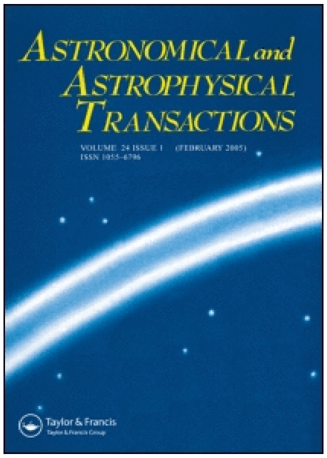

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VELOCITY FIELD OF YOUNG OPEN CLUSTERS AND CEPHEIDS AND THE EFFECTS OF THE SPIRAL DENSITY WAVE

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Space velocities of young open clusters and cepheids with periods greater then 9 days show systematic deviations from purely circular motion that can be considered as arguments in favour of the wave nature of the galactic disk. The radial scale length of radial and azimuthal deviations is close to 2 kpc, whereas the corresponding amplitudes are close to 7 and 2 km s^{-1} respectively. This value of the radial period well fits the spiral pattern with a pitch angle $i = 5°$ and two arms rather then four arms near the Sun. The most likely solution for the space velocity field has been derived by taking into account pure rotation and noncircular perturbations due to the effects from the spiral density wave. Estimates of the spiral pattern angular speed, Ω_p, calculated from radial and azimuthal amplitudes of the residuals, seem to be unreliable.

KEY WORDS Kinematics, spiral structure, open clusters, cepheid variables

1 INTRODUCTION

Precise HIPPARCOS (1997) absolute proper motion measurements, taken together with radial velocities, for the first time enabled the detailed investigation of the space velocity field of young objects. It is well known that the effects due to galactic spiral density waves are comparable or less than the residual velocity dispersion. Mishurov *et al.* (1997) have shown from the analysis of cepheid radial velocities only, that the Sun is located near corotation. We tried to check this conclusion on the basis of space velocities of the youngest disk populations. We also derived a full maximum-likelihood solution for kinematical parameters of young populations in the model that includes pure rotation and noncircular deviations due to density waves.

2 OBSERVATIONAL DATA

We base our analysis on young objects with reliable and mutually adjusted distance scales: open clusters and classical cepheids. The sample of young open clusters includes 55 clusters with an estimated age less then 40 Myr and with heliocentric distances $r < 4$ kpc. The ages and distances of young open clusters have been derived by Dambis (1999) from UBV photoelectric and CCD-data using Kholopov's (1980) ZAMS, and evolutionary deviation curves calculated with the isochrones of Maeder and Meynet (1991). Mean radial velocities have been compiled from published data for cluster members by E. Glushkova, whereas mean HIPPARCOS proper motions have been calculated by Baumgardt *et al.* (2000). Cluster members have been carefully selected by taking into account all ground based information (photoelectric photometry and the position on the HR diagram, radial velocities, precise relative proper motions, and projected distances from the cluster center).

We used also 67 classical cepheids with the periods greater then 9 days (younger than 40 Myr, according to the period-age relation of Efremov (1989)) and with heliocentric distances $r < 4$ kpc. These cepheids are all fundamental mode pulsators, unlike the cepheids with $P < 9$ days, whose distances can be underestimated on average. Cepheid distances have been calculated with the period-luminosity relation of Berdnikov *et al.* (1996): $\langle M_V \rangle_I = -1.01^m - 2.87^m \log P(\text{days})$, derived for cepheids – members of open clusters. Thus, it can be expected that the distance scales of long-period cepheids and young open clusters are in good agreement. Radial velocities of cepheids have been collected from published data, and have a typical accuracy better then 0.5 km s^{-1}. Absolute proper motions of cepheids have been taken from the HIPPARCOS catalogue. Open clusters with $T < 40$ Myr and cepheids with $P > 9$ days form a uniform sample of the youngest objects, with good space velocities up to the distance of 4 kpc.

3 KINEMATICAL MODEL

We represented the space velocity field as a combination of pure rotation and non-circular motions due to the density waves. The residual velocity can be written as $\delta\boldsymbol{V} = \boldsymbol{V}_{\text{obs}} + \boldsymbol{V}_{\text{Sun}} - \boldsymbol{V}_{\text{rot}} - \boldsymbol{V}_{\text{spir}}$, where $\boldsymbol{V}_{\text{obs}}$ is the measured heliocentric space velocity, $\boldsymbol{V}_{\text{Sun}}$ is the solar velocity relative to local centroid, $\boldsymbol{V}_{\text{rot}}$ – the contribution from pure rotation, and $\boldsymbol{V}_{\text{spir}}$ is due to the perturbation from the density wave. Radial and azimuthal components of the perturbation can be written in the classical form (Lin, Yuan and Shu, 1969): $\Delta V_R = f_R \cos\chi$, $\Delta V_\theta = f_\theta \sin\chi$, where f_R and f_θ are the amplitudes of radial and azimuthal deviations from pure rotation, and the wave phase angle is $\chi = \chi_0 + m(\varphi + \cot(i)\ln(R/R_0))$. Here χ_0 is the phase angle of the Sun, m is the number of spiral arms, i is the pitch angle of the pattern, R_0 is the galactocentric distance of the Sun (which was set to 7.5 kpc), and φ is the positional angle of the object (measured contrary to the galactic rotation). The distribution function of $\delta\boldsymbol{V}$ can be expressed in the following general form

