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Kinematic Control of the Inertiality of the System of Tycho-2 and UCAC2 Stellar Proper Motions

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Abstract—Based on the Ogorodnikov–Milne model, we analyze the proper motions of Tycho-2 and UCAC2 stars. We have established that the model component that describes the rotation of all stars under consideration around the Galactic y axis differs significantly from zero at various magnitudes. We interpret this rotation found using the most distant stars as a residual rotation of the ICRS/Tycho-2 system relative to the inertial reference frame. For the most distant ($d \approx 900$ pc) Tycho-2 and UCAC2 stars, the mean rotation around the Galactic y axis has been found to be $M_{13}^{-} = -0.37 \pm 0.04$ mas yr^{-1}. The proper motions of UCAC2 stars with magnitudes in the range $12{-}15^m$ are shown to be distorted appreciably by the magnitude equation in $\mu_\alpha \cos\delta$, which has the strongest effect for northern-sky stars with a coefficient of -0.60 ± 0.05 mas yr^{-1} mag^{-1}. We have detected no significant effect of the magnitude equation in the proper motions of UCAC2 stars brighter than $\approx 11^m$.

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INTRODUCTION

The current standard International Celestial Reference System (ICRS) is realized by a catalog of radio positions for 212 compact extragalactic sources uniformly distributed over the entire sky and observed by very long baseline interferometry (Ma et al. 1998). In the optical range, the first ICRS realization was the Hipparcos catalog (ESA 1997). Application of various methods of analysis reveals a small residual rotation of ICRS/Hipparcos relative to the inertial reference system with $\approx -0.4 \pm 0.1$ mas yr^{-1} (Bobylev 2004a, 2004b).

The method considered here is based on the study of two rigid-body rotation tensor components that describe the rotation around the y and x axes in the Galactic coordinate system. Application of this method to the proper motions of TRC stars (Høg et al. 1998) showed that the determination of the rotation around the y axis is noticeably affected by the actual rotation of the Local system's stars (Bobylev 2004a). In this paper, we consider the Tycho-2 catalog (Høg et al. 2000), which does not differ systematically from the TRC catalog, but contains twice as many stars. We expect a confirmation of the results obtained using TRC stars.

Invoking fairly distant stars that are free from the effects of both streams close to the Sun and the Local system of stars as a whole is topical for a reliable application of the method. The UCAC2 catalog (Zacharias et al. 2004), which contains positions and proper motions for some 48 million stars, is of great interest in this connection. This catalog extends the ICRS/Tycho-2 system to the 17th magnitude.

The goal of this paper is to study the kinematic parameters of a large number of stars as a function of their distance. To estimate the distances, we use the method of comparing the statistical parallaxes with the solar velocity (Olling and Dehnen 2003); the latter is currently known well (Dehnen and Binney 1998).

THE MODEL

In this paper, we use a rectangular Galactic coordinate system with the axes directed away from the observer toward the Galactic center ($l = 0°$, $b = 0°$, the x axis or axis 1), along the Galactic rotation ($l = 90°$, $b = 0°$, the y axis or axis 2), and toward the North Galactic pole ($b = 90°$, the z axis or axis 3). In the Ogorodnikov–Milne model, we use the notation introduced by Clube (1972, 1973) and employed by du Mont (1977, 1978). When only the stellar proper

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motions are used, one of the diagonal terms of the local deformation tensor is known (Ogorodnikov 1958) to remain indeterminate. Therefore, we determine differences of the form $(M_{11}^+ - M_{22}^+)$ and $(M_{33}^+ - M_{22}^+)$. The conditional equations can be written as

$$\mu_l \cos b = (1/r)(X_\odot \sin l - Y_\odot \cos l) \quad (1)$$
$$- M_{32}^- \cos l \sin b - M_{13}^- \sin l \sin b + M_{21}^- \cos b$$
$$+ M_{12}^+ \cos 2l \cos b - M_{13}^+ \sin l \sin b$$
$$+ M_{23}^+ \cos l \sin b - 0.5(M_{11}^+ - M_{22}^+) \sin 2l \cos b,$$

$$\mu_b = (1/r)(X_\odot \cos l \sin b + Y_\odot \sin l \sin b \quad (2)$$
$$- Z_\odot \cos b) + M_{32}^- \sin l - M_{13}^- \cos l$$
$$- 0.5 M_{12}^+ \sin 2l \sin 2b + M_{13}^+ \cos l \cos 2b$$
$$+ M_{23}^+ \sin l \cos 2b - 0.5(M_{11}^+ - M_{22}^+) \cos^2 l \sin 2b$$
$$+ 0.5(M_{33}^+ - M_{22}^+) \sin 2b,$$

where $X_\odot$, $Y_\odot$, and $Z_\odot$ are the peculiar solar velocity components and $M_{12}^-, M_{13}^-, and M_{23}^-$ are the components of the vector of solid-body rotation of a small solar neighborhood around the corresponding axes. In accordance with the adopted rectangular coordinate system, the following rotations are positive: from axis 1 to axis 2, from axis 2 to axis 3, and from axis 3 to axis 1. The quantity M_{21}^- (mas yr^{-1}) is related to the Oort constant B (km s^{-1} kpc^{-1}) via the proportionality coefficient 4.74. Each of the quantities M_{12}^+, M_{13}^+, and M_{23}^+ describes the deformation in the corresponding plane. The quantity M_{12}^+ (mas yr^{-1}) is related to the Oort constant A (km s^{-1} kpc^{-1}) via the proportionality coefficient 4.74. The diagonal components of the local deformation tensor M_{11}^+, M_{22}^+, and M_{33}^+ describe the overall contraction or expansion of the entire stellar system. The system of conditional equations (1) and (2) includes 11 sought-for unknowns to be determined by the least-squares method. As can be seen from Eq. (1), the two pairs of unknowns M_{13}^- and M_{13}^+, as well as M_{32}^- and M_{23}^+, have the same coefficients, $\sin l \sin b$ and $\cos l \sin b$, respectively. As a result, the variables are ill-separated. In the UCAC2 section, we analyze the results of both the simultaneous solution of Eqs. (1) and (2) and the separate solution of only Eq. (2). The quantity $1/r$ is a parallactic factor that is taken to be unity when solving Eqs. (1) and (2). In this case, the stars are referred to a unit sphere. In this approach, all of the parameters being determined are proportional to the heliocentric distance of the stellar centroid under consideration and are expressed in the same units as the stellar proper motion components, i.e., in mas yr^{-1}. Using this approach, we can completely eliminate the effect of distance errors in the data being analyzed. Indeed, when using the method with known distances to stars, we must multiply the left-hand and right-hand sides of Eqs. (1) and (2) by $4.74r$ and r, respectively; the unknowns being determined will then be distorted by errors in the distances to stars. At present, reliable distances to individual stars (with errors < 10%) allow us to analyze a solar neighborhood ∼100 pc in radius, which is not enough for our purposes.

Let us also consider a Galactocentric cylindrical (R, θ, z) coordinate system specified as follows: the z axis is directed toward the North Galactic Pole from the Galactic center, the azimuthal angle θ is measured from the x axis to the y axis counterclockwise, and R is the Galactocentric distance of a star. In the cylindrical coordinate system, the local deformation and local rotation tensor components are

$$M_{11}^+ = \frac{\partial V_R}{\partial R}, \quad (3)$$
$$M_{22}^+ = \frac{1}{R}\frac{\partial V_\theta}{\partial \theta} + \frac{V_R}{R},$$
$$M_{33}^+ = \frac{\partial V_z}{\partial z},$$
$$M_{12}^+ = 0.5\left(\frac{1}{R}\frac{\partial V_R}{\partial \theta} - \frac{V_\theta}{R} + \frac{\partial V_\theta}{\partial R}\right),$$
$$M_{13}^+ = 0.5\left(\frac{\partial V_R}{\partial z} + \frac{\partial V_z}{\partial R}\right),$$
$$M_{23}^+ = 0.5\left(\frac{\partial V_\theta}{\partial z} + \frac{1}{R}\frac{\partial V_z}{\partial \theta}\right),$$
$$M_{21}^- = 0.5\left(\frac{\partial V_\theta}{\partial R} - \frac{1}{R}\frac{\partial V_R}{\partial \theta} + \frac{V_\theta}{R}\right),$$
$$M_{32}^- = 0.5\left(\frac{1}{R}\frac{\partial V_z}{\partial \theta} - \frac{\partial V_\theta}{\partial z}\right),$$
$$M_{13}^- = 0.5\left(\frac{\partial V_R}{\partial z} - \frac{\partial V_z}{\partial R}\right),$$

provided that the derivatives are taken at point $(R_0, \theta_0, z_0) = (R_0, 0°, 0)$.

