A Giant Step: from Milli- to Micro-arcsecond Astrometry
Proceedings IAU Symposium No. 248, 2007
W. J. Jin, I. Platais & M. A. C. Perryman, eds.

doi:10.1017/S1743921308019819

Structure and kinematics of the Milky Way spirals traced by open clusters†

Z. Zhu

Department of Astronomy, Nanjing University, China
email: zhuzi@nju.edu.cn

Abstract. Selecting 301 open clusters with complete spatial velocity measurements and ages, we are able to estimate the disk structure and kinematics of the Milky Way. Our analysis incorporates the disk scale height, the circular velocity of the Galactic rotation, the Galactocentric distance of the Sun and the ellipticity of the weak elliptical potential of the disk. We have derived the distance of the Sun to the Galactic center $R_0 = 8.03 \pm 0.70$ kpc, that is in excellent agreement with the literature. From kinematic analysis, we found an age-dependent rotation of the Milky Way. The mean rotation velocity of the Milky Way is obtained as 235 ± 10 km s^{-1}. Using a dynamic model for an assumed elliptical disk, a clear weak elliptical potential of the disk with ellipticity of $\epsilon(R_0) = 0.060 \pm 0.012$ is detected, the Sun is found to be near the minor axis with a displacement of $30^\circ \pm 3^\circ$. The motion of clusters is suggested to be on elliptical orbits other than the circular rotation.

Keywords. Galaxy: disk, astrometry, Galaxy: kinematics and dynamics, Galaxy: structure, open clusters and associations: general

1. Introduction

The young open clusters have an unusual superiority over other tracers of the disk structure in the Milky Way, providing crucial information and constraints for understanding of the Galactic kinematics and dynamics. Due to the increase of available data on open clusters in the recent years, we are able to refine our study of the Galactic structure. In this paper, we concentrate on a kinematical analysis based on proper motions, distances, radial velocities, and ages of open clusters. Considering the systematic consistency of kinematical data, we decide to use the internally homogeneous Catalogue of Open Cluster Data compiled by Kharchenko *et al.* (2005). In order to increase the number of clusters, we used the New Catalog of Optically Visible Open Clusters and Candidates, that includes 1689 clusters collected from the literature (Dias *et al.* 2002). Finally, a total amount of 301 clusters with complete spatial velocity measurements is selected for this study.

The velocity data are used to inspect the peculiar motions for the individual clusters. The components of peculiar motion are derived from the first order expansion of an asymmetric rotation of the systematic velocity field. Rejecting 22 clusters with peculiar velocities over 50 km s^{-1} (roughly 2.6σ of the total velocity dispersion), 269 clusters are finally used for the kinematic analysis. Figure 1 shows the kinematical structures and distributions of 269 clusters on the Galactic plane.

† Supported by the National Natural Science Foundation of China(Grant Nos. 10333050 and 10673005)

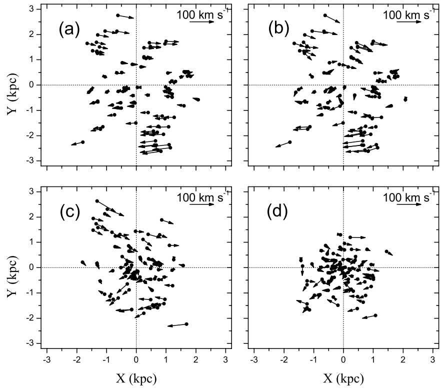

Figure 1. Observed space velocities of clusters projected on the Galactic plane. The solar motion components u_0 and v_0 are removed from the observational data. Panel (a): Simulation of 90 clusters younger than 18 Myr, assuming R_0=8 kpc, V_0=220 km s^{-1}, and $(\partial V/\partial R)_{R=R_0}$=4 km s^{-1} kpc^{-1}. Panel (b): 90 clusters younger than 18 Myr. Panel (c): 88 clusters with ages in the range of 18–120 Myr. Panel (d): 91 clusters older than 120 Myr.

Table 1. Solution of the parameters of the vertical distribution.

	10 pc bins		20 pc bins	
	z_0 [pc]	z_h [pc]	z_0 [pc]	z_h [pc]
all ages	-16.1 ± 4.0	58.3 ± 4.0	-15.6 ± 3.5	56.8 ±3.5
$\leqslant$ 50 Myr	-12.3 ± 4.2	51.8 ± 4.6	-12.4 ± 4.2	49.6 ±4.4
> 50 Myr	-20.5 ± 5.6	67.8 ± 5.8	-19.5 ± 5.7	67.1 ±5.7
all ages (PKRSS 2006)			-22 ± 4	56 ± 3
all ages (BKBS 2006)			-14.8 ± 2.4	57.2 ± 2.8
$\leqslant$ 200 Myr (BKBS 2006)				47.9 ± 2.8
200 $\sim$ 1000 Myr (BKBS 2006)				149.8 ± 26.3

