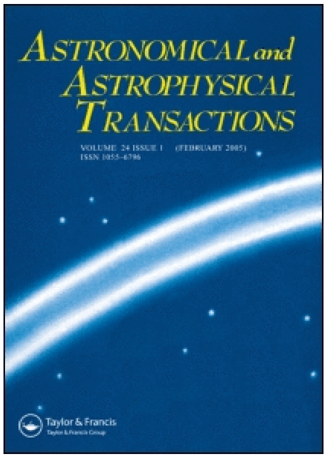

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ROTATION CURVE OF THE MILKY WAY

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We performed a rotation-curve solution on an extensive sample consisting of 770 Population-I objects with well-established, homogeneous, and consistent distance scales. The sample under study includes 202 young open clusters ($\log A < 8.1$), 440 classical Cepheids, and 128 red supergiants with distances derived on a homogenized scale based on Kholopov's (1980) ZAMS, $M_V(B-V)_0$, multicolour PL relation for classical Cepheids by Berdnikov *et al.* (1996a), and the absolute-magnitude calibration for red supergiants by Dambis (1993), which uses photometric data in Wing's eight-colour narrow-band near-infrared system. We inferred $R_0 = 7.4 \pm 0.3$ kpc for the distance of the Sun to the Galactic centre and found the following parameters of the solar apex and Galactic rotation curve: $U_0 = 10.2 \pm 1.0$ km s^{-1}, $V_0 = 14.1 \pm 0.9$ km s^{-1}, $W_0 = 8.2 \pm 1.0$ km s^{-1}, $\omega_0 = 27.5 \pm 2.0$ km s^{-1} kpc^{-1}, $A = 18.7 \pm 0.4$ km s^{-1} kpc^{-1}, and $(d^2\omega/dr^2)_0 = 0.96 \pm 0.10$ km s^{-1} kpc^{-1}. 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) and with most recent determinations of the distance from the Sun to the Galactic centre.

KEY WORDS Galaxy, kinematics, open clusters and associations, Cepheids, red supergiants

1 INTRODUCTION

Kinematical data for Population-I objects make it possible to study the large-scale velocity fields of the young Galactic disk, analyse the Galactic rotation curve, and infer the parameters of spiral density waves (Karimova and Pavlovskaya, 1973; Hron and Maitzen, 1985; Nikiforov and Petrovskaya, 1994; Caldwell and Coulson, 1987; Fich *et al.*, 1989; Pont *et al.*, 1994; Dambis *et al.*, 1995; Mishurov *et al.*, 1997; Glushkova *et al.*, 1998; Frink *et al.*, 1996; Feast and Whitelock, 1997). This in because the young disk population, which includes neutral hydrogen, H II-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 studies of Population-I kinematics are based on radial-velocity data for objects with homogeneous distance scales and only rotation-curve solutions for radial-velocity maps of neutral hydrogen require no explicit distance, determinations. Proper-motion based analyses were a rather rare exception. However, the emergence of new mass catalogues of proper motions (e.g., Hipparcos, the

PPM and the so-called four-million star catalogue – see below) made it possible to substantially increase the number of luminous young objects of the Galactic disk (Cepheids, red supergiants, OB stars, and open clusters) stars used in such analyses (see, e.g., Dambis *et al.*, 1995; Frink *et al.*, 1996; Glushkova *et al.*, 1988; Feast and Whitelock, 1997) to study kinematics of Cepheids, open clusters, red supergiants, and OB stars. Here we refine our our previous analysis (Glushkova *et al.*, 1998) whose Cepheid subsample was based on the old version of Berdnikov's (1987) catalogue of Cepheid parameters, which contained photometric data and distances for 363 fundamental-mode classical Cepheids. The Cepheid distances in this catalogue were based on the old PL relation in the V-band (Berdnikov and Efremov, 1985) and a rather high total-to-selective extinction ratio, $R \sim 3.45$ (Straizys, 1977). However, recent analyses of Cepheid multicolour data yielded a substantially lower total-to-selective extinction ratio for Cepheids, $R \sim 3.26$ (Berdnikov *et al.*, 1996a), a refined multicolour PL relation and a new algorithm for computing Cepheid distances with allowance for radial abundance gradient in the Galaxy (Berdnikov *et al.*, 1996b), culminating in a new version of the catalogue of Cepheid parameters (Berdnikov *et al.*, 1998). Our improved rotation-curve solution on the Population-I sample is based on new Cepheid data, which allowed us, in particular, to increase the number of objects from 693 to 770, and further refine the distance to the Galactic centre.

