Estimation of the Solar Galactocentric Distance and Galactic Rotation Velocity from Near-Solar-Circle Objects

V.V. Bobylev

1 Pulkovo Astronomical Observatory, Russian Academy of Sciences
2 Sobolev Astronomical Institute, St. Petersburg State University, Russia

Abstract—We have tested the method of determining the solar Galactocentric distance $R_0$ and Galactic rotation velocity $V_0$ modified by Sofue et al. using near-solar-circle objects. The motion of objects relative to the local standard of rest has been properly taken into account. We show that when such young objects as star-forming regions or Cepheids are analyzed, allowance for the perturbations produced by the Galactic spiral density wave improves the statistical significance of the estimates. The estimate of $R_0 = 7.25 \pm 0.32$ kpc has been obtained from 19 star-forming regions. The following estimates have been obtained from a sample of 14 Cepheids (with pulsation periods $P > 5^4$): $R_0 = 7.66 \pm 0.36$ kpc and $V_0 = 267 \pm 17$ km s$^{-1}$. We consider the influence of the adopted Oort constant $A$ and the character of stellar proper motions (Hipparcos or UCAC4). The following estimates have been obtained from a sample of 18 Cepheids with stellar proper motions from the UCAC4 catalog: $R_0 = 7.64 \pm 0.32$ kpc and $V_0 = 217 \pm 11$ km s$^{-1}$.

1 Introduction

The solar Galactocentric distance $R_0$ and Galactic rotation velocity $V_0$ are the most important parameters for studying the structure, kinematics, and dynamics of our Galaxy.

There exist various methods for estimating $R_0$. Reid (1993) published a review of the $R_0$ determinations made by then by various methods and obtained the “best value” as a weighted mean of the measurements published over a period of 20 years, $R_0 = 8.0 \pm 0.5$ kpc. Taking into account the main types of errors and correlations related to the classes of measurements, Nikiforov (2004) obtained the “best value” of $R_0 = 7.9 \pm 0.2$ kpc. In the review by Foster and Cooper (2010), the weighted mean $R_0 = 8.0 \pm 0.4$ kpc was derived by analyzing the $R_0$ determinations published in the last decade. We see that the present-day value of $R_0$ is known with an error of 0.5%.

Individual independent methods can give an estimate of $R_0$ with an error of $10-15\%$. Note several important individual measurements. Based on Cepheids and RR Lyr stars belonging to the bulge (Groenewegen et al. 2008) and using improved calibrations derived from Hipparcos data and 2MASS photometry, Feast et al. (2008) found $R_0 = 7.64 \pm 0.21$ kpc. By analyzing the orbits of stars moving around the massive black hole at the Galactic center (the dynamical parallax method), Gillessen et al. (2009) found $R_0 = 8.33 \pm 0.35$ kpc. According to VLBI measurements, the radio source Sqr A* has a proper motion of $6.379 \pm 0.026$ mas yr$^{-1}$ relative to extragalactic sources (Reid and Brunthaler...
2004); using this value, Schönenrich (2012) found $R_0 = 8.27 \pm 0.29$ kpc and $V_0 = 238 \pm 9$ km s$^{-1}$. Two H$_2$O maser sources, Sgr B2N and Sgr B2M, lie in the immediate vicinity of the Galactic center, where the source Sgr A* is located. Based on their direct trigonometric VLBI measurements, Reid et al. (2009a) obtained $R_0 = 7.9^{+0.8}_{-0.7}$ kpc.

The method for estimating $R_0$ and $V_0$ from near-solar-circle stars is of considerable interest. For example, using only one maser source, Onsala2, with a high accuracy of determining its trigonometric parallax, $\approx 3\%$, Sofue et al. (2011) obtained $R_0 = 7.80 \pm 0.39$ kpc and $V_0 = 212 \pm 10$ km s$^{-1}$. Based on a sample of seven selected star-forming regions, they found $R_0 = 7.54 \pm 0.77$ kpc. For the star-forming regions, these authors used rather old kinematic data from Brand and Blitz (1993) without posing the question about a wide coverage of near-solar-circle objects.

The goal of this paper is to test the method of determining the solar Galactocentric distance $R_0$ and Galactic rotation velocity $V_0$ from young near-solar circle objects. We use the largest amount of homogeneous data on near-solar-circle objects with the necessary measurements. These are star-forming regions and young Cepheids. A peculiarity of our approach is the elimination of the systematic noncircular stellar motions related to the influence of the Galactic spiral density wave and a proper allowance for the motions of objects relative to the local standard of rest.

