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Derivation of the Galactic rotation curve using space velocities

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Abstract. We present rotation curves of the Galaxy based on the space-velocities of 197 OB stars and 144 classical cepheids, respectively, which range over a galactocentric distance interval of about 6 to 12 kpc. No significant differences between these rotation curves and rotation curves based solely on radial velocities assuming circular rotation are found. We derive an angular velocity of the LSR of $\Omega_0 = 5.5 \pm 0.4$ mas/a (OB stars) and $\Omega_0 = 5.4 \pm 0.5$ mas/a (cepheids), which is in agreement with the IAU 1985 value of $\Omega_0 = 5.5$ mas/a. If we correct for probable rotations of the FK5 system, the corresponding angular velocities are $\Omega_0 = 6.0$ mas/a (OB stars) and $\Omega_0 = 6.2$ mas/a (cepheids). These values agree better with the value of $\Omega_0 = 6.4$ mas/a derived from the VLA measurement of the proper motion of Sgr A*.

Key words: Galaxy: kinematics and dynamics – Stars: kinematics – Reference systems

1. Introduction

The galactic rotation curve has been determined for the inner parts of the galactic disk, interior to the solar annulus, from H I-measurements using the tangential point method (Burton & Gordon 1978), whereas the outer rotation curve has been determined using radial velocities of objects with individually known distances, e. g. OB stars (Fich et al. 1989), planetary nebulae (Schneider & Terzian 1983), young open clusters (Hron 1987) and carbon stars (Metzger & Schechter 1994). An alternative method is based on the vertical thickness of the galactic H I-layer (Merrifield 1992). Recently Brand & Blitz (1993) have rederived the outer rotation curve from CO radial velocities of OB stars associated with H II regions, and Pont et al. (1994) have used new radial velocity measurements of classical cepheids for this purpose. All these methods rely on

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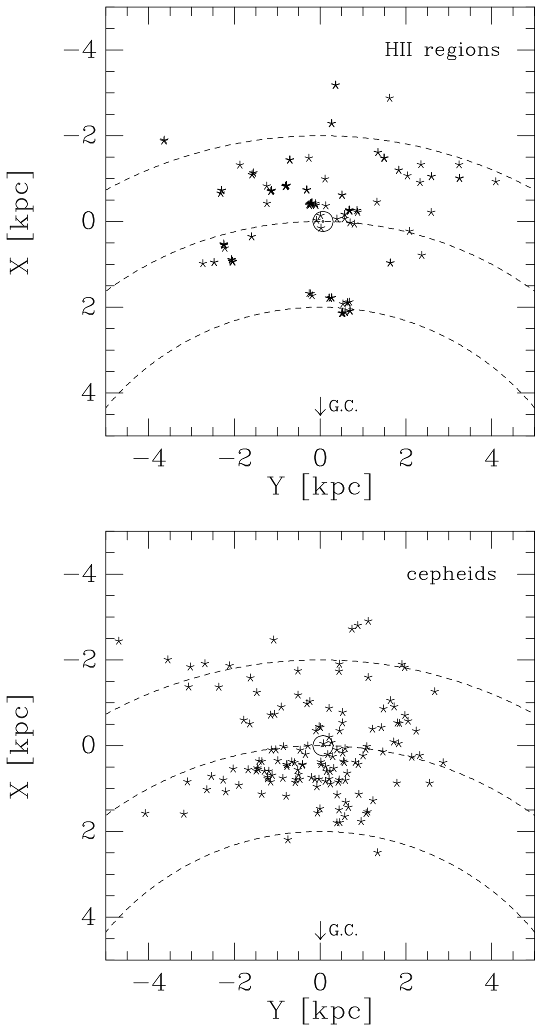

Fig. 1. Positions of the H II regions (upper panel) and the cepheids (lower panel), for which the proper motions are well-known, projected onto the galactic plane. The position of the Sun is in the centre of the panels. The dashed lines indicate circles around the galactic centre with radii 6.5, 8.5 and 10.5 kpc, respectively.