2 THE SAMPLE

Our initial sample consisted of 202 young open clusters ($\log t \leq 8.1$) with published UBV photoelectric and CCD photometry collected by Mermilliod (1988, 1992); 128 red supergiants observed in Wing's eight-colour, narrow-band, near-infrared photometric system (White and Wing, 1978), and 440 classical Cepheids with accurate photoelectric $UBVRI$ light curves (Berdnikov *et al.*, 1997), making up for a total of 770 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, 1999). 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 long 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 3.29^m and the Pleiades distance modulus of 5.47^m (Kholopov, 1980; Dambis, 1999). A preliminary comparison of the distances to six clusters inferred from Hipparcos trigonometric parallaxes with those adopted in this paper revealed no systematic bias ($DM_{\rm Dambis} - DM_{\rm Hip} = 0.0 \pm 0.1$).

3.2 Red Supergiants

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

$$\log r = 0.2 \cdot (I(104) - M(104) - A(104)) + 1, \tag{1}$$

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 ($\lambda_{\rm eff} = 1.0395\mu$), and $A(104)$ is the interstellar extinction in this filter (Warner and Wing, 1977). The absolute magnitude, $M(104)$, is given by the following calibration (Dambis, 1993, a printing error corrected in Glushkova *et al.*, (1998)):

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

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. We calculate interstellar extinction, $A(104)$, as follows (Warner and Wing, 1977; Dambis, 1993):

$$A(104) = 1.25 \cdot \Delta\theta, \tag{3}$$

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

$$\theta_0 = 1.330 + 0.00289 \cdot TiO. \tag{4}$$

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 the new catalogue of Cepheid parameters (Berdnikov *et al.*, 1999). This is the most complete catalogue of this type and contains data (periods, colour excesses, positions and distances, as well as $UBVRI(RI)_C$ JHK intensity-mean magnitudes and photometric amplitudes) for 440 Cepheids. In contrast to our previous papers (Dambis *et al.*, 1995; Glushkova *et al.*, 1997), we did not exclude first-overtone Cepheids (i.e., Cs-type Cepheids according to the GCVS classification - Kholopov *et al.* (1985–1987)) from our sample.

The distances to Cepheids listed in the catalogue are computed using the multicolour PL relation by Berdnikov *et al.* (1996a). This catalogue, in turn, is