2. The disk scale height and kinematics

The recent work concerning the structure and distribution of the Galactic open clusters is detailed by Piskunov *et al.*(2006, PKRSS), and by Bonatto et al.(2006, BKBS). In this Section, we first extend the study on the vertical structure based on open cluster data. In order to study the properties of clusters in different age range, we divide the sample into two subsets: young clusters with ages less than 50 Myr, and old clusters with ages larger than 50 Myr. The results are given in Table 1, where z_0 is the position about the Galactic symmetry plane, z_h is the scale height of the distribution. Note that 17 clusters associated with the Gould's Belt are removed from the samples. Comparing our results with those given by PKRSS and BKBS, we found that most of the solutions are matching very well. However, the value $z_h \simeq 150$ pc for clusters with 200 $\sim$ 1000 Myr obtained by BKBS significantly deviates from our determination for older clusters. We found that the oldest clusters in BKBS have mostly erroneous distance estimate, explaining the extremal value of $z_h \simeq 150$ pc for clusters older than 200 Myr as derived by BKBS.

Because the objects in our sample are confined to the Galactic plane with a small scale height of ∼60 pc, a two dimensional asymmetric model is sufficient to describe their motion. In this case, we define the Oort's constants A, C (denote the azimuthal and

https://doi.org/10.1017/S1743921308019819 Published online by Cambridge University Press

Table 2. Kinematic parameters derived from proper motions and radial velocities. The unit is in km s^{-1} for components of the solar motion. The Oort's constants are measured in km s^{-1} kpc^{-1}.

	u_0	v_0	w_0	A	B	C	K
all ages (269)	11.8±0.6	13.3±0.6	8.1±0.5	16.4±0.9	-12.9±0.9	0.5±1.0	-2.6±0.9
$\leqslant$ 50 Myr (137)	10.8±0.7	14.6±0.7	7.9±0.8	16.5±0.9	-14.6±0.9	2.9±0.8	-1.1±0.9
$>$ 50 Myr (132)	12.3±0.9	12.8±0.8	8.2±0.8	16.4±1.7	-10.9±1.6	-2.7±1.7	-4.6±1.8

radial directions of the velocity field), B (characterizes the vorticity), and K (implies an overall contraction or expansion measured at the Sun). Based on proper motions, radial velocities and heliocentric distances of open clusters, these parameters including solar motions are given in (Table 2).

In an axisymmetric and stationary disk, the Oort's constants A and B describe a differential circular rotation of the Milky Way at the place of the Sun. Feast & Whitelock (1997) found a low angular velocity ($A = 14.8 \pm 0.8$, $B = -12.4 \pm 0.6$ km s^{-1} kpc^{-1}) from the Hipparcos proper motions of the Galactic Cepheids. But the majority of measurements in the recent year have shown a more or less enhanced angular velocity, including our present determination. From the Hipparcos proper motions of the Galactic O-B5 stars, Miyamoto & Zhu (1998) derived $A = 16.1 \pm 1.1$ and $B = -15.6 \pm 0.8$ in km s^{-1} kpc^{-1}. From proper motions of the old red giants from ACT/Tycho-2 catalogues, Olling & Dehnen (2003) found $A - B \simeq 32.8$ km s^{-1} kpc^{-1}. According to observations of the massive compact radio source Sgr A* at the Galactic center by VLBA with respect to the extragalactic sources, Reid & Brunthaler (2004) reported the apparent proper motion of Sgr A* $\mu_\ell = -6.379 \pm 0.026$ and $\mu_\mathrm{b} = -0.202 \pm 0.019$ mas yr^{-1}. This apparent motion should fully reflect the Galactic rotation at the Sun, assuming Sgr A* is in rest. Then we have $A - B = -\kappa\mu_\ell - v_0/R_0$, where $v_0 = 5.25 \pm 0.62$km s^{-1} is the component of the solar motion in the direction of Galactic rotation given by Dehnen & Binney (1998). Adopting $R_0 = 8.0\,\mathrm{kpc}$, $A - B = 29.58 \pm 0.14$km s^{-1} kpc^{-1} was calculated. This is in excellent agreement with our determination. The present determination gives a rotation velocity $V_0 = 235 \pm 10$ km s^{-1} from the complete sample, while $V_0 = 248 \pm 9$ km s^{-1} is for the young and $V_0 = 218 \pm 19$ km s^{-1} for the older sub-sample.

The precision of R_0 is directly related to many astronomical quantities, measurements and theory. According to the statistical analysis from the individual determinations by Reid (1993), $R_0 = 8.0 \pm 0.5\,\mathrm{kpc}$ is currently considered as the best value, whereas the 1985 IAU standard value is 8.5 kpc. Considerable bias and uncertainties may still exist in the determinations of R_0, even if researchers have employed various efforts to improve it, e.g. from the latitude proper motion of the Sgr A* ($\mu_\mathrm{b} = -0.202 \pm 0.019$ mas yr^{-1}), we get $R_0 = w_0/\mu_\mathrm{b}/\kappa = 7.49 \pm 0.81$ kpc, assuming Sgr A* is at rest. Here $w_0 = 7.17 \pm 0.38$km s^{-1} is the component of the solar motion.