TYCHO-2

The results of solving the system of equations (1) and (2) using Tycho-2 stars of mixed spectral composition as a function of magnitude are presented in Fig. 1. We used almost all the stars in the catalog with the following constraint imposed on the absolute value of a star's tangential velocity: $|\mu_t| = \sqrt{\mu_\alpha \cos\delta^2 + \mu_\delta^2} < 300$ mas yr^{-1}. The stars were divided into magnitude ranges in such a way that each of them contained approximately the same number of stars (≈250 000). In each magnitude range, the random errors of all sought-for parameters

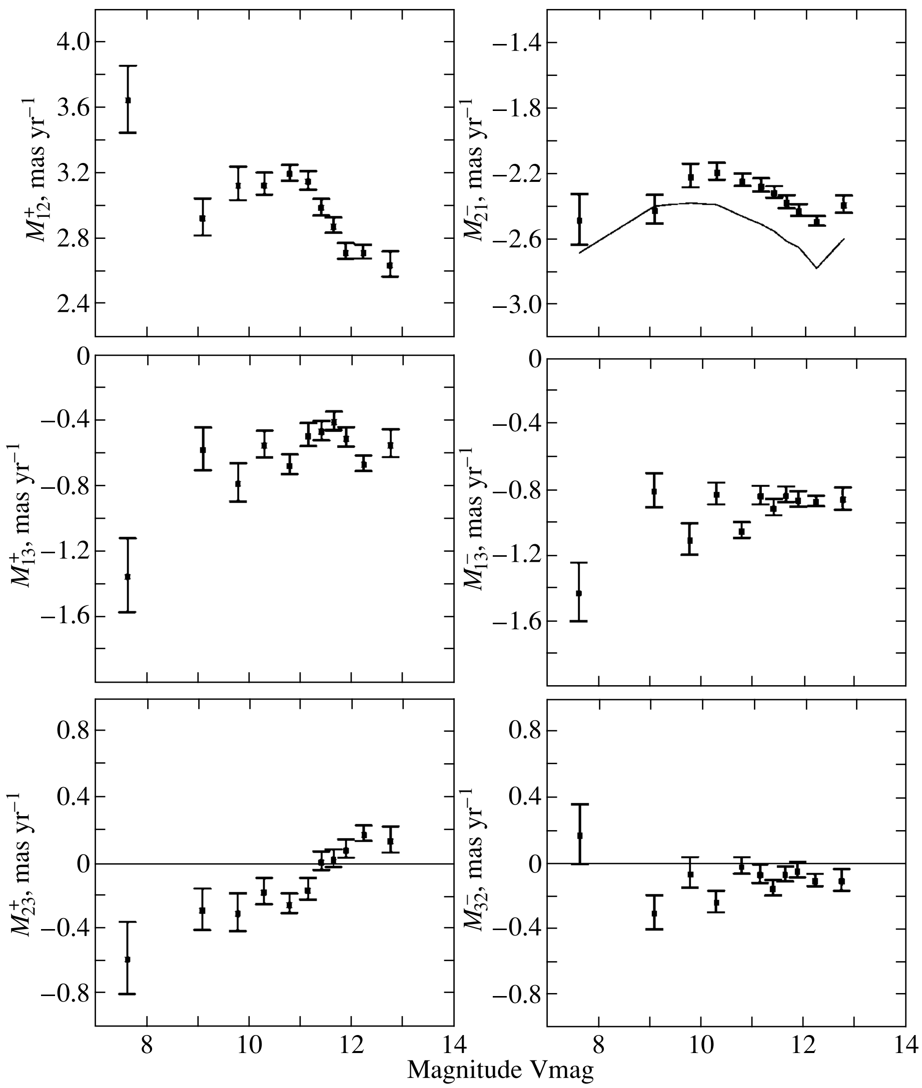

Fig. 1. Kinematic parameters inferred from the proper motions of Tycho-2 stars vs. magnitude.

are ≈0.05 mas yr^{-1}; the errors in $(M_{11}^{+} - M_{22}^{+})$ and $(M_{33}^{+} - M_{22}^{+})$ are twice as large. As can be seen from Fig. 1, the parameters that describe the deformation in the yz plane and the rotation around the x axis, i.e., M_{23}^{+} and M_{32}^{-}, are almost equal to zero. The parameters that describe the deformations in the xy and yz planes and the rotations around the z and y axes differ significantly from zero. The parameter M_{13}^{-} is nonzero up to the faintest Tycho-2 stars. The magnitude dependence of M_{13}^{-} agrees well with that found using the TRC catalog, where the mean is $M_{13}^{-} = -0.86 \pm 0.11$ mas yr^{-1} (Bobylev 2004a). For Tycho-2 stars fainter than $8^{m}\!.5$, the mean value (the mean of ten points) is $M_{13}^{-} = -0.88 \pm 0.10$ mas yr^{-1}. This is because the fraction of stars belonging to the Local system or local nearby streams is large even among the faintest (≈13^{m}) Tycho-2 stars.

We obtained the following Galactic rotation parameters from stars fainter than $8^{m}\!.5$: $M_{12}^{+} = 2.93 \pm 0.21$ mas yr^{-1} and $M_{21}^{-} = -2.35 \pm 0.10$ mas yr^{-1}. In this case, the Oort constants are $A = 4.74 M_{12}^{+} = 13.88 \pm 0.98$ km s^{-1} kpc^{-1} and $B = 4.74 M_{21}^{-} = -11.13 \pm 0.47$ km s^{-1} kpc^{-1}. These Oort constants serve as an indicator of the consistency of our approach (constraints, sky coverage). On the whole, they are in agreement, for example, with the results of analyzing the proper motions of ACT/Tycho-2 stars (Olling and Dehnen 2003), where only equatorial stars ($|b| < 5^{\circ}\!.73$) were used.

We use the proper motions of Tycho-2 stars to check whether nonuniformities in the latitudinal distribution of stars affect the determination of the Ogorodnikov–Milne model parameters. For this purpose, we averaged the stellar proper motions in fields of equal area that covered the entire sky. In contrast to 48 fields used in the well-known Charlier method (Ogorodnikov 1958), we divided the sky into 432 fields. The essence of the method is that, despite the difference in the number of stars, a unit weight is assigned to each field when solving the system of conditional equations (1) and (2). As a result, the random errors of the main sought-for parameters in each magnitude range were ≈0.15 mas yr^{-1}; no marked differences from the previous approach were found. The parameter M_{21}^-, for which the values calculated by this method are indicated in Fig. 1 by the solid line, constitutes an exception. As can be seen from the figure, all of the points found have approximately the same displacement of ≈0.2 mas yr^{-1} along the coordinate axis. The mean Oort constant B is -12.13 ± 0.63 km s^{-1} kpc^{-1}. Application of the method with fields showed that the correlation coefficients between all of the unknowns being determined do not exceed 0.1, except the correlations between two unknowns, $(M_{11}^+ - M_{22}^+)$ and $(M_{33}^+ - M_{22}^+)$, for which the correlation coefficient is 0.5. Below, we use the method with individual stars and will return to our comparison of the results obtained by the two methods.

UCAC2

The First Approximation

The UCAC2 astrometric catalog is currently the only mass catalog that contains highly accurate proper motions of faint stars (fainter than $12^m\!.5$) in much of the celestial sphere. There is full sky coverage in the declination zone $-90° < \delta < 40°$ and partial sky coverage up to $\delta = 52°$. The accuracy of the proper motions of faint UCAC2 stars given by the authors of the catalog lies within the range 4 to 7 mas yr^{-1}. The catalog extends the ICRS/Tycho-2 system to faint stars.

