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Kinematics of the Open Cluster System in the Galaxy *

Jun-Liang Zhao, Li Chen and Zhong-Liang Zu

Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030
chenli@shao.edu.cn

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Abstract Absolute proper motions and radial velocities of 202 open clusters in the solar neighborhood, which can be used as tracers of the Galactic disk, are used to investigate the kinematics of the Galaxy in the solar vicinity, including the mean heliocentric velocity components (u_1, u_2, u_3) of the open cluster system, the characteristic velocity dispersions $(\sigma_1, \sigma_2, \sigma_3)$, Oort constants (A, B) and the large-scale radial motion parameters (C, D) of the Galaxy. The results derived from the observational data of proper motions and radial velocities of a subgroup of 117 thin disk young open clusters by means of a maximum likelihood algorithm are: $(u_1, u_2, u_3) = (-16.1 \pm 1.0, -7.9 \pm 1.4, -10.4 \pm 1.5)$ km s^{-1}, $(\sigma_1, \sigma_2, \sigma_3) = (17.0 \pm 0.7, 12.2 \pm 0.9, 8.0 \pm 1.3)$ km s^{-1}, $(A, B) = (14.8 \pm 1.0, -13.0 \pm 2.7)$ km s^{-1} kpc^{-1}, and $(C, D) = (1.5 \pm 0.7, -1.2 \pm 1.5)$ km s^{-1} kpc^{-1}. A discussion on the results and comparisons with what was obtained by other authors is given.

Key words: Galaxy: kinematics and dynamics — open clusters and associations: general

1 INTRODUCTION

For a long time, the distribution and kinematics of stars in the solar neighborhood have been used to study the structure and large-scale kinematics of the Galaxy. Kinematic parameters, including the mean solar motion, the Oort constants which describe the Galactic differential rotation, Galactic radial motion parameters and velocity ellipsoid principal axes, are introduced to describe the kinematical properties of the Galaxy, and the new Oort constants were proposed by the IAU in 1985.

Studies on open clusters are very important in the investigation of the structure and kinematics of the Galaxy, especially the Galactic disk. First, open clusters belong to the extreme population I objects, being the ideal tracers of the young disk. Secondly, proper motion and radial velocity data of open clusters can be obtained more precisely than those of individual field stars, even when they are far away from the Sun. These two factors make it obvious that the system of open cluster can play an important role in the research of large-scale kinematical properties of the Galaxy. For many years various kinds of celestial objects have been used to derive the kinematical parameters of the Galaxy. For examples, Johnson & Svolopoulos (1961) used a sample of 36 open clusters with radial velocities available to determine the Oort constant A, Taff & Littleton (1972) discussed the discrepancy between the values of the Oort constant A obtained from kinematical data of open clusters and supergiants, Creze (1973) derived the Oort constant A and the components of the mean solar motion from radial velocities of three kinds of population I objects: Population I Cepheids, HII regions and open clusters; Glushkova et al. (1998) determined the Oort constant A and the

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components of the mean solar motion from some 700 Population I objects including young open clusters, classical Cepheids and red supergiants. Recently, Rastorguev et al. (1999) applied the method of statistical parallax to derive the mean solar motion, the Oort constants and the velocity ellipsoid principal axes from 270 classical Cepheids and 117 young open clusters. Based on the Hipparcos proper motion and available radial velocity data of O-B stars, Zhu (2006) examined the local kinematical structure of the young disk population.

Our present work is to adopt a rigorous statistical approach to determine the kinematic parameters of the open cluster system based on the greatly increased volume of observed proper motions and/or radial velocities of open clusters published in recent years. This enables us to make a re-examination of the mean heliocentric velocity, the velocity ellipsoid of the system, the Oort constants and the radial motion parameters of the Galaxy.

2 OBSERVATIONAL SAMPLES OF OPEN CLUSTERS

Before performing further analyses, we first obtain a proper sample of open clusters with enough members. From the Dias et al.'s catalog (Dias et al. 2002), we compiled a list of 209 open clusters with both proper motions and radial velocities available (see Table 1, only a portion of the data is shown here. The whole table is only available in an electric version) and a list of 41 clusters with only radial velocity measurements (Table 2). In Table 1, column 1 is the serial number of the cluster, column 2 its name, columns 3 and 4 its galactic longitude and latitude in degrees, columns 5 and 6 its heliocentric and galactocentric distances in parsecs, columns 7, 8 and 9 its radial velocity in km s^{-1} and proper motions along galactic longitude and latitude in mas yr^{-1}, columns 10, 11 and 12 their corresponding rms errors, and column 13 the age of the cluster in Gyr. For Table 2, columns 1–6 are the same as in Table 1, columns 7 and 8 the radial velocity and the corresponding rms error in km s^{-1}, and column 9 is its age in Gyr.