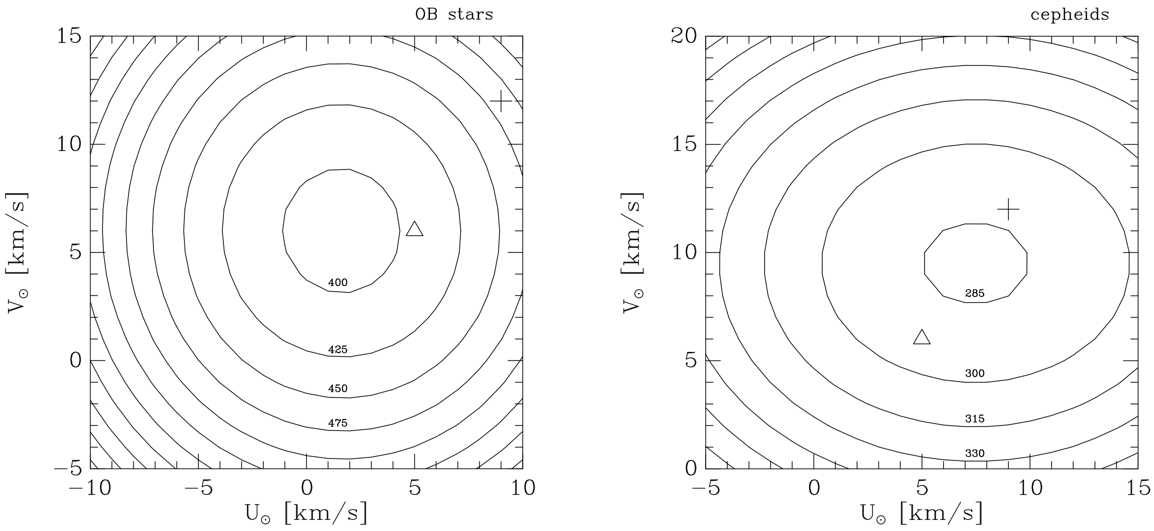

Fig. 2. Contourmaps of the numerical value of χ^2 as a function of the solar motion U_0 and V_0. A cross indicates the standard value of $U_0 = 9\,\mathrm{km/s}$, $V_0 = 12\,\mathrm{km/s}$, a triangle the value $U_0 = 5\,\mathrm{km/s}$, $V_0 = 6\,\mathrm{km/s}$ used in the present study. Note that the contours are steeper in the fit to the OB star data (left panel) than in the fit to the cepheid data (right panel).

the assumption of circular orbits around the galactic centre, so that radial velocities can be converted to circular velocities. Obviously proper motions of the objects may provide independent information on the rotation curve. The PPM catalogue which has recently been compiled at the Astronomisches Rechen-Institut (Röser & Bastian 1991, Bastian et al. 1993, Röser et al. 1994) is well suited as a broad data base of proper motions of high accuracy for such purposes.

2. Data

2.1. OB stars

Brand & Blitz (1993) give a list containing radial velocities of H II regions and their associated molecular cloud complexes which is the basis of our analysis. The exciting OB stars in the northern hemisphere are tabulated by Georgelin (1975) and others (see Blitz et al. 1982 for references) and can be identified by cross reference numbers. For the exciting OB stars of the H II regions in the southern hemisphere finding charts are given by Brand (1986). Using cross reference numbers, spectral types, magnitudes or accurate stellar positions, which we derived in an intermediate identification step using the HST Guide Star Catalog (Lasker et al. 1990), we have identified as many stars from the source lists in the PPM Star Catalogue as possible.

In total we have been able to identify 228 OB stars associated with 71 H II regions.

2.2. Cepheids

Radial velocities and distances of classical cepheids are taken from the recent work of Pont et al. (1994). Using again accurate stellar positions and cross reference numbers, which we obtained from the HIPPARCOS Input Catalogue (Turon et al. 1992) and from Kholopov et al. (1985-1987), we were able to identify 152 cepheids in the PPM Star Catalogue.

The PPM Star Catalogue is tied into the FK5 system (Fricke et al. 1988). Lindegren et al. (1995) have shown by a systematic comparison of the FK5 system with preliminary HIPPARCOS data that the FK5 positional system has still deficiencies, in particular in a strip at about $\delta \approx -40°$, corresponding to $l \approx 260°$, $b \approx 0°$. Unfortunately a number of H II regions and cepheids fall into this area, which we have omitted from our analysis because of this systematic uncertainty, leaving us with 197 OB stars associated with 59 H II regions and 144 cepheids with well-determined proper motions for our final analysis. Tables 1 and 2 give the identification numbers of these stars in the PPM catalogue.

Using the positions and proper motions of the stars given in the PPM Star Catalogue and the distances and the radial velocities given by Brand & Blitz (1993) or Pont et al. (1994), respectively, we have calculated the positions and the velocities of the stars in galactic coordinates. Fig. 1 shows the projection of the positions of the objects onto the galactic plane. X and Y are the cartesian spatial coordinates of the stars relative to the Sun. The X-axis points towards the galactic centre and the Y-axis into the direction of galactic rotation.

Table 1. H II regions and their associated OB stars. The first column gives the Sharpless or Brand identification numbers of the H II regions. The second column gives the identification numbers of the OB stars in this region which could be found in the PPM Star Catalogue.