Since the catalog contains no observations at declinations $\delta > +60°$, we do not consider the southernmost stars at declinations $\delta < -60°$ in order that the sky coverage be symmetric.

The results of solving the system of equations (1) and (2) using UCAC2 stars of mixed spectral composition are presented in Fig. 2 as a function of magnitude. We used a constraint on the absolute of the tangential stellar velocity, $|\mu_t| < 300$ mas yr^{-1}. There were ∼250 000 stars in each magnitude range. In the range $12^m\!.05$–$16^m\!.01$, the stars were taken selectively. In the ranges of magnitudes brighter than $11^m\!.17$ and fainter than $16^m\!.34$, we used all the stars from the catalog. Thus, we are considering a total of ∼4.4 million UCAC2 stars. As can be seen from Fig. 2, the parameters that describe the deformations in the xy, yz, zx planes and the rotation around the z and y axes differ significantly from zero. The parameter M_{13}^- is nonzero for the faintest UCAC2 stars.

As can be seen from Fig. 2, there is a noticeable jump in the magnitude dependence of M_{13}^- for stars fainter than 13^m, which is inconsistent with the assumption that this parameter monotonically tends (in absolute value) to a minimum. This jump can be explained by the presence of a magnitude equation in the proper motions of UCAC2 stars. Analysis of Eqs. (1) and (2) in the equatorial coordinate system (du Mont 1977, 1978) leads us to conclude that the rotation around the Galactic y axis can be affected by a systematic error only in $\mu_\alpha \cos\delta$. Our simulation shows that the coefficient of the magnitude equation for the entire catalog is 0.3–0.4 mas yr^{-1} mag^{-1} for stars fainter than 13^m. Eliminating this magnitude equation yields $M_{13}^- \approx -1$ mas yr^{-1} for 13^m stars.

On the other hand, we can study the magnitude equation of the UCAC2 catalog by an independent method, by comparison with the original Pulkovo data. As Bobylev et al. (2004) showed, the Pulkovo stellar proper motions do not have a noticeable magnitude equation.

The Magnitude Equation in UCAC2

To find the magnitude equation in the proper motions of UCAC2 stars, we used the new proper motions of faint stars calculated using the stellar coordinates from the Pul-3 catalog (Khrutskaya et al. 2004) and currently available astrometric catalogs: M2000 (Rapaport et al. 2001), CMC13 (2003), and UCAC2.

The Pul-3 astrometric catalog was compiled at the Pulkovo Observatory by measuring photographic plates taken with a normal astrograph as part of A.N. Deutsch's plan to determine the absolute proper motions of stars in fields with galaxies. The catalog contains equatorial coordinates for more than 50 000 faint stars to $16^m\!.5$ in 146 fields north of $\delta = -5°$ for the mean epoch of the Pulkovo observations (1963.25) in the ICRS/Tycho-2 system. The positional accuracy of faint stars in the catalog is 80 mas.

The M2000 (2.3 million stars) and CMC13 (36.2 million stars) catalogs were compiled using CCD observations with the Bordeaux and La Palma automated meridian circles. The two catalogs realize the ICRS/Tycho-2 system in the declination zones 11°–18° and −3°–30°, respectively, and contain stars to 16^m–17^m. The positional accuracy of faint stars in these catalogs is, on average, 40–60 mas at epoch 2000.

Mutual identifications of stars in these catalogs made it possible to compile a new version of the

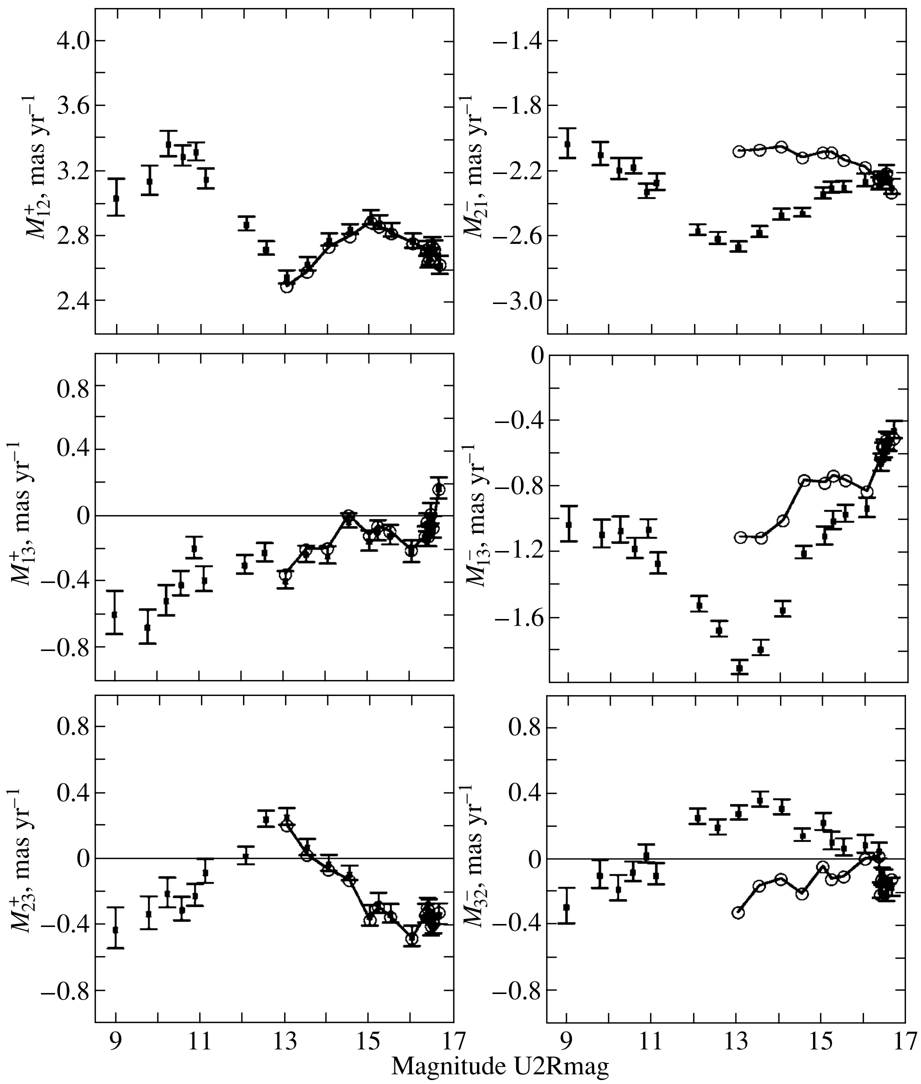

Fig. 2. Kinematic parameters inferred from the proper motions of UCAC2 stars vs. magnitude.

catalog of proper motions for 34 000 stars. We designate the new version of the catalog as PUL3SE. Owing to the high positional accuracy of the stars in the original catalogs and the large epoch difference between Pul-3 and the catalogs for epoch 2000, the estimated internal accuracies of the proper motions ($\epsilon_{\mu_\alpha \cos\delta}$ and ϵ_{μ_δ}) lie within the range 2–4 mas yr^{-1}.

For each star included in both catalogs, we formed the PUL3SE–UCAC2 differences between the proper motions in both coordinates. The mean differences for all data are 1 and -0.5 mas yr^{-1} for the proper motions in right ascension and declination, respectively. The errors of a single difference were found to be $\sigma_{\mu_\alpha \cos\delta} = 6.3$ mas yr^{-1} and $\sigma_{\mu_\delta} =$ 5.7 mas yr^{-1}. For the groups of stars formed as a function of magnitude U2Rmag at $0^m_.25$ steps, the ratios $(\epsilon^2_{\mu_\alpha \cos\delta} + \epsilon^2_{\mu_\alpha \cos\delta ucac2})/\sigma^2_{\mu_\alpha \cos\delta}$ and $(\epsilon^2_{\mu_\delta} + \epsilon^2_{\mu_\delta ucac2})/\sigma^2_{\mu_\delta}$ are close to unity. This confirms that the formal estimates of the accuracies are realistic for both the new proper motions and the UCAC2 proper motions presented in this catalog.