2 THE METHOD

To estimate the Galactocentric distance $R_0$ and the Galaxy’s circular rotation velocity at the near-solar distance $V_0$ using near-solar-circle objects, we apply the method proposed by Sofue et al. (2011):

$$R_0 = \frac{r}{2 \cos l} (1 - d/r),$$

$$V_0 = -\frac{V_p}{2 \cos l} (1 - d/r) + V_r \cot l,$$

where $r$ is the Galactocentric distance of the star; $d$ is the distance of the star from the solar circle along the line of sight (it is desirable that $d \ll r$),

$$d = -\frac{V_r}{A \sin 2l},$$

$V_r$ is the radial velocity of the star relative to the local standard of rest; $V_p$ is the velocity perpendicular to $V_r$ directed along the Galactic longitude ($V_p = V_l = 4.74r \mu_l \cos b$; and $A$ is the Oort constant, which is assumed to be $A = 15$ km s$^{-1}$ kpc$^{-1}$, except for the specially noted cases. Note that the velocities $V_r$ and $V_p$ should be given relative to the local standard of rest. The errors of $R_0$ and $V_0$ are estimated in accordance with the formulas

$$\delta R_0 = \frac{1}{2 \cos l} \left[ \delta r^2 + \left( \frac{\delta V_r}{A \sin 2l} \right)^2 \right]^{1/2},$$

$$\delta V_0 = \frac{1}{2 \cos l} \left[ \delta V_p^2 + \left( \frac{V_p^2 \delta V_r^2}{A \sin 2l} - \frac{2 \cos^2 l}{V_p \sin l} \right)^2 \right]^{1/2}.$$
This method is applicable only for sources located in the first and fourth Galactic quadrants ($-90^\circ < l < 90^\circ$). A simplified version of Eq. (1), without the term $d/r$, is occasionally used to estimate $R_0$ (Schechter et al. 1992). According to the approach by Sofue et al. (2011), the fact that a star belongs to the solar-circle region should be reconciled with its observed velocities and parameters of the Galactic rotation curve. Therefore, stringent requirements are placed on the quality of the observed stellar velocities.

Taking into account the experience of Sofue et al. (2011), we use the following source selection criteria, having calculated their Galactocentric distances $R_0$ with a preliminary value of $R_0 = 8$ kpc:

$$-85^\circ < l < 85^\circ,$$  \hspace{1cm} (6)

$$7 \text{ kpc} < R < 9 \text{ kpc},$$ \hspace{1cm} (7)

$$2.5 \text{ kpc} < r,$$  \hspace{1cm} (8)

$$d/r < 1.5.$$ \hspace{1cm} (9)

without imposing any preliminary constraints on the object’s radial velocity. Note that the milder criterion (8) is used for Cepheids,

$$2 \text{ kpc} < r$$ \hspace{1cm} (10)

to obtain a statistically significant sample. The sample of Cepheids is of great interest in applying Eqs. (2) and (5) using the stellar proper motions. The number of maser sources with measured trigonometric parallaxes and proper motions is currently quite insufficient for this method to be applied.

Equations (1)–(5) were derived by Sofue et al. (2011) under the assumption of purely circular stellar motions around the Galactic center. A peculiarity of our approach is the elimination of the systematic noncircular stellar motions related to the influence of the Galactic density wave. Such motions are clearly revealed in the velocities of young objects (Clemens 1985; Bobylev et al. 2008; Bobylev and Bajkova 2010; Stepanishchev and Bobylev 2011). The following formulas serve as a basis for taking into account the above effects:

$$V_r = -u_\odot \cos b \cos l$$
$$- v_\odot \cos b \sin l - w_\odot \sin b$$
$$+ f_r(GR)$$
$$+ \tilde{v}_\theta \sin(l + \theta) \cos b$$
$$- \tilde{v}_R \cos(l + \theta) \cos b$$
$$+ V',$$ \hspace{1cm} (11)

$$V_p = u_\odot \sin l - v_\odot \cos l$$
$$+ f_p(GR)$$
$$+ \tilde{v}_\theta \cos(l + \theta) + \tilde{v}_R \sin(l + \theta)$$
$$+ V',$$ \hspace{1cm} (12)

where $(u_\odot, v_\odot, w_\odot)$ is the group velocity of the stars under consideration caused by the Sun’s peculiar motion; $f_r$ (GR) and $f_p$ (GR) denote the functions describing the
differential Galactic rotation, whose specific form is unimportant our case; and $V'$ denotes the influence of the residual effects.

To take into account the influence of the spiral density wave, we use the simplest kinematic model based on the linear theory of density waves by Lin and Shu (1964), where the potential perturbation has the form of a traveling wave. Then,

$$
\begin{align*}
\tilde{v}_R &= f_R \cos \chi, \\
\tilde{v}_\theta &= f_\theta \sin \chi,
\end{align*}
$$

where $f_R$ and $f_\theta$ are the perturbation amplitudes of the radial (directed toward the Galactic center in the arm) and azimuthal (directed along the Galactic rotation) velocities; the wave radial phase \( \chi \) is

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

\( i \) is the spiral pitch angle (\( i < 0 \) for winding spirals); \( m \) is the number of arms, we take \( m = 2 \) here; \( \theta \) is the star’s position angle (measured in the direction of Galactic rotation); \( \chi_\odot \) is the radial phase angle of the Sun measured here from the center of the Carina-Sagittarius spiral arm (\( R \approx 7 \) kpc). The parameter \( \lambda \) is the distance (along the Galactocentric radial direction) between the adjacent segments of the spiral arms in the solar neighborhood (spiral wave length) calculated from the relation \( \tan(i) = \lambda m/(2\pi R_0) \).

Initially, we do not constrain the radial velocity, as distinct from the approach by Sofue et al. (2011), who used the constraint \( |V_r| < 15 \) km s\(^{-1} \). This is because apart from purely circular motions, the stars have a space velocity dispersion (enters into the residual velocity \( V' \) in Eqs. (11)–(12), which is \( \approx 8 \) km s\(^{-1} \) for star-forming regions and \( \approx 14 \) km s\(^{-1} \) for Cepheids. Therefore, stars with absolute values of their radial velocities reaching \( \approx 40 \) km s\(^{-1} \) contain useful information. At the final stage, we check the result based on the 3\( \sigma \) criterion to eliminate the outliers.