Among these open clusters, some may not belong to the thin disk of the Galaxy. In order to reduce the impact of those clusters on the final results, we impose the criterion $|r \sin b| \leq 0.4$ kpc (Zhao 1984a), r being the heliocentric distance of the cluster and b its galactic latitude. Hence, 202 clusters are selected from the total 209 objects listed in Table 1, which are regarded as belonging to the thin disk. We also use this criterion to verify that all of the 41 open clusters in Table 2 belong to the thin disk. These two subsamples of 202 and 41 open clusters are used in the following analyses.

There are two factors which should be noted before further discussion: the age and the heliocentric distance of the clusters. Since open clusters with different ages may have different kinematical characteristics, it is necessary to make a detailed discussion on kinematics of open clusters with different ages. As for the second factor, the Oort formulae used to describe the large-scale kinematics of the Galaxy are usually only applicable to stars or clusters with heliocentric distances not greater than 2 kpc. Therefore, if the cluster

Table 1 List of Galactic Open Clusters with both Radial Velocity and Proper Motion Data Available

No. (1)	Name (2)	l (3)	b (4)	$r_\odot$ (5)	R_{gc} (6)	ρ (7)	μ_l (8)	μ_b (9)	σ_ρ (10)	σ_l (11)	σ_b (12)	age (13)
1	NGC 129	120.2	–02.5	1625	9423	–036.8	–00.92	+01.68	00.3	2.81	2.81	0.07
2	NGC 188	122.8	+22.3	2047	9689	–045.0	–01.49	–00.54	10.0	1.25	1.24	4.28
3	NGC 436	126.1	–03.9	3014	10557	–074.4	+01.34	–04.00	00.3	0.24	0.22	0.08
4	NGC 457	126.6	–04.3	2429	10134	–025.1	–00.40	–01.96	03.0	2.47	2.47	0.02
5	NGC 581	128.0	–01.8	2194	10002	–043.7	–01.69	+00.39	05.3	2.40	2.14	0.02
6	NGC 637	128.5	+01.7	2160	9989	–046.0	+01.62	–02.64	10.0	1.11	0.65	0.01
7	NGC 654	129.0	–00.3	2041	9914	–033.8	–01.17	–00.98	01.4	0.51	0.64	0.01
8	NGC 663	129.4	–00.9	1952	9856	–032.0	–00.97	–02.56	02.0	0.85	0.89	0.01
9	NGC 752	137.1	–23.2	457	8814	+004.7	+10.38	–08.98	00.8	2.24	2.24	1.12
...	...	...	...	...	...	...	...	...	...	...	...	...
207	King 11	117.1	+06.4	2892	10144	–035.0	–04.96	–00.37	16.0	0.73	0.76	1.11
208	NGC 7789	115.5	–05.3	2337	9734	–064.0	+04.03	–00.65	09.0	0.72	0.68	1.71
209	Berkeley 58	116.5	–01.0	2944	10164	–078.0	–01.15	–01.95	00.5	2.13	1.58	0.05

Table 2 List of Galactic Open Clusters with Radial Velocity (but no proper motion) Data Available

