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Is the Sun located near the corotation circle?

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Abstract. The line-of-sight velocity field of Cepheids was analysed in terms of a disk galaxy model perturbed by spiral density waves in order to estimate the parameters of the galactic rotation curve and the free parameters of density waves. It was shown that: 1) the Sun is located near the corotation circle because the angular rotation velocity of the Galaxy $\Omega_\odot \approx 26.0$ km s^{-1} kpc^{-1}(Kerr & Lynden-Bell, 1986; Dambis, Mel'nik & Rastorguev, 1995) is close to that of the spiral pattern $\Omega_p \approx 28.1 \pm 2.0$ km s^{-1} kpc^{-1} and the corotation radius $R_\mathrm{c} \approx 7.2 \pm 1.3$ kpc (we adopt the galactocentric distance of the Sun $R_\odot \approx 7.5$ kpc); 2) the spiral pitch angle $i \approx -6.8° \pm 0.7°$; 3) the Sun is at the spiral wave phase $\chi_\odot \approx 290° \pm 16°$; 4) Oort's constant $A \approx 20.9 \pm 1.2$ km s^{-1} kpc^{-1}; the second term in the expansion of the galactic rotation velocity is $R_\odot \Omega''_\odot \approx 13.3 \pm 3.1$ km s^{-1} kpc^{-2}.

Key words: Galaxy: kinematics and dynamics – structure – Cepheids

1. Introduction

The idea about a wave nature of galactic spirals is well known to belong to B.Lindblad. However, a huge growth of interest in it is associated with the papers by Lin and his collaborators (Lin & Shu, 1964; Lin, Yuan & Shu, 1969, hereafter LYS, and others). Such a success was, in particular, a result of the quasi-stationary spiral structure hypothesis (hereafter the QSSS hypothesis) suggested by the above authors as a working one. They deferred until later time the problem of the origin of spiral arms and suggested as a first step to examine various observational manifestations of the galactic density waves (GDW). Obvious physical ideas that Lin et al. incorporated in their theory gave rise to a large number of investigations both theoretical and observational. Owing to these investigations we now better understand the structure and evolution of spiral galaxies.

However, in the framework of Lin's et al. QSSS hypothesis the GDW parameters are free and must be inferred from observations. The most frequently mentioned parameter in the papers dealing with the spiral structure of galaxies is the angular velocity of the spiral pattern, Ω_p. It is important to note that in spite of the fact that galactic rotation is differential, i.e., the angular velocity of galactic rotation Ω is a function of the galactocentric distance R, the spiral pattern rotates as a solid body ($\Omega_p = const$). The distance R_c at which the two velocities are equal ($\Omega(R_\mathrm{c}) = \Omega_p$) is referred to as the corotation radius.

Lin and his collaborators have proposed for the Ω_p values between 11 km s^{-1} kpc^{-1} to 13.5 km s^{-1} kpc^{-1}. In their model the corotation circle is located somewhere at the very end of Our Galaxy.

Marochnik, Mishurov & Suchkov (1972, hereafter MMS) used a composite galactic model and found that $\Omega_p \approx 23$ km s^{-1} kpc^{-1} ,i.e., the Sun is near the corotation circle. This is one of cardinal differences between their model and the american one.

In the past years a number of papers were published with the aim to determine these parameters from observations. Some of them give Ω_p values that are close to that predicted by MMS (e.g. Creze & Mennessier, 1973; Mishurov, Pavlovskaya & Suchkov, 1979; Pavlovskaya & Suchkov, 1980). However, some papers supported the point of view of the american group (e.g. Comeron & Torra, 1990). Byl and Ovenden (1978) found Ω_p to be intermediate between those of MMS and of LYS. However, Fridman et al. (1994) analyzed motions of the star formation regions and concluded that the Sun is located near the corotation. Thus, so far the problem of deriving Ω_p and other parameters of the spiral pattern has not been unambiguously resolved.

