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Investigation of the kinematics of young disk populations

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Abstract. We used both radial-velocity and proper-motion data to perform a rotation-curve solution on a combined sample of about 700 Population-I objects including young open clusters (lg $A < 8.1$), classical Cepheids, and red supergiants. The distances of all objects are derived on a homogenized scale based on Kholopov's (1980) ZAMS, $M_V(B-V)_0$, PL relation for classical Cepheids by Berdnikov & Efremov (1985), and the absolute-magnitude calibration for red supergiants involving photometric data in Wing's eight-color narrow-band near-infrared system. We inferred R_0 = 7.3 $\pm$ 0.3 kpc for the distance of the Sun to the Galactic center and found the following parameters of the solar apex and Galactic rotation curve: U_0 = 8.8 $\pm$ 0.9 km s^{-1}, $V_0 = 13.5 \pm 0.9$ km s^{-1}, $W_0 = 11.7 \pm 1.5$ km s^{-1}, $\omega_0 = 27.3 \pm 2.0$ km s^{-1} kpc^{-1}, A = 19.5 $\pm$ 0.5 km s^{-1} kpc^{-1}, and $(\mathrm{d}^2\omega/\mathrm{d}r^2)_0$ = 1.13 $\pm$ 0.12 km s^{-1} kpc^{-3}. These values are in good agreement with the results of our analysis of the radial-velocity and proper-motion fields of classical Cepheids (Dambis et al. 1995).

Key words: Galaxy: kinematics and dynamics – open clusters and associations – Cepheids – supergiants – Galaxy: structure – Galaxy: fundamental parameters

1. Introduction

The analysis of large-scale velocity fields of objects that belong to the young Galactic disk is the principal tools used by many investigators to study the Galactic rotation curve and infer the parameters of spiral density waves (Karimova & Pavlovskaya 1973; Hron & Maitzen 1985; Nikiforov & Petrovskaya 1994; Caldwell & Coulson 1987; Fich et al. 1989; Pont et al. 1994; Dambis et al. 1995, and Mishurov et al. 1997). This is because the young disk population, which includes neutral hydrogen, HII-regions, OB- and supergiant stars, classical Cepheids, and young open clusters, is characterized by small velocity dispersion (6-15 km s^{-1}) and, consequently, by small rotational lag relative to the LSR. Most of the studies of Population-I kinematics are based on radial-velocity data for objects with well-established and homogeneous distance scales and only rotation-curve solutions for radial-velocity maps of neutral hydrogen require no explicit distance determinations. Few works make use of proper-motion data and among them are our previous paper (Dambis et al. 1995), where we used radial-velocity and proper-motion data for classical Cepheids to derive rotation-curve parameters and infer the distance to the Galactic center, and a recent work by Frink et al (1996), who studied the Galactic rotation law using both radial velocities and proper motions of classical Cepheids and OB stars. Here, we extend our kinematical analysis to a combined sample including, in addition to classical Cepheids, young open clusters and red supergiants. We perform rotation-curve solution for this combined sample and further refine the distance to the Galactic center.

2. The sample

Our initial sample consisted of 202 young open clusters (lg $t \leq$ 8.1) with published *UBV* photoelectric and CCD photometry collected by Mermilliod (1988, 1992); 128 red supergiants observed in Wing's eight-color, narrow-band, near-infrared photometric system (White & Wing 1978), and 363 classical Cepheids with accurate photoelectric *UBVRI* light curves (Berdnikov 1987), making up for a total of 693 Population-I objects with accurate distances.

3. The distances

3.1. Open clusters

For young open clusters we adopted distance moduli from our own list of cluster parameters (Dambis 1997). These distance moduli were derived by fitting the cluster main sequences, $V((B-V)_0)$, to Kholopov's (1980) ZAMS, $M_V((B-V)_0)$ and are accurate, on the average, to 0.1^m as far as we ignore possible errors in the zero point of the adopted ZAMS. The distance scale of our cluster sample is tied up, through Kholopov's ZAMS, to the Hyades distance modulus of 3.30^m and Pleiades distance modulus of 5.47^m (Kholopov 1980).