No. (1)	Name (2)	l (3)	b (4)	$r_\odot$ (5)	$R_{\rm gc}$ (6)	ρ (7)	σ_ρ (8)	age (9)
1	NGC 6649	21.6	–0.8	1369	7245	–8.8	4.0	0.04
2	Trumpler 35	28.3	0.0	1206	7460	–4.7	0.7	0.07
3	NGC 6939	95.9	12.3	1185	8699	–42.00	10.0	2.22
4	NGC 7128	97.3	0.4	2307	9088	–48.0	5.0	0.02
5	NGC 7789	115.5	–5.3	2337	9734	–64.00	9.0	1.72
6	King 11	117.1	6.4	2892	10145	–34.00	12.0	1.12
7	NGC 436	126.1	–3.9	3014	10557	–74.4	0.3	0.08
8	NGC 637	128.5	1.7	2160	9989	–46.00	10.0	0.01
9	IC 166	130.0	–0.1	3970	11465	–0.178	0.20	0.43
10	Upgren 1	143.7	–4.2	1900	10091	–52.00	12.0	1.00
11	Berkeley 17	175.6	–3.6	2700	11190	–84.00	11.0	12.02
12	NGC 2158	186.6	1.7	5071	13548	+28.00	10.0	1.05
13	Berkeley 29	197.9	8.0	14871	23054	–0.18	0.15	1.06
14	NGC 2420	198.1	19.6	3085	11345	+84.00	13.0	1.12
15	Berkeley 20	203.5	–17.2	8400	16366	–0.75	3.0	6.01
16	NGC 2251	203.5	0.1	1329	9733	+24.7	0.4	0.27
17	Berkeley 32	207.9	4.4	3100	11326	+101.0	10.0	3.39
18	Bochum 2	212.3	–0.3	2661	10843	+66.3	4.4	0.01
19	Berkeley 39	223.4	10.0	4780	12376	+55.00	10.0	7.94
20	NGC 2204	226.0	–16.1	2629	10440	+59.00	27.0	0.79
21	Haffner 8	227.5	1.3	1182	9339	+0.060	0.04	1.41
22	NGC 2506	230.5	9.9	3460	11001	+94.00	10.0	1.11
23	Tombaugh 2	232.8	–6.8	13260	19578	+114.0	12.0	1.02
24	NGC 2384	235.3	–2.3	2116	9856	+51.00	7.0	0.01
25	NGC 2367	235.5	–3.8	2004	9771	+41.00	8.0	0.01
26	NGC 2243	239.4	–18.0	4458	11346	+62.00	9.0	1.08
27	Haffner 19	243.0	0.5	5094	11722	+68.00	6.0	0.01
28	Ruprecht 55	250.6	0.8	4892	11121	+96.2	3.0	0.01
29	NGC 2477	253.5	–5.8	1222	8921	+7.00	7.0	0.70
30	Melotte 66	259.5	–14.2	4313	10185	+23.00	6.0	2.79
31	Ruprecht 67	262.7	–0.7	1504	8816	–15.4	0.8	0.18
32	Ruprecht 79	277.0	–0.8	1979	8456	+21.4	1.2	0.01
33	Pismis 16	277.8	0.6	1824	8447	+11.0	4.4	0.07
34	Collinder 223	286.0	–1.6	1686	8196	+2.00	1.0	0.01
35	Trumpler 16	287.6	–0.6	2673	8103	–20.00	5.0	0.01
36	NGC 3572	290.7	0.2	1995	8015	–4.1	1.7	0.01
37	IC 2714	292.4	–1.7	1238	8109	–14.1	1.7	0.35
38	NGC 3960	294.3	6.1	2258	7849	–12.00	6.0	0.66
39	Stock 16	306.1	0.1	1640	7648	–45.00	20.0	0.01
40	Pismis 20	320.5	–1.2	2018	7061	–49.00	15.0	0.01
41	Ruprecht 127	352.8	–2.5	1466	7049	–29.9	4.0	0.02

sample contains objects with heliocentric distances greater than 2 kpc, these clusters will probably exert an impact on the final solution. It is necessary to analyze the kinematical properties of open clusters with different heliocentric distances.

Table 3 lists the number of open clusters in different ranges of heliocentric distance r and different age t; those younger than 0.8 Gyr are regarded as young clusters, and those older than 0.8 Gyr, old clusters (Chen et al. 2003). Because of the reasons mentioned above, in the following discussion we will pay more attention to the clusters with ages younger than 0.8 Gyr and heliocentric distances between 0.5 kpc and 2.0 kpc, since these clusters can be regarded as proper tracers of the kinematics of the Galactic thin disk.

Table 3 Numbers of Open Clusters in Different Distance and Age Groups

	Range	Number of clusters
Heliocentric distances	(a) $r < 0.5$ kpc	31
	(b) $0.5 < r < 2.0$ kpc	128
	(c) $r > 2.0$ kpc	43
Ages $(0.5 - 2.0\,\mathrm{kpc})$	(d) $t < 0.8$ Gyr	117
	(e) $t > 0.8$ Gyr	11
Total		202

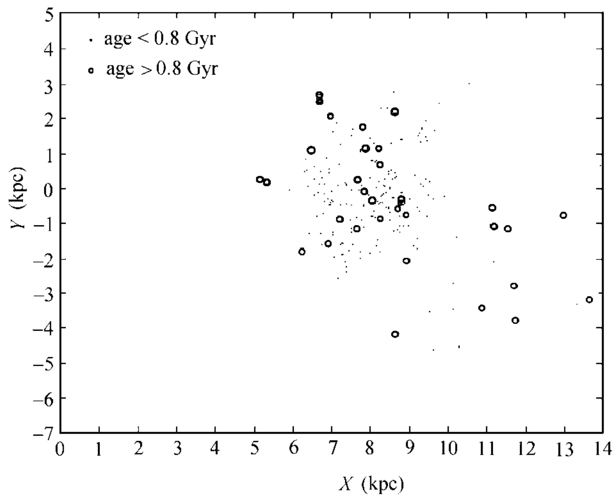

Fig. 1 Projected distribution of open clusters on the disk plane.