A good opportunity to revise this problem is opened now by the papers of Pont et al (1994) and Gorynya et al (1992, 1996) who published new radial (line-of-sight) velocities of Cepheids measured with excellent accuracy (~ 1 km s^{-1}). Furthermore, it is also well known that Cepheids are stars with the most precisely determined distances. Hence, this new observational material represents the best up to date sample for our task.

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Table 2 is only available in electronic form at the CDS via anonymous ftp 130.79.128.5".

The aim of this investigation is to thoroughly analyze the observational data on the stellar kinematics in order to infer the GDW parameters.

2. Method of estimating the galactic parameters

Let us represent the galactic gravitational potential φ_G as the sum:

$$\varphi_{\rm G} = \varphi_\circ + \varphi_{\rm S} \; , \tag{1}$$

where $\varphi_\circ$ is the unperturbed regular axisymmetric potential, φ_S is its perturbation by a GDW. Regular gravitational field keeps the Galaxy in equilibrium, i.e. $\varphi'_\circ = \Omega^2 R$ (hereafter the prime denotes a derivative with respect to R). So the unperturbed gravitational field results only in the pure rotation of the Galaxy.

The spiral potential has the form of a running wave:

$$\varphi_{\rm S} = \mathscr{A}\cos(\chi) \; , \tag{2}$$

where $\mathscr{A}$ is the amplitude of the wave (note that $\mathscr{A} < 0$), χ is the wave phase:

$$\chi = 2\left[\cot(i)\;\ln(R/R_\odot) - \vartheta + \Omega_p {\rm t}\right] + \chi_\circ \; , \tag{3}$$

i is the pitch angle of spirals ($i < 0$ for trailing arms), t is the time, $\chi_\circ$ is the initial phase. Here R, ϑ, z is the cylindrical coordinate system with the origin at the Galactic center, the z-axis being directed along the axis of the Galactic rotation. If as usual for the Sun $\vartheta_\odot = 0$, then $\chi_\odot = 2\Omega_p{\rm t} + \chi_\circ$ is the wave phase at the Sun position (we call it the Sun phase) at a given time. As one can see from Eq. (3) we adopt a two armed logarithmic spiral for the pattern of the Galaxy.

The gravitational field of the spiral GDW perturbs the stellar motions and makes them deviate from circular rotation.

The problem is to derive the amplitude $\mathscr{A}$, the angular rotational velocity Ω_p , the pitch angle i, and the Sun phase $\chi_\odot$ (we simultaneously redetermine the galactic rotation constants taking into account perturbations by GDW, see below).

Two of these parameters - i and $\chi_\odot$ - can be in principle derived directly by independent methods, e.g., by analyzing the optical or radio picture of the Galaxy [1]. If we were able to look at the Galaxy say, for several ten million years, we could also directly measure Ω_p. However, we have no such opportunity [2] and we must infer both the Ω_p and other parameters indirectly by investigating the response of some objects to the gravitational field of the GDW.

We believe that the most convenient method for our aims is that of statistical analysis of a velocity field like that proposed by Creze and Mennessier (1973, hereafter CM). Therefore we consider this method in more detail and revise some of its particulars.

In accordance with Eq. (1) let us divide the systematic velocity of any star into two parts: unperturbed with components $\{0\,,\Omega R\}$ and a perturbation $\{\tilde v_R, \tilde v_\vartheta\}$. By analogy with Ogorodnikov (1958) the line-of-sight projection of the heliocentric systematic velocity of a star, v_r, is given by:

$$v_r + V_\odot\left[\sin(b)\,\sin(B_\odot) + \cos(b)\,\cos(B_\odot)\,\cos(l - L_\odot)\right] =$$
$$\{[-2A + 0.5R_\odot\Omega''_\odot(R - R_\odot)](R - R_\odot)\sin(l)$$
$$-\tilde v_R\cos(l+\vartheta) + \tilde v_\vartheta\sin(l+\vartheta) + u_\odot\cos(l) - v_\odot\sin(l)\}\cos(b) \; , \tag{4}$$

where $A = -0.5R_\odot\Omega'_\odot$ is Oort's constant, l and b are the galactic coordinates of the star, $\boldsymbol{V}_\odot$ is the Sun velocity relative to the local centroid of nearby main-sequence stars ($V_\odot$ = 15.5 km s^{-1}, the galactic coordinates of the apex are $L_\odot = 45°$, $B_\odot = 23.6°$, e.g. Kulikovskij, 1985), $u_\odot, v_\odot$ are the velocity components of the local centroid with respect to galactic rotation.