3.2. Red supergiants

We calculate the distances to red supergiants, r, from the following formula:

$$\lg r = 0.2 \cdot (I(104) - M(104) - A(104)) + 1, \quad (1)$$

where $I(104)$ and $M(104)$ are the observed and absolute magnitudes of the star in question measured in the fifth filter of Wing's system (λ_{eff} = 1.0395μ), and $A(104)$ is interstellar extinction in this filter (Warner & Wing 1977). The absolute magnitude, $M(104)$, is given by the following calibration (Dambis 1993):

$$M(104) = -4.63 - 0.240 \cdot \sqrt{TiO} - 0.0768 \cdot CN, \qquad (2)$$

where TiO and CN are reddening-free photometric indices (in 0.01^m) in Wing's photometric system, which measure the strengths of the corresponding molecular bands in the stellar spectrum and are sensitive to the temperature and luminosity, respectively. Note that here we give the correct version of the formula, which was misprinted in the original paper. We calculate interstellar extinction, $A(104)$, as follows (Warner & Wing 1977; Dambis 1993):

$$A(104) = 1.25 \cdot \Delta\theta, \qquad (3)$$

where $\Delta\theta = \theta_{obs} - \theta_0$ is the excess of the color index θ used in Wing's system and the intrinsic color index, θ_0, is given by the following calibration formula (Dambis 1993):

$$\theta_0 = 1.330 + 0.00289 \cdot TiO. \qquad (4)$$

The distances of red supergiants thus obtained are accurate, on the average, to 0.19^m (Dambis 1993) and the distance scale of these stars as a whole is tied up to the distance modulus of 11.4^m for the χ and h Per cluster and is thereby consistent with our distance scale for open clusters (see Kholopov 1980).

3.3. Cepheids

Our Cepheid sample is based on Berdnikov's (1987) catalog of the Galactic fundamental-mode classical Cepheids with available $UBVRI$ photoelectric photometry. This is the most complete catalog of this type and contains data (periods, color excesses, positions and distances, as well as $UBVRI$ intensity-mean, maximum, and minimum magnitudes and photometric amplitudes) for 363 Cepheids. As in our previous paper (Dambis *et al.* 1995), we excluded first-overtone Cepheids (i.e., Cs-type Cepheids according to the GCVS classification - Kholopov *et al.* (1985-1987)) from our sample as well as those that were observed only photographically and lack photoelectric observations or those with scarce and unreliable photoelectric data. The point is that the distances derived for these stars are highly uncertain and might suffer from large random and systematic errors, which may cast doubt on our results or significantly bias them.

The color excesses in Berdnikov's (1987) list were determined from the period-color relation by Dean et al. (1978) and the distances, from the PL relation of Berdnikov & Efremov (1985). The typical error of a Cepheid distance modulus thus derived is about 0.22^m (Caldwell & Laney 1991). The PL relation of Berdnikov & Efremov (1985), in turn, is based on the distance moduli of open star clusters derived using Kholopov's (1980) ZAMS and thereby ensuring the consistency of our Cepheid distances with those of open clusters and red supergiants (see above).

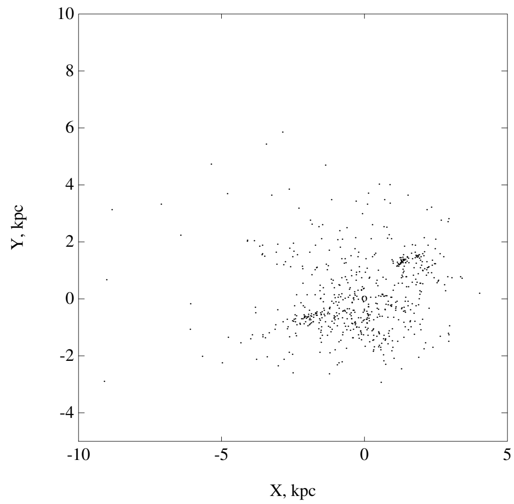

Fig. 1. The distribution of cepheids, young open clusters and red supergiants projected onto the XY plain. The Sun (indicated by a small circle) is at (0,0) and the Galactic center is in the bottom part of this figure. Only nearest objects are shown.

Thus, our initial sample consisted of almost 700 Population-I objects with distances derived in a homogenized distance scale with a typical relative accuracy of 0.05 - 0.10. Fig. 1 shows the distribution of these objects projected on the Galactic plane.

4. Radial-velocity data

4.1. Open clusters

We critically analyzed all published radial-velocity data for stars in 67 young open clusters collected in the database of Mermilliod (1988, 1992) and used them to derive our own mean cluster velocities. We further adopted the mean radial velocities for another 40 clusters from Hron's (1987) list thereby making up for a total of 107 clusters with known radial velocity components. Unfortunately, for most of young open clusters only the radial velocities of their early-type members were measured, which are not very accurate because of the scarcity and large width of spectral lines in these stars. Therefore the typical accuracy of an individual radial-velocity measurement for an OB star is on the order of 10 km s^{-1} and only the radial velocities of Cepheids and red supergiants, which enter only a small fraction of young open clusters, can be measured to an accuracy of 1 km s^{-1} (see below). Taking into account the fact that for most of young clusters radial velocity have been measured only for few members, we can conclude that the typical accuracy of a mean radial velocity for a young cluster must be about 5-10 km s^{-1}.