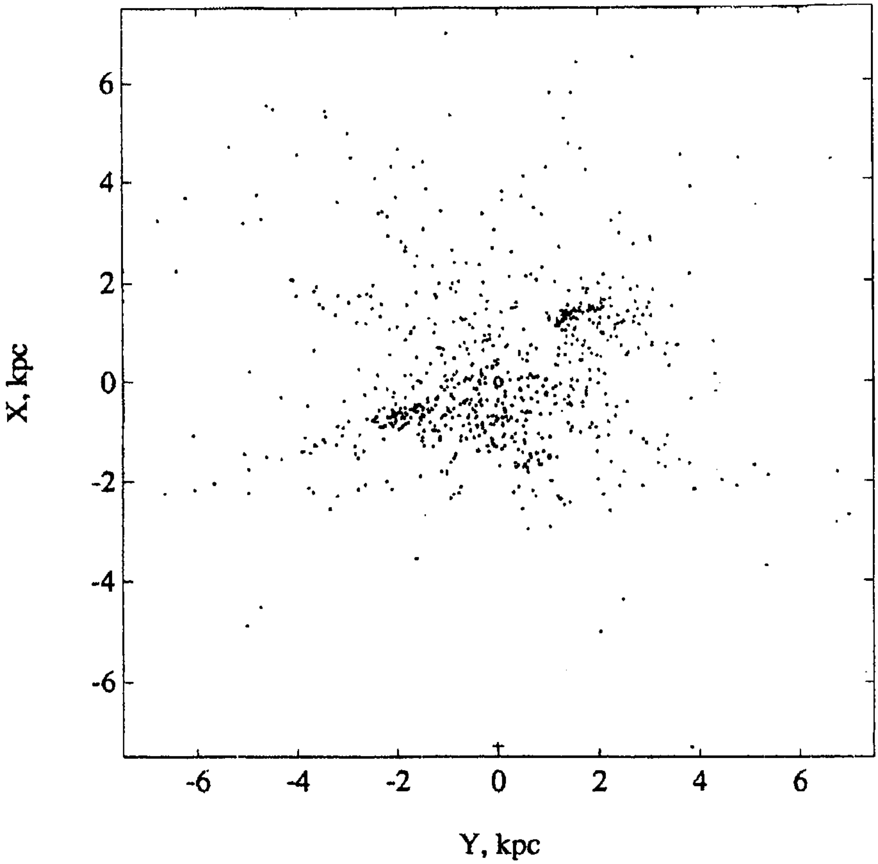

Figure 1 The distribution of Cepheids, young open clusters and red supergiants projected onto the XY plane. The Sun (indicated by a small circle) is at (0,0) and the Galactic centre is in the bottom part of the figure.

based on the distance moduli of open star clusters derived using Kholopov's (1980) ZAMS (these distance moduli are consistent with Hipparcos parallax measurements), thereby ensuring the consistency of our Cepheid distances with those of open clusters and red supergiants (see above). We consider the parallaxes of nearby open young clusters to be more trustworthy data than the Cepheid parallaxes because the former are several fold more accurate than the latter due to averaging over several or even several dozen stars. It is therefore our opinion that adopting the substantially longer Cepheid distance scale inferred from Hipparcos parallaxes of Cepheids (Feast and Catchpole, 1997) is at, least premature.

Thus, our initial sample consisted of almost 800 Population-I objects with distances derived in a homogenized distance scale with a typical relative accuracy of 0.05–0.10. Figure 1 shows the distribution of these objects projected on the Galactic plane.

4 RADIAL-VELOCITY DATA

4.1 *Open Clusters*

We critically analysed 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 a total of 107 clusters with known radial velocity components. Unfortunately, for most young open clusters only the racdial 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 young clusters the radial velocity has been measured only for a few members, we can conclude that the typical accuracy of the mean radial velocity for a young cluster must be about 5–10 km s^{-1}.

4.2 *Red Supergiants*

For almost half of the stars m 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 catalogues by Abt and 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 the recent list of Pont *et al.* (1997), which 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 lie 0.3–0.5 km s^{-1}. Our final list contains 306 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 two sources. We used the PPM catalogue (Roser *et al.*, 1991) for brighter stars. The proper motions for fainter stars were taken from the so-called Four-Million Star catalogue of proper motions (Volchkov *et al.*, 1992), hereafter referred to as the 4M-catalogue. These proper motions were derived from the coordinate differences for common stars in the Guide Star Catalogue of the Hubble Space Telescope and the computer-readable version of the Astrographic Catalogue also known as the Carte du Ciel catalogue (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 326 Cepheids with homogeneous absolute proper motions taken from the PPM catalogue (156 stars) and the 4M-catalogue (170 stars). The absolute proper motions are also available for 116 red supergiants (80 from the PPM and 36 from the 4M-catalogue). 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-catalogue (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 catalogue 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-catalogue proper motions of their members selected on the basis of the photometric colour-magnitude diagrams. We estimate the typical accuracy of our absolute proper motions for open clusters to be on the order of $0.004'' \text{ yr}^{-1}$.