3 DATA

We used the radial velocities and photometric distance estimates for star-forming regions from the catalog by Russeil (2008). All of the regions satisfying our selection criteria are listed in Table 1, where alternative names are given in parentheses. These four regions enter into the sample of seven regions used by Sofue et al. (2011) to find \( R_0 = 7.54 \pm 0.77 \) kpc. In addition, the catalog by Russeil (2008) provides an estimate of the photometric distance for the region BWW 324, \( r = 2.1 \pm 0.6 \) kpc; therefore, it does not enter into our sample. The remaining two regions used by Sofue et al. (2009), BWW 287 and BWW 328, do not enter into the catalog by Russeil (2003). The only exception is the region W 49 farthest from the Sun without any distance estimate in the catalog by Russeil (2003). Moisés et al. (2011) estimated the spectrophotometric distance for this region, \( r = 12.76 \pm 4.5 \) kpc, using infrared photometry for a single star. However, following Sofue et al. (2011), we use a more accurate distance estimate, \( r = 11.4 \pm 1.2 \) kpc, obtained by Gwinn et al. (1992) from VLBI observations of several water masers and the radial velocity \( V_r (LSR) = 5.4 \pm 2.9 \) km s\(^{-1} \) determined by Roshi et al. (2006). The distribution
of the selected star-forming regions in the Galactic plane is presented in Fig. 1, where, as an example, the distances $r$ and $d$ for one of the regions are shown.

We used data on $\approx 200$ classical Cepheids with proper motions from an improved version of the Hipparcos catalog (ESA, 1997; van Leeuwen 2007). The data from Mishurov et al. (1997), Gontcharov (2006), and the SIMBAD database served as the sources of radial velocities. To calculate the distances to Cepheids, the calibration from Fouqu et al. (2007) is used: $\langle M_V \rangle = -1.275 - 2.678 \cdot \log P$, where the period is in days. Given $\langle M_V \rangle$, and taking the period-averaged apparent magnitudes $\langle V \rangle$ and extinction $A_V = 3.23 \cdot E(\langle B \rangle - \langle V \rangle)$ mainly from Acharova et al. (2012) and, for several stars, from Feast and Whitelock (1997), we determine the distance $r$ from the relation

$$ r = 10^{-0.2(\langle M_V \rangle - \langle V \rangle - 5 + A_V)} ,$$

and then assume the relative error in the distances to Cepheids determined by this method to be 10%. We used the following constraint on the absolute value of the residual velocity (after the subtraction of the Galactic rotation parameters): $|V_{UVW}| < 60 \text{ km s}^{-1}$. Bobylev and Bajkova (2012) used this same sample of Cepheids to determine the parameters of the Galactic spiral density wave.

Fourteen Cepheids with proper motions from the Hipparcos catalog satisfy criteria (6)–(9), given (10); most of them (10 stars) are long-period ones, with pulsation periods $P \geq 9^d$, i.e., fairly young stars with a mean age of $\approx 55 \text{ Myr}$ (Bobylev and Bajkova 2012).
Table 1: Data on star-forming regions

| No. (Russell, 2003) | $l^\circ$ | $b^\circ$ | $r \pm \delta r$, kpc | $V_r$, km/s | $d/r$ | $R_0 \pm \delta R_0$, kpc |
|---------------------|---------|---------|----------------------|------------|------|---------------------|
| 85 (W49)            | 43.2    | 0.0     | 11.4 ± 1.2           | −2.1 ± 2.9 | .01  | 7.72 ± 1.01         |
| 105                 | 65.0    | 0.5     | 3.9 ± 0.5            | 21.5 ± 3.0 | .48  | 6.83 ± 0.59         |
| 108                 | 68.1    | 0.9     | 3.6 ± 1.1            | 0.6 ± 3.0  | .02  | 4.91 ± 1.30         |
| 112                 | 70.3    | 1.6     | 7.0 ± 1.5            | −30.6 ± 3.0| .46  | 5.61 ± 1.84         |
| 114                 | 71.6    | 2.8     | 2.8 ± 0.8            | 11.6 ± 3.0 | .46  | 6.48 ± 1.04         |
| 116 (S104)          | 77.0    | 0.5     | 3.1 ± 0.9            | −2.8 ± 3.0 | .14  | 5.94 ± 1.38         |
| 117                 | 77.4    | −3.7    | 2.6 ± 0.8            | 6.2 ± 3.0  | .37  | 8.19 ± 1.25         |
| 310                 | 281.8   | −2.0    | 4.7 ± 1.0            | 1.1 ± 3.0  | .04  | 11.05 ± 1.60        |
| 314                 | 282.6   | −1.9    | 3.1 ± 0.5            | −0.9 ± 3.0 | .04  | 7.41 ± 0.82         |
| 320                 | 284.0   | −1.0    | 3.3 ± 0.7            | −3.1 ± 3.0 | .13  | 7.72 ± 1.05         |
| 321                 | 284.2   | −0.3    | 5.5 ± 0.3            | 6.9 ± 3.0  | .18  | 9.25 ± 0.47         |
| 328                 | 287.5   | −0.5    | 2.6 ± 0.3            | −16.8 ± 3.0| .75  | 7.57 ± 0.42         |
| 329 (BBW311)        | 288.2   | −2.9    | 3.1 ± 0.9            | −4.4 ± 3.0 | .16  | 5.75 ± 1.17         |
| 332                 | 289.5   | 0.2     | 2.9 ± 0.2            | −19.9 ± 3.0| .73  | 7.51 ± 0.36         |
| 333 (BBW323)        | 290.4   | −2.9    | 4.2 ± 0.5            | −12.6 ± 3.0| .31  | 7.87 ± 0.65         |
| 334                 | 290.4   | 1.5     | 2.7 ± 0.3            | −15.8 ± 3.0| .60  | 6.18 ± 0.39         |
| 336                 | 290.6   | 0.2     | 2.8 ± 0.3            | −21.8 ± 3.0| .79  | 7.12 ± 0.39         |
| 338                 | 291.3   | −0.7    | 2.7 ± 0.2            | −21.3 ± 3.0| .78  | 6.60 ± 0.34         |
| 341                 | 291.6   | −0.7    | 7.9 ± 0.3            | 20.0 ± 3.0 | .25  | 8.08 ± 0.38         |