H II	PPM
S8	296225
	296206
S11	296337
S25	267779
	267782
	267822
	267797
S29	267950
S31	267973
S32	267965
	267970
	267964
S27	231915
S41	234340
	234237
	234243
	234273
	234280
	234293
	234337
	234362
S44	234275
S45	234399
	234410
S46	234023
S49	234332
	234333
	234345
	234348
S54	234320
	234299
	234306
	234321
	234336
	234352
	234357
S86	109578
	109560
	109575
S101	83984
S112	60147
S117	60726
S119	61260
S124	39725
S126	88031
S129	39225
S132	40485
S134	40324
S137	23309
	23333
S140	23638
	23640
S142	41076
	41098
S154	23983
S155	24016
	24060
	24070
	24074
	24030
	24072
	23979
	24019
	24021
	24036
	24043
	24049
	24098
	24093
	24117
	24148
	24150
	24162
	24169
	24185
	24186
S157	24306
S161	24309
	24329
S162	24384
S170	11863
S173	12143
S184	25788
	25791
S190	13731
	13702
	13720
	13721
	13723
	13712
	13718
S199	28316
	28326
S202	14174
	14185
	14227
S206	28874
S220	68961
S232	70744
S234	70403
S234	70368
	70374
S236	70266
	70271
	70273
S238	119824
S252	95519
S263	148818
S264	149155
	149166
S273	151033
	151058
	151028
	151013
	151053
	151030
	151073
	151050
S275	150705
	150694
	150692
	150670
	150682
	150706
S277	188303
S279	188224
S281	187839
	175945
	188455
	175888
	188218
	188223
	188225
	188149
	215598
S292	218092
S293	218026
S295	218051
S296	218372
	218096
	218138
	218164
	218171
	218242
	218262
	218324
S297	218121
S310	252114
S311	253358
	253404
BBW16	727432
	252138
	727439
	727444
BBW17B	252139
	252148
	252158
BBW23	252308
	252289
	252363
	252304
BBW29	252486
BBW104B	284824
BBW106	740844
BBW127	285005
	740995
	740981
	740980
BBW133	285078
	741033
BBW283	769065
	338612
BBW300B	338995
	339034
	339041
	338930
BBW316D	339247
BBW347	339851
BBW348A	358562
	358560
BBW362A	358835
	358846
	358849
	358855
	358857
	358862
	358863
	358865
	358869
	358872
	358875
	358876
	358883
	358884
BBW362C	358747
	358742
BBW362F	358755

Table 2. Cepheids used to calculate the rotation curve.

cepheid	PPM	cepheid	PPM	cepheid	PPM	cepheid	PPM
η Aql	168843	SU Cas	13918	V1334 Cyg	86379	U Sgr	234663
U Aql	202954	SW Cas	41496	β Dor	354837	W Sgr	267817
SZ Aql	167110	SZ Cas	27633	ζ Gem	96982	X Sgr	267303
TT Aql	167242	XY Cas	12507	W Gem	122711	Y Sgr	234421
FF Aql	135550	DL Cas	12258	V Lac	41123	WZ Sgr	234281
FM Aql	135861	FM Cas	25159	X Lac	41132	XX Sgr	234503
FN Aql	167384	V636 Cas	13051	Y Lac	40284	YZ Sgr	235075
V336 Aql	167002	V Cen	342919	Z Lac	40952	AP Sgr	268062
V496 Aql	202574	UZ Cen	358897	RR Lac	40959	AY Sgr	719227
V600 Aql	167670	XX Cen	342137	BG Lac	62336	BB Sgr	268971
Y Aur	48141	BB Cen	359040	GH Lup	343690	V350 Sgr	268853
RT Aur	71665	BK Cen	358996	T Mon	150465	RV Sco	295723
RX Aur	69838	V378 Cen	360023	SV Mon	150342	RY Sco	296879
SY Aur	47840	V381 Cen	342310	R Mus	359566	KQ Sco	762230
RY CMa	218422	V419 Cen	340152	S Mus	371417	V482 Sco	296427
RZ CMa	713898	δ Cep	40731	RT Mus	358941	V500 Sco	296821
SS CMa	252386	CR Cep	41067	UU Mus	359025	V636 Sco	322879
TV CMa	713601	AX Cir	361050	S Nor	344832	X Sct	234646
TW CMa	713915	R Cru	359375	U Nor	344085	Y Sct	201965
VZ CMa	727576	S Cru	341409	Y Oph	201153	Z Sct	202059
RW Cam	28771	T Cru	359350	BF Oph	266398	RU Sct	202038
RX Cam	28898	X Cru	341282	RS Ori	122354	SS Sct	202078
ι Car	357533	VW Cru	359483	SV Per	47393	EV Sct	707164
U Car	339614	AG Cru	341197	SX Per	46949	ST Tau	121352
V Car	356744	BG Cru	341066	VX Per	27145	SZ Tau	120081
Y Car	339156	X Cyg	85419	AW Per	69651	R Tra	361350
UW Car	339046	SU Cyg	109630	V440 Per	27565	S Tra	361800
UX Car	339090	SZ Cyg	60114	X Pup	252643	U Tra	361877
XX Car	358358	TX Cyg	60815	RS Pup	284941	α UMi	431
XY Car	358418	VX Cyg	60748	VX Pup	252632	V Vel	337875
XZ Car	358450	VY Cyg	85963	VZ Pup	727776	SV Vel	339405
YZ Car	339070	VZ Cyg	62131	WX Pup	252971	BG Vel	337630
ER Car	339816	CD Cyg	84139	WZ Pup	728158	T Vul	112020
GI Car	339882	DT Cyg	86036	AQ Pup	253563	U Vul	109337
IT Car	358563	V386 Cyg	61152	AT Pup	284926	X Vul	110094
RY Cas	42304	V532 Cyg	61309	S Sge	137241	SV Vul	109871