6 GALACTIC ROTATION MODEL

We estimated rotation-curve parameters for the 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 ± 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 the spiral pattern is analysed by Mishurov *et al.* (1997). The models used in subsequent calculations involve no 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:

$$\begin{aligned} & V_r + (u_0 \cos b \cos l + v_0 \cos b \sin l + w_0 \sin b) \\ &= R_0(\omega - \omega_0) \sin l \cos b + R_0 \Delta\omega \sin l \cos b + V_r', \end{aligned} \tag{5}$$

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 centre; the y-axis, in the direction of the galactic rotation, and the z-axis, toward the North Galactic Pole); R_0 is the Galactocentric distance of the Sun; ω and ω_0 are the angular velocities of rotation of centroids under study at distances R and R_0, respectively; $\Delta\omega = \omega(S) - \omega_0(S_0)$ is 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 the 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 ω_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 $0.001'' \ \mathrm{yr}^{-1}$) will look as follows:

$$\begin{aligned} 4738\mu_l + (v_0 \cos l - u_0 \sin l)/r &= (R_0/r \cos l - cosb)(\omega - \omega_0) \\ &+ R_0/r\Delta\omega \cos l - \omega_0 \cos b + 4378\mu_l', \end{aligned} \tag{6}$$

where μ_l' is the peculiar component of the proper motion; r is 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, $d\omega/dR$, 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 the 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 $d\omega/dR$ 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 to be reliable. We solved equations (5) and (6) using the weighted least squares method (the so-called χ^2-minimization, Press *el 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 second order in $(R - R_0)$. We restricted our sample by excluding objects with large proper-motion components along the z-coordinate (with μ_b beyond $0.015'' \ \mathrm{yr}^{-1}$ 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.

Here we use only objects that are within 6 kpc from the Sun (more distant stars and clusters require higher-order rotation-curve approximations which will inevitably degrade the accuracy of parameters inferred). We also excluded objects that are far from the formal Galactic plane (with $|z| > 0.5$ kpc) and those located within 1 kpc from the Sun). The point is that the former can belong to thick disk or halo populations and most of the latter belong to the local system, which can have a rotation law of its own and very different from the overall galactic rotation. We found this to be true: nearby stars and clusters substantially bias the resulting values of kinematical constants, especially the angular velocity and its first derivative (and hence Oort's constant A) inferred from proper-motion data. In particular, the exclusion of objects within 1 kpc from the Sun increases A from 14.4 to 18.0 km s^{-1} kpc^{-1}.

7 DETERMINATION OF THE DISTANCE TO THE GALACTIC CENTRE

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 $R_0 = 7.4$ 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 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 nature 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 $R_0 = 7.4 \pm 0.3$ kpc and it is this value that we adopt throughout all subsequent calculations.

Note that this result does not differ significantly from our previous estimate (Glushkova *et al.*, 1998) and 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). Our value is also rather close to the one inferred recently from radial velocities of eight distant Cepheids at $l \sim 300° - R_0 = 7.66 \pm 0.32$ kpc (Metzger *et al.*, 1998) and in excellent agreement with a value $R_0 = 7.1 \pm 0.4$ kpc found by Olling and Merrifield (1998). Note that kinematical estimates of R_0 depend linearly on the adopted distance scale.

8 DISCUSSION

Tables 1 and 2 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

Table 1. Kinematical parameters derived from radial velocities

U_0 ($km\ s^{-1}$)	V_0 ($kms\ s^{-1}$)	A ($kms\ s^{-1}\ kpc^{-1}$)	$d^2\omega/dr^2$ ($km\ s^{-1}\ kpc^{-3}$)	RMS ($km\ s^{-1}$)
10.0 ± 1.0	14.1 ± 0.9	18.7 ± 0.4	0.96 ± 0.10	11.4

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 $A = 18.7 \pm 0.4$ 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 favour of the zero points of the adopted distance scales. The much lower value found by Feast and Whitelock (1997) from Hipparcos proper motions of Cepheids is due to fact that the above authors did not exclude from their solution nearby Cepheids located within 1 kpc from the Sun. Most of these stars belong to the local system, which is characterized by its own local kinematics different from the overall Galactic rotation law.

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 systematic errors when she studied residual velocities of OB associations based on the proper motions from the PPM catalogue.