The perturbed velocity can also be represented in the form similar to (2):

$$\tilde v_R = f_R\,\cos(\chi)\;;\;\; \tilde v_\vartheta = f_\vartheta\,\sin(\chi)\; , \tag{5}$$

where f_R and f_ϑ are the amplitudes which are connected with the sought for parameters through the known relations (see LYS and below).

Similar equations can be written for the transversal velocities of stars, however, we restricted ourselves only to radial velocities.

For tightly wound spirals the amplitudes of perturbed velocities and the pitch angle are slowly varying quantities compared to the wave phase. Thus at a first step we can consider them to be constant.

In the following the problem breaks into two stages. At the *first stage* the parameters of galactic rotation (A and $R_\odot\Omega''_\odot$), the parameters of the wave in the velocity field (f_R, f_ϑ, i and $\chi_\odot$) and the additional components of the local centroid velocity ($u_\odot$ and $v_\odot$) are found by means of statistical analysis of observed stellar velocity field, i.e. by minimizing the residual δ^2, where:

$$\delta^2 = \frac{1}{N - p}\sum(v_r - v_r^\circ)^2 \; , \tag{6}$$

v_r° are the observed stellar velocities, N is the number of stars in a sample, p is the number of parameters to be derived. The sum in (6) is taken over all stars in a sample.

In a *second stage* we can estimate the quantities $\mathscr{A}$ and Ω_p from the velocity amplitudes f_R and f_ϑ using the results of LYS (see below).

[1] One must keep in mind that the maximum in the distribution of spiral-wave indicators is shifted with respect to the bottom of the spiral gravitational potential well (e.g., Roberts,1969).

[2] In some sense Strömgren (1967), Yuan (1969) and others tried to realize such possibility by studying the stellar migration across spiral arms. However this method can not provide reliable estimates of Ω_p. Indeed, apart from using stars only in the immediate vicinity of the Sun ($\sim$ 100 pc - at distances much smaller than interarm distance) the method used in cited papers is subject to various errors, particularly inaccuracy of ages of individual stars. Based on data on open clusters Palouš et al.(1977) showed that the method does not allow one to distinguish between the LYS or the MMS values of the Ω_p.

Operating in this way CM have derived the $\Omega_p \approx 20 - 22$ km s^{-1} kpc^{-1} and the $\chi_\odot \approx -8°$. They do not give the pitch angle (its error is large) but they point out that it is very small and is most likely positive. CM also do not give the amplitude $\mathscr{A}$.

It is well known from independent observations that the Sun is not located near the center of any basic arm and that the spiral pattern of Our Galaxy is of the trailing type (i.e. $i < 0$). Hence at first sight the kinematic method fails to determine the parameters of interest. However, this is not the case.

In fact the kinematic method does not make it possible to determine whether arms are trailing or leading. Indeed the structure of Eqs. (3) to (5) is such that simultaneous substitution $i \to -i$ and $\chi_\odot \to \chi_\odot + \pi$ does not change the v_r. Thus using only the kinematic method does not allow one to simultaneously resolve the ambiguity of the sign of i and the Sun phase $\chi_\odot$. In order to resolve this ambiguity we have to take into account additional observations. Proceeding from the assumption that the spiral arms in the Galaxy are trailing we should postulate that $i < 0$. A change of sign i from positive to negative in CM's computation will lead to a change for Sun phase from $-8°$ to $172°$ and the Sun as expected to be situated between arms.

The conclusion of CM about the Sun being close to the corotation circle remains valid because such a substitution does not change Ω_p .

