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Galactocentric distance of the Sun derived from kinematic data

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Abstract. Based on radial velocity data and *Hipparcos* proper motions, we present a new determination of the Galactocentric distance based on a purely kinematic model. We have selected three subgroups of Galactic thin-disk components (O–B5 stars, classical Cepheids and Galactic open clusters) to trace the local structure and kinematics of the Galactic disk. Adopting the approximation of axisymmetric circular rotation, we have derived the Sun's distance to the Galactic Center, $R_0 = 8.25 \pm 0.79$ kpc based on O–B5 stars, $R_0 = 7.98 \pm 0.79$ kpc based on Galactic Cepheids and $R_0 = 8.03 \pm 0.70$ kpc using open clusters, all of which are in excellent agreement with the current-best estimate of the Galactocentric distance.

Keywords. Galaxy: disk, Galaxy: fundamental parameters, Galaxy: kinematics and dynamics, solar neighborhood

1. Observational data

Three separate data sets, namely O–B5 stars, classical Cepheids and Galactic open clusters, will be used for our analysis of the local kinematic structure and to derive the Galactocentric distance.

1.1. *O–B5 stars*

The astrometric data are taken from the revised *Hipparcos* Catalogue compiled by van Leeuwen (2007), including proper motions and trigonometric parallaxes. The radial velocity data are taken from the General Catalogue of Mean Radial Velocities: 1190 O–B5 stars were selected for our analysis. All of these are single stars listed in the *Hipparcos* Catalogue; stars belonging to Gould's Belt have been individually excluded.

1.2. *Open clusters*

The data are based on two catalogues: the Catalog of Open Cluster Data (COCD) compiled by Kharchenko *et al.* (2005), and the new catalog of optically visible open clusters and candidates compiled by Dias *et al.* (2006). We selected 301 clusters with measurements of heliocentric distances, mean proper motions, mean radial velocities, ages, etc.

1.3. *Galactic Cepheids*

Cross-linking radial-velocity and photometric data of Cepheids in previous studies by several different authors, we selected 215 Galactic Cepheids with complete radial-velocity and photometric data from 249 sample stars in the *Hipparcos* Catalogue. Since the observing period covering the *Hipparcos* data was relatively short, we rejected a number of suspect binaries. The zeropoint of the period–luminosity relation, $\rho = -1.37 \pm 0.07$, is given by Zhang & Zhu (2009), derived from *Hipparcos* parallaxes and photometric measurements of Cepheids.

Figs 1 and 2 show distributions of the selected data projected onto the Galactic plane.

2. Models

2.1. *Proper motions*

Assuming that the Galaxy's rotation is axisymmetric, the observed proper motions of objects should represent Oort's model of differential rotation. To first-order approximation we have

$$\kappa\mu_\ell \cos b = (u_0 \sin\ell - v_0 \cos\ell)/r + A\cos 2\ell \cos b + B\cos b; \tag{2.1}$$

$$\kappa\mu_b = (u_0 \cos\ell \sin b + v_0 \sin\ell \sin b - w_0 \cos b)/r - \tfrac{1}{2}A \sin 2\ell \sin 2b, \tag{2.2}$$

where the constant $\kappa = 4.74047$. Proper motions are expressed in mas yr^{-1} and the heliocentric distances, r, are in units of kpc. The parameters u_0, v_0 and w_0 are components of the solar motion, pointing to the Galactic Center, in the direction of Galactic rotation, and to the North Galactic Pole, respectively. The Oort constants A and B are defined as

$$A = -\frac{1}{2}\mathrm{R}_0(\mathrm{d}\Omega/\mathrm{d}R)_0; \tag{2.3}$$

$$B = -\Omega_0 - \frac{1}{2}\mathrm{R}_0(\mathrm{d}\Omega/\mathrm{d}R)_0, \tag{2.4}$$

where Ω is the angular velocity, the subscript '0' refers to the Sun and r is the distance between the object of interest and the Sun.

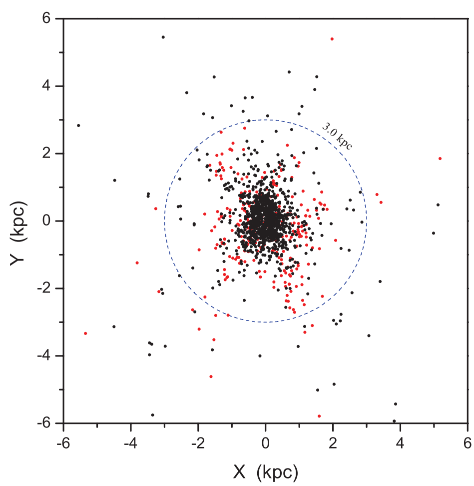

Figure 1. Distributions of 1190 O–B5 stars and 301 open clusters with respect to the Galactic plane. Black dots mark the O–B5 stars, red dots the open clusters. The blue dashed circle marks a heliocentric distance of 3.0 kpc.