3. Data reduction

3.1. Angular velocity of the LSR

In the FK5 system the velocities of the stars have a component of rigid rotation due to the motion of the LSR around the galactic centre. Assuming now that the stars move on circular orbits around the galactic centre and that the rotation curve is flat, one may fit a model of the form

$$\begin{aligned} U &= \Omega_0 R_0 \sin\varphi \\ V &= \Omega_0 R_0 (\cos\varphi - 1) \end{aligned} \quad (1)$$

to the space velocities of the stars. U and V correspond to the directions of the X- and Y-axis of Fig. 1 and denote the space velocities of the stars which have been corrected for the solar motion with respect to the LSR (cf. section 3.3). R_0 is the distance of the Sun from the galactic centre which we assume as 8.5 kpc throughout the present study, φ denotes the galactic azimuthal angle of a star.

Since some of the stars are fairly distant from the Sun we do not use Oort's approximation but adopt rigorous formulae describing a flat rotation curve. Deviations of the stars from the midplane are ignored.

From a χ^2-fit of eq. (1) to the space velocities of the 197 OB stars we find

$$\Omega_0 = 5.5 \pm 0.4\,\mathrm{mas/a} \quad (2)$$

for the angular velocity of the LSR which corresponds to a circular velocity of 223 ± 14 km/s in good agreement with the IAU 1985 value of 220 km/s.

Table 3. Effects of the correction of the constant of precession by $\Delta p_1 = -3.2\,\mathrm{mas/a}$ and different corrections of the motion of the equinox Δe on the angular velocities Ω_0, Ω_1 and Ω_2. Ω_0 is the angular velocity of the LSR and $\sqrt{\Omega_1^2 + \Omega_2^2}$ is the tilting of the galactic plane which should be minimized by adjusting Δe. Only OB stars with distances greater than 800 pc from the sun are considered in order to avoid contamination by Gould's Belt. The mean error of an angular velocity component is about 0.5 mas/a.

OB stars

Δe [mas/a]	Ω_0 [mas/a]	Ω_1 [mas/a]	Ω_2 [mas/a]	$\sqrt{\Omega_1^2 + \Omega_2^2}$ [mas/a]
0.0	7.19	1.26	-2.99	3.24
-1.0	6.77	0.59	-2.14	2.22
-2.0	6.37	-0.06	-1.30	1.30
-3.0	5.96	-0.72	-0.46	0.85
-4.0	5.55	-1.38	0.40	1.44
-2.9	5.98	-0.68	-0.50	0.84

cepheids

Δe [mas/a]	Ω_0 [mas/a]	Ω_1 [mas/a]	Ω_2 [mas/a]	$\sqrt{\Omega_1^2 + \Omega_2^2}$ [mas/a]
0.0	6.86	-0.43	-1.96	2.01
-1.0	6.43	-0.93	-1.21	1.53
-2.0	6.02	-1.41	-0.47	1.49
-3.0	5.59	-1.90	0.29	1.92
-4.0	5.18	-2.39	1.04	2.61
-1.5	6.23	-1.17	0.84	1.44

From the data of the 144 cepheids we obtain

$$\Omega_0 = 5.4 \pm 0.5\,\mathrm{mas/a} \tag{3}$$

in good agreement with the OB stars.

The estimated error of Ω_0 has been calculated from the errors given individually for the proper motions of each star in the PPM catalogue and the errors of the radial velocities and the distances given in our reference lists. Furthermore we took into account the velocity dispersion of the stars relative to the circular orbits by an additional error of 6.5 km/s in both velocity components for the OB stars (Brand & Blitz 1993) and of 13 km/s in the U- and 9 km/s in the V-direction for the cepheids (Pont et al. 1994), respectively.

Judging from the numerical value of χ^2 and the statistical distribution of the velocity residuals we found that the error estimates obtained this way were too low and have increased the errors of the proper motions by 30 %. This is apparently due to systematic errors of the proper motions in the PPM catalogue defined in the reference frame of the FK5 system, which are not fully represented by the individual errors given there.

3.2. Influence of the reference system

Moreover there is a further source of potentially serious errors of the proper motions which is related to non-physical global rotations of the reference system. There is now a general agreement that the IAU (1976) value of the constant of precession, proposed by Fricke (1977) and used in the construction of the FK5, has to be corrected by about $\Delta p = -3.2 \pm 0.3\,\mathrm{mas/a}$ (Williams et al. 1994). This corresponds to a rigid rotation with a spin vector pointing to the ecliptical pole.

