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.
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 $\delta \approx -40^\circ$, corresponding to $l \approx 260^\circ$, $b \approx 0^\circ$. 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.

![Fig. 2. Contourmaps of the numerical value of $\chi^2$ as a function of the solar motion $U_0$ and $V_0$. A cross indicates the standard value of $U_0 = 9$ km/s, $V_0 = 12$ km/s, a triangle the value $U_0 = 5$ km/s, $V_0 = 6$ 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).]
Table 1. \( \text{H} \pi \) regions and their associated OB stars. The first column gives the Sharpless or Brand identification numbers of the \( \text{H} \pi \) regions. The second column gives the identification numbers of the OB stars in this region which could be found in the PPM Star Catalogue.

| \( \text{H} \pi \) | PPM  | \( \text{H} \pi \) | PPM  | \( \text{H} \pi \) | PPM  | \( \text{H} \pi \) | PPM  |
|----------------|------|----------------|------|----------------|------|----------------|------|
| S8             | 296225 | S140          | 23638| S234          | 70368| BBW16         | 727432|
|                | 296206 |               | 23640|               | 70374|              | 252138|
| S11            | 296337 | S142          | 41076| S236          | 70266|              | 727439|
| S25            | 267779 |               | 41098|               | 70271|              | 727444|
|                | 267782 | S154          | 23983|               | 70273|              | BBW17B|
|                | 267822 | S155          | 24016| S238          | 119824|            | 252148|
|                | 267977 |               | 24060| S252          | 95519|              | 252158|
| S29            | 267950 |               | 24070| S263          | 148818|           | BBW23|
| S31            | 267973 |               | 24074| S264          | 149155|            | 252308|
| S32            | 267965 |               | 24072|               | 149166|            | 252363|
|                | 267970 |               | 24072| S273          | 151033|            | 252304|
|                | 267964 |               | 23979|               | 151058|              | BBW29|
| S27            | 231915 |               | 24019|               | 151028|              | BBW104B|
| S41            | 234340 |               | 24021|               | 151013|              | BBW106|
| S42            | 234237 |               | 24036|               | 151053|              | BBW127|
|                | 234243 |               | 24043|               | 151030|              | 740995|
|                | 234273 |               | 24049|               | 151073|              | 740981|
|                | 234280 |               | 24098|               | 151050|              | 740980|
|                | 234293 |               | 24093| S275          | 150705|              | BBW133|
|                | 234337 |               | 24117|               | 150694|              | 741033|
|                | 234362 |               | 24148|               | 150692|              | BBW283|
| S44            | 234275 |               | 24150|               | 150670|              | 338612|
| S45            | 234399 |               | 24162|               | 150682|              | BBW300B|
| S46            | 234023 |               | 24185| S277          | 188303|            | 339041|
| S49            | 234332 |               | 24186| S279          | 188224|            | 338930|
|                | 234333 | S157          | 24306| S281          | 187839|              | BBW316D|
|                | 234345 | S161          | 24309|               | 175945|              | BBW347|
|                | 234348 |               | 24329|               | 188455|              | BBW348A|
| S54            | 234320 | S162          | 24384|               | 175888|              | 358560|
|                | 234299 | S170          | 11863|               | 188218|              | 358600|
|                | 234306 | S173          | 12143|               | 188223|              | 358835|
|                | 234321 | S184          | 25788|               | 18825 |              | 358846|
|                | 234336 |               | 25791|               | 188149|              | 358849|
|                | 234352 | S190          | 13731|               | 215598|              | 358855|
|                | 234357 |               | 13702| S292          | 218092|            | 358857|
| S86            | 109578 |               | 13720| S293          | 218026|            | 358862|
|                | 109560 |               | 13721| S295          | 218051|            | 358863|
|                | 109575 |               | 13723| S296          | 218372|            | 358865|
| S101           | 83984  |               | 13712|               | 218096|            | 358872|
| S112           | 60147  |               | 13718|               | 218138|            | 358855|
| S117           | 60726  | S199          | 28316|               | 218164|            | 358876|
| S119           | 61260  |               | 28326|               | 218171|            | 358883|
| S124           | 39725  | S202          | 14174|               | 218242|            | 358884|
| S126           | 88031  |               | 14185|               | 218262|            | BBW362C|
| S129           | 39225  |               | 14227|               | 218324|            | 358747|
| S132           | 40485  | S206          | 28874| S297          | 218121|            | BBW362F|
| S134           | 40324  | S220          | 68961| S310          | 252114|            | 358755|
| S137           | 23309  | S232          | 70744| S311          | 253358|            |            |
|                | 23333  | S234          | 70403|               | 253404|            |            |
Table 2. Cepheids used to calculate the rotation curve.