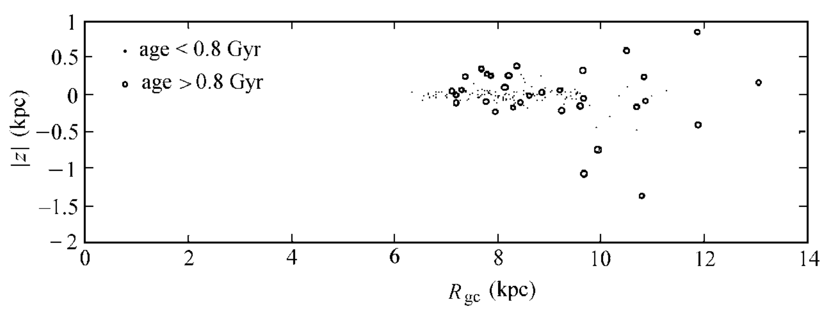

Fig. 2 Projected distribution of open clusters on the $R_{\rm gc}$–$|z|$ plane.

Figure 1 shows the projected distribution of the sample clusters on the disk plane, while Figure 2 gives the projected distribution on the $R_{\rm gc}$–z plane, $R_{\rm gc}$ being the galactocentric distance and z perpendicular to the Galactic plane. It can be seen from Table 3 that about 63% of the open clusters in the sample have heliocentric distances between 0.5 kpc and 2.0 kpc. At heliocentric distances greater than about 2 kpc the sample clusters are obviously incomplete. If we use R to denote the galactocentric distance of the cluster and $|z|$ its distance to the Galactic plane, then we find that 68% of the sample clusters have values of R in the range 7.5–9.5 kpc. From Figure 2 it can be seen that about 50% of the clusters in our sample have $|z|$

less than 50 pc and most of them have $|z|$ less than 400 pc. This indicates that the sample clusters with ages younger than 0.8 Gyr, heliocentric distances of 0.5–2.0 kpc and $|z|$ less than 400 pc should belong to the thin disk and can be used as thin disk markers when studying the kinematical properties of our Galaxy.

3 MAXIMUM LIKELIHOOD ESTIMATION OF THE KINEMATICAL PARAMETERS

3.1 Kinematical Parameters

The kinematical parameters considered in the present work should include the mean heliocentric motion (u_1, u_2, u_3), the velocity ellipsoid principal axes or characteristic velocity dispersions $(\sigma_1, \sigma_2, \sigma_3)$, the Oort constants (A, B), and the large-scale radial motion parameters (C, D) of the Galaxy. The relations between (A, B) and (ω_0, ω_0') and between (C, D) and $(\varepsilon_0, \varepsilon_0')$ are as follows:

$$\left.\begin{array}{l} A = -\frac{1}{2}R_0\omega_0', B = A - \omega_0 \\ C = \frac{1}{2}R_0\varepsilon_0', D = C + \varepsilon_0 \end{array}\right\}, \tag{1}$$

where ω is the angular velocity around the Galactic center, ω' is the rate of change of ω with the galactocentric distance R, $\varepsilon = dR/Rdt = \dot{R}/R$, where $\dot{R}$ is the rate of change of the galactocentric distance R of the object with time, and $\varepsilon'$is the rate of change of ε with R. The subscript "0" refers to evaluation at the galactocentric distance of the Sun, R_0. It can be found from Equation (1) that the Oort constants A and B are not independent of each other, and same is the case for the radial motion parameters C and D. Thus, we should use ω_0, ω_0', ε_0 and ε_0', rather than A, B, C and D, when determining the parameters.

Therefore, what we should do is to simultaneously determine all the 10 kinematical parameters (u_1, u_2, u_3), $(\sigma_1, \sigma_2, \sigma_3)$, ω_0, ω_0', ε_0 and ε_0' and their corresponding uncertainties in a reasonable and strict mathematical way.

3.2 Mathematical Model

In 1971, Clube & Jones (1971) developed a maximum likelihood technique to solve the kinematical parameters of the Galaxy, and we will in principle use their mathematical model to estimate the above 10 kinematical parameters. However, the present case is not exactly the same as what was presented by Clube & Jones (1971): the kinematical parameters in the present problem coincide with only six out of the eight parameters in Clube & Jones' model, namely, the three mean heliocentric velocity components and three characteristic velocity dispersions. Thus, we should first establish a mathematical model appropriate for our purpose.