4.2. Red supergiants

For almost half of stars in our red-supergiant sample we derived γ-velocities based on our own measurements (Rastorguev et al. 1990, 1997) taken in 1987-1995 with a correlation spectrometer designed and constructed by A.A.Tokovinin. The typical accuracy of a single measurement is about 1 km s^{-1} and that of the derived γ-velocity, about 1-3 km s^{-1} (this is due to radial-velocity variability of most of red supergiants). We then calculated the γ-velocities for another 40 red supergiants based on critical analysis of published radial-velocity data compiled in the bibliographic catalogs by Abt & Biggs (1972) and Barbier-Brossat et al. (1994) giving the preference to the results of measurements taken with correlation spectrometers. We thus obtained γ-velocities for a total of 106 red supergiants of our sample.

4.3. Cepheids

We used the list by Pont et al (1994) as the main source of radial-velocity data for Cepheids. It contains both original data and radial velocities collected from other lists. Most of the γ-velocities listed in this paper were determined from few radial-velocity measurements (less than 5 - 6, as a rule), randomly distributed by phase. Evidently, the mean velocities derived from such a small number of individual measurements can suffer from random and systematic errors of the order of 2 - 5 km s^{-1}, which are difficult to allow for. However, considering the fact that the dispersion of peculiar velocities of Cepheids relative to the general rotation curve is close to 10 - 12 km s^{-1}, the use of such data can hardly bias the results to a significant degree. Therefore, we used these velocities if more precise data were not available.

We added new radial velocities of faint cepheids, taken from recent list of Pont et al (1997), that includes nearly 40 cepheids.

Finally, we used our own radial-velocity data for 85 Cepheids. The radial-velocity measurements were carried out in 1987 - 1996 with a correlation spectrograph. We took the γ-velocities for 85 Cepheids (including a number of binary cepheids) from our own lists (Gorynya *et al.* 1992, 1996a,b). All γ-velocities in these two lists are based on a large number of individual radial-velocity measurements for each Cepheid (more than 25 - 30, as a rule), and the accuracy of γ-velocities, which were calculated using second to fifth-order trigonometric expansions, is estimated to be 0.3 - 0.5 km s^{-1}. Our final list contains 264 Cepheids with mean radial velocities.

A number of Cepheids are known to be members of open clusters. Our sample of young objects contains some of these clusters and their assumed member Cepheids. The proper motions of all such stars have been determined independently of those of the corresponding clusters and therefore we included them into our proper-motion subsample as separate objects. However, the radial velocities of Cepheids are usually measured with much higher accuracy than those of open clusters and in such cases we ignored the latter and did not include host clusters into our radial-velocity subsample.

5. Proper motions

The absolute proper motions for all objects of our kinematic sample are taken from or based on the two sources. We used the PPM catalog (Roser et al. 1991) for brighter stars. The proper motions for fainter stars were taken from the so-called Four-Million Star catalog of proper motions (Volchkov et al. 1992), hereafter referred to as the 4M-catalog. These proper motions were derived from the coordinate differences for common stars in the Guide Star Catalog of the Hubble Space telescope and the computer-readable version of the Astrographic Catalog, also known as the Carte du Ciel catalog, (hereafter referred to as AC) (Kuimov *et al.* 1992) and reduced to the PPM system of proper motions. Our final sample contains a total of 271 Cepheids with homogeneous absolute proper motions taken from the PPM catalog (129 stars) and the 4M-catalog (142 stars). The absolute proper motions are also available for 116 red supergiants (80 from the PPM and 36, from the 4M-catalog). To derive accurate and homogeneous absolute proper motions for 21 open clusters with published relative proper motions of stars in their fields, we averaged the absolute proper motions of confident cluster members (selected on the basis of relative proper motions) taken from the 4M-catalog (Glushkova et al. 1996). We also compared the relative motions with the corresponding absolute proper motions and found the random errors of the latter to be of the order of 0.003 - 0.004 " yr $^{-1}$, which slightly exceeds the errors quoted in the PPM catalog and thereby provides an independent estimate for the accuracy of the proper motions adopted for red supergiants and Cepheids (see above). We then derived the absolute proper motions for another 181 clusters by averaging the 4M-catalog proper motions of their members selected on the basis of the photometric color-magnitude diagrams. We estimate the typical accuracy of our absolute proper motions for open clusters to be on the order of 0.004 " yr^{-1}.

There is no doubt, the proper motions that we adopted for open clusters, red supergiants, and Cepheids are enough accurate to allow statistical analysis of the Population-I kinematics.

6. Galactic rotation model and approach to the solution

We estimated rotation-curve parameters for purely circular rotation model. The authors of many works on the kinematics of disk stars pointed out a -2 - -4 km s^{-1} heliocentric K-effect in radial velocities. We fitted our kinematical data to various rotation model versions. One of them involved the K-term, which we estimated to be -3.5 $\pm$ 0.9 km s^{-1}. Presently this effect is explained by deviation of the Cepheid motion from the circular rotation law due to perturbations induced by spiral arms (the so-called Grand Design). The velocity field of the system of Cepheids with allowance for perturbations due to spiral pattern is analyzed in Mishurov et al. (1997). The models used in subsequent calculations do not involve the K-term.