Mean, $R_0$: $7.25$

dispersion, $\sigma_{R_0}$: $1.41$

error, $\varepsilon_{R_0}$: $0.32$

Note. The radial velocities $V_r$ are given relative to the local standard of rest (Schönrich et al. 2010) and were corrected for the influence of the spiral density wave.

4 RESULTS AND DISCUSSION

4.1 Star-Forming Regions

Initially, using data on 19 star-forming regions, we obtained a solution where the radial velocities are given relative to the standard value for the local standard of rest, $(U_\odot, V_\odot, W_\odot) = (10.3, 15.3, 7.7)\text{ km s}^{-1}$. In this case, the radial velocities were taken directly from the catalog by Russell (2003). The mean value of $R_0$ and dispersion $\sigma_{R_0}$ are

$$R_0 = 8.04\text{ kpc}, \quad \sigma_{R_0} = 2.07\text{ kpc}.$$  

Then, we formed the radial velocities relative to the local standard of rest with values from Schönrich et al. (2010): $(U_\odot, V_\odot, W_\odot) = (11.1, 12.2, 7.3)\pm(0.7, 0.5, 0.4)\text{ km s}^{-1}$. When these velocities were determined, the stellar metallicity gradient in the Galactic disk and the radial mixing of stars in the disk were taken into account and modeled. Therefore, the values of these components currently seem most plausible and are widely used by various
authors. Then,

\[ R_0 = 7.42 \text{ kpc}, \quad \sigma_{R_0} = 1.73 \text{ kpc}. \]  

Finally, we corrected the radial velocities derived at the previous stage for the influence of the spiral density wave using the following two-armed spiral pattern parameters: the velocity perturbation amplitudes \( f_R = -9 \text{ km s}^{-1} \) and \( f_\theta = 0 \text{ km s}^{-1} \), the pitch angle \( i = -5^\circ \) (corresponding to the wavelength \( \lambda = 2 \text{ kpc} \)). These parameters are close to those found by analyzing both maser sources (Bobylev and Bajkova 2010; Bajkova and Bobylev 2012) and Cepheids (Bobylev and Bajkova 2012).

The phase of the Sun in the spiral wave \( \chi_\odot \) for star-forming regions is known poorly. To determine its suitable value, we analyzed the dispersion squared \( \sigma^2 \) derived at all fixed parameters except the phase when solving Eq. (1). The results are presented in Fig. 2, based on which we adopted the Sun’s phase \( \chi_\odot = -5^\circ \). At this value, \( \sigma^2 \) reaches its minimum. This result is also of interest in its own right, because it fits well into the sequence of solar phases as a function of stellar age (Bobylev and Bajkova, 2012): \(-91^\circ, -148^\circ, -193^\circ \) and \(-234^\circ \) for stars with ages of 8, 55, 95, and 135 Myr. Thus, \( \chi_\odot = -5^\circ \) can be associated with the youngest objects of almost zero age. The fact that the radial velocities of star-forming regions in the catalog by Russeil (2003) were determined from the gas component can serve as grounds for this association.

The results of the last step are presented in Table 1. Column 1 gives the ordinal number from the catalog by Russeil (2003); columns 2 and 3 contain the Galactic coordinates \( l \) and \( b \); column 4 gives the heliocentric distance \( r \); column 5 provides the radial velocity \( V_r \) relative to the local standard of rest corrected for the influence of the spiral density wave with the above parameters, the measurement errors of the radial velocities (except for the
region W 49) were taken to be $\delta V_r = \pm 3.0$ km s$^{-1}$; column 6 contains the $d/r$ ratio; and column 7 gives the $R_0$ estimate. Based on the $3\sigma$ criterion, we rejected region no. 343 (not listed in Table 1). Comparison of the mean value in the lower row of Table 1 with results (16) and (17) shows that the dispersion $\sigma_{R_0}$ decreased considerably. The lowest row of the table gives the error of the mean, $\varepsilon_{R_0} = \sigma_{R_0}/\sqrt{n}$.

