6.6 \pm 2.5 \) km s\(^{-1}\) and \( f_\theta = 0.4 \pm 2.3 \) km s\(^{-1}\), and a sample of Cepheids with close values of these parameters.

At the same time, it can be seen from Fig. 4b that a wave with a significant amplitude (\( \approx 10 \) km s\(^{-1}\)) but with a wavelength \( \lambda \approx 1 \) kpc is present in the azimuthal velocities. As we see from the figure, the local standard of rest turns out to be shifted in the region
Table 3: Candidates for runaway stars

| HIP   | $|V_{pec}|$, km s$^{-1}$ | Remark |
|-------|-------------------------|--------|
| 18350 | 63±11                   | R.     |
| 18614 | 54±15                   | R.     |
| 22783 | 58±12                   |        |
| 24575 | 115±12                  | R.     |
| 27204 | 97±3                    | R.     |
| 29147 | 101±28                  |        |
| 31348 | 61±19                   |        |
| 32067 | 40±6                    | R.     |
| 43158 | 58±14                   | R.     |
| 54475 | 63±29                   | R.     |
| 63170 | 59±15                   | R.     |
| 64896 | 54±21                   |        |
| 65129 | 42±7                    |        |
| 78310 | 46±9                    |        |
| 81100 | 44±6                    | R.     |
| 81305 | 46±10                   | R.     |
| 81696 | 68±125                  | R.     |
| 81702 | 48±26                   |        |
| 82171 | 71±10                   | R.     |
| 82685 | 41±20                   |        |
| 82775 | 110±8                   | R.     |
| 83499 | 65±10                   |        |
| 84687 | 48±37                   | R.     |
| 85331 | 113±22                  | R.     |
| 89218 | 56±18                   |        |
| 89750 | 78±40                   |        |
| 98863 | 48±21                   |        |
| 100287| 48±22                   |        |
| 101186| 42±6                    | R.     |
| 109556| 86±16                   | R.     |
| 114695| 42±23                   |        |

Note. R denotes a runaway star according to Tetzlaff et al. (2011).
$R \rightarrow R_0$ in the direction opposite to the Galactic rotation. When a sample of masers was analyzed (Bobylev and Bajkova 2010; Stepanishchev and Bobylev 2011), a special allowance for the perturbations from the spiral wave in the region $R \rightarrow R_0$ made it possible to estimate the velocity components $(U_\odot, V_\odot, W_\odot)_{LSR}$.

(3) The parameters of the Galactic rotation curve $\Omega_0$ and $\Omega'_0$ calculated from 102 OB3 stars using the refined “calcium” distance scale (solutions 1,2,3, and 5 from Table 2) are in good agreement with the results of the analysis of Cepheids and blue supergiants (Zabolotskikh et al. 2002), OB associations (Melnik and Dambis 2009), and masers (Bobylev and Bajkova 2010; Stepanishchev and Bobylev 2011).

**CONCLUSIONS**

We tested the distances derived from the equivalent widths of interstellar CaII spectral lines by Megier et al. (2009). For this purpose, we used a sample of 102 relatively distant OB3 stars with known proper motions and radial velocities.

The internal reconciliation of the distance scales using the first derivative of the angular velocity of Galactic rotation $\Omega'_0$ and the external reconciliation with Humphreys’s distance scale for OB associations refined by Mel’nik and Dambis (2009), we showed that the initial distances should be reduced by $\approx 20\%$.

In the refined distance scale, our OB3 stars are located at heliocentric distances in the range from 0.6 to 2.6 kpc. We used them to construct the Galactic rotation curve and to determine the parameters of the spiral density wave.

For a fixed distance to the Galactic center, $R_0 = 8$ kpc, we found the solar peculiar velocity components $(u_\odot, v_\odot, w_\odot) = (8.9, 10.3, 6.8) \pm (0.6, 1.0, 0.4) \text{ km s}^{-1}$; the angular velocity of Galactic rotation $\Omega_0 = -31.5 \pm 0.9 \text{ km s}^{-1} \text{ kpc}^{-1}$ and its derivatives $\Omega'_0 = +4.49 \pm 0.12 \text{ km s}^{-1} \text{ kpc}^{-2}$, $\Omega''_0 = -1.05 \pm 0.38 \text{ km s}^{-1} \text{ kpc}^{-3}$. The corresponding Oort constants are $A = 17.9 \pm 0.5 \text{ km s}^{-1} \text{ kpc}^{-1}$ and $B = -13.6 \pm 1.0 \text{ km s}^{-1} \text{ kpc}^{-1}$; the circular rotation velocity of the solar neighborhood is $|V_0| = 252 \pm 14 \text{ km s}^{-1}$; the amplitudes of the spiral density wave are $f_R = -12.5 \pm 1.1 \text{ km s}^{-1}$ and $f_\theta = 2.0 \pm 1.6 \text{ km s}^{-1}$; the pitch angle of the two-armed spiral pattern is $i = -5.3^\circ \pm 0.3^\circ$ and the phase of the Sun in the spiral wave is $\chi_\odot = -91^\circ \pm 4^\circ$; and the direction to the Galactic center is $l_0 = -1.5^\circ \pm 1.3^\circ$.

The wavelength of the spiral density wave at the solar distance is $\lambda = 2.3 \pm 0.2$ kpc. It is particularly pronounced in the Galactocentric radial velocities $V_R$. The residual azimuthal velocities $\Delta V_\theta$ have a more complex structure.

**ACKNOWLEDGMENTS**

We are grateful to the referees for valuable remarks that contributed to a significant improvement of the paper. The SIMBAD search database provided a great help to our study. This work was supported by the Russian Foundation for Basic Research (project no. 08-02-0040) and in part by the “Origin and Evolution of Stars and Galaxies” Program of the Presidium of the Russian Academy of Sciences and the Program of State Support for Leading Scientific Schools of the Russian Federation (project. NSh–3645.2010.2, “Multiwavelength Astrophysical Studies”).
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Translated by N. Samus’