Let us return to our method. The sample that we processed contains sufficiently distant stars (up to 4 kpc from the Sun). These stars provide important information on the large-scale structure of the Galaxy, however this circumstance prevents us from reducing the first stage (statistical analysis) to linear statistics as it was in the case in CM. Indeed, because the parameter $r/R_\odot$ (r is the distance of a star from the Sun) is not small for distant stars we do not expand the phase χ and the azimuthal angle ϑ in Eq. (4) into power series of this parameter and we keep the expressions for perturbed velocities in the form (5). Therefore, two quantities - i and $\chi_\odot$ enter Eqs. (4,5) nonlinearly. To find them we proceeded in the following way. For any given pair $(i, \chi_\odot)$ we solve the statistical problem, i.e. find $min\, \delta^2$ over all other parameters for fixed values of the pitch angle and the Sun phase [3] (the range of $\chi_\odot$ is from $0°$ to $360°$ and that of i is $-1°$ to $-20°$). We then construct the surface of $min\, \delta^2$ as a function of two arguments $(i, \chi_\odot)$ and look for $(i^\circ, \chi_\odot^\circ)$ corresponding to the global minimum of δ^2. After that we linearise v_r from Eq. (4) with respect to $\cot(i) - \cot(i^\circ)$ and $\chi_\odot - \chi_\odot^\circ$ and use the iterative procedure described by Draper & Smith (1966) to revise i and $\chi_\odot$ and estimate their errors. Simultaneously we revise all other parameters and their errors.

To solve the second-stage problem, i.e., to determine the Ω_p and the $\mathscr{A}$ - we use the results of GDW theory (see LYS):

$$f_R = \frac{k\mathscr{A}}{\kappa}\,\frac{\nu}{1-\nu^2}\,\mathscr{F}_\nu^{(1)}(x)\,, \tag{7}$$

[3] This part of the problem can be solved by means of the standard least squares method; here we used the SVD-method described by Forsite et al (1980).

$$f_\vartheta = -\frac{k\mathscr{A}}{2\Omega}\,\frac{1}{1-\nu^2}\,\mathscr{F}_\nu^{(2)}(x)\,. \tag{8}$$

where $k = 2\cot(i)/R$ is the radial wave number (for trailing arms $k < 0$),

$$\nu = 2(\Omega_p - \Omega)/\kappa \tag{9}$$

is the dimensionless spiral wave frequency, $\kappa = 2\Omega(1 - A/\Omega)^{1/2}$ is the epicyclic frequency,

$$x = (k\,C_R/\kappa)^2\,, \tag{10}$$

C_R is the dispersion of radial (galactocentric) velocities of stars, $\mathscr{F}_\nu^{(1)}$ and $\mathscr{F}_\nu^{(2)}$ are the reduction factors:

$$\mathscr{F}_\nu^{(1)}(x) = \frac{(1-\nu^2)}{x}\Big[1 - \frac{\nu\pi}{\sin(\nu\pi)}\,\frac{1}{2\pi} \times \int_{-\pi}^{\pi} e^{-x(1+\cos s)}\cos(\nu s)\,ds\Big], \tag{11}$$

$$\mathscr{F}_\nu^{(2)}(x) = (\nu^2 - 1)\,\frac{\nu\pi}{\sin(\nu\pi)}\,\frac{\partial}{\partial x}\,\frac{1}{2\pi} \times \int_{-\pi}^{\pi} e^{-x(1+\cos s)}\cos(\nu s)\,ds\,. \tag{12}$$

So, if we know the values of $f_R, f_\vartheta, i,$ parameters of rotation curve and the dispersion of stellar radial velocity we use Eqs. (7-12) to calculate the dimentionless frequency ν. Then by means of Eqs. (7,9) the values of $\mathscr{A}$ and Ω_p can be derived.