Here we note a certain increase of the angular velocity, ω_0, inferred from the entire combined sample compared to 26 ± 2 km s^{-1} kpc^{-1} given by the solution based on the 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

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

W_0 ($km\ s^{-1}$)	ω_1 ($km\ s^{-1}\ kpc^{-1}$)	ω_2 ($km\ s^{-1}\ kpc^{-1}$)	A ($km\ s^{-1}\ kpc^{-1}$)	$d^2\omega/dr^2$ ($km\ s^{-1}\ kpc^{-3}$)	RMS ($arcsec\ yr^{-1}$)
8.2 ± 1.0	31.2 ± 1.3	27.5 ± 2.0	18.0 ± 2.2	2.4 ± 0.4	0.0061

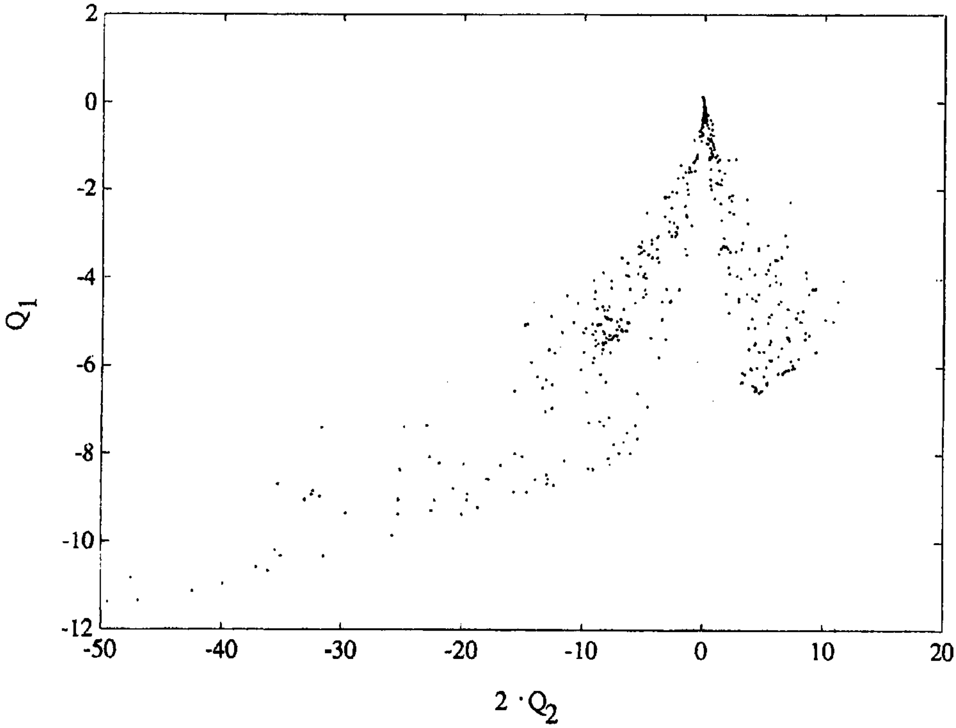

Figure 2 The effect of the "tangent circle". The distribution of all objects on the Q_2, Q_1 plane. The objects strongly concentrate toward the narrow region near zero values of Q_1, Q_2, i.e., toward the "tangent circle".

of faint stars that do not enter the PPM catalogue (Roeser *et al.*, 1991) whereas the proper motions of almost half of the Cepheids, which are on the average brighter than most cluster stars, were taken from the PPM catalogue. Feast and Whitelock (1997) also found (using Hipparcos proper motions for Cepheids) a value similar to our own for the angular velocity (27.2 ± 0.8 km s^{-1} kpc^{-1}), and their result is virtually independent of the adopted distance scale. (Note also an even higher value for ω_0 given by recent VLA measurements of the proper motion of the Sgr A* radio source in the Galactic center – -6.55 ± 0.34 mas yr^{-1} (Backer, 1998) and $\sim -6.0 \pm 0.5$ mas yr^{-1} (Reid *et al.*, 1997) – implying, after subtraction of the peculiar velocity of the Sun, $\omega_0 = 30.7 \pm 1.6$ km s^{-1} kpc^{-1} or 28.0 ± 2.4 km s^{-1} kpc^{-1} for $R_0 = 7.4$ 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 objects that concentrate on the Sagittarius-