The immediate effects on our results are illustrated in Table 3. To each star the correction has been applied and both data sets have been reduced again according to the procedure described above. Ω_0 is again the angular velocity of the LSR wiht respect to the galactic centre. Ω_1 and Ω_2 are angular velocities of the mean rotation of all stars about axes lying in the galactic plane, pointing towards the galactic centre ($l = 0°$) and the direction of galactic rotation ($l = 90°$), respectively.

As can be seen from Table 3 the introduction of the correction of the constant of precession leads to an unacceptably large apparent tilting of the galactic plane. Following Fricke (1977) we have therefore considered a simultaneous correction of the motion of the vernal equinox Δe. This corresponds to a rigid rotation of the reference frame about an axis pointing towards the celestial pole. Table 3 shows that the apparent tilting of the galactic plane can be minimized by adopting a value of $\Delta e = -2.9\,\mathrm{mas/a}$ for the OB stars or of $\Delta e = -1.5\,\mathrm{mas/a}$ for the cepheids. Nevertheless the remaining tilting is significantly higher than in the case where no correction at all was applied, i.e. 0.35 mas/a for OB stars with distances greater than 800 pc and 1.10 mas/a for cepheids. In all these cases Ω_0 agrees within 1 mas/a with the values given above. This discrepancy cannot be solved on the basis of the present material.

The corrections Δe of the motion of the equinox suggested here are of the same order of magnitude as those proposed by Miyamoto and Sôma (1993) and by Wielen (unpublished). They do not agree exactly mainly because of different samples of stars used. Miyamoto and Sôma derived $\Delta e = -1.2\,\mathrm{mas/a}$ from K giants. Wielen obtained $\Delta e = -3.2\,\mathrm{mas/a}$ from 512 FK5 stars which were used by Fricke (1977) for deriving the constant of precession and the motion of the equinox and which were re-investigated by Schwan (1988) after the FK5 was completed. We conclude that the spurious, non-physical rotations of the FK5 system seem to be in total of the order of $\pm 1\,\mathrm{mas/a}$ in each component of the rotation vector. This is consistent with the claimed accuracy of the FK5 system with respect to

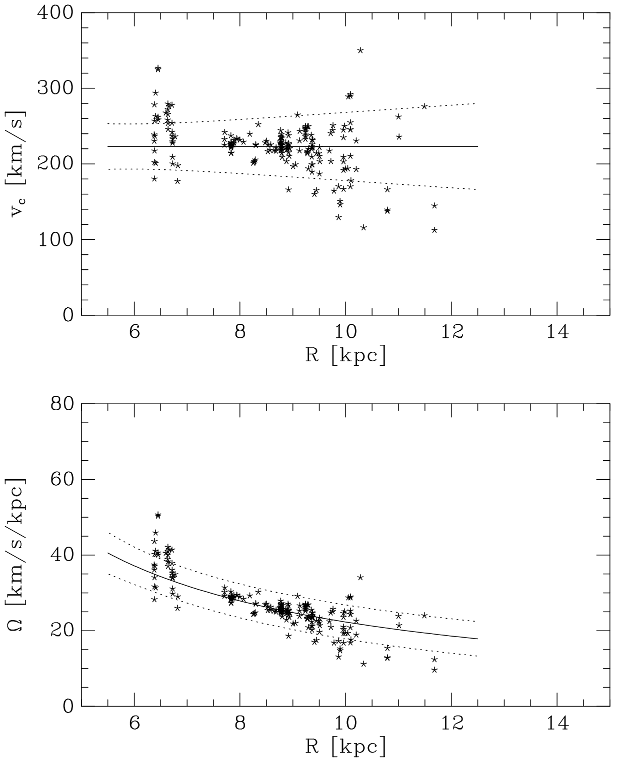

Fig. 3. Rotation curve derived from the OB star data using the full space velocities. The upper panel shows the circular velocity, whereas the lower panel shows the angular velocity of the 197 OB stars associated with 59 H II regions. The solid lines indicate the rotation law of a flat rotation curve. The dotted lines indicate error estimates based on the errors of the proper motions, radial velocities and distances of the stars.