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2.2. *Radial velocities*

For a star observed at Galactic coordinate (ℓ, b) and Galactocentric radius R, its radial velocity can be written as

$$v_{\rm r} = 2A{\rm R}_0 \left(\frac{{\rm R}_0}{R} - 1\right) \sin\ell\cos b - u_0 \cos\ell\cos b - v_0 \sin\ell\cos b - w_0 \sin b - \delta v_{\rm r}. \quad (2.5)$$

In this equation, $\delta v_{\rm r}$ expresses a possible systematic offset of the zeropoint defined by the radial velocities, which has been recognized for a long time. Due to the present thin sheets of our samples formed by O–B5 stars, open clusters and Cepheids, the component of the solar motion in the direction of the North Galactic Pole cannot be determined based on radial velocities. In the following analysis of our radial velocity data, w_0 will be fixed at the value $w_0 = 7.2 \pm 0.4$ km s^{-1} of Dehnen & Binney (1998).

The Galactocentric radius R of a star is given by

$$R = ({\rm R}_0^2 + r^2\cos^2 b - 2r{\rm R}_0\cos\ell\cos b)^{\frac{1}{2}}. \quad (2.6)$$

3. Results

Using the different subsamples, we derive the Oort constants A and B from proper motions, based on an axisymmetric kinematic model, i.e., Eqs (2.1) and (2.2). Then, by applying least-squares minimization to Eq. (2.5), the parameter $2A{\rm R}_0$ can be obtained from the radial velocities. Taking the constant A from the proper-motion solution, the Galactocentric distance ${\rm R}_0$ can be obtained. Note that the final solution of ${\rm R}_0$ is obtained in an iterative way. Table 1 shows all kinematic parameters, including the Sun's Galactocentric distance, separately determined from the proper motions and radial velocities of the selected O–B5 stars, open clusters and classical Cepheids.

The present determinations of ${\rm R}_0$ are based on independent observations of proper motions and radial velocities, derived from three different data sets characterizing the disk component. All results differ from the value of ${\rm R}_0 = 8.5$ kpc recommended by the IAU in 1985 (Kerr & Lynden-Bell 1986). Based on a careful statistical analysis, an averaged 'best' value of ${\rm R}_0 = 8.0 \pm 0.5$ kpc was proposed by Reid (1993), using data obtained during

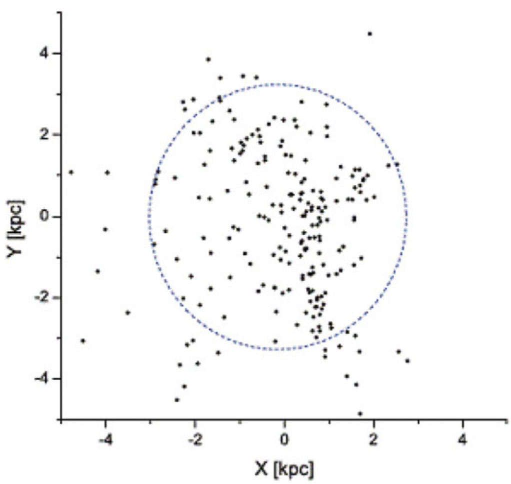

Figure 2. Projected positions of 215 classical Cepheids on the Galactic plane. Most sample stars are found within 3.0 kpc from the Sun.

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Table 1. Galactocentric distance of the Sun and other kinematic parameters obtained from O–B5 stars, open clusters and classical Cepheids. The units are km s^{-1} for δv_r, $2AR_0$ and the solar-motion components. The Oort constants are measured in km s^{-1} kpc^{-1}, R_0 is expressed in kpc.

Sample	Data	u_0	v_0	w_0	A	B	$2AR_0$	δv_r	R_0
O–B5 stars	Proper motions	10.08 ± 0.49	9.33 ± 0.46	5.74 ± 0.43	14.82 ± 1.16	−14.80 ± 0.85			
	Radial velocities	9.78 ± 0.56	13.31 ± 0.47	7.2 (fixed)	14.82 (fixed)		244.4 ± 13.4	2.69 ± 0.48	8.25 ± 0.79
Open clusters	Proper motions	10.82 ± 0.69	11.41 ± 0.70	7.75 ± 0.52	16.16 ± 1.07	−13.19 ± 0.76			
	Radial velocities	9.92 ± 1.24	12.34 ± 1.18	7.2 (fixed)	16.16 (fixed)		259.5 ± 14.7	2.42 ± 0.86	8.03 ± 0.70
Classical Cepheids	Proper motions	12.58 ± 1.09	14.52 ± 1.06	8.98 ± 0.98	17.42 ± 1.17	−12.46 ± 0.86			
	Radial velocities	5.75 ± 0.96	12.05 ± 0.84	7.2 (fixed)	17.42 (fixed)		238.5 ± 11.7	4.21 ± 0.88	7.98 ± 0.79

the 1970s and 1980s. Avedisova (2005) summarized estimates of R_0 derived during the decade prior to their study, and found an average value of $R_0 = 7.80 \pm 0.33$ kpc. Analyzing 52 determinations published in the period 1992—2011, Malkin (2012) recommends $R_0 = 8.0 \pm 0.25$ kpc as the current 'best' estimate of the Sun's Galactocentric distance. Our present determinations are consistent with those average values.

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