The dependences of $\Delta\mu$ on magnitude U2Rmag are presented in Fig. 3. Analysis of these dependences reveals no magnitude equation in the proper motions of faint stars in both coordinates for relatively bright stars (brighter than $12^m_.5$). This may be interpreted as a result of the fact that all of the catalogs used to calculate the proper motions realize the ICRS/Tycho-2 system. The Tycho-2 catalog is known to be complete to 11^m and to contain a considerable number of stars to $12^m_.5$. For fainter stars, systematic magnitude-dependent errors in the coordinates show up in different catalogs.

On the whole, we may conclude that the magnitude equation for the proper motions of faint stars in declination is indistinct (about -0.5 mas yr^{-1}) and may be disregarded in our kinematic analysis at the stage of our studies in question.

As can be seen from Fig. 3, the magnitude equation for the proper motions in right ascension in the magnitude range 13–15$^m_{\cdot}$5 lies within the range from 1 to 2 mas yr^{-1}. In this magnitude range, the variation in differences can be represented by a linear law with a coefficient of -0.60 ± 0.05 mas yr^{-1} mag^{-1}.

The presence of systematic errors in the coordinates of stars in the catalogs of early epochs can be one of the main reasons for the existence of a magnitude equation for faint stars. Studies by Khrutskaya and Khovritchev (2003, 2004) showed that the YS4.0 catalog (Yellow Sky plates), which was used as the first epoch to derive the UCAC2 proper motions, could be the the source of the magnitude equation. As was noted in the description to the UCAC2 catalog, the Yellow Sky plates were remeasured, but the results have not yet been published.

Platais et al. (1998) showed that there is also a significant magnitude equation with a coefficient of ∼1 mas yr^{-1} mag^{-1} in the published proper motions of NPM stars (blue plates) $\mu_\alpha \cos\delta$. In contrast to our case, the magnitude dependence of the Hipparcos–NPM differences is positive in sign.

Solution with the Elimination of the Magnitude Equation

We again solved Eqs. (1) and (2) for UCAC2 magnitudes fainter than 13$^m_{\cdot}$0. The proper motions of stars $\mu_\alpha \cos\delta$ with declinations $\delta > -5°$ were corrected for the magnitude equation with a coefficient of -0.60 ± 0.05 mas yr^{-1} mag^{-1}. The magnitude equation for 16$^m_{\cdot}$5 stars was assumed to be zero. Since there is a mixed effect of the first epochs of the various sources used to derive the proper motions in the magnitude range 11.5–13^m, we do not consider these stars.

The derived kinematic parameters are indicated in Fig. 2 by the solid line and open circles. As can be seen from the figure, including the magnitude equation affected the three rotation tensor components. Comparison of Figs. 1 and 2 leads us to conclude that, first, the magnitude dependence of M^-_{21} (the rotation around the z axis) for UCAC2 stars corrected for the magnitude equation is in better agreement with that found from Tycho-2 stars and, second, the magnitude dependence of M^-_{13} (the rotation around the y axis) corrected for the magnitude equation is monotonic, as we expected. We attribute the small jump for stars fainter than 16^m to the fact that a transition to distant stars occurs. The magnitude dependence of M^-_{32} (the rotation around the x axis) corrected for the magnitude equation changes sign, but its absolute value

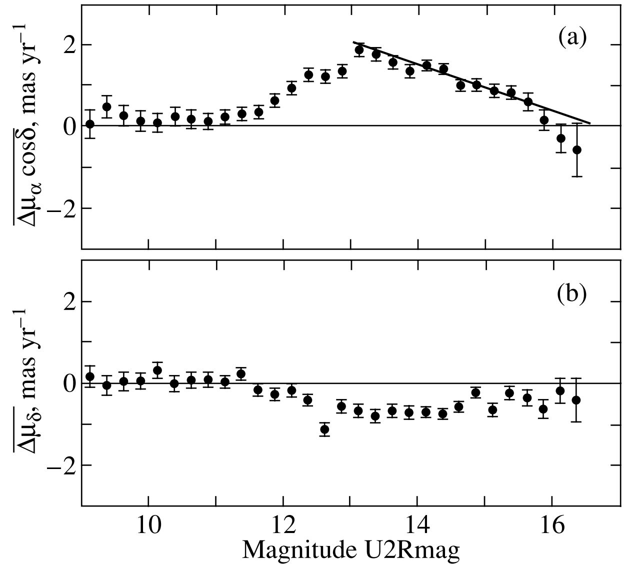

Fig. 3. PUL3SE–UCAC2 stellar proper motion differences vs. magnitude: (a) $\Delta\mu_\alpha \cos\delta$, (b) $\Delta\mu_\delta$.

is close to zero. At the same time, the deformation in the yz plane undergoes noticeable variations with magnitude with an amplitude of ≈0.6 mas yr^{-1}; for the faintest stars, $M^+_{23} \approx -0.3 \pm 0.05$ mas yr^{-1}.

Eliminating the magnitude equation for 13^m stars changes M^-_{21} by 25% and M^-_{13} by 100%.

On the whole, we may conclude that the proper motions of UCAC2 stars corrected for the magnitude equation in the magnitude range 13–15^m became systematically closer to the Tycho-2 system.

Estimating the Group Distances

To estimate the distances to stars, we use a statistical method (Olling and Dehnen 2003). As the peculiar solar velocity relative to the local standard of rest, we take the values from Dehnen and Binney (1998): $(U_\odot, V_\odot, W_\odot) = (10.00, 5.25, 7.17) \pm (0.36, 0.62, 0.38)$ km s^{-1}. We calculate the parallaxes using the formulas

$$\pi_U = \frac{4.74 X_\odot}{U_\odot}, \quad \pi_W = \frac{4.74 Z_\odot}{W_\odot},$$

where $X_\odot$ and $Z_\odot$ are the stellar group velocity components that we found by solving Eqs. (1) and (2), in mas yr^{-1}. Since the $Y_\odot$ component is distorted appreciably by the asymmetric drift (Dehnen and Binney 1998), this component is not used to determine the group parallaxes. We find the distance d from the relation $d = 1/\pi$. In this case, the distance error can be estimated from the relation

$$e_d = \left(\frac{e_\pi}{\pi}\right) d;$$

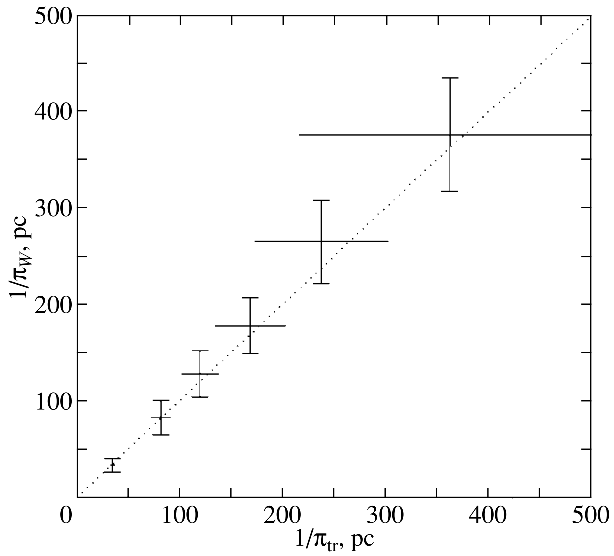

Fig. 4. Statistical distances to stars vs. trigonometric distances calculated using Hipparcos data. The division into groups was performed using trigonometric parallaxes.