We follow the conventional practice which assumes that the open clusters in the sample have a mean motion relative to the Sun and each component of the residual motions of individual clusters with respect to the mean component follows a Gaussian distribution. The residual velocities of of the i-th cluster can be written in the following form:

$$\Delta v_{is} = v_{is} - V_{is}, \tag{2}$$

where $v_{is} = (kr\mu_l \cos b, kr\mu_b, V_r)_i$ are the observed velocities of the cluster; $V_{is} = (V_1, V_2, V_3)_i$ are the theoretical expected velocities of the cluster, which are dependent on the mean heliocentric velocities $u_j\,(j = 1, 2, 3)$ of the sample and of the differential rotation and large-scale radial motion of the Galaxy. From the Oort theory we have

$$\begin{array}{rcl} \Delta v_1 &=& kr\mu_l \cos b - V_1 \\ &=& kr\mu_l \cos b + \sin l \cdot u_1 - \cos l \cdot u_2 \\ && +r\omega_0 \cos b - (R - R_0)\,(R_0 \cos l - r \cos b)\,\omega_0' \\ && -R_0\,(R - R_0)\,\varepsilon_0' \sin l, \\ \Delta v_2 &=& kr\mu_b - V_2 \\ &=& kr\mu_b + \cos l \sin b \cdot u_1 + \sin l \sin b \cdot u_2 - \cos b \cdot u_3 \\ && +R_0\,(R - R_0)\,\omega_0' \sin l \cos b \end{array} \tag{3}$$

$$
\begin{aligned}
& +r\varepsilon_0 \sin b \cos b - (R - R_0)\,(R_0 \cos l - r \cos b)\,\varepsilon_0' \sin b, \quad (4)\\
\Delta v_3 &= V_r - V_3\\
&= V_r - \cos l \cos b \cdot u_1 - \sin l \cos b \cdot u_2 - \sin b \cdot u_3\\
& -R_0\,(R - R_0)\,\omega_0' \sin l \cos b\\
& -r\varepsilon_0 \cos^2 b + (R - R_0)\,(R_0 \cos l - r \cos b)\,\varepsilon_0' \cos b, \quad (5)
\end{aligned}
$$

where $k = 4.74$, (μ_l, μ_b) and V_r are the observed proper motions (mas yr^{-1}) and radial velocity (km s^{-1}) of the cluster, respectively; Δv_1, Δv_2 and Δv_3 are the residuals of the tangent velocities and the radial velocity; r, l, b are the heliocentric galactic coordinates of the cluster; (R_0, R) are the galactocentric distances of the Sun and the cluster. In Equations (3)–(5) we have omitted the subscript i.

The variances ε_{is}^2 of the residual velocities can be written as

$$\varepsilon_{is}^2 = \sigma^2\,(v_{is}) + \sigma^2\,(V_{is}),$$

where $\sigma^2\,(v_{is})$ and $\sigma^2\,(V_{is})$ are the variances of the observed and expected velocities, respectively. For a sample of n open clusters, the likelihood function is

$$L = \prod_{i=1}^{n} \prod_{s=1}^{3} p_{is}\,(x_q)\,, \quad (6)$$

where $p_{is}\,(x_q)$ $(i = 1, 2, ..., n; s = 1, 2, 3)$ is the 'a posteriori' probability for each observational value (i, s),

$$p_{is}\,(x_q) = \left(2\pi\varepsilon_{is}^2\right)^{-\frac{1}{2}} \exp\left(\frac{-\frac{1}{2}\Delta v_{is}^2}{\varepsilon_{is}^2}\right), \quad (7)$$

and $(x_q, q = 1, 10) \equiv (u_1, u_2, u_3, \omega_0, \omega_0', \varepsilon_0, \varepsilon_0', \sigma_1, \sigma_2, \sigma_3)$ are the unknown parameters to be determined. Let n_1 be the number of the clusters with both proper motions and radial velocities available, and n_2 the number of clusters with only radial velocities available, then the total number of observational values is $N = 3n_1 + n_2$.

3.3 Development of Formulae

For the convenience of developing the formulae, we rewrite V_{is} in Equations (3)–(5),

$$V_{is} = \sum_{j=1}^{7} a_{isj} u_j,$$

where $(u_j, j = 1, 7) = (u_1, u_2, u_3, \omega_0, \omega_0', \varepsilon_0, \varepsilon_0')$ and a_{isj} are the corresponding coefficients of u_j in Equations (3)–(5). Then, we have the variances of V_{is},

$$\sigma^2\,(V_{is}) = \sum_{j=1}^{3} a_{isj}^2 \sigma_j^2.$$

Thus

$$\varepsilon_{is}^2 = \sigma^2\,(v_{is}) + \sum_{j=1}^{3} a_{isj}^2 \sigma_j^2.$$