We determine kinematical constants using expressions based on the well known Bottlinger formulas (Kulikovskii 1985). The radial velocity V_r of a star can be expressed in the following form:

$$V_r + (u_0 \cos b \cos l + v_0 \cos b \sin l + w_0 \sin b)$$
$$= R_0(\omega - \omega_0)\sin l \cos b + R_0 \Delta\omega \sin l \cos b + V_r', \quad (5)$$

where u_0, v_0, and w_0 are the components of the solar motion toward the adopted apex in the Galactocentric rectangular coordinate system (the x-axis is directed toward the galactic Center; the y-axis, in the direction of the galactic rotation, and the z-axis, toward the North Galactic Pole); R_0, the Galactocentric distance of the Sun; ω and ω_0, the angular velocities of rotation of centroids under study at distances R and R_0, respectively; $\Delta\omega = \omega(S) - \omega_0(S_0)$, the difference of angular velocities of the centroid under study (S) and the reference centroid S_0 used to specify the solar motion with components u_0, v_0, and w_0, referred to the distance R_0, and V_r', the residual of the equation. Note that we preserve the term with $\Delta\omega$ in the expression (5) only if the solar motion toward the adopted apex is preset. In this paper the apex parameters are among derived quantities and therefore $\Delta\omega$ should be set to zero.

We solve our equations for the components of the solar motion u_0 and v_0 and for derivatives of the angular velocity with respect to R. We fixed the parameter w_0 at +7 km s^{-1} (the standard apex), because, due to a small factor sin b, the kinematical (radial-velocity) data for a flat subsystem do not constrain this quantity. But we derived an estimate of w_0 from the proper motions along galactic latitude. This estimate is given in Table 2 below.

The equation for the proper motion component along the Galactic longitude (in 0.001 " yr^{-1}) will look as follows:

$$4738\mu_l + (v_0 \cos l - u_0 \sin l)/r = (R_0/r \cos l - \cos b)(\omega - \omega_0)$$

$$+R_0/r\Delta\omega\cos l - \omega_0 \cos b + 4378\mu_l', \qquad (6)$$

where μ_l' is the peculiar component of the proper motion; r, the heliocentric distance of the star (all distances are in kpc), and all other designations are the same as in (5).

We solved the sets of equations (5) and (6) separately. It can be easily understood that the most reliable estimates of R_0, $\mathrm{d}\omega/\mathrm{d}R$, and higher-order derivatives can be inferred from radial-velocity analysis, whereas the angular velocity ω_0 can be determined only from proper motions.

Therefore we solved the equations for proper motions (6) in two ways: (1) we determined ω_0 and its derivatives and (5) we determined only ω_0 and fixed its derivatives at their values inferred from radial-velocity solution. We considered version 1 because the Galactocentric distance of the Sun, R_0, and, therefore, the derivatives of the angular velocity inferred from radial velocities are sensitive to systematic changes in the distance scale of the objects used, whereas the distance-scale effects on the rotation-curve parameters derived from proper motions are much weaker. Therefore, the closeness of the values of $\mathrm{d}\omega/\mathrm{d}R$ obtained by separately solving equations (5) and (6) serves as an independent test for the distance scale used. If the distance scale requires no systematic correction then we can consider the angular velocity derived in version 2 reliable. We solved equations (5) and (6) using weighted least squares method (the so-called χ^2-minimization, Press *et al.* (1987)).

We always adopted $\Delta\omega = 0$ in equations (6) in spite of the fact that in this case the apex parameters were not solved for and were preset. However, we consider this approach justified because the apex parameters in equations (6) refer to the same centroid as those derived from equations (5). We expanded the angular velocity ω into a power series in $(R - R_0)$ up to the second order in $(R - R_0)$ and limited the Cepheid sample to heliocentric distances $0.5 < r < 6$ kpc. The lower boundary is due to the fact that the Sun, together with nearby Population-I objects, is a member of the Local System - a stellar complex that can possess its own rotation which can differ from the overall Galactic rotation. This can strongly bias the results obtained from proper motions, especially the Oort constant A and the angular velocity ω_0. We noted this effect in our calculations: the inclusion of a relatively small number of objects with $r <$ 0.5 kpc significantly decreases A and increases ω_0. We further restricted our sample to objects with small proper-motion components along the z-coordinate (with μ_b within 0.015" yr^{-1} of the mean value) assuming true vertical velocity components of young Galactic disk objects to be small and large deviations of μ_b from the mean value to be due entirely to proper-motion errors in Galactic latitude. We considered it undesirable to use the proper motions of these objects in our rotation-curve solution because they can have large errors not only in the μ_b but also in the μ_l component.