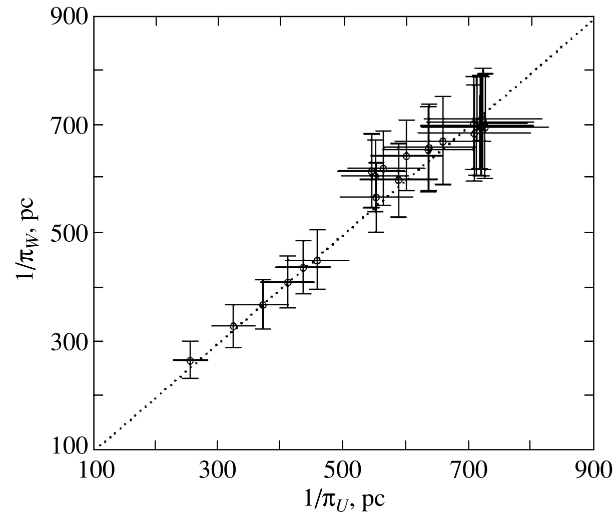

Fig. 5. Statistical distances to stars calculated from the solar velocity component $W_\odot$ vs. distances calculated from the component $U_\odot$ using UCAC2 data.

we estimate e_π for the motion along the z axis as

$$e_\pi = 4.74\sqrt{\left(\frac{e_{W_\odot} Z_\odot}{W_\odot^2}\right)^2 + \left(\frac{e_{Z_\odot}}{W_\odot}\right)^2}.$$

A similar relation can be derived for the motion along the x axis. Practice shows (Dehnen and Binney 1998; Olling and Dehnen 2003) that the z components of the solar velocity are more stable than the x velocity components for stars of various Galactic subsystems; therefore, the parallaxes π_W are preferred to π_U.

First, we apply the method to the Hipparcos catalog. The division into groups is performed using trigonometric parallaxes of the catalog with $e_\pi/\pi < 1$. In Fig. 4, our statistical distances to stars are plotted against trigonometric distances. We see from the figure that there are no significant systematic distortions in the statistical distances and that the errors in the statistical distances at distances of more than 200 pc are smaller than those in the trigonometric distances. In particular, we estimated the mean distance for 4216 Hipparcos stars with negative trigonometric parallaxes and obtained the following values: $d_U = 838 \pm 244$ pc and $d_W = 716 \pm 211$ pc. This confirms our assumption that such stars are, on average, far from the Sun (Bobylev 2004a).

Next, we use the method to analyze UCAC2 stars. The proper motions of northern-sky stars fainter than $13^m.0$ were corrected for the magnitude equation found. In Fig. 5, the statistical distances to stars calculated using the parallaxes π_W are plotted against the distances found using π_U. As can be seen from the figure, there is a difference in the distances $1/\pi_W$ and $1/\pi_U$ at ~600 pc that gradually disappears near 700 pc. This difference corresponds to the stars in the magnitude range $12-13^m$ and stems from the fact that the magnitude equation (which was not compensated for in this range) affects the determination of the $X_\odot$ velocity component. We see that stars fainter than $16^m.0$ are, on average, farther than 650–700 pc, with the error in the group distances being no larger than 14%. The distance found shows that these stars are located, on average, outside the local (Orion) spiral arm or the Local system of stars. This gives reason to consider the rotation around the Galactic y axis found using the faintest stars (Fig. 2) as a residual rotation of the ICRS/Tycho-2 system relative to the extragalactic coordinate system.

Estimating the Residual Rotation of the ICRS/Tycho-2 *System*

Results of the simultaneous solution of Eqs. (1) and (2). Let us estimate the limit to which M_{13}^- tends as the distance to the stars increases. We proceed from the fact that, on the whole, distant stars of various spectral types belonging to various Galactic components may not have any rotation around the y axis. At the same time, we consider the presence of a significant rotation as a residual rotation of the ICRS/Tycho-2 system relative to the extragalactic coordinate system.

To solve the formulated problem, we use almost all of the Tycho-2 stars fainter than $8^m.5$ and all of the UCAC2 stars fainter than $16^m.34$ (about 1 million stars). We gave preference to the Tycho-2 catalog in

Table 1. Local rotation tensor components M^-_{13} and M^-_{32} calculated using distant Tycho-2 (solutions 1–3) and UCAC2 (solutions 4–8) stars based on the simultaneous solution of Eqs. (1) and (2)

No.	$N_\star$	d_W, pc	$B-V$	$\overline{V}$	$J-K_s$	$\overline{m}$	M^-_{13}, mas yr^{-1}	M^-_{32}, mas yr^{-1}
1	89089	637 ± 55	≤0.2	10.17			-0.488 ± 0.046	-0.247 ± 0.047
2	228230	578 ± 58	1–1.4	10.32			-0.455 ± 0.033	-0.251 ± 0.033
3	130938	873 ± 100	>1.4	10.40			-0.371 ± 0.035	-0.266 ± 0.035
4	319129	641 ± 60			≥0.5	16.41	-0.597 ± 0.032	-0.137 ± 0.031
5	269675	643 ± 63			≥0.5	16.55	-0.486 ± 0.033	-0.177 ± 0.033
6	192852	747 ± 76			<0.5	16.41	-0.487 ± 0.030	-0.014 ± 0.030
7	156702	774 ± 87			<0.5	16.55	-0.486 ± 0.032	-0.058 ± 0.033
8	211086	975 ± 127			≥0.8	10.31	-0.493 ± 0.045	-0.018 ± 0.043
Mean							-0.485 ± 0.023	-0.140 ± 0.036
1		486 ± 116	≤0.2	10.17			-0.25 ± 0.17	-0.27 ± 0.17
2		470 ± 90	1–1.4	10.32			-0.50 ± 0.11	-0.17 ± 0.11
3		749 ± 196	>1.4	10.40			-0.38 ± 0.13	-0.28 ± 0.13
4		604 ± 126			≥0.5	16.41	-0.45 ± 0.10	-0.35 ± 0.11
5		651 ± 138			≥0.5	16.55	-0.42 ± 0.10	-0.39 ± 0.10
6		744 ± 177			<0.5	16.41	-0.35 ± 0.11	-0.13 ± 0.11
7		754 ± 177			<0.5	16.55	-0.37 ± 0.10	-0.18 ± 0.11
8		967 ± 292			≥0.8	10.31	-0.32 ± 0.13	-0.22 ± 0.14
Mean							-0.39 ± 0.02	-0.25 ± 0.04

Note. No. is the solution (or sample) number, $N_\star$ is the number of stars; solutions 1–8 in the upper and lower parts of the table were obtained, respectively, from individual stars and from the same data with a division into Charlier fields.

the range of bright stars because of its full sky coverage. In the UCAC2 catalog, we selected the range with a small magnitude equation that we disregard.

To extend the distance scale where possible, we rely on a well-known effect related to the fact that stars of different brightnesses and colors are, on average, located at different distances. As a result, we divided the Tycho-2 stars into two parts in magnitude with the boundary $V = 11\overset{m}{.}25$, into bright and faint ones, and then divided each part into seven parts in $B-V$ color in the following ranges: <0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1, 1–1.4, and >1.4.

We use only those stars from the UCAC2 catalog for which the photometric magnitudes from the 2MASS survey are given, $J, H,$ and K_s. In this case, it is important to ensure that the stars cover the entire sky. As a result, we divided the stars into four parts in both magnitude and $J-K_s$ color (with the $0\overset{m}{.}5$ boundary).

The results obtained are presented in Fig. 6 and Table 1. As we see from Fig. 6, the rotation, M^-_{13}, and deformation, M^+_{13}, tensor components undergo noticeable and coherent variations with increasing distance. Analysis of the plots leads us to conclude that there is an actual rotation of the stars confirmed by deformations up to a distance of ∼600 pc. This effect stems from the fact that the stars belong to the Local system. This boundary is most distinct in Fig. 6b, where M^+_{13} decreases sharply to zero at distances larger than 600 pc.