According to the principle of maximum likelihood

$$\frac{\partial \ln L}{\partial x_q} = 0\ , \qquad (q = 1, 2,\ \cdots,\ 10), \quad (8)$$

then we have

$$\sum_{i=1}^{n}\sum_{s=1}^{3}\varpi_{is}\left(\frac{\partial\Delta v_{is}^2}{\partial x_q}+R_{is}\frac{\partial\varepsilon_{is}^2}{\partial x_q}\right)=0\ ,\qquad (q=1,2,\ \cdots,\ 10),$$

where

$$\left.\begin{array}{l}\varpi_{is}=\varepsilon_{is}^{-2}\\ R_{is}=1-\frac{\Delta v_{is}^2}{\varepsilon_{is}^2}\end{array}\right\}.$$

Then, from Equation (8) we can obtain the following system of 10 non-linear equations:

$$\sum_{i=1}^{n}\sum_{s=1}^{3}\left[\varpi_{is}a_{isk}\left(\sum_{j=1}^{7}a_{isj}u_j\right)\right]=\sum_{i=1}^{n}\sum_{s=1}^{3}\varpi_{is}a_{isk}v_{is}\ ,\qquad (k=1,2,\ldots,7)\,,$$

and

$$\sum_{i=1}^{n}\sum_{s=1}^{3}\left[\varpi_{is}^2a_{isk}^2\left(\sum_{j=1}^{3}a_{isj}^2\sigma_j^2\right)\right]=\sum_{i=1}^{n}\sum_{s=1}^{3}\left[\varpi_{is}^2a_{isk}^2\left(\Delta v_{is}^2-\sigma^2\left(v_{is}\right)\right)\right],\quad (k=1,2,3)\,.$$

From the above equations, the maximum likelihood estimators of the 10 unknown parameters can be derived simultaneously.

3.4 Uncertainties in the Kinematical Parameters

In order to estimate the uncertainties ε_q of all the parameters x_q, we set up the covariance matrix E,

$$E=\left(\frac{\partial^2\ln L}{\partial x_q\partial x_m}\right),\quad (q,m=1,2,\ \cdots,\ 10)\,.$$

From Equation (8) all the elements of the covariance matrix E can been derived,

$$\frac{\partial^2\ln L}{\partial x_q\partial x_m}=2\sum_{i=1}^{n}\sum_{s=1}^{3}\left[\varpi_{is}a_{isk}a_{isj}\right],\quad (q,m=1,2,\ \cdots,7;k=q;j=m)\,,$$

$$\frac{\partial^2\ln L}{\partial x_q\partial x_m}=-2\sum_{i=1}^{n}\sum_{s=1}^{3}\left[\varpi_{is}^2a_{isk}a_{isj}^2\right],\quad (q=1,2,\ \cdots,7;m=8,9,10;k=q;j=m-7)\,,$$

$$\frac{\partial^2\ln L}{\partial x_q\partial x_m}=2\sum_{i=1}^{n}\sum_{s=1}^{3}\left[\varpi_{is}^2a_{isk}^2\Delta v_{is}a_{isj}\right],\ (q=8,9,10;m=1,\ 2,\cdots,7;k=q-7;j=m)\ ,$$

$$\frac{\partial^2\ln L}{\partial x_q\partial x_m}=\sum_{i=1}^{n}\sum_{s=1}^{3}\left[2\varpi_{is}^4a_{isk}^2\Delta v_{is}^2a_{isj}^2-\varpi_{is}^2a_{isk}^2a_{isj}^2\right],$$
$$(q=8,9,10;\ m=8,9,10;\ k=q-7;\ j=m-7)\ .$$

Thus, let

$$F=E^{-1}=\left(f_{lm}\right)\ ,$$

where E^{-1} is the inverse matrix of E and $f_{lm}(l,m=1,2,\ldots,10)$ are the elements of the symmetric matrix F, we have

$$\varepsilon_q=\sqrt{-f_{qq}}\ ,\qquad (q=1,2,\ \cdots\ 10)\ .$$

4 RESULTS AND DISCUSSION

As mentioned in Section 1, open clusters with different ages and/or different heliocentric distances may present different kinematical properties in the Galaxy, so we use the maximum likelihood approach developed in Section 3 to determine the kinematical parameters of groups of different ages and heliocentric distances. Table 4 lists the results for our cluster samples obtained by the maximum likelihood technique, including the kinematical parameters and their uncertainties. Here, $u_1, u_2, u_3, \sigma_1, \sigma_2$ and σ_3 are in units of km s^{-1} and A, B, C and D, in units of km s^{-1} kpc^{-1}. Tables 5 and 6 list respectively the results of the galactic components of the mean heliocentric velocity and the Oort constants published by other authors, which will be used for the following comparisons and discussion.