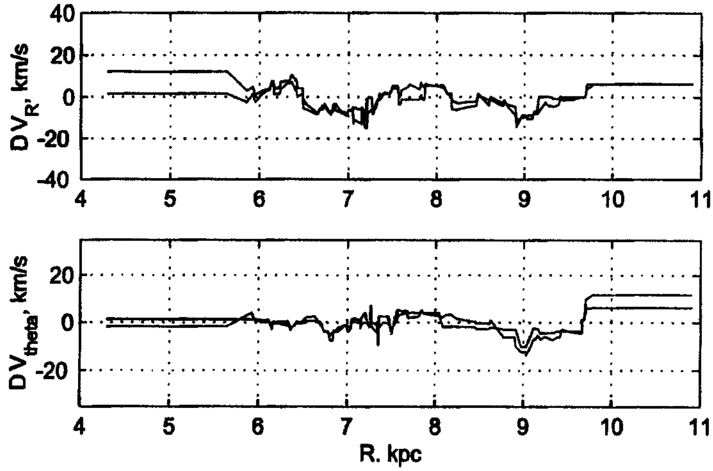

Figure 1 The deviations from purely circular motions (in km s^{-1}) of young open clusters and cepheids as a function of galactocentric distance R (kpc). Upper panel – radial residual velocity ΔV_R (positive from the galactic center); bottom panel – azimuthal residual velocity ΔV_θ (positive along galactic rotation). Solid lines - moving mean and median.

$f(\delta V) = (2\pi)^{-3/2}|L_{obs}|^{-3/2}\exp[-0.5\delta V^T \times L_{obs}^{-1} \times \delta V]$, where L_{obs} is the covariance matrix, which includes the triaxial distribution of residual velocities and the errors in observational data (Rastorguev *et al.*, 1999). The kinematical parameters have been estimated by minimizing the likelihood function, $LF = -\prod_{i=1}^{N} f(\delta V)$.

4 RESULTS AND DISCUSSION

The systematic deviations are clearly revealed on Figure 1, with amplitudes approximately 7 and 2 km s^{-1} for radial and azimuthal residuals respectively. This special pattern of residuals can be considered an argument for the wave nature of the disk's spiral arms. A similar pattern of residuals was detected by Melnik *et al.* (2001) for OB-associations. The characteristic distance between consecutive maxima (or minima) is close to 2 kpc. This means that the pitch angle can be estimated as 5–6° for the two-arm model and 10–12° for the four-arm model.

We present a full set of kinematical parameters for two-arm galaxy model, estimated by the maximum-likelihood method:

$V_0 = (6.9 \pm 3.2, 11.1 \pm 2.2, 6.9 \pm 1.3)$ km s^{-1} – solar velocity with respect to the local centroid, including the noncircular motion of the centroid;

$(\sigma_U, \sigma_V, \sigma_W) = (12.1 \pm 1.4, 8.0 \pm 1.0, 7.2 \pm 1.3)$ km s^{-1} – the components of the velocity dispersion tensor;

$(\Omega_0, \Omega_0', \Omega_0'') = (28.0 \pm 1.3, -4.67 \pm 0.24$ kps$^{-1}, 1.16 \pm 0.27$ kpc$^{-2})$ km s^{-1} kpc^{-1} – disk angular speed and its derivatives;

$(f_R, f_\theta) = (-6.8 \pm 2.7, 1.4 \pm 1.9)$ km s^{-1} – the amplitudes of systematic deviation;

$(i, \chi_0) = (5.8 \pm 0.6, 86 \pm 22)^\circ$ – pitch angle and phase angle of the Sun respectively. It should be noted that a positive value of the pitch angle corresponds to a trailing arm, and the phase angle χ increases from the galactic center.

Calculations of the four-arm model give nearly the same values for these kinematical parameters, but the amplitudes are slightly less, and the pitch angle is close to 12°. The two-arm solution is characterized by a smaller value of the goal function compared to the four-arm solution. But the question of the true number of spiral arms needs special discussion. To estimate the angular speed of the spiral pattern, Ω_p, according to the linear theory of density waves (Mishurov *et al.*, 1997), we have used the parameters of the rotation curve and the amplitudes calculated. The value of Ω_p can be found only with very large formal errors, and we put only a crude lower limit as $\Omega_p \sim 10$ km s^{-1} kpc^{-1}, in contrast to the result of Mishurov *et al.* (1997), derived from the analysis of radial velocities of all galactic cepheids, without taking into account the difference between the cepheids of short and long periods. We think that the corotation position cannot be resolved from kinematical fata alone.

Separate calculations, performed for the I+BI (galactic longitudes $0 < l < 180°$) and III+IV (galactic longitudes $110 < l < 269°$) quadrants give the following results: $(f_R, f_\theta) \simeq (-5.0 \pm 4.6, 3.9 \pm 3.4)$ km s^{-1} (I + II) and $(f_R, f_\theta) \simeq (-8.6 \pm 3.9, 0 \pm 2.4)$ km s^{-1} (III + IV). The small overall value of f_θ can be explained by the difference in kinematics between the two longitude intervals and by the poorly populated far spiral arm in tsx third galactic quadrant.

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