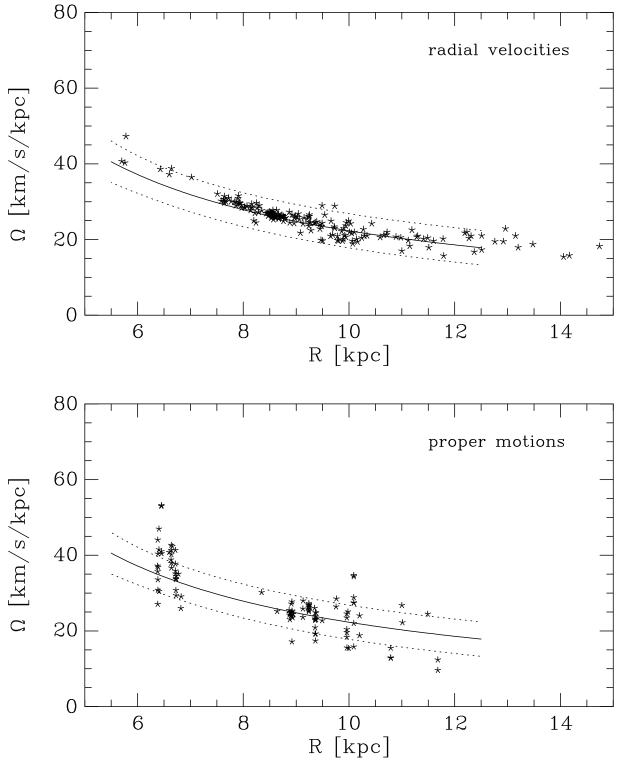

Fig. 4. Rotation curves derived from the OB star data using only radial or tangential velocity components, respectively, assuming circular orbits of the stars. There are 193 H II regions with measured radial velocities (upper panel; this is essentially the rotation curve derived by Brand & Blitz (1993)) and 104 OB stars with known proper motions and suitable projection angles.

non-physical rotations of about $\pm 0.7\,\mathrm{mas/a}$ (Fricke 1977, Schwan 1988).

Finally we note that the VLA measurement of the proper motion of the Sgr A* radio source in the galactic centre of $-6.55 \pm 0.34\,\mathrm{mas/a}$ (Backer 1996), implying after substraction of the peculiar velocity of the Sun an angular velocity of the LSR of $\Omega_0 = 6.4\,\mathrm{mas/a}$, deviates only insignificantly from the values found here.

3.3. Solar motion

Before applying Eq. (1) the space velocities have to be corrected for the solar motion with respect to the LSR. The standard values for this motion are $U_0 = 9\,\mathrm{km/s}$ and $V_0 = 12\,\mathrm{km/s}$ (Delhaye 1965).

We introduced U_0 and V_0 as additional free parameters in Eq. (1) and checked the goodness of the fit for various combinations of U_0 and V_0. The results are shown in Fig. 2.

The χ^2-fit to the OB star data rejects the standard values of 9 and 12 km/s at a $4\,\sigma$ confidence level, whereas the fit to the cepheid data is in good agreement with the classical values. The minimum of the numerical value of χ^2 for the cepheids however is quite flat and the errors are larger than those for the OB stars, so we decided to use values of $U_0 = 5\,\mathrm{km/s}$ and $V_0 = 6\,\mathrm{km/s}$, which correspond within the errors simultaneously to the minima of χ^2 of both data sets.

Note that the value of V_0 is closely related to the asymmetric drift of the sample of stars under consideration. Jahreiß and Wielen (1983) found $V_0 = 5\,\mathrm{km/s}$ relative to the youngest stars in the solar neighbourhood in close agreement with the value used here. The low value of U_0 reflects the apparent inward motion of stars relative to the LSR which was noted previously by Fich et al. (1989). This effect is usually interpreted as an outward motion of the LSR (Blitz & Spergel 1991).

3.4. Oort's constants

We have determined Oort's constants A and B using stars within a circle of 1 kpc around the Sun, assuming a constant radial gradient of the rotation curve near the Sun. By means of a χ^2-fit to the circular velocity

$$v_c(R) = v_c(R_0) + \left(\frac{\mathrm{d}v_c}{\mathrm{d}R}\right)_0 (R - R_0) \qquad (4)$$

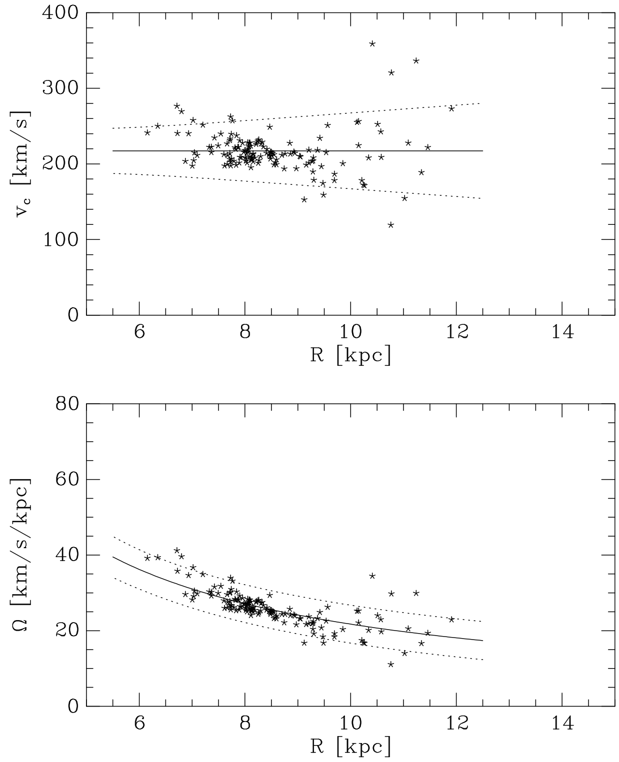

Fig. 5. Rotation curve derived from the cepheid data using the full space velocities of 144 cepheids. The representation is the same as in Fig. 3.