Let us now draw attention to one important fact. The point is that the structure of Eqs. (3) to (6) is such that simultaneous substitution $\chi_\odot \to \chi_\odot + \pi$, $f_R \to -f_R$ and $f_\vartheta \to -f_\vartheta$ does not change δ^2 . In other words δ^2 is periodic in $\chi_\odot$ with a period of π while $\tilde{v}_R$ and $\tilde{v}_\vartheta$ have periods 2π. Therefore we encounter the problem: in what region $0° - 180°$ or $180° - 360°$ lies the true value of $\chi_\odot$? To resolve this ambiguity let us analyse the signs of f_R and f_ϑ.

The spiral wave pattern is known to extend over a galactic region - the so-called "principal part" where $|\,\nu\,| < 1$. In this region as known $\mathscr{F}_\nu^{(1)} > 0$, but $\mathscr{F}_\nu^{(2)}$ may have an arbitrary sign (see, e.g. CM). However, it may be shown that for $|\,\nu\,| \leq 0.5$ (this is the case in our computation) $\mathscr{F}_\nu^{(2)} > 0$. Hence in this region must be hold the inequality

$$f_\vartheta < 0\,. \tag{13}$$

Thus, we should choose for the Sun phase the value that would satisfy condition (13).

Analyzing only the line of sight velocities does not allow us to derive the angular rotational velocity of the Galaxy $\Omega_\odot$ at the Sun position. Therefore we adopt $\Omega_\odot = 26 \pm 2$ km s^{-1} kpc^{-1} (Kerr & Lynden-Bell, 1986; Dambis et al, 1995). All computations were performed with $R_\odot = 7.5 \pm 1$ kpc (see, e.g., arguments in favour of decreasing $R_\odot$ down to 7.5 kpc in Rastorguev et al (1994), Dambis et al (1995), and Nikiforov & Petrovskaya (1994) and references therein).

3. Observational data

As observational material we used the radial (line of sight) velocity data for Cepheids. There are three reasons for this: 1) the Cepheids have the most accurate (in terms of random errors) and homogeneous distance scale; 2) because of high luminosities they can be seen at large distances and 3) the line of sight velocities are measured most precisely. All the above points are of extreme importance for our task. However, we would like to emphasize here the large space volume occupied by our sample of stars. Indeed, our problem is to define the parameters of galactic spiral structure with a typical spatial scale length (the interarm distance) of about 3 kpc. Hence, a star sample can be considered representative for our task if it occupies the space volume in the Galaxy of the size comparable with the typical scale length mentioned above [4].

We took radial velocities from Pont et al (1994), Gorynya et al (1992, 1996), Dambis et al (1995) and Caldwell & Coulson (1987) and the Cepheid distances from the catalog of Berdnikov (1987). We chose this catalog because it contains a set of homogenous parameters for the largest number (363) of Galactic Cepheids based solely on the results of photoelectric photometry. Seventy-eight Cepheids were observed by Berdnikov himself and all available published individual measurements for these and other stars were corrected for systematical errors and reduced to a unified photometric system. These homogenized individual photometric measurements were then used to obtain standard light curves for all stars under study, derive light-curve parameters, and infer Cepheid distances.

We did not try to collect the most possible extensive sample involving inhomogeneous observational data for objects with different kinematic properties. On the contrary, we thoroughly selected stars from the above-cited catalogues.
1) First of all, we restrict ourselves to the stars within the region of $r \leq 4$ kpc excluding the most distant stars.
2) Further, we excluded all binary systems.
3) To eliminate the local effects like Gould's Belt we excluded from our sample nearby stars in the region of $r \leq 0.5$ kpc.
4) We also excluded the stars with pulsation periods P exceeding 9 days. As is well known, they are extremely young objects. Therefore their kinematics is unlikely to fit a simple linear theory of small amplitude galactic density waves. This is corroborated by Efremov(1989) who showed that long-period Cepheids concentrate to the inner edge of spiral arms.
Our final sample contains 122 stars. Table 2 gives observational data about them thereby allowing one to independently reproduce our results. Fig. 1 shows the distribution of stars of our sample projected on the galactic plane.