7. Determination of the distance to the Galactic center

Whatever the distance scale adopted for the objects in question, it can be used to determine the optimal value of R_0, which is the parameter that provides the best agreement between the observed and the modeled velocity fields. Here, we attempted to refine the Sun's Galactocentric distance based on the combined sample including open clusters, red supergiants, and classical Cepheids. The sum of squares of weighted residuals in V_r (i.e., χ^2) as a function of R_0 for our entire sample, takes its minimum value at R_0 = 7.3 kpc.

We used numerical simulations to assess the error of this estimate. To this end, we fixed the space distribution of the objects in our sample and R_0, and performed a number of Monte-Carlo simulations by adding Gaussian noise with a dispersion of 12 km s^{-1} to the radial-velocity values given by the Galactic rotation model of the second order in $(R - R_0)$. We then determined the parameter R_0 for each sample using the above technique.

Our simulations revealed no systematic bias in the mean R_0 value and yielded a dispersion of 0.2 kpc for R_0. The discrete character of the space distribution of a finite number of objects, the imperfect Galactic rotation model, and other poorly known factors, contribute additionally to the error in R_0. Therefore, we estimate its actual value to be of the order of 0.3 - 0.5 kpc, or R_0 = 7.3 $\pm$ 0.3 kpc and it is this value that we adopt in all subsequent calculations.

Note that this result is in good agreement with R_0 = 7.1 $\pm$ 0.5 kpc, the value obtained from Cepheids alone (Dambis et al. 1995), thereby corroborating our initial assumption about the mutual consistency of kinematics and the adopted distance scales of open clusters, red supergiants, and classical Cepheids. It also agrees well with R_0 = 7.1 kpc inferred from the space distribution of globular clusters (Rastorguev et al. 1994). Note that kinematical estimates of R_0 depend linearly on the adopted distance scale.

8. Discussion

Table 1 shows that our rotation model yields from both radial-velocity and proper-motion data, similar values for the Oort constant A, which agree well with each other within the quoted errors. And this is in spite of the fact that the open clusters, red supergiants, and classical Cepheids have different space distribution with respect to spiral arms. Such agreement provides additional independent support for the mutual consistency of the distance scales adopted for the three classes of objects mentioned above.

Because, obviously, radial velocity data yield a more precise result for the constant A, we finally adopted A = 19.5 $\pm$ 0.5 km s^{-1} kpc^{-1}, a mean value based on the entire sample. The fact that this value is in general agreement with the result derived from proper motion data only (see Table 2), which is virtually independent of the adopted distance scale, provides additional evidence in favor of the zero points of the adopted distance scales.

Table 2 lists kinematical parameters inferred from the solution based on the entire proper-motion sample. Angular-velocity values ω_1 and ω_2 were derived using the above methods (1) and (2). The discrepancy between these two values can be partly explained by large random errors in proper motions preventing accurate estimation of the angular-velocity derivatives, and by inevitable systematic errors, which are difficult to account for. Mel'nik (1995), in particular, drew attention to the importance of these systematical errors when she studied residual velocities of OB associations based on the proper motions from the PPM catalog.

Here we note a certain increase of the angular velocity, ω_0, inferred from the entire combined sample compared to 26 $\pm$ 2 km s^{-1} kpc^{-1} given by the solution based on Cepheid sample alone (Dambis et al. 1995). Glushkova et al. (1997) pointed out that this discrepancy might be due, to a certain extent, to different content of the samples involved. Thus, the open clusters under study consist mostly of faint stars that do not enter the PPM catalog (Roeser & Bastian 1991) whereas the proper motions of almost half of Cepheids, which are on the average brighter than most of cluster stars, were taken from the PPM catalog. (Note also an even higher value for ω_0 given by recent VLA measurement of the proper motion of the Sgr A* radio source in the Galactic center - -6.55 $\pm$ 0.34 mas yr^{-1} (Backer 1966) - implying, after subtraction of the peculiar velocity of the Sun, ω_0 = 30.3 $\pm$ 1.6 km s^{-1} kpc^{-1} for R_0 = 7.3 kpc.)