### 4.2 Cepheids

Using data on 14 Cepheids, we obtained a solution where the stellar velocities $V_r$ and $V_p$ are given relative to the local standard of rest with values from Schönrich et al. (2010). Then,

$$
\begin{align*}
R_0 &= 7.72 \text{ kpc}, \quad \sigma_{R_0} = 1.42 \text{ kpc}, \\
V_0 &= 255 \text{ km s}^{-1}, \quad \sigma_{V_0} = 65 \text{ km s}^{-1}.
\end{align*}
$$

Subsequently, we corrected the stellar velocities $V_r$ and $V_p$ derived at the previous stage for the influence of the spiral density wave. For this purpose, we used the following two-armed spiral pattern parameters: the velocity perturbation amplitudes $f_R = -9$ km s$^{-1}$ and $f_{\theta} = 0$ km s$^{-1}$, the pitch angle $i = -5^\circ$ (wavelength $\lambda = 2$ kpc), and the phase of the Sun in the spiral wave $\chi_\odot = -150^\circ$. These are close to the parameters of the sample of young Cepheids found by Bobylev and Bajkova (2012).

The results are presented in Table 2. Two stars were rejected according to the $3\sigma$ criterion: HIP 47177 and HIP 103433 (not listed in Table 2). The velocities $V_r$ and $V_p$ are given relative to the local standard of rest and were corrected for the influence of the spiral density wave with the above parameters. Comparison of the corresponding mean values in the lower row of Table 2 with solution (18) shows a slight decrease in the errors.

We can see that the dispersion $\sigma_{R_0}$ in our case (Tables 1 and 2) is twice the value of $\sigma_{R_0} = 0.77$ kpc derived by Sofue et al. (2011). Since we imposed no stringent constraints on the radial velocities of sources, used the largest amount of available homogeneous data on near-solar-circle objects, and took into account the systematic effects in the kinematic data, we obtained a more objective estimate of the method.

As can be seen from Table 2, the radial velocities have a better accuracy than the $V_p$ components in random terms. The errors in the proper motions affect significantly the accuracy of determining the $V_p$ component (see Eq. (5) and Table 2). At present, a new version of the UCAC4 catalog has been published (Zacharias et al. 2012), where about 140 catalogs were used to derive the mean stellar proper motions. Therefore, the velocities $V_0$ calculated using these proper motions are of considerable interest. We repeated our calculations for the sample of 14 Cepheids for the case where their proper motions were taken from the UCAC4 catalog. It turned out to be necessary to retain the proper motions from the Hipparcos catalog for two stars, HIP 51262 and HIP 57884. Based on this combined sample of Cepheids (with the UCAC4 proper motions for 12 stars and the Hipparcos proper motions for two stars), we obtained the following parameters:

$$
\begin{align*}
R_0 &= 7.66 \text{ kpc}, \quad \sigma_{R_0} = 1.35 \text{ kpc}, \\
V_0 &= 229 \text{ km s}^{-1}, \quad \sigma_{V_0} = 44 \text{ km s}^{-1}, \quad \text{for} \\
A &= 15 \text{ km s}^{-1} \text{ kpc}^{-1},
\end{align*}
$$

(19)
Table 2: Parameters found from Cepheids using stellar proper motions from the Hipparcos catalog

| HIP  | $l^\circ$ | $b^\circ$ | $r$, kpc | $V_r$, km/s | $V_p$, km/s | $d/r$ | $R_0 \pm \delta R_0$, kpc | $V_0 \pm \delta V_0$, km/s |
|------|-----------|-----------|----------|-------------|-------------|-------|---------------------------|---------------------------|
| 96596 | 66.9      | 5.3       | 4.2      | 19.0 ± 0.3  | −112 ± 40   | .41   | 7.64 ± 0.14               | 209 ± 45                  |
| 98852 | 71.1      | 1.4       | 2.4      | 18.5 ± 0.3  | −61 ± 17    | .83   | 6.85 ± 0.15               | 179 ± 21                  |
| 51894 | 284.8     | 2.0       | 3.1      | −2.0 ± 1.0  | −112 ± 14   | .09   | 6.53 ± 0.20               | 239 ± 21                  |
| 51262 | 285.6     | −1.4      | 2.7      | −16.6 ± 7.4 | −97 ± 9     | .80   | 8.96 ± 0.74               | 331 ± 50                  |
| 50722 | 285.8     | −3.3      | 2.8      | −15.8 ± 5.0 | −118 ± 11   | .72   | 8.88 ± 0.51               | 379 ± 40                  |
| 52570 | 286.0     | 2.4       | 2.2      | −12.2 ± 4.0 | −97 ± 12    | .71   | 6.71 ± 0.42               | 307 ± 35                  |
| 53397 | 289.3     | −1.2      | 3.9      | −27.8 ± 5.0 | −123 ± 15   | .75   | 10.44 ± 0.46              | 337 ± 29                  |
| 54101 | 290.3     | −0.8      | 2.5      | −14.2 ± 4.0 | −92 ± 13    | .59   | 5.66 ± 0.37               | 215 ± 25                  |
| 54891 | 291.1     | 0.6       | 3.3      | −33.2 ± 1.0 | −99 ± 11    | .99   | 9.21 ± 0.16               | 286 ± 14                  |
| 53536 | 291.3     | −4.9      | 3.4      | −26.2 ± 4.0 | −111 ± 11   | .75   | 8.29 ± 0.36               | 280 ± 21                  |
| 53945 | 291.4     | −3.9      | 2.7      | −21.4 ± 5.0 | −96 ± 9     | .77   | 6.60 ± 0.43               | 242 ± 24                  |
| 57130 | 294.2     | 2.7       | 5.5      | −12.6 ± 5.0 | −138 ± 57   | .21   | 8.05 ± 0.40               | 209 ± 64                  |
| 57884 | 296.8     | −3.2      | 3.3      | −29.8 ± 2.7 | −93 ± 15    | .74   | 6.44 ± 0.23               | 195 ± 18                  |
| 59575 | 298.4     | 0.4       | 3.0      | −46.1 ± 0.6 | −130 ± 28   | 1.22  | 7.01 ± 0.13               | 328 ± 28                  |