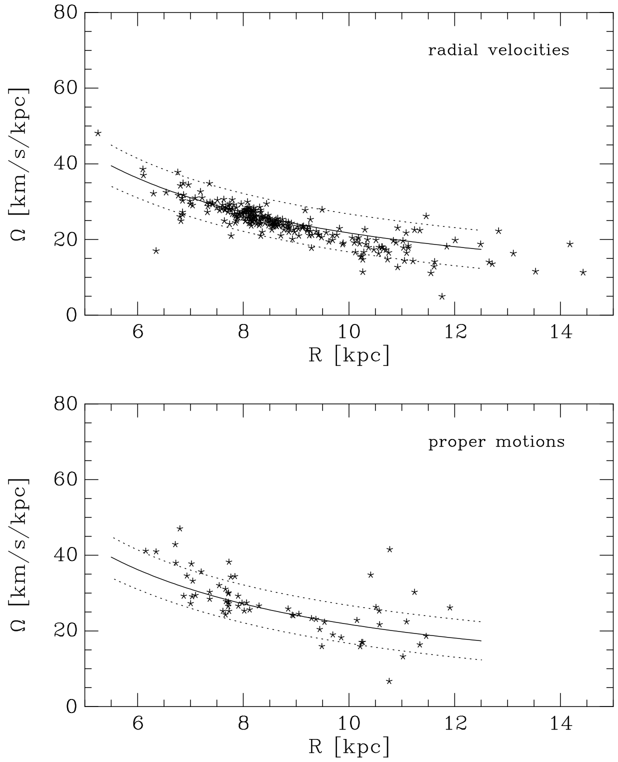

Fig. 6. Rotation curve derived from cepheid data using only radial velocities or proper motions, respectively. The upper panel shows essentially the rotation curve from Pont et al. (1994) using radial velocity components of 249 cepheids. The lower panel shows the rotation curve using proper motions of 63 cepheids with suitable deprojection angles.

we find for the OB stars $A = 14.0 \pm 1.2\,\mathrm{km/s/kpc}$ and $B = -12.3 \pm 1.2\,\mathrm{km/s/kpc}$, which agree nicely with the flat shape of the rotation curve over larger distance intervals. The cepheids give $A = 15.8 \pm 1.6\,\mathrm{km/s/kpc}$ and $B = -9.7 \pm 1.6\,\mathrm{km/s/kpc}$. Obviously Oort's constants only reflect the local behaviour of the rotation curve. Over larger distance intervals the rotation curves show a flatter shape than one would assume from the above values.

4. Results and Discussion

4.1. Rotation curves

Once the velocities have been corrected for the solar motion, it is straightforward to determine the circular velocity $v_c(R)$ for according to the formula

$$v_c = (U - \Omega_0 Y)\sin\varphi + (V + \Omega_0 X)\cos\varphi + \Omega_0 R\ , \tag{5}$$

where R is the distance of the star from the galactic centre. It is now no longer necessary to assume that the stars move on circular orbits around the galactic centre, because the full space velocities are used.

Alternatively, assuming again circular orbits, one may derive rotation curves based solely on radial or tangential velocity components of the stars,

$$\Omega_0(R) = \frac{v_{\mathrm{rad}}}{R_0 \sin l \cos b} + \Omega_0 \tag{6}$$

$$\Omega_0(R) = \frac{(\mu_l + \Omega_0) r \cos b}{R\cos(\varphi + l)} + \Omega_0 \quad , \tag{7}$$

where r denotes the distance of the star from the Sun, v_{rad} the radial velocity, and μ_l the proper motion in the direction of galactic longitude l. Both velocities have to be corrected again for the solar motion. r is the distance of the star from the Sun.

The resulting rotation curves determined using either the full space velocities or deprojected radial or tangential velocity components are shown in Figs. 3 to 6. They agree very closely and are all consistent with a flat shape of the rotation curve $\Omega(R) = \Omega_0 R_0 / R$.

Stars with unsuitable projection angles onto the supposed circular velocities have been excluded. In the case where only radial velocity data are used stars with $|\sin l| < 0.3$ have been rejected. If only proper motion data are used stars with $|\cos(\varphi + l)| < 0.7$ have been rejected. Therefore the overlap between these two samples is small and we cannot correlate directly the rotation curve derived from radial velocities with the rotation curve based on proper motions or both.