| cepheid    | PPM   | cepheid    | PPM   | cepheid    | PPM   |
|------------|-------|------------|-------|------------|-------|
| η Aql      | 168843| SU Cas     | 13918 | V1334 Cyg  | 86379 |
| U Aql      | 202954| SW Cas     | 41496 | β Dor      | 35487 |
| SZ Aql     | 167110| SZ Cas     | 27633 | ζ Gem      | 96982 |
| TT Aql     | 167242| XY Cas     | 12507 | W Gem      | 12271 |
| FF Aql     | 135550| DL Cas     | 12258 | V Lac      | 41123 |
| FM Aql     | 135861| FM Cas     | 25159 | X Lac      | 41132 |
| FN Aql     | 167384| V636 Cas   | 13051 | Y Lac      | 40284 |
| V336 Aql   | 167002| V Cen      | 34209 | Z Lac      | 40952 |
| V496 Aql   | 202574| UZ Cen     | 35889 | RR Lac     | 40959 |
| V600 Aql   | 167670| XX Cen     | 34213 | BG Lac     | 62336 |
| Y Aur      | 48141 | BB Cen     | 35040 | GH Lup     | 34369 |
| RT Aur     | 71665 | BK Cen     | 35896 | T Mon      | 15046 |
| RX Aur     | 69838 | V378 Cen   | 360023| SV Mon     | 150342|
| SY Aur     | 47840 | V381 Cen   | 342310| R Mus      | 35966 |
| RY CMa     | 218422| V419 Cen   | 340152| S Mus      | 37147 |
| RZ CMa     | 713898| δ Cep      | 40731 | RT Mus     | 35894 |
| SS CMa     | 252386| CR Cep     | 41067 | UU Mus     | 35905 |
| TV CMa     | 713601| AX Cir     | 361060| S Nor      | 34482 |
| TW CMa     | 713915| R Cru      | 359375| U Nor      | 34405 |
| VZ CMa     | 727576| S Cru      | 341409| Y Oph      | 201153|
| RW Cam     | 28771 | T Cru      | 359350| BF Oph     | 266398|
| RX Cam     | 28898 | X Cru      | 341282| RS Ori     | 122354|
| ι Car      | 357533| VW Cru     | 359483| SV Per     | 47393 |
| U Car      | 339614| AG Cru     | 341197| SX Per     | 46949 |
| V Car      | 356744| BG Cru     | 341066| VX Per     | 27145 |
| Y Car      | 339156| X Cyg      | 85419 | AW Per     | 69651 |
| UW Car     | 339046| SU Cyg     | 109630| V440 Per   | 27565 |
| UX Car     | 339090| SX Cyg     | 60114 | X Pup      | 25264 |
| XX Car     | 358358| TX Cyg     | 60815 | RS Pup     | 28494 |
| XY Car     | 358418| VX Cyg     | 60748 | VX Pup     | 25263 |
| XZ Car     | 358450| VY Cyg     | 85963 | VZ Pup     | 72777 |
| YZ Car     | 339070| VZ Cyg     | 62131 | WX Pup     | 25297 |
| ER Car     | 339816| CD Cyg     | 84139 | WZ Pup     | 72815 |
| GI Car     | 339882| DT Cyg     | 86036 | AU Pup     | 19036 |
| IT Car     | 358563| V836 Cyg   | 61152 | AT Pup     | 28492 |
| RY Cas     | 42304 | V532 Cyg   | 61309 | S Sge      | 13724 |
|            |       |            |       |            | SV Sge| 10987 |