Note. The errors of the heliocentric distances $r$ were taken to be 10%; the velocities $V_r$ and $V_p$ are given relative to the local standard of rest (Schönrich et al. 2010) and were corrected for the influence of the spiral density wave.

They have slightly smaller random errors than those in Table 2. We also see that $V_0$ decreased by $\approx 1\sigma$. Based on the same sample of Cepheids, we repeated solution (19) for two different values of the Oort constant $A$:

$$R_0 = 7.47 \text{ kpc}, \quad \sigma_{R_0} = 1.31 \text{ kpc},$$
$$V_0 = 224 \text{ km s}^{-1}, \quad \sigma_{V_0} = 43 \text{ km s}^{-1}, \quad \text{for}$$
$$A = 16 \text{ km s}^{-1} \text{ kpc}^{-1}, \quad \text{(20)}$$

and

$$R_0 = 7.31 \text{ kpc}, \quad \sigma_{R_0} = 1.27 \text{ kpc},$$
$$V_0 = 219 \text{ km s}^{-1}, \quad \sigma_{V_0} = 42 \text{ km s}^{-1}, \quad \text{for}$$
$$A = 17 \text{ km s}^{-1} \text{ kpc}^{-1}. \quad \text{(21)}$$

It can be seen that $R_0$ and $V_0$ decrease with increasing Oort constant $A$, but their dispersions change insignificantly. The present-day values of the Oort constant $A$ lie within the range 14–18 km s$^{-1}$ kpc$^{-1}$. For example, $A = 14.8 \pm 0.8 \text{ km s}^{-1} \text{ kpc}^{-1}$ was found using Cepheids from the Hipparcos catalog (Feast and Whitelock 1997), while its value derived from 44 maser sources with measured trigonometric parallaxes is $A = 16.7 \pm 0.6 \text{ km s}^{-1} \text{ kpc}^{-1}$ (Bajkova and Bobylev 2012).
Table 3: Parameters found from Cepheids using stellar proper motions from the UCAC4 catalog

| star   | $l^\circ$ | $b^\circ$ | $r$, kpc | $V_r$, km/s | $V_p$, km/s | $d/r$ | $R_0 \pm \delta R_0$, kpc | $V_0 \pm \delta V_0$, km/s |
|--------|----------|----------|---------|------------|------------|------|-----------------------------|----------------------------|
| S Vul  | 63.4     | 0.8      | 3.6     | 32.0 ± 2.0 | −72 ± 22   | .73  | 7.05 ± 0.19                | 157 ± 24                   |
| DG Vul | 65.0     | −0.9     | 2.1     | 33.3 ± 4.0 | −56 ± 64   | 1.39 | 5.89 ± 0.33                | 175 ± 71                   |
| 96596  | 66.9     | 5.3      | 4.2     | 19.0 ± 0.3 | −119 ± 22  | .41  | 7.64 ± 0.14                | 222 ± 25                   |
| 98852  | 71.1     | 1.4      | 2.4     | 18.5 ± 0.3 | −78 ± 12   | .83  | 6.85 ± 0.15                | 228 ± 15                   |
| 51894  | 284.8    | 2.0      | 3.1     | −2.0 ± 1.0 | −127 ± 15  | .09  | 6.53 ± 0.20                | 271 ± 23                   |
| CS Car | 285.6    | 0.2      | 3.4     | −6.1 ± 3.0 | −70 ± 5    | .23  | 7.86 ± 0.33                | 162 ± 13                   |
| 51262  | 285.6−1.4| 2.7      | −16.6 ± 7.4 | −97 ± 11 | .80 | 8.96 ± 0.74 | 331 ± 51 |
| 50722  | 285.8−3.3| 2.8      | −15.8 ± 5.0 | −63 ± 17 | .72 | 8.88 ± 0.51 | 204 ± 30 |
| 52570  | 286.0    | 2.4      | −12.2 ± 4.0 | −82 ± 12 | .71 | 6.71 ± 0.42 | 261 ± 31 |
| II Car | 288.2−0.7| 6.8      | 7.4 ± 3.0 | −141 ± 46 | .12 | 9.52 ± 0.31 | 196 ± 60 |
| 53397  | 289.3−1.2| 3.9      | −27.8 ± 5.0 | −88 ± 10 | .75 | 10.44 ± 0.46 | 244 ± 20 |
| 54101  | 290.3−0.8| 2.5      | −14.2 ± 4.0 | −107 ± 16 | .59 | 5.66 ± 0.37 | 250 ± 29 |
| 54891  | 291.1    | 0.6      | 3.3      | −33.2 ± 1.0 | −83 ± 47 | .99 | 9.21 ± 0.16 | 244 ± 56 |
| 53536  | 291.3−4.9| 3.4      | −26.2 ± 4.0 | −82 ± 11 | .75 | 8.29 ± 0.36 | 208 ± 17 |
| 53945  | 291.4−3.9| 2.7      | −21.4 ± 5.0 | −64 ± 9  | .77 | 6.60 ± 0.43 | 165 ± 19 |
| 57130  | 294.2    | 2.7      | 5.5      | −12.6 ± 5.0 | −138 ± 85 | .21 | 8.05 ± 0.40 | 208 ± 95 |
| 57884  | 296.8−3.2| 3.3      | −29.8 ± 2.7 | −93 ± 30 | .74 | 6.44 ± 0.23 | 195 ± 32 |
| 59575  | 298.4    | 0.4      | 3.0      | −46.1 ± 0.6 | −61 ± 47 | 1.22 | 7.01 ± 0.13 | 168 ± 49 |