4. Results

Stage 1. Statistical analysis of the velocity field of Cepheids. Fig. 2 illustrates the dependence of the $min\ \delta^2$ as function of two arguments i and $\chi_\odot$. Here one can see the minimum near $i^\circ \approx -7^\circ$ and $\chi^\circ_\odot \approx 290^\circ$. However we also note the lowering of the $min\ \delta^2$ with increasing of $|i|$ to 20°. It is possible that this fall of $min\ \delta^2$ is not an artefact and could reflect some kind of peculiarities in velocity field due to Orion arm. However, the analysis of the residuals of stellar velocities computed for the parameters corresponding to the $min\ \delta^2$ mentioned above (for $i^\circ \approx -7^\circ$; $\chi^\circ_\odot \approx 290^\circ$) shows that four stars (KL Aql, CG Cas, V Vel and AY Sgr) as appeared should be excluded because their residuals are about or more than $3\sigma_r$ ($\sigma_r = (min\ \delta^2)^{1/2}$). The revised surface $min\ \delta^2(i, \chi_\odot)$ constructed over remaining 118 stars is shown in Fig. 3. Comparing this picture with Fig. 2.

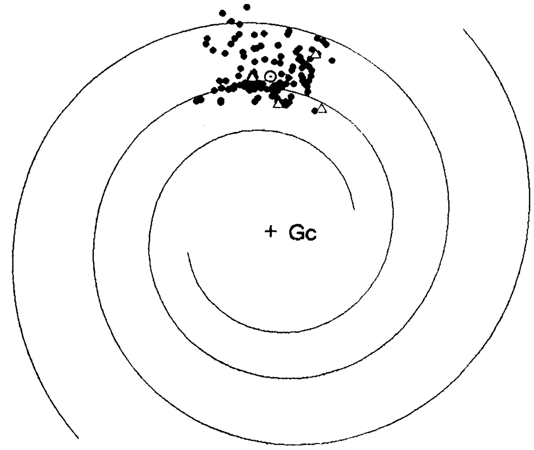

Fig. 1. The displacement of Cepheids on the galactic plane. The open circle denotes the Sun. The triangles are for excluded stars (see text, Sect. 4). The spiral lines are the locus of the spiral potential minimum (χ = 0 and 2π) for the best fitting model of Table 1.

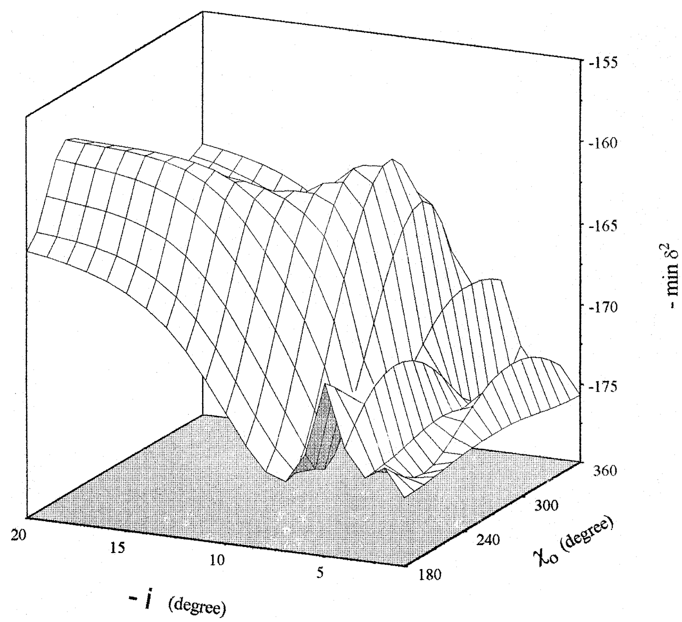

Fig. 2. The surface $-min\ \delta^2$ versus pitch angle i and Sun phase $\chi_\odot$ constructed over 122 stars. The distance scale of Cepheids accordiny to Berdnikov.

[4] We are sure that it is impossible to reliably derive the parameters of the galactic spiral structure by studying stellar motions at small distances ($\sim$ 100 pc) from the Sun.