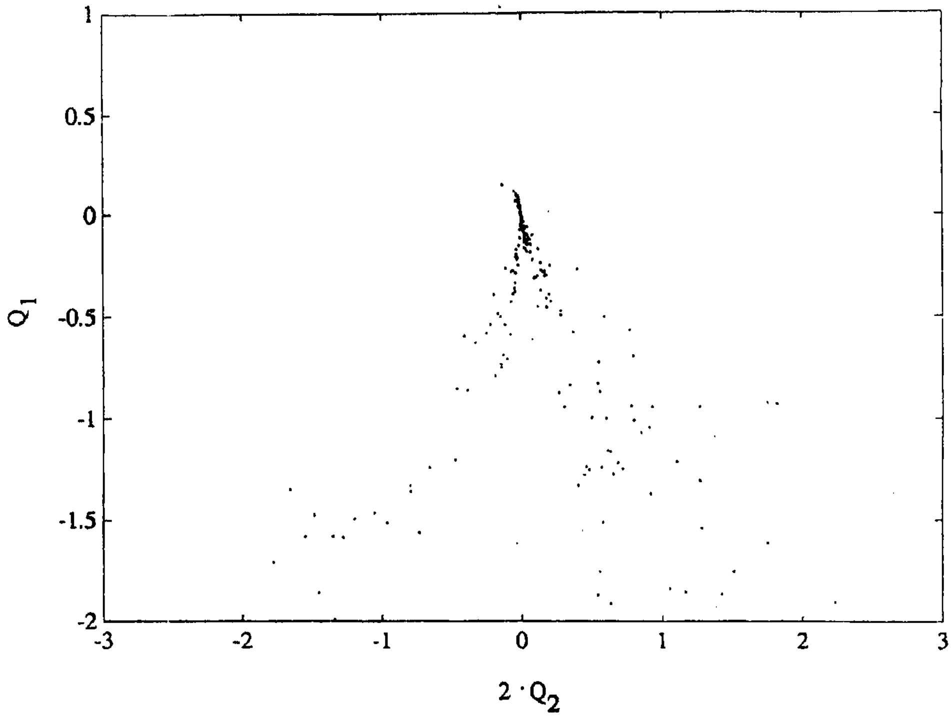

Figure 3 The Q_2, Q_1 diagram for 210 "tangent-circle" objects used to derive the angular velocity, ω_0.

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 the coefficients, Q_n, have the following form:

$$Q_n \cdot N! = (R_0/r \cos l - cosb) \cdot (R - R_0)^n, \tag{7}$$

where R_0 is the distance of the Sun to the Galactic centre; r and R are the distances of the object, to the Sun and the rotation axis of the Galaxy, respectively, and n is the order of the 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.

Figures 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. Figure 4 shows how the calculated angular velocity, ω_1 and ω_2, varies with $Q_{\min}$, the