Furthermore, Glushkova et al. (1997) showed that systematic differences of the inferred angular velocity values are partly due to peculiarities in the space distribution of young objects. The point is that a major part (up to 25 - 30 %) of these objects concentrate to the so-called 'tangent circle' (i.e., the circle located in the Galactic plane with a diameter formed by the line connecting the Sun and the Galactic center).Here we deal with

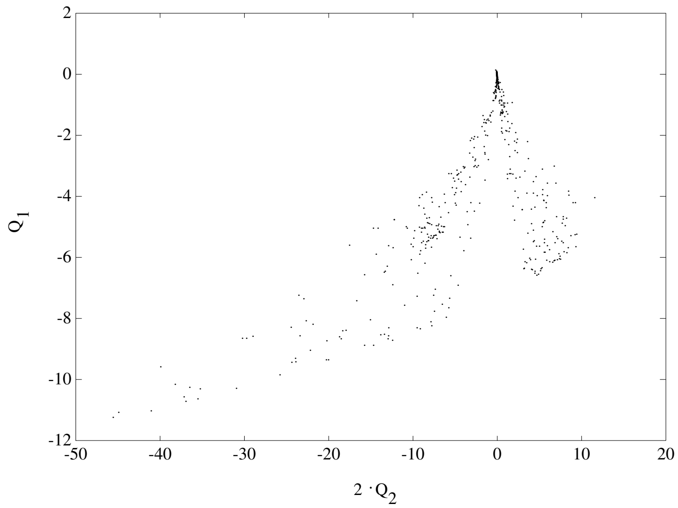

Fig. 2. The effect of the 'tangent circle'. The distribution of all objects on the Q_2, Q_1 plane. The objects strongly concentrate toward the narrow region near zero values of Q_1, Q_2, i.e., toward the 'tangent circle'.

objects that concentrate to the Sagittarius-Carina and Cygnus-Orion spiral arms located near the 'tangent circle'. It is easy to see that for objects in the vicinity of the 'tangent circle' the columns of the matrix of conditional equations for proper motions (i.e., the coefficients, Q_n, at the derivatives of the angular velocity) are close to zero. The expressions for coefficients, Q_n, have the following form:

$$Q_n \cdot n! = (R_0/\mathrm{r} \cos l - \cos b) \cdot (R - R_0)^n, \qquad (7)$$

where R_0 is the distance of the Sun to the Galactic center; r and R, the distance of the object to the Sun and the rotation axis of the Galaxy, respectively, and n, the order of derivative. Therefore the above-mentioned group of objects does not make it possible to constrain the derivatives of ω_0 with any reasonable accuracy, and conversely, these very objects yield the most accurate estimate for the angular velocity, ω_0, because their proper motions are virtually insensitive to the angular velocity gradient.

Recently, Kuimov (1997) analyzed systematic differences between the stellar proper motions given in the PPM and ACRS catalogs, and found them to be rather small and uniform in the declination interval, -20^o $< \delta <$ +60^o (see Fig. 2 in the above paper). He attributed large systematic differences outside this interval to systematic errors in the proper motions in the PPM star catalog: the point is that the PPM catalog (and, consequently, the 4M catalog) is partly based on star positions derived from the Astrographic Catalog, whereas the ACRS catalog was prepared without making use of the Astrographic Catalog data. Therefore we obtained a separate solution by limiting our sample to the objects in the above declination interval, or, to be more precise, to the equivalent Galactic longitude interval $10^o < l < 230^o$. Table 3 gives the rotation-curve parameters for this solution (269 objects in the heliocentric distance range from 0.5 to 6 kpc). Note that in this case the rms error in the proper-motion component in the Galactic longitude (0.0056 arcsec yr^{-1}) is smaller

Table 1. Kinematical parameters derived from radial velocities

U_0	V_0	A	$d^2\omega$ / dr^2	RMS
(km s^{-1})	(km s^{-1})	(km s^{-1} kpc^{-1})	(km s^{-1} kpc^{-3})	(km s^{-1})
8.8 ± 0.9	13.5 ± 0.9	19.5 ± 0.5	1.13 ± 0.12	12.2

Table 2. Kinematical parametes derived from proper motions of the entire sample

W_0	ω_1	ω_2	A	$d^2\omega/dr^2$	RMS
(km s^{-1})	(km s^{-1} kpc^{-1})	(km s^{-1} kpc^{-1})	(km s^{-1} kpc^{-1})	(km s^{-1} kpc^{-3})	(arcsec yr^{-1})
11.7 ± 1.5	31.5 ± 1.3	27.3 ± 2.0	17.0 ± 2.0	2.4 ± 0.4	0.0061

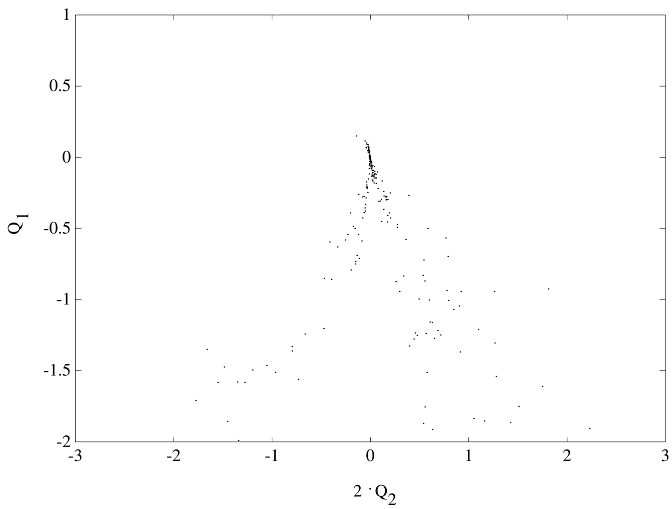

Fig. 3. The Q_2, Q_1 diagram for 210 'tangent-circle' objects used to derive the angular velocity, ω_0.