Table 1 lists the following parameters: the solution (or sample) number, the number of stars, the distance d_W, the $B-V$ and V ranges for Tycho-2 stars, $J-K_s$ and the mean magnitude (U2R) for UCAC2 stars; the last two columns give the derived components of the vector of rotation around the y and x axes. Solution nos. 1–3 pertain to bright ($8\overset{m}{.}5$–$11\overset{m}{.}25$) Tycho-2 stars; solution nos. 4–8 were obtained from UCAC2 stars. The solutions obtained using individual stars and the same data, but with a division into Charlier fields, are given in the upper and lower parts of the table, respectively. The maximum number of fields

Table 2. Cross-correlation coefficients derived when simultaneously solving the system of conditional equations (1) and (2) using individual stars (above the diagonal) and by the method with Charlier fields (below the diagonal)

Parameter	No.	1	2	3	4	5	6	7	8	9	10	11
$X_\odot$	1	1.0	0.01	−0.01	0.01	0.0	−0.05	0.02	0.15	−0.04	−0.01	0.0
$Y_\odot$	2	0.0	1.0	−0.01	0.15	0.05	0.0	0.20	0.03	−0.01	−0.04	0.0
$Z_\odot$	3	0.0	0.0	1.0	−0.01	0.0	−0.10	0.0	0.0	0.08	−0.02	−0.05
M^+_{21}	4	0.0	0.0	0.0	1.0	−0.02	0.01	0.03	0.0	0.0	0.01	0.0
M^-_{32}	5	0.0	0.0	0.0	0.0	1.0	0.0	−0.02	0.02	0.0	−0.62	0.03
M^-_{13}	6	0.0	0.0	0.0	0.0	0.0	1.0	−0.02	0.01	0.61	0.0	0.0
M^-_{21}	7	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.01	−0.02	0.02	0.0
M^+_{11-22}	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	−0.02	0.39
M^+_{13}	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.03
M^+_{23}	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	−0.01
M^+_{33-22}	11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.50	0.0	0.0	1.0

Note. The coefficients are given for sample no. 3 from Table 1.

is 432 for Tycho-2 and 367 for UCAC2. For each method, the table gives the corresponding weighted mean parameters M^-_{13} and M^+_{13}.

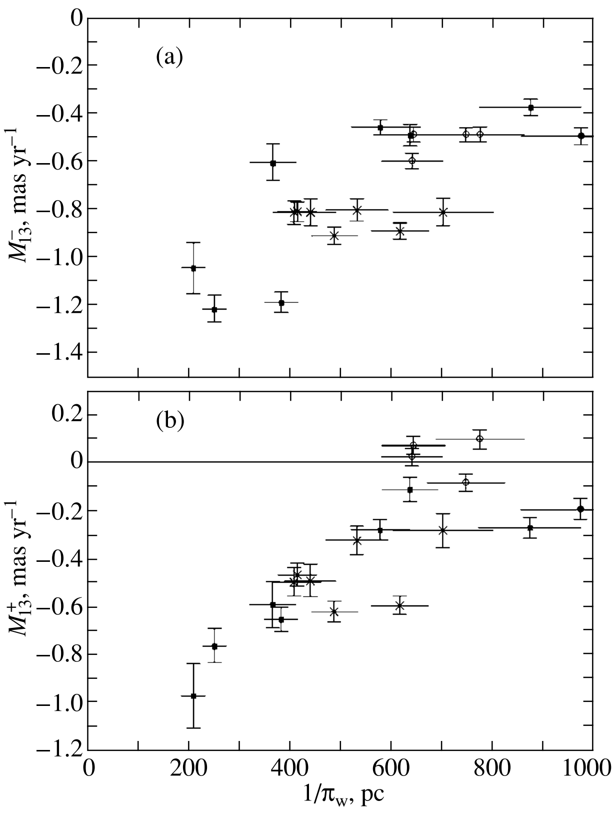

Fig. 6. Rotation, M^-_{13} (a), and deformation, M^+_{13} (b), tensor components vs. distance. The dots are bright Tycho-2 stars, the crosses are faint Tycho-2 stars, the open circles are the faintest UCAC2 stars, and the filled circles are bright UCAC2 stars; the horizontal bars indicate the distance errors.

Table 2 gives the correlation coefficients obtained when simultaneously solving the system of conditional equations (1) and (2) for sample no. 3. As we see, applying the method with fields reduces significantly the correlation between the unknowns (M^-_{13})–(M^+_{13}) and (M^-_{32})–(M^+_{23}) being determined.

As can be seen from the upper part of Table 1, M^-_{13} obtained from bright Tycho-2 stars with $B-V > 1.4$ (solution no. 3) is the minimum one (in absolute value). Together with distant M-type giants, sample no. 3 also includes nearby main-sequence dwarfs. Giants can be separated more reliably from dwarfs using 2MASS photometry (see, e.g., Majewski et al. 2003; Babusiaux and Gilmore 2005). We decided to check this result using bright (U2Rmag: $8^m_.0$–$11^m_.17$) stars from the UCAC2 catalog, where the magnitude equation is negligible (solution no. 8). For this purpose, we selected 211 086 stars according to the criterion $J-K_s > 0.8$; the stars lie in the K_s magnitude range 3–7^m (the mean is $6^m_.75$). We chose the boundary $J-K_s > 0.8$ empirically so as to have a representative sample. Most importantly, ≈50% of the stars lie outside the zone of the Galactic plane, i.e., have $|b| > 10°$. We have an opposite picture for other distance indicators, distant O and B stars (solution no. 1), since almost all of them are distributed in the Galactic equatorial plane, which, in particular, reduces the reliability of the M^-_{13} estimate. For solution no. 1, the correlation coefficients between the unknowns (M^-_{13})–(M^+_{13}) and (M^-_{32})–(M^+_{23}) being determined are ≈0.85. Comparison of our estimates of the distances d_U and d_W for bright UCAC2 stars with the photometric distances from Babusiaux and Gilmore (2005) for the (K_s)–$(J-K_s)$ plane leads us to conclude that the

Table 3. Kinematic parameters calculated from distant Tycho-2 stars using only Eq. (2)

$\overline{V}$	d_W, pc	A, km s^{-1} kpc^{-1}	M_{13}^-, mas yr^{-1}	M_{13}^+, mas yr^{-1}	M_{32}^-, mas yr^{-1}	M_{23}^+, mas yr^{-1}
$10^m.32$	572 ± 55	13.8 ± 0.4	-0.30 ± 0.05	-0.09 ± 0.06	-0.20 ± 0.05	-0.05 ± 0.06
10.40	856 ± 94	13.9 ± 0.5	-0.27 ± 0.06	-0.15 ± 0.07	-0.20 ± 0.06	-0.07 ± 0.07
10.32	484 ± 82	12.5 ± 1.0	-0.33 ± 0.09	-0.36 ± 0.17	-0.19 ± 0.09	$+0.16 \pm 0.17$
10.40	714 ± 165	11.1 ± 1.2	-0.29 ± 0.11	-0.37 ± 0.21	-0.22 ± 0.11	$+0.04 \pm 0.21$

Note. The solutions obtained from individual stars and from the same data with a division into Charlier fields are given in the upper and lower parts of the table, respectively.

Table 4. Kinematic parameters calculated from distant UCAC2 stars using only Eq. (2)

$\overline{m}$	d_W, pc	A, km s^{-1} kpc^{-1}	M_{13}^-, mas yr^{-1}	M_{13}^+, mas yr^{-1}	M_{32}^-, mas yr^{-1}	M_{23}^+, mas yr^{-1}
$16^m.41$	731 ± 65	12.3 ± 0.4	-0.41 ± 0.04	0.05 ± 0.04	-0.14 ± 0.04	-0.28 ± 0.11
16.55	727 ± 68	13.4 ± 0.4	-0.42 ± 0.04	0.06 ± 0.05	-0.20 ± 0.04	-0.31 ± 0.06
10.31	1122 ± 128	13.9 ± 0.4	-0.17 ± 0.05	0.26 ± 0.06	-0.17 ± 0.06	$+0.19 \pm 0.06$
16.41	701 ± 142	10.9 ± 1.4	-0.32 ± 0.10	0.26 ± 0.15	-0.16 ± 0.11	-0.12 ± 0.15
16.55	719 ± 149	11.2 ± 1.4	-0.29 ± 0.11	0.35 ± 0.15	-0.26 ± 0.11	-0.15 ± 0.15
10.31	1184 ± 274	12.2 ± 1.0	-0.27 ± 0.08	0.05 ± 0.11	-0.12 ± 0.09	$+0.18 \pm 0.11$

Note. The solutions obtained from individual stars and from the same data with a division into Charlier fields are given in the upper and lower parts of the table, respectively.

estimate of $d \approx 1$ kpc for our sample no. 8 of stars is quite realistic.