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

\[ U = \Omega_0 R_0 \sin \varphi \]
\[ V = \Omega_0 R_0 (\cos \varphi - 1) \]  \hspace{1cm} (1)

to the space velocities of the stars. \( U \) and \( V \) correspond to the directions of the X- and Y-axis of Fig. 4 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, \( \varphi \) 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 \( \chi^2 \)-fit of eq. (1) to the space velocities of the 197 OB stars we find

\[ \Omega_0 = 5.5 \pm 0.4 \text{ mas/a} \]  \hspace{1cm} (2)

for the angular velocity of the LSR which corresponds to a circular velocity of \( 223 \pm 14 \text{ km/s} \) in good agreement with the IAU 1985 value of \( 220 \text{ km/s} \).
Table 3. Effects of the correction of the constant of precession by $\Delta p_1 = -3.2 \text{ mas/a}$ and different corrections of the motion of the equinox $\Delta e$ on the angular velocities $\Omega_0$, $\Omega_1$ and $\Omega_2$. $\Omega_0$ 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 $\Delta e$. 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.

| $\Delta e$ [mas/a] | $\Omega_0$ [mas/a] | $\Omega_1$ [mas/a] | $\Omega_2$ [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                           |

| $\Delta e$ [mas/a] | $\Omega_0$ [mas/a] | $\Omega_1$ [mas/a] | $\Omega_2$ [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                           |

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.
From the data of the 144 cepheids we obtain
\[ \Omega_0 = 5.4 \pm 0.5 \text{ mas/a} \quad (3) \]
in good agreement with the OB stars.

The estimated error of \( \Omega_0 \) 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 \( \chi^2 \) 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\%.

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 \( \Delta p = -3.2 \pm 0.3 \text{ mas/a} \) (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. \( \Omega_0 \) is again the angular velocity of the LSR with respect to the galactic centre. \( \Omega_1 \) and \( \Omega_2 \) are angular velocities of the mean rotation of all stars about axes lying in the galactic plane, pointing towards the galactic centre (\( l = 0^\circ \)) and the direction of galactic rotation (\( l = 90^\circ \)), 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 \( \Delta \varepsilon \). 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 $\Delta e = -2.9 \text{ mas/a}$ for the OB stars or of $\Delta e = -1.5 \text{ mas/a}$ for the cepheids. Nevertheless the remaining tilting is significantly higher than in the case where no correction at all was applied, i.e. $0.35 \text{ mas/a}$ for OB stars with distances greater than 800 pc and $1.10 \text{ mas/a}$ for cepheids. In all these cases $\Omega_0$ agrees within $1 \text{ mas/a}$ with the values given above. This discrepancy cannot be solved on the basis of the present material.

The corrections $\Delta e$ 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 $\Delta e = -1.2 \text{ mas/a}$ from K giants. Wielen obtained $\Delta e = -3.2 \text{ mas/a}$ 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 $\pm 1 \text{ mas/a}$ in each component of the rotation vector. This is consistent with the claimed accuracy of the FK5 system with respect to non-physical rotations of about $\pm 0.7 \text{ mas/a}$ (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 $-6.55 \pm 0.34 \text{ mas/a}$ (Backer 1996), implying after subtraction of the peculiar velocity of the Sun an angular velocity of the LSR of $\Omega_0 = 6.4 \text{ mas/a}$, 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 $U_0 = 9 \text{ km/s}$ and $V_0 = 6 \text{ km/s}$ (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 $\chi^2$-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 $\chi^2$ 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 $U_0 = 5 \text{ km/s}$ and $V_0 = 6 \text{ km/s}$, which correspond within the errors simultaneously to the minima of $\chi^2$ 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 $V_0 = 5 \text{ km/s}$ relative to the youngest stars in the solar neighbourhood in close agreement with the value used here. The low value of $V_0$ 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 $\chi^2$-fit to the circular velocity

$$ v_c(R) = v_c(R_0) + \left( \frac{dv_c}{dR} \right)_0 (R - R_0) \tag{4} $$

we find for the OB stars $A = 14.0 \pm 1.2 \text{ km/s/kpc}$ and $B = -12.3 \pm 1.2 \text{ km/s/kpc}$, which agree nicely with the flat shape of the rotation curve over larger distance intervals. The cepheids give $A = 15.8 \pm 1.6 \text{ km/s/kpc}$ and $B = -9.7 \pm 1.6 \text{ km/s/kpc}$. 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,

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

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

where $r$ denotes the distance of the star from the Sun, $v_{\text{rad}}$ the radial velocity, and $\mu_t$ 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 8. 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 velocities derived 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).

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