Mean dispersion error | 7.64 | 217 |
|                     | 1.34 | 46  |
|                     | 0.32 | 11  |

Note. The proper motions for two stars, HIP 51262 and HIP 57884, remained the same, these were taken from the Hipparcos catalog; the velocities $V_r$ and $V_p$ are given relative to the local standard of rest (Schönrich et al. 2010) and were corrected for the influence of the spiral density wave.

Table 3 presents the results of our analysis for 18 stars with proper motions from the UCAC4 catalog (except for HIP 51262 and HIP 57884). It turned out that four more stars, S Vul, DG Vul, CS Car, and II Car, have fairly reliable measurements of their radial velocities and proper motions. Therefore, they were included in the sample. To find such stars, we identified all Cepheids ($\approx$450 stars) from the catalog by Berdnikov et al. (2000), whose distances were determined from infrared photometry, with the UCAC4 catalog. In particular, the distances to the Cepheids CS Car and II Car were taken from the catalog by Berdnikov et al. (2000). Not all of the near-solar-circle Cepheids entered into the sample, because their proper motions are not always reliable; for example, we encountered the cases where $V_0$ was found to be negative, etc. Just as in other tables, the calculations were made with the Oort constant $A = 15$ km s$^{-1}$ kpc$^{-1}$. On the whole, we can conclude that adding the stellar proper motions from the UCAC4 catalog had
a favorable effect on the determination of the sought-for parameters, in particular, the dispersion $\sigma_{V_0}$ decreased.

The values of $R_0$ found (Tables 1, 2, and 3) agree, within $1\sigma$, with those discussed in the Introduction.

Our Galactic rotation velocities (Tables 2 and 3) agree, within $1\sigma$, with the results of a kinematic analysis for various samples of stars. For example, the velocity derived from maser sources with measured trigonometric parallaxes is $V_0 = 254 \pm 16$ km s$^{-1}$ for $R_0 = 8.4$ kpc (Reid et al. 2009b), $V_0 = 244 \pm 13$ km s$^{-1}$ for $R_0 = 8.2$ kpc (Bovy et al. 2009), or $V_0 = 248 \pm 14$ km s$^{-1}$ for $R_0 = 8$ kpc (Bobylev and Bajkova 2010). Analysis of blue supergiants (Zabolotskikh et al. 2002) and OB associations (Mel’nik and Dambis 2009) also shows that the velocity $V_0 = 240 - 250$ km s$^{-1}$ for $R_0 = 8$ kpc. At the same time, young Cepheids rotate somewhat more slowly, with $V_0 = 209 \pm 16$ km s$^{-1}$, than slightly older Cepheids with $V_0 = 243 \pm 18$ km s$^{-1}$ for $R_0 = 8$ kpc (Bobylev and Bajkova, 2012).

5 CONCLUSIONS

We tested the method of determining the solar Galactocentric distance $R_0$ and Galactic rotation velocity $V_0$ modified by Sofue et al. (2011) using data on star-forming regions and young Cepheids near the solar circle. A peculiarity of this method is that the belonging of a star to the solar-circle region is reconciled with its observed velocities and parameters of the Galactic rotation curve.

We attempted to encompass the largest amount of homogeneous data on near-solar-circle objects with the necessary measurements. We properly took into account the motions of objects relative to the local standard of rest. For this purpose, we used the parameters of not the standard solar motion relative to the local standard of rest, which are commonly used by radio astronomers to retain the continuity of their results, but more reliable, present-day parameters of this motion. We showed that when young objects are analyzed, the perturbations produced by the Galactic spiral density wave should be taken into account, which causes the dispersion of the estimated parameters to decrease.

We obtained the estimate $R_0 = 7.25 \pm 0.32$ kpc from 19 star-forming regions. Based on a sample of Cepheids, we studied the influence of the adopted Oort constant $A$ and the character of the stellar proper motions used on the parameters being determined. For this purpose, we invoked the proper motions from the Hipparcos and UCAC4 catalogs. Based on a sample of 14 long-period Cepheids with Hipparcos proper motions, we obtained the following estimates: $R_0 = 7.66 \pm 0.36$ kpc and $V_0 = 267 \pm 17$ km s$^{-1}$. Based on a sample of 18 Cepheids obtained by invoking the UCAC4 stellar proper motions, we found $R_0 = 7.64 \pm 0.32$ kpc and $V_0 = 217 \pm 11$ km s$^{-1}$. Note that we considered almost all of the known Galactic Cepheids with the necessary photometric and kinematic data.