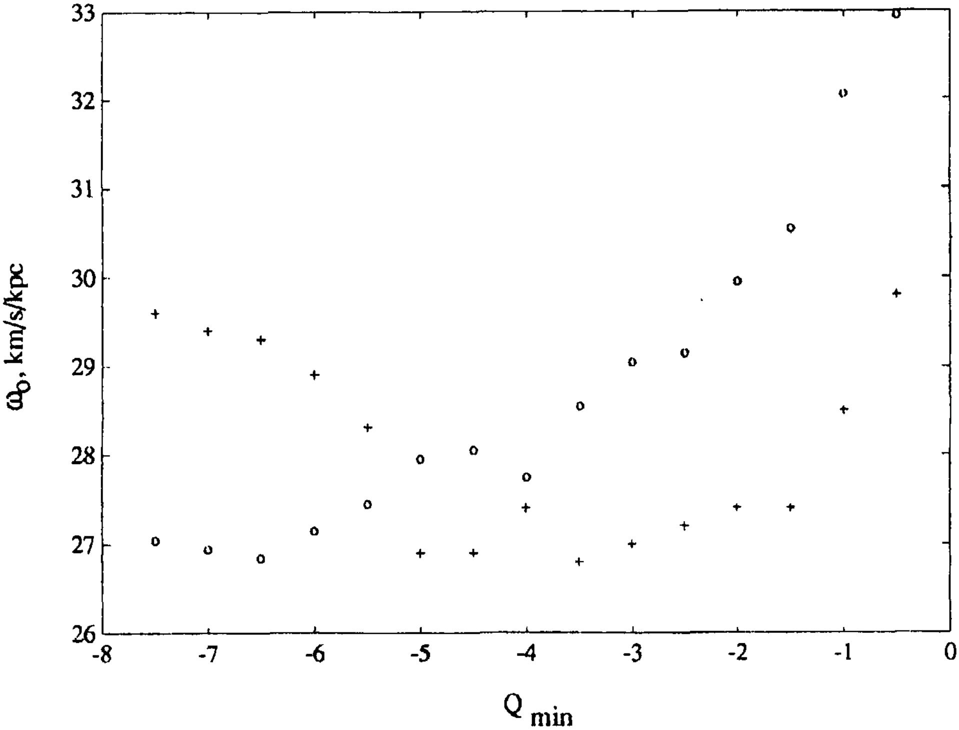

Figure 4 The inferred angular velocity ω_1 (crosses) and ω_2 (circles) as a function of $Q_{\min}$, the minimum value of Q_1. The behaviour of ω_1 and ω_2 in the vicinity of $Q_{\min} = 0$ can be explained by an abrupt decrease of the sample size. The behaviour of ω_2 in the $-2.5 < Q_{\min} < -0.5$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

minimum value of Q_1. One can readily see that, in the $Q_{\min}$ interval from -2.5 to $-0.5\,\omega_1$ 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 behaviour of both angular-velocity estimates in the vicinity of zero Q value must be due to an abrupt decrease of the sample size.

We adopt $\omega_0 = 27.5 \pm 2$ 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. In view of $R_0 = 7.4$ kpc, it yields a linear velocity of rotation of $V_0 = 204 \pm 15$ km s^{-1} at the Solar Galactocentric distance.

This result is corroborated by Honma and 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}. Olling and Merrifield