Encouraged by the kinematic analysis, in which we found that the Oort's constant A is independent on the cluster age, we decided to derive the Galactocentric distance of the Sun R_0. Because only small values for C and K of the Oort's constants are found, we are able to simply use an axisymmetric rotation model. The Oort's constant A is independently derived from the proper motions of clusters. We apply this constant to constrain a kinematical model from the radial velocities

$$v_r = 2AR_0(\frac{R_0}{R} - 1)\sin\ell\cos b - u_0\cos\ell\cos b - v_0\sin\ell\cos b - w_0\sin b - \delta v_r, \quad (2.1)$$

where, δv_r is a possible offset of the radial velocity zero-point. The parameter $2AR_0$ can

https://doi.org/10.1017/S1743921308019819 Published online by Cambridge University Press

be calculated from the radial velocities. Using the constant A from the proper-motion solution, the Galactocentric distance R_0 is derived in an iterative way.

The present determination of R_0, based on independent observations for proper motions and radial velocities of clusters, gives $R_0 = 8.03 \pm 0.70$ kpc that is consistent with the current "best estimate" of $R_0 = 8.0 \pm 0.5$ kpc proposed by Reid (1993).

3. The weak elliptical distortion of the disk potential

The persistence of a significant K-term or δv_r for the radial velocities of Galactic young objects has been recognized before. It can be explained either as an overall kinematic contraction or expansion on the Galactic plane, or as a systematic error of the measured radial velocities. On the other hand, if the axisymmetric model is not sufficient to describe the rotation defined by the young disk stars on non-circular orbits in the Galactic plane, a non-axisymmetric model should be introduced to describe such kinematic behavior. Considering rotation velocities of clusters as a function of azimuthal angle, we find that the circular speed gradually decreases in the direction of the Galactic rotation. This fact might be an evidence for the open clusters moving on non-circular orbits. Based on the model of an elliptical disk given by Kuijken & Tremaine (1994), the potential is expressed by

$$\Phi(R, \phi) = \Phi_0(R) + \Phi_1(R) \cos 2(\phi - \phi_{\mathrm{b}}) , \tag{3.1}$$

where $\Phi_0(R)$ is the circular velocity depended axisymmetric part of the potential. In this potential, the mean tangential velocity is expressed by

$$V_\phi(R, \phi) = V_c(R)(1 - c(R) \cos 2\phi - s(R) \sin 2\phi) , \tag{3.2}$$

with two components of the ellipticity $c(R) = \epsilon(R) \cos 2\phi_{\mathrm{b}}$, $s(R) = \epsilon(R) \sin 2\phi_{\mathrm{b}}$. Here, $\epsilon(R)$ is the potential ellipticity with its minor axis in the direction ϕ_{b}. In order to have a more rigorous evaluation for the ellipticity of the gravitational potential, we have test various solutions by using the observed spatial velocities of clusters. Finally, we obtain the components $c(R_0)$ and $s(R_0)$. The present solution suggest

$$\epsilon(R_0) = 0.060 \pm 0.012, \qquad \phi_b = 30^\circ \pm 3^\circ . \tag{3.3}$$

The present work is the first to succeed in quantifying the two elliptical components of the Milky Way potential via a consistent data set of the disk population of open clusters and based on a simple dynamic model by Kuijken & Tremaine. Using our solution from the open clusters, the motion of objects near the Sun is suggested to be on elliptical orbits.

References

Bonatto, C., Kerber, L. O., Bica, E., & Santiago, B. X. 1997, *A&A* 446,121 (BKBS)
Dehnen, W. & Binney, J. J. 1998, *MNRAS* 298, 387
Dias, W. S., Alessi, B. S., Moitinho, A., & Lépine, J. R. D. 2002, *A&A* 389, 871
Feast, M. W. & Whitelock, P. 1997, *MNRAS* 291, 683
Kharchenko, N. V., Piskunov, A. E., Röser, S., Schilbach, E., & Scholz, R. D. 2005, *A&A* 438, 1163
Kuijken, K. & Tremaine, S. 1994, *ApJ* 421, 178
Miyamoto, M. & Zhu, Z. 1998, *AJ* 115, 1483
Olling, R. P. & Dehnen, W. 2003, *ApJ* 955, 275
Piskunov, A. E., Kharchenko, N. V., Röser, S., *et al.* 2006, *A&A* 445, 545 (PKRSS)
Reid, M. J. 1993, *ARA&A* 31, 345
Reid, M. J. & Brunthaler, A. 2004, *ApJ* 616, 872