Applying the method with fields showed that solution no. 1 is least reliable. This is because the number of stars outside the zone of the Galactic plane ($b > 10°$) is from eight to ten; in all the remaining solutions, the number of stars in such fields is an order of magnitude larger. Solutions nos. 3 and 8 are most reliable. In the strict sense, they are not independent, since the Hipparcos and Tycho-2 catalogs were used (Zacharias et al. 2004) as the first epoch to determine the proper motions of bright (to U2R $\approx 12^m.5$) UCAC2 stars.

The mean Oort constants were found from all of the UCAC2 stars fainter than $16^m.34$ using the method of fields to be $A = 12.10 \pm 0.58$ km s^{-1} kpc^{-1} and $B = -10.63 \pm 0.46$ km s^{-1} kpc^{-1}.

The estimate of $M_{13}^- = -0.37 \pm 0.04$ mas yr^{-1} obtained from solution no. 3 in the upper part of Table 1 is in good agreement with $M_{13}^- = -0.38 \pm 0.13$ mas yr^{-1} calculated by the method of fields (the lower part of Table 1) and with the mean $M_{13}^- = -0.39 \pm 0.02$ mas yr^{-1} calculated using all of the data in the lower part of Table 1.

The mean M_{13}^- calculated using the data in the lower part of Table 1 is fairly stable, depending on the constraint imposed on $|\mu_t|$. Above, we used the criterion $|\mu_t| < 300$ mas yr^{-1} (in two iterations, with analysis of the residuals using the 3σ criterion), which allows nearby stars with high velocities to be rejected. We calculated the lower part of Table 1 for various constraints on $|\mu_t|$, from 300 to 25 mas yr^{-1}. The constraint $|\mu_t| < 25$ mas yr^{-1} implies that at a mean stellar distance of 700 pc, the maximum stellar space velocity is 110 km s^{-1}, i.e., only disk stars fall into the sample. The means (sample no. 1 was not considered because of the small number of stars at high latitudes remaining under these constraints) are

$$M_{13}^- = -0.33 \pm 0.02 \text{ mas yr}^{-1}, \quad (4)$$
$$M_{13}^+ = +0.05 \pm 0.06 \text{ mas yr}^{-1},$$
$$M_{32}^- = -0.26 \pm 0.04 \text{ mas yr}^{-1},$$
$$M_{23}^+ = +0.03 \pm 0.04 \text{ mas yr}^{-1},$$
$$|\mu_t| < 25 \text{ mas yr}^{-1}. \quad (5)$$

Results of the solution of only Eq. (2). Tables 3 and 4 give the kinematic parameters that were determined by solving only Eq. (2). We used two approaches: the solution based on individual stars (the upper parts of Tables 3 and 4) and the method with fields (the lower parts of Tables 3 and 4). For

Table 5. Cross-correlation coefficients obtained when solving Eq. (2) using individual stars (above the diagonal) and by the method with Charlier fields (below the diagonal)

Parameter	No.	1	2	3	4	5	6	7	8	9	10
$X_\odot$	1	1.0	0.0	−0.02	0.01	−0.01	−0.06	0.12	−0.04	0.0	−0.01
$Y_\odot$	2	0.0	1.0	−0.02	0.14	0.05	0.01	−0.02	0.0	−0.03	−0.03
$Z_\odot$	3	0.0	0.0	1.0	−0.02	0.01	−0.06	0.0	0.04	−0.02	−0.03
M^+_{21}	4	0.0	0.0	0.0	1.0	0.0	0.03	0.01	0.02	−0.01	0.0
M^-_{32}	5	0.0	0.0	0.0	0.0	1.0	0.0	0.01	0.0	−0.89	0.03
M^-_{13}	6	0.0	0.0	0.0	0.0	0.0	1.0	−0.02	0.88	0.0	−0.01
M^+_{11-22}	7	0.0	0.0	0.0	0.0	0.0	0.0	1.0	−0.04	−0.01	0.81
M^+_{13}	8	0.0	0.0	0.0	0.0	0.0	0.02	0.0	1.0	0.0	−0.01
M^+_{23}	9	0.0	0.0	0.0	0.0	−0.02	0.0	0.0	0.0	1.0	−0.02
M^+_{33-22}	10	0.0	0.0	0.0	0.0	0.0	0.0	0.82	0.0	0.0	1.0

Note. The coefficients are given for sample no. 3 from Table 1.

the Tycho-2 catalog (Table 3), we used the samples of stars corresponding to solutions nos. 2 and 3, whose parameters are listed in Table 1. We imposed the constraint $|\mu_t| < 100$ mas yr^{-1} on the absolute value of the tangential stellar velocity. Using this constraint reduced considerably the random errors of the unknowns in the method with fields and affected noticeably sample no. 8: the mean distance to the stars increased to $d_W \approx 1100$ pc.

For the UCAC2 catalog (Table 4), we used the faintest stars (the stars whose parameters are listed in Table 1 for solutions nos. 4 and 6 as well as for solutions nos. 5 and 7 were combined into two groups); about 450 000 stars were used in each magnitude range.

The results of solving Eq. (2) obtained by the two methods show that the Oort constant A and the local rotation tensor components are determined reliably and confirm the results that we obtained by simultaneously solving the system of conditional equations (1) and (2).

Table 5 gives the correlation coefficients derived when solving Eq. (2) for sample no. 3. As we see from Table 5, applying the method with fields reduces the correlation between the unknowns (M^-_{13})–(M^+_{13}) and (M^-_{32})–(M^+_{23}) being determined by an order of magnitude. Comparison of Tables 5 and 2 leads us to conclude that the correlation between the above unknowns is lower when Eqs. (1) and (2) are solved simultaneously; therefore, the simultaneous solution is preferred.

In our model, we did not abandon the unknowns $(M^+_{11} - M^+_{22})$ and $(M^+_{33} - M^+_{22})$. The kinematic meaning of the first difference is that $0.5(M^+_{11} - M^+_{22}) = C$, where C is the Oort constant. We can determine the vertex deviation l_{xy} in the xy plane from the relation $\tan 2l_{xy} = -C/A$ by analyzing the Oort constants A and C. Our results show that the vertex deviation for the most distant stars under consideration (sample no. 8) differs significantly from zero; it is $l_{xy} = 7° \pm 1°$ and, for sample no. 3, $l_{xy} = 6° \pm 2°$.

DISCUSSION

On the whole, we may conclude that the estimate $M^-_{13} = -0.37 \pm 0.04$ mas yr^{-1} can be interpreted as a residual rotation of the ICRS/Tycho-2 system relative to the inertial reference frame. This value is in good agreement with $M^-_{13} = -0.36 \pm 0.09$ mas yr^{-1} that we obtained by analyzing distant Hipparcos stars (Bobylev 2004a) using trigonometric parallaxes to analyze the residual rotation of the ICRS/Hipparcos system as a function of distance. Previously (Bobylev 2004b), based on an independent astrometric method, we found the following equatorial components of the vector of residual rotation of the ICRS/Hipparcos system relative to the inertial reference frame: $\omega_x = +0.04 \pm 0.15$ mas yr^{-1},

$\omega_y = +0.18 \pm 0.12$ mas yr^{-1}, and $\omega_z = -0.35 \pm 0.09$ mas yr^{-1}. Transforming the ω_z component to the Galactic coordinate system yields $M_y = M_{13}^- = -0.26 \pm 0.07$ mas yr^{-1}, which is also in agreement with the above estimate.

Inaccurate realization of the ICRS/Hipparcos system, in other words, a residual rotation of the ICRS/Hipparcos system relative to ICRF, can be one of the main causes of the rotation found (Ma et al. 1998). Since a linear model of solid-body rotation (Kovalevsky et al. 1997) was used to link the ICRS/Hippacros system to ICRF, we believe it appropriate to use the linear Ogorodnikov–Milne model to solve the formulated problem.