(1) Although the criteria on heliocentric distances and age that we adopt for dividing the sample clusters into groups is more or less arbitrary, it is obvious from the results listed in Table 4 that almost all the kinematical parameters are significantly different for groups of different heliocentric distances. Furthermore, the differences in the parameters between the young and old clusters are also significant, which shows that it is necessary to divide the open clusters into a number of groups according to their heliocentric distances and ages when we examine the kinematical properties of the system of open clusters of the Galaxy.

(2) Because the 117 clusters with heliocentric distances of 0.5–2.0 kpc and ages younger than 0.8 Gyr can be considered to be typical thin disk objects in the Galaxy, to which the Oort theory is applicable, the kinematical parameters determined from these clusters can be reasonably used to represent the kinematical properties of thin disk objects in the vicinity of the Sun. Thus, we finally deduced the galactic components of the mean heliocentric velocity of the open cluster system to be $(u_1, u_2, u_3) = (-16.1 \pm 1.0, -7.9 \pm 0.4, -10.4 \pm 1.5)$ km s^{-1}, the characteristic velocity dispersions to be $(\sigma_1, \sigma_2, \sigma_3) = (17.0 \pm 0.7,\ 12.2 \pm 0.9, 8.0 \pm 1.3)$ km s^{-1}, the Oort constants to be $(A, B) = (14.8 \pm 1.0, -13.0 \pm 2.7)$ km s^{-1} kpc^{-1} and the radial motion parameters to be $(C, D) = (1.5 \pm 0.7, -1.2 \pm 1.5)$ km s^{-1} kpc^{-1}. The parameters determined from these clusters have accuracies significantly higher than those obtained from other groups of clusters.

(3) The results given in Tables 5 and 6 were gained by some authors based on studies of different Galactic objects, rather than using young open clusters only, so some of them are significantly different from each other. For the same reason the parameters determined by us which are given in Table 4 are more or less different from some of those listed in Tables 5 and 6. What should be pointed out is that the mean heliocentric velocity components derived by Rastorguev et al. (1999) are different from ours, although their sample is also composed of young clusters, this is probably mainly due to the fact that they only used proper motion data, whereas we used both radial velocity and proper motion data and that our samples are not completely the same. It can also be seen that the precisions of our values of (u_1, u_2, u_3) and A are all better than those of determined by Rastorguev et al. (1999).

(4) It can be seen from a comparison between Tables 4 and 6 that the Oort constants A and B derived by us and other authors are not of significant difference within the uncertainties. Besides, our result of A=14.8 $\pm$ 1.0 km s^{-1} kpc^{-1} is in good agreement with the value $A = 14.4 \pm 1.2$ km s^{-1} kpc^{-1} proposed by IAU 1985 standard (Cox 1999) and our $B = -13.0 \pm 2.7$ km s^{-1} kpc^{-1} is also not significantly different from the value -12.0 ± 2.8 km s^{-1} kpc^{-1} proposed by the IAU standard. This demonstrates that the group of open clusters with heliocentric distances of 0.5–2.0 kpc and ages younger than 0.8 Gyr can be reasonably used to study the differential rotation of the Galaxy in the vicinity of the Sun.

(5) It can be found from Table 4 that the velocity dispersions in the three galactic directions are in the ratios 17:12:8, and for comparison the corresponding ratios of the extreme population I are 20:10:8 (Cox 1999). The differences between these two sets of ratios are probably caused by the fact that the group of open clusters with heliocentric distances of 0.5–2.0 kpc and ages younger than 0.8 Gyr is not a pure sample composed of young thin disk objects and is probably polluted by some old thin disk objects. On the other hand, the value $\sigma_3 = 8.0 \pm 1.3$ km s^{-1} listed in Table 4 is in very good agreement with what was given by Cox (1999) for the extreme population I. Rastorguev et al. (1999) gave $(\sigma_1, \sigma_2, \sigma_3) = (15.0 \pm 1.0, 10.3 \pm 1.0, 8.5 \pm 1.0)$ km s^{-1} from 117 young open clusters, which are also quite consistent with our results.