This independent method may turn out to be useful in the case of a considerable increase in the amount of kinematically homogeneous data with highly accurate distance estimates (the distance errors make a crucial contribution to the dispersion of the results) and proper motions. These include, for example, Galactic maser sources whose trigonometric parallaxes are determined by various research groups by the VLBI method.
The number of open star clusters with known kinematic parameters increases. Finally, as a result of the accomplishment of the GAIA space mission, the number of distant stars with measured parallaxes, radial velocities, and proper motions increases considerably.

ACKNOWLEDGMENTS

I am grateful to the referee for valuable remarks that contributed to a significant improvement of this paper. This work was supported in part by the “Nonstationary Phenomena in Objects of the Universe” Program of the Presidium of the Russian Academy of Sciences and grant NSh–1625.2012.2 from the President of the Russian Federation. In our study, we used the SIMBAD search database.

REFERENCES

1. I.A. Acharova, Yu. N. Mishurov, and V.V. Kovtyukh, Mon. Not. R. Astron. Soc. 420, 1590 (2012).
2. A.T. Bajkova and V.V. Bobylev, Astron. Lett. 38, 549 (2012).
3. L.N. Berdnikov, A.K. Dambis, and O.V. Vozyakova, Astron. Astrophys. Suppl. Ser. 143, 211 (2000).
4. V.V. Bobylev and A.T. Bajkova, Mon. Not. R. Astron. Soc. 408, 1788 (2010).
5. V.V. Bobylev and A.T. Bajkova, Astron. Lett. 38, 638 (2012).
6. V.V. Bobylev, A.T. Bajkova, and A.S. Stepamishchev, Astron. Lett. 34, 515 (2008).
7. J. Bovy, D.W. Hogg, and H.-W. Rix, Astrophys. J. 704, 1704 (2009).
8. J. Brand, and L. Blitz, Astron. Astrophys. 275, 67 (1993).
9. D.P. Clemens, Astrophys. J. 295, 422 (1985).
10. M. Feast and P. Whitelock, Mon. Not. R. Astron. Soc. 291, 683 (1997).
11. M.W. Feast, C.D. Laney, T.D. Kinman, et al., Mon. Not. R. Astron. Soc. 386, 2115 (2008).
12. T. Foster and B. Cooper, ASP Conf. Ser. 438, (2010).
13. P. Fouqu, P. Arriagada, J. Storm, et al., Astron. Astrophys. 476, 73 (2007).
14. S. Gillessen, F. Eisenhauer, S. Trippe, et al., Astrophys. J. 692, 1075 (2009).
15. G.A. Gontcharov, Astron. Lett. 32, 759 (2006).
16. M.A.T. Groenewegen, A. Udalski, and G. Bono, Astron. Astrophys. 481, 441 (2008).
17. C.R. Gwinn, J.M. Moran, and M.J. Reid, Astrophys. J. 393, 149 (1992).
18. The HIPPARCOS and Tycho Catalogues, ESA SP1200 (1997).
19. F. van Leeuwen, Astron. Astrophys. 474, 653 (2007).
20. C.C. Lin and F.H. Shu, Astrophys. J. 140, 646 (1964).
21. A.M. Mel’nik and A.K. Dambis, Mon. Not. R. Astron. Soc. 400, 518 (2009).
22. Yu.N. Mishurov, I.A. Zenina, A.K. Dambis, et al., Astron. Astrophys. 323, 775 (1997).
23. A.P. Moisés, A. Damineli, E. Figueirêdo, et al., Mon. Not. R. Astron. Soc. 411, 705 (2011).
24. I.I. Nikiforov, ASP Conf. Ser. 316, 199 (2004).
25. M.J. Reid, Annu. Rev. Astron. Astrophys. 31, 345 (1993).
26. M. Reid and A. Brunthaler, Astrophys. J. 616, 872 (2004).
27. M. Reid, K.M. Menten, X.W. Zheng, et al., Astrophys. J. 705, 1548 (2009a).
28. M. Reid, K.M. Menten, X.W. Zheng, et al., Astrophys. J. 700, 137 (2009b).
29. D.A. Roshi, C.G. De Pree, W.M. Goss, et al., Astrophys. J. 644, 279 (2006).
30. D. Russeil, Astron. Astrophys. 397, 133 (2003).
31. P.L. Schechter, I.M. Avruch, J.A.R. Caldwell, et al., Astron. J. 104, 1930 (1992).
32. R. Schörich, arXiv: 1207.3079 (2012).
33. R. Schörich, J. Binney, and W. Dehnen, Mon. Not. R. Astron. Soc. 403, 1829 (2010).
34. Y. Sofue, T. Nagayama, M. Matsui, et al., Publ. Astron. Soc. Jpn. 63, 867 (2011).
35. A.S. Stepanishchev and V.V. Bobylev, Astron. Lett. 37, 254 (2011).
36. M.V. Zabolotskikh, A.S. Rastorguev, and A.K. Dambis, Astron. Lett. 28, 454 (2002).
37. N. Zacharias, C.T. Finch, T.M. Girard, et al., I/322 Catalogue, Strasbourg Data Base (2012).