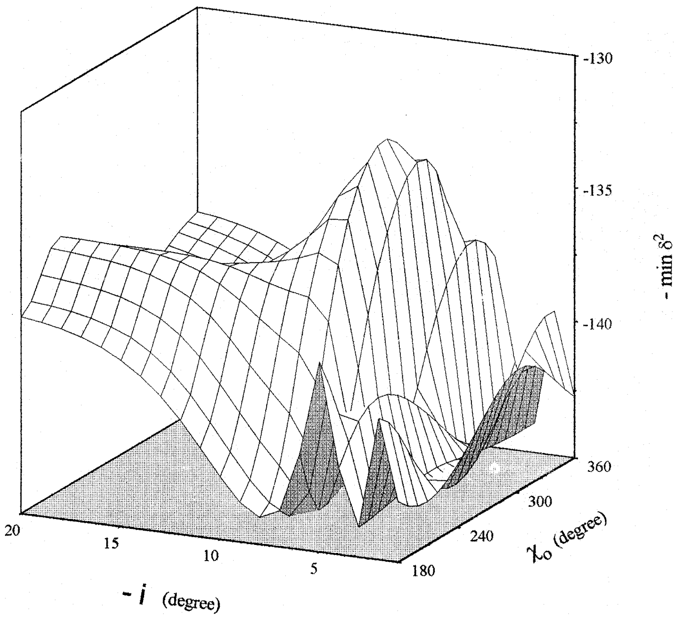

Fig. 3. Those as Fig. 2 but 4 stars excluded.

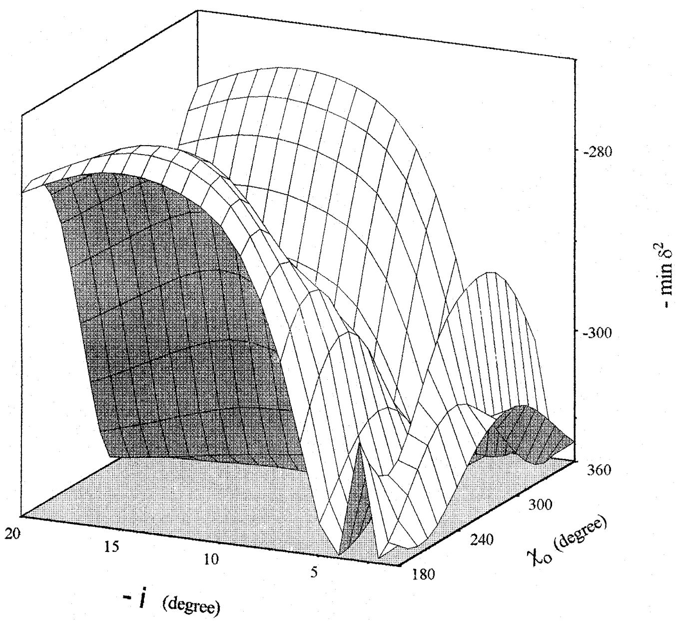

Fig. 4. Those as Fig. 3 but the distance scale of Cepheids according Feast and Walker.

it is worth noting that the $min\ \delta^2$ under study becomes global and substantially sharper. Furthermore, the overall level of the residuals in Fig. 3 is lower.

To obtain more precise values of the sought for parameters corresponding to the minimum with their standard errors we used the iterative procedure described in Sect. 2. Table 1 gives the resulting values.

Before analysing the results of Table 1 we consider the very important question about influence of distance scale for Cepheids on inferred parameters. Besides the argument in favour of Berdnikov's distance scale given in Sect. 3 we adduce here the kinematical one. Fig. 4 shows the surface $min\ \delta^2(i, \chi_\odot)$ for the same stars as in previous case, but with distances adopted according to Feast and Walker as indicated in Pont et al (1994) and the distance to the Galactic center, $R_\odot$, also taken from Pont et al (1994). It can be seen that scale $min\ \delta^2$ for the Feast and Walker's scale is twice that for Berdnikov's scale. Hence a more self-consistent the Berdnikov's distance scale for Cepheids is should also be preferred from the kinematical point of view.