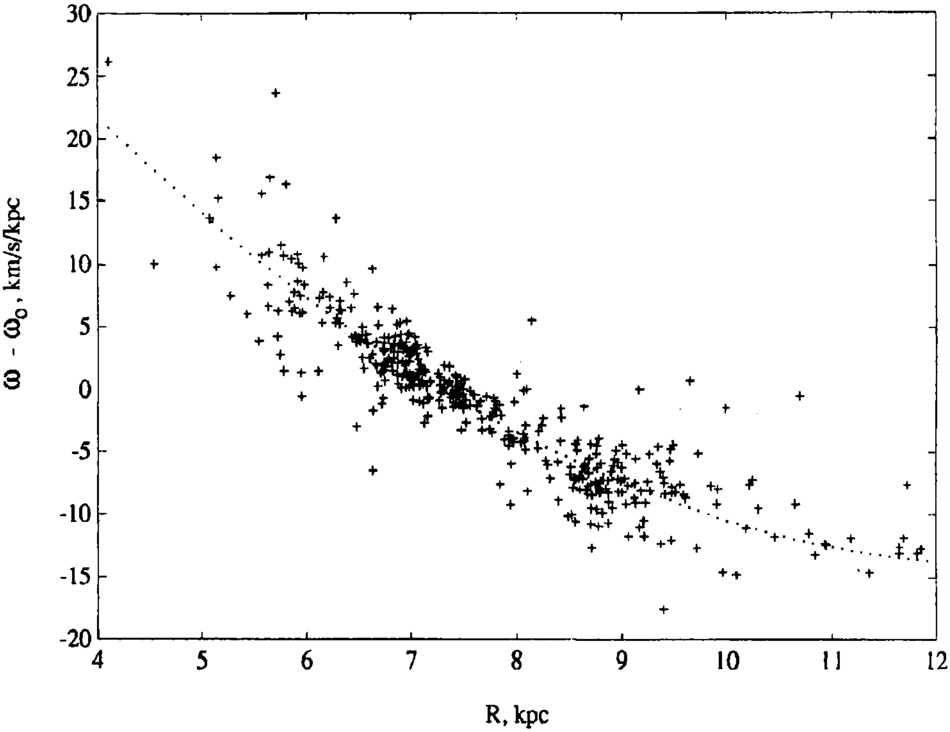

Figure 5 The Kamm function for the entire sample of objects. Solid line shows the polynomial fit and crosses, individual objects. We did not exclude the objects in the direction of the Galactic centre and anticentre and tins explains the large scatter about the rotation curve $(\omega - \omega_0)$.

(1998) argue for even a lower value: $V_0 = 189 \pm 4$ km s^{-1}. Note that our value, combined with the results of recent statistical-parallax solutions for RR Lyrae stars – $\langle V_{\rm RRLyr} \rangle = -200$ km s^{-1} (Layden *et al.*, 1996; Dambis and Rastorguev 1999) – implies that the halo RR Lyrae population is virtually non-rotating.

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 – $V_{\rm rot} = 170$ km s^{-1} (see Figure 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 $V_{\rm rot} = 167 \pm 4$ km s^{-1} for the outer Galactic disk, and our rotation curve is in excellent agreement with this result.

Figure 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 $\sin l$.

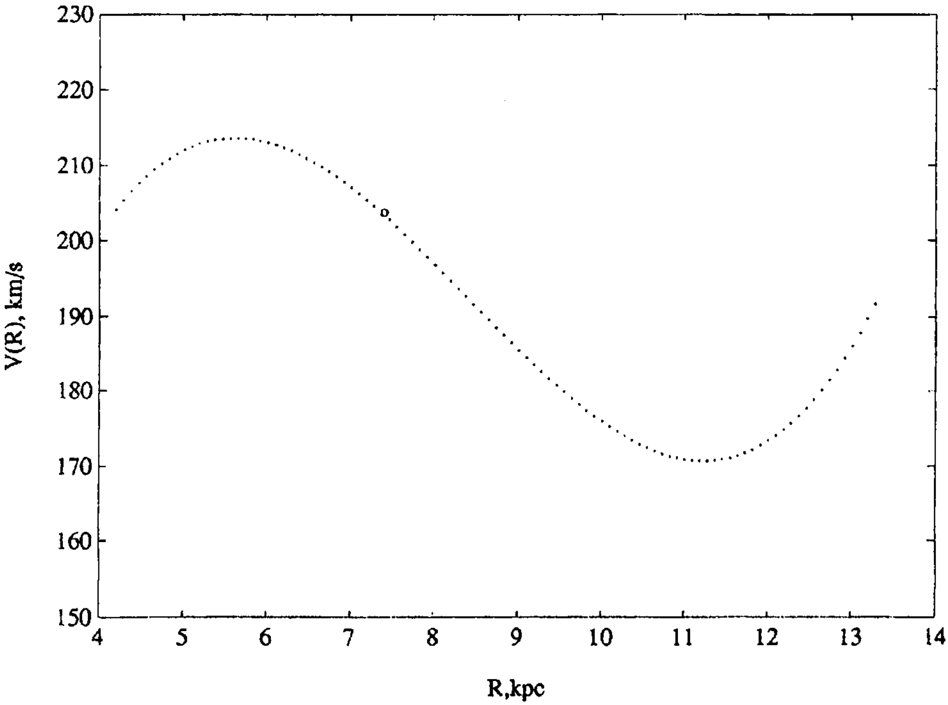

Figure 6 Schematic rotation curve of the Galaxy, $V_0(R)$. The Sun is indicated by a circle ($R_0 = 7.4$ kpc, $V_0 = 204$ km s^{-1}).

Figure 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 H I and H II data by Nikiforov and Petrovskaya (1994) and derived from Cepheids alone 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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