Instead, we show in Fig. 7 the deviations of circular velocities derived from the space velocities from circular

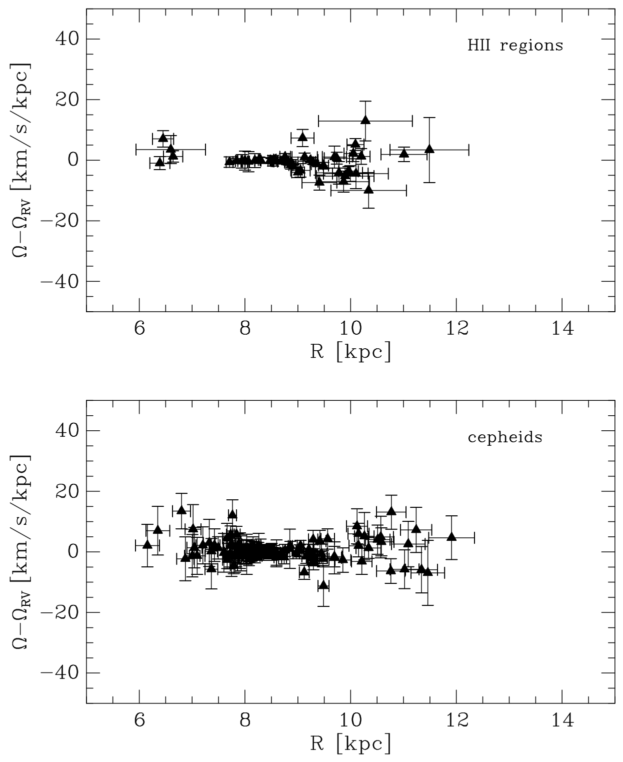

Fig. 7. The rotation curve derived solely from radial velocities assuming circular orbits around the galactic centre, subtracted from the rotation curve based on the space velocities of 48 H II regions (upper panel, where stars belonging to the same H II region have been grouped together) and 124 cepheids (lower panel). Stars in the direction of the galactic centre or anticentre have been excluded. Individual errors are indicated.

velocities based solely on deprojected radial velocities of the stars illustrating again that both methods give consistent results.

4.2. Residual velocities

The orientations of the velocity residuals after subtraction of the systematic velocity components due to a flat rotation curve from the space velocities of the stars are shown in Fig. 8 projected onto the galactic plane. The velocity residuals are dominated by the errors of the proper motions. Most of the velocity residuals can be shown to be randomly orientated with the exception of the Perseus spiral arm. There is a trend of coherent motion along the spiral arm with the effect that the OB stars in the spiral arm tend to lag behind the general rotation of the disk. Exactly such a behaviour is predicted by the density wave theory of spiral structure for stars recently born in the shock front of the interstellar gas included by the spiral density wave (Shu et al. 1972). This is not observed for the cepheids. They are about 100 times older than the OB stars and their systematic flow pattern is already dissolved (Wielen 1979).

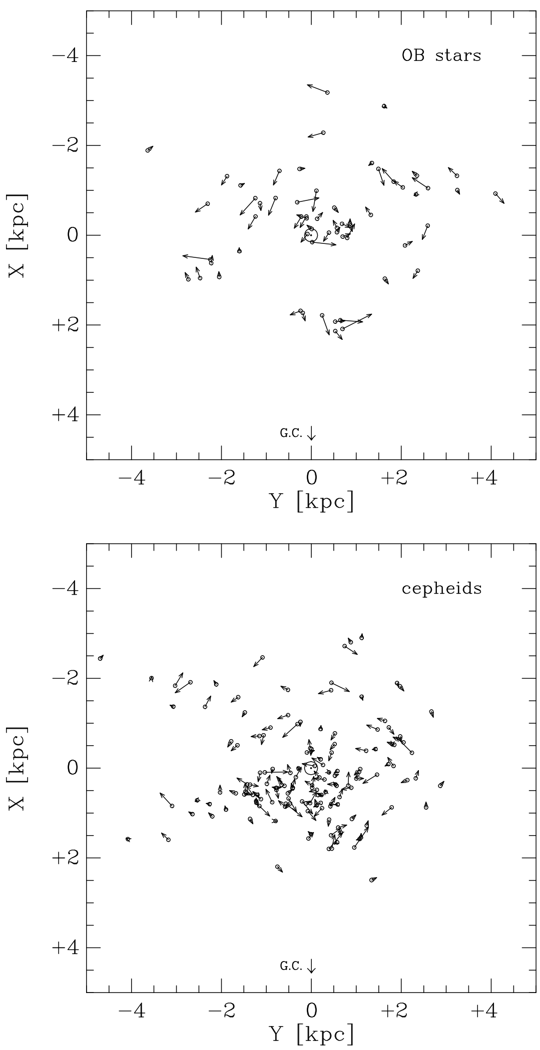

Fig. 8. Velocity residuals projected onto the galactic plane after subtraction of a flat rotation curve, normalized by the individual errors of the space velocities. A normalized residual of unit one corresponds to a vector with a length of 150 pc in the diagram. Notice the aligned velocity pattern in the Perseus spiral arm in the upper right hand quadrant for the OB stars (upper panel). The cepheids (lower panel) do not show a similar feature.

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