(6) Since observational kinematical data, i.e., proper motions and radial velocities, of stars or clusters in the Galaxy are relatively limited, there have only been a few authors who investigated the large-scale radial motion of the Galaxy that included a determination of the parameters C and D, which are small quantities in comparison with the Oort constants A and B reflecting the differential rotation of the Galaxy. In an early work, Rubin & Burley (1964) derived $(C, D) = (1 \pm 1, -2 \pm 1)$ km s^{-1} kpc^{-1} by using some 800 early-type stars. Later, Zhao (1984b) used 1412 O, B type stars and found $(C, D) = (0.5 \pm 0.5, -2.0 \pm 0.4)$ km s^{-1} kpc^{-1}. Now, based on the sample composed of 117 thin disk open clusters we have $(C, D) = (1.5 \pm 0.7, -1.2 \pm 1.5)$ km s^{-1} kpc^{-1}. Obviously, all of these values of C or D are in fairly good agreement with each other within the corresponding uncertainties. Using the C and D values given in Table 4 and $R_0 = 8.0$ kpc, we have $\varepsilon_0 = D - C = -2.7 \pm 1.7$ km s^{-1} kpc^{-1} and $\varepsilon'_0 = 2C/R_0 = 0.38 \pm 0.18$ km s^{-1} kpc^{-2}, which means that so far as the thin disk open clusters in the vicinity of the Sun are concerned, there may be a large-scale radial motion with a velocity of $(dR/dt)_0 = \varepsilon_0 R_0 = 22 \pm 14$ km s^{-1} or so, towards the galactic center, and the rate of change ε' of the radial motion velocity ε with R increasing is quite small.

Table 4 Kinematical Parameters of Sample Clusters with Different Ages and Heliocentric Distances

	Heliocentric distance r (kpc)			Age t (Gyr) $(0.5 < r < 2.0$ kpc)		Total
n	31	128	43	117	11	202
	$(r < 0.5)$	$(0.5 < r < 2.0)$	$(r > 2.0)$	$(t < 0.8)$	$(t > 0.8)$	
u_1	–14.4 ± 1.0	–16.0± 1.0	–5.5±0.8	–16.1±1.0	–9.9±2.0	–14.0±0.7
u_2	–15.8±1.2	–5.2±0.4	–19.9±3.0	–7.9±0.4	–3.9±1.3	–13.8±0.8
u_3	2.2±1.4	–11.8±0.9	–12.0±2.4	–10.4±1.5	–14.1±3.0	–9.7±0.5
A	5.6±2.8	15.6±0.5	12.9±1.5	14.8±1.0	27.9±3.6	14.9±0.5
B	–12.5±5.9	–13.0±1.9	–17.5±3.0	–13.0±2.7	–30.0±5.8	–16.4 ±0.6
C	–2.6±7.4	1.5±0.7	1.9±0.7	1.5±0.7	12.3±3.7	–0.2±0.6
D	–7.0±3.1	–1.6±1.3	2.0±2.0	–1.2±1.5	–9.1±7.3	–3.3±0.5
σ_1	12.0±2.6	19.4±0.5	36.0±0.7	17.0±0.7	27.4±2.5	21.0±0.5
σ_2	6.5±4.8	12.3±1.2	10.7±0.5	12.2±0.9	17.9±4.0	14.9±0.7
σ_3	6.9±5.5	7.1±1.7	5.9±3.0	8.0±1.3	5.5±9.7	6.3±1.2

Table 5 Mean Heliocentric Velocity Components Obtained by other Authors

Authors	Year	Observational samples	u_1	u_2	u_3
Crèzè	1973	41 young open clusters	–7.4±3.1	–21.4±3.1	
Crèzè	1973	32 old open clusters	–11.5±3.6	–13.7±3.8	
Rastorguev	1999	117 young open clusters	–9.7±2.0	–13.2±2.2	–10.7±16.5
Frink	1996	OB stars in HII region	–2.0±0.7	–6.2±1.7	–5.5±0.4
Dehnen	1998	dwarfs	–10.0±0.4	–5.3±0.6	–7.1±0.4
Mignard	2000	K giants	–9.9±0.6	–14.1±0.6	–7.7±0.5

Table 6 Oort Constants Obtained by other Authors

Authors	Year	Observational samples	A	B
Johnson	1961	36 open clusters	16.4±1.3	
Mennessier	1972	young open clusters	15.6±1.0	–11.8±1.5
Crèzè	1973	41 open clusters	12.6±1.7	
Crèzè	1973	32 old open clusters	13.8±2.9	
Rastorguev	1999	117 young open clusters	17.4±1.5	
Mignard	2000	giants	14.5±1.0	–11.5±1.0
Nakashima	2003	SiO maser sources	14.4±1.2	–12.0±2.8

5 CONCLUSIONS

From 202 open clusters with absolute proper motions and/or radial velocities available, we formed a sample composed of 117 thin disk clusters according to distances above the Galactic plane, heliocentric distances and ages of individual clusters. Based on the observational data of proper motions and radial velocities of these clusters, we simultaneously determined the kinematical parameters of the Galactic thin disk in the solar vicinity, including the mean solar motion components, characteristic velocity dispersions, Oort constants and radial motion parameters, and estimated their corresponding accuracies by using a maximum likelihood technique. It is shown from above discussion that both the approach used for solution and the results of the kinematical parameters we obtained are quite reasonable. With observational data being further improved in future, one can expect that better results on the Galactic kinematics will be retrieved.

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