The best solution of the problem of controlling the inertiality of the ICRS/Tycho-2 system may be associated with the use of images for extragalactic objects in the UCAC2 catalog. As follows from the description to the electronic version of UCAC2, the measured images of starlike extragalactic objects are present. In the catalog, they are not marked in any way and are not identified; their total number is unknown. As follows from our work, for the random errors in the sought-for parameters to be $\sim$0.05 mas yr^{-1}, we must have $\sim$100 000 objects.

On the other hand, we see from Fig. 6 that the variations in the rotation and deformation parameters with distance are nonlinear in pattern. This is attributable to peculiarities of the structure of the Local system of stars and larger-scale Galactic structures (the spiral arms and the disk warp). The possibilities for a more detailed study of these peculiarities will emerge soon, when the next version of the UCAC2 catalog, providing full coverage of the celestial sphere, will be published. In this case, the magnitude equation should be completely eliminated from the proper motions of its stars.

Our results have a bearing on the problem of studying the Galactic disk warp (Miyamoto and Sôma 1993; Miyamoto et al. 1993b; Miyamoto and Zhu 1998). Since O–B5 stars concentrated near the Galactic plane are mainly analyzed in these papers, the correlation coefficients between the parameters with subscript 3 are close to 0.95. To reduce the correlations, the Ogorodnikov–Milne model is simplified by making the assumptions (in our notation) $M_{13}^+ = -M_{13}^-$ and $M_{32}^- = M_{23}^+$, suggesting that $\partial V_R/\partial z = \partial V_\theta/\partial z = 0$. Under these assumptions, the above terms disappear from Eq. (1). In this case, the key equation is Eq. (2), which allows us to determine the quantities $2M_{13}^+ = -2M_{13}^- = \partial V_z/\partial R$ and $2M_{32}^- = 2M_{23}^+ = (1/R)(\partial V_z/\partial \theta)$. The other model of these authors is constructed by assuming that $M_{13}^- = M_{13}^+ = 0$, $M_{32}^- = M_{23}^+$. In this case, only one quantity, $2M_{32}^-$, is determined from the solution of the system of conditional equations (1) and (2). As we showed, using the method with fields, which is almost free from any correlations between the unknowns (M_{13}^-)–(M_{13}^+) and (M_{32}^-)–(M_{23}^+), allows the problem to be considered without any preliminary assumptions. The parameters in Tables 3 and 4 show that M_{13}^+, M_{32}^-, and M_{23}^+ have statistically significant differences, depending on the method of analysis and the sample.

Using Galactic stars to solve our problem has a number of peculiarities related to the structure of the Galaxy. Let us consider some of them.

(1) The yz plane, rotation around the x axis. Chiba and Beers (2000) showed that old (metal-poor) thick-disk stars lag well behind the circular Galactic rotation velocity, $dV_\theta/d|z| = -30 \pm 3$ km s^{-1} kpc^{-1}; for halo stars, this gradient is almost twice as large. This quantity expressed in mas yr^{-1} is $30/4.74 = 6.3$ mas yr^{-1}; it can have an effect if the distribution of sample stars is asymmetric in z. As can be seen from Eqs. (3), the gradient $\partial V_\theta/\partial z$ enters into the parameters M_{23}^+ and M_{32}^-. Applying the method with fields and using the constraint on $|\mu_t|$ (condition (5)) allows this effect to be minimized. The presence of an appreciable component M_{32}^- (solution (4)) should be considered as a manifestation of a particular effect in the actual kinematics of stars, since we consider M_{13}^- as the main component in the problem of controlling the inertiality of the ICRS system as a residual rotation (Bobylev 2004b). The relationship between distant giants and kinematics of the warped Galactic disk may be such an effect. However, a detailed analysis of this problem is beyond the scope of this paper.

(2) The xy plane, rotation around the z axis. The linear Ogorodnikov–Milne model we used allows a parabolic fit to the Galactic rotation curve ($V_\theta(R)$) near R_0 to be obtained. Analysis of the currently available data shows that the Galactic rotation curve at the solar distance is flat (Popova and Loktin 2005; Avedisova 2005; Zabolotskikh et al. 2002). Previously (Bobylev 2004c), we determined the following parameters of the angular velocity ($\omega(R)$) of Galactic rotation by analyzing distant ($\overline{d} = 1$ kpc) O and B stars: $\omega_0 = -28.0 \pm 0.6$ km s^{-1} kpc^{-1}, $\omega_0' = +4.17 \pm 0.14$ km s^{-1} kpc^{-2}, $\omega_0'' = -0.81 \pm 0.12$ km s^{-1} kpc^{-3}, and $R_0 = 7.1$ kpc. Based on these data and assuming that $R - R_0 = 1$ kpc, we can see that the effect of the second derivative $|0.5(R - R_0)^2\omega_0''| = 0.4$ km s^{-1} kpc^{-1} is not significant, is comparable to the random errors in the Oort constant A and B. Thus, disregarding the second derivative ω_0'' gives a contribution to the amplitude of the waves that we see in the upper plots of Figs. 1 and 2 (M_{12}^+ and

M_{21}^{-}) of $\sim$0.1 mas yr^{-1}, which is considerably smaller than the amplitude observed in the plots.

CONCLUSIONS

Our analysis showed that the proper motions of UCAC2 stars are distorted by a complex magnitude equation. Thus, for example, no noticeable effect of the magnitude equation was found in the proper motions of stars brighter than $\approx 11^m$, but this effect is significant in the magnitude range $12-15^m$. We showed that the magnitude equation has the greatest effect in $\mu_\alpha \cos\delta$ of northern-sky stars. This is because different sources for the southern and northern skies were used as the first epoch in deriving the proper motions of UCAC2 stars. We determined the coefficient of the magnitude equation for northern-sky stars fainter than 13^m by comparing the proper motions of UCAC2 and PUL3SE stars, -0.60 ± 0.05 mas yr^{-1} mag^{-1}. We associate this magnitude equation with the effect of the NPM catalog, Yellow Sky plates. The derived magnitude equation mainly affects the determination of the rotation tensor components. Its elimination leads to a 25% change in the rotation around the z axis (the Oort constant B) and to a 100% change in the rotation around the y axis for 13^m stars.

The method of statistical parallaxes was used to estimate the distances to stars with random errors no larger than 14%. The linear solar velocity relative to the local standard of rest, which is well determined for the local centroid ($d \approx 150$ pc), was used as a reference. This could affect the distance estimates for distant stars.

The method with fields was shown to reduce the correlations between the unknowns (M_{13}^{-})–(M_{13}^{+}) and (M_{32}^{-})–(M_{23}^{+}) being determined by an order of magnitude. When Eqs. (1) and (2) are solved simultaneously, the correlations between these unknowns are lower (than those for the solution of only Eq. (2)); therefore, the simultaneous solution is preferred.

The mean Oort constants estimated from Tycho-2 stars ($8\overset{m}{.}5-11\overset{m}{.}25$) are $A = 13.88 \pm 0.98$ km s^{-1} kpc^{-1} and $B = -12.13 \pm 0.63$ km s^{-1} kpc^{-1}. The analogous means that we estimated from bright ($8^m-11\overset{m}{.}17$) UCAC2 stars have no statistically significant differences. The mean Oort constants estimated from UCAC2 stars fainter than $16\overset{m}{.}34$ are $A = 12.10 \pm 0.58$ km s^{-1} kpc^{-1} and $B = -10.63 \pm 0.46$ km s^{-1} kpc^{-1}.

We established that the two components of the Ogorodnikov–Milne model that describe the rotation around the Galactic y axis and the deformation in the xz plane depend on heliocentric distance. For the nearest stars ($d \approx 200$ pc), these parameters are $\approx -1.0 \pm 0.1$ mas yr^{-1} and decrease, on average, by a factor of 2 at distances of $\sim$600 пк. We associate this with kinematic peculiarities of the Local system of stars. For more distant stars, there are, on average, no statistically significant deformation in the xz plane.

For distant Tycho-2/UCAC2 stars at heliocentric distances of $\approx$900 pc, the mean rotation around the Galactic y axis is -0.37 ± 0.04 mas yr^{-1}, which we interpret as a residual rotation of the ICRS/Tycho-2 system relative to the inertial reference frame.

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