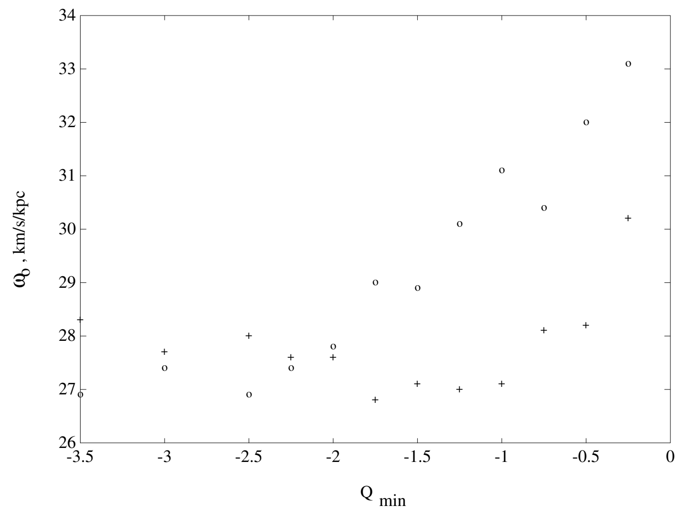

Fig. 4. The inferred angular velocity ω_1 (crosses) and ω_2 (circles) as a function Q_{min}, the minimum value of Q_1. The behavior of ω_1 and ω_2 in the vicinity of Q_{min} = 0 can be explained by abrupt decrease of the sample size. The behavior of ω_2 in the -2.5 $< Q_{min} <$ -0.5 interval is due to 'tangent-circle' objects failure to constrain the derivatives of angular velocity.

Table 3. Kinematical parameters derived from proper motions of objects with $10^o < l < 230^o$

ω	A	$d^2\omega/dr^2$	RMS
(km s^{-1} kpc^{-1})	(km s^{-1} kpc^{-1})	(km s^{-1} kpc^{-3})	(arcsec yr^{-1})
27.0 ± 3.1	19.7 ± 2.8	3.2 ± 0.5	0.0056

than that for the solution based on the entire sample (0.0061 arcsec yr−1). Here we point out a very good agreement between values of Oort's constant, A, given by the above solution and that inferred from radial-velocity data alone (19.7 ± 2.8 km s^{-1} kpc^{-1} and 19.5 ± 0.5 km s^{-1} kpc^{-1}, respectively). The problem of a possible effect on ω_0 of systematic errors in the proper motions given in the PPM catalog was also addressed by Frink et al. (1996), who found that allowance for these errors increases the resulting ω_0 value by $\sim$ 0.5 mas yr^{-1} ($\sim$ 2.4 km s^{-1} kpc^{-1}), i.e., to ω_0 = 28.4 - 29.4 ± 2.4 km s^{-1} kpc^{-1}.

Figs. 2 and 3 show the distribution of the entire sample of young objects on the (Q_2, Q_1) diagram. It is easy to see that a large number of stars and clusters are concentrated in a narrow region in the vicinity of zero values of Q_1, Q_2. Fig. 4 shows how the calculated angular velocity, ω_1 ω_2, varies with Q_{min}, the minimum value of Q_1. One can readily see that in the Q_{min} interval from -2.5 to -0.5 ω_1 are more stable than ω_2. A comparison of this figure with the results listed in Table 2 leads us to conclude that transition from the complete sample to objects located along the 'tangent circle', up to Q_{min} -0.5, results in a systematic decrease of ω_1 and increase of ω_2. The behavior of both angular-velocity estimates in the vicinity of zero Q value must be due to abrupt decrease of the sample size.

We adopt ω_0 = 27.5 ± 2 km s^{-1} kpc−1 as our best angular-velocity estimate. This value coincides, within the quoted errors, with ω_1 and ω_2 solutions in the Q_{min} interval from -2.5 to -1.5, where the effect of the angular-velocity derivatives on the proper motions is small while the sample size remains sufficiently large. Furthermore, this result is in surprisingly good agreement with ω_0 = 27.3 ± 2 km s^{-1} kpc^{-1} inferred from the solution based on