Let us now return to Table 1 and discuss the parameters of the spiral density wave. We first consider the geometric quantities. The pitch angle is derived with sufficient accuracy $i \approx -6.8° \pm 0.7°$. Its value is close to that obtained from other data, e.g., from radio observations (Burton, 1971). We also find the Sun to be located between the basic arms ($\chi_\odot \approx 290° \pm 16°$) but closer to the Sagittarius arm (see Fig. 1 which shows the best fitting spiral pattern with parameters from Table 1). How can we explain the fact that according to the optical picture of Galactic structure the Sun is located approximately halfway between the basic arms (Bok & Bok, 1974) and here we find the Sun to be closer to the inner arm? As we pointed out above (Sect. 2) $\chi_\odot$ fixes the position of the Sun in the spiral wave relative to the bottom of the gravitational potential of the density wave. The optical indicators are shifted (and perhaps strongly shifted) upstream of the bottom. That explains the illusory contradiction between our results and those inferred from the optical picture. However, this problem requires further analysis.

Stage 2. Estimation of Ω_p, R_c and $\mathscr{A}$. At first we compute the dimensionless frequency ν as described in Sect. 2. To derive this quantity one needs the information on the velocity dispersion of stars C_R (see Eq. (10)). We did not calculate this quantity but we computed ν for a set of C_R between 10 km s^{-1} and 15 km s^{-1} and for various values of other parameters from Table 1 taking into account their errors. The value of ν appears to be restricted within limits from 0.22 to 0.15. Thus the mean value of ν to be 0.18 and the error ± 0.04. Hence the angular velocity of the rotation of the spiral pattern proves to be equal to $\Omega_p \approx 28.1 \pm 2.0$ km s^{-1} kpc^{-1} and the corotation radius $R_c \approx 7.2 \pm 1.3$ kpc.

Thus our main conclusion is: the Sun is located near the corotation circle.

Our result for the amplitude $\mathscr{A}$ of the spiral gravitational field is less certain. This quantity is derived with substantial error. For instance, in the simplest, the so-called "cold system" approximation ($C_R = 0$) $\mathscr{A} \approx -361 \pm 202$ km^2 s^{-2}, that is the relative error is on the order of $50 - 60\%$, and increases several times if $C_R \neq 0$. Therefore, this question needs more careful investigation.

5. Conclusions

Investigation of a radial velocity field of Cepheids in the Galaxy in terms of the model of a galactic rotation involving spiral wave perturbations shows that:

Table 1. The parameters and their errors (the bottom line) derived by means of statistical analysis.

A $(\frac{km}{s\,kpc})$	$R_\odot\Omega''_\odot$ $(\frac{km}{s\,kpc^2})$	i $(^\circ)$	$\chi_\circ$ $(^\circ)$	f_R $(\frac{km}{s})$	f_ϑ $(\frac{km}{s})$	$u_\odot$ $(\frac{km}{s})$	$v_\odot$ $(\frac{km}{s})$	σ_r $(\frac{km}{s})$
20.9	13.3	−6.8	290	6.3	−4.4	2.3	4.7	11.5
±1.2	±3.1	±0.7	±16	±2.4	±2.4	±1.9	±1.8	

– the Sun is located at a small distance from the corotation circle: perhaps about several hundreds parsecs. The corotation radius $R_c \approx 7.2 \pm 1.3\,\mathrm{kpc}$ whereas the galactocentric distance of the Sun $R_\odot \approx 7.5 \pm 1.0\,\mathrm{kpc}$;
– we find the pitch angle of the spiral arms to be close to that derived in various other investigations based on both optical and radio observations: $i \approx -6.8^\circ \pm 0.7^\circ$;
– the Sun phase is: $\chi_\odot \approx 290^\circ \pm 16^\circ$; i.e. the Sun is located between arms and is closer to the Sagittarius arm (see Fig. 1);
– the amplitude of GDW gravitational potential is determined with substantial error; to derive it more accurately, more precise radial-velocity data or a more detailed nonlinear model are needed.

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