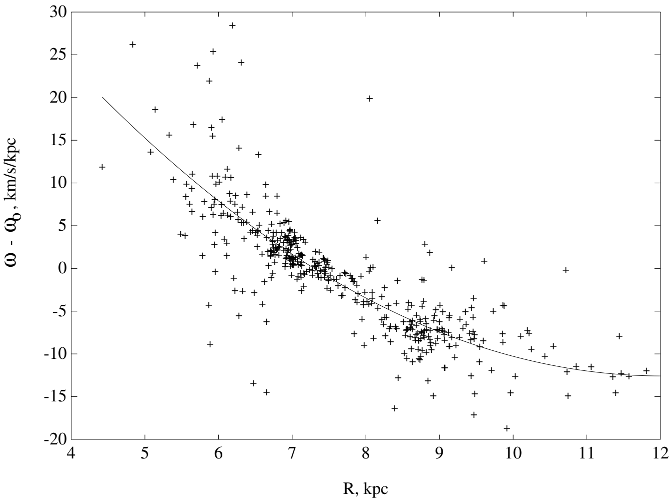

Fig. 5. The Kamm function for the entire sample of objects. Solid line shows the polynomial fit and crosses, individual objects. We did not exclude the objects in the direction of the Galactic center and anticenter and this explains large scatter about the rotation curve (ω - ω_0).

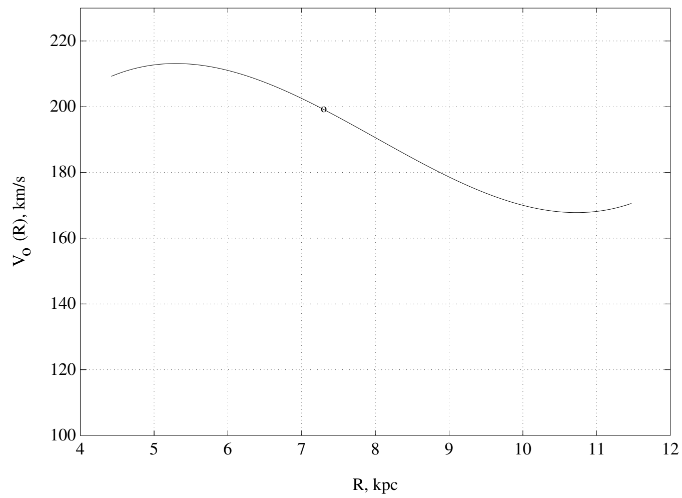

Fig. 6. Schematic rotation curve of the Galaxy, $V_0(R)$. The Sun is indicated by a circle (R_0 = 7.3 kpc, V_0 = 200 km s^{-1}).

the entire sample (see Table 2) and with $\omega_0 = 27.0 \pm 3.1$ km s^{-1} kpc^{-1} inferred from the data for longitude-limited sample (see table 3). In view of R_0 = 7.3 kpc, it yields the linear velocity of rotation of V_0 = 200 $\pm$ 15 km s^{-1} at the Solar Galactocentric distance.

This result is corroborated by Honma & Sofue (1996) who found that V_0 = 200 km s^{-1} can be better reconciled with the rotation-curve data for the outer Galaxy than the standard IAU value of V_0 = 220 km s^{-1}. Note that our value, combined with the results of recent statistical-parallax solutions for RR Lyrae stars – $< V_{RRLyr} >$ = -200 km s^{-1} (Layden et al. 1996; Dambis & Rastorguev 1997) – implies that the halo RR Lyrae population is virtually nonrotating.

Note that our rotation curve for the outer Galaxy is in overall agreement with that of Pont et al. (1997). Although our minimum value of linear rotation velocity at R = 10 - 11 kpc - V_{rot} = 170 km s^{-1} (see Fig. 6 below) - is much lower than that quoted by Pont et al. (1997), this seeming discrepancy is entirely due to the difference in the adopted V_0 values (220 and 200 km s^{-1}, respectively). Thus, adopting R_0 = 8 kpc and V_0 = 200 km s^{-1} Pont et al. (1997) obtained V_{rot} = 167 $\pm$ 4 km s^{-1} for the outer Galactic disk, and our rotation curve is in excellent agreement with this result.

Fig. 5 shows the calculated and observed Kamm functions $f(R, R_0)/R_0 = (\omega(R) - \omega_0(R_0))$. Crosses give the values derived from data for individual Cepheids of the entire sample. Large deviations of some stars in this figure from the average curve do not necessarily imply large deviations from the rotation law, because these deviations can be due to small sin l.

Fig. 6 shows schematically the Galactic rotation curve. It can be seen from the figure that the Sun is located at the decreasing part of the rotation curve, in agreement with the rotation curve inferred from HI and HII data by Nikiforov & Petrovskaya (1994) and from Cepheids alone derived by Dambis et al. (1995). It is also interesting to note a depression in the rotation curve in the region beyond the solar circle, at Galactocentric distances of 8.5 - 10.5 kpc. This feature looks real, whereas the subsequent increase of the rotation curve requires additional analysis.

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