A clear kinematical evidence of a weak elliptical distortion of the Milky Way potential

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Outline

- ☆ Data selection
- ☆ Kinematical parameters
- ☆ Distance to the Galactic center
- ☆ Elliptical distortion of the potential

1. Data selection

- Karchenko et al. 2005, A&A 438, 520 clusters
- Karchenko et al. 2005, A&A 440, 130 clusters
  - Based on ASCC-2.5 catalogue, an all-sky compiled catalogue of 2.5 million stars (Karchenko 2001)
- Catalogue of Open Clusters Data (COCD, 2006)

  Dias et al. 2006

1. Data selection

- Total 370 clusters with PMs, RVs, distances, and ages
  - 253 clusters from COCD
  - 69 clusters from COCDnew (problematic in kinematics)
  - 19 clusters from DIAS (non-COCD OCs)
  - 5 clusters with RVs in DIAS, but no PMs available:

    NGC 2506, NGC 2477, Ruprecht 67, IC 2714, NGC 7789
  - 24 clusters with PMs and RVs in DIAS, but no RVs in COCD
  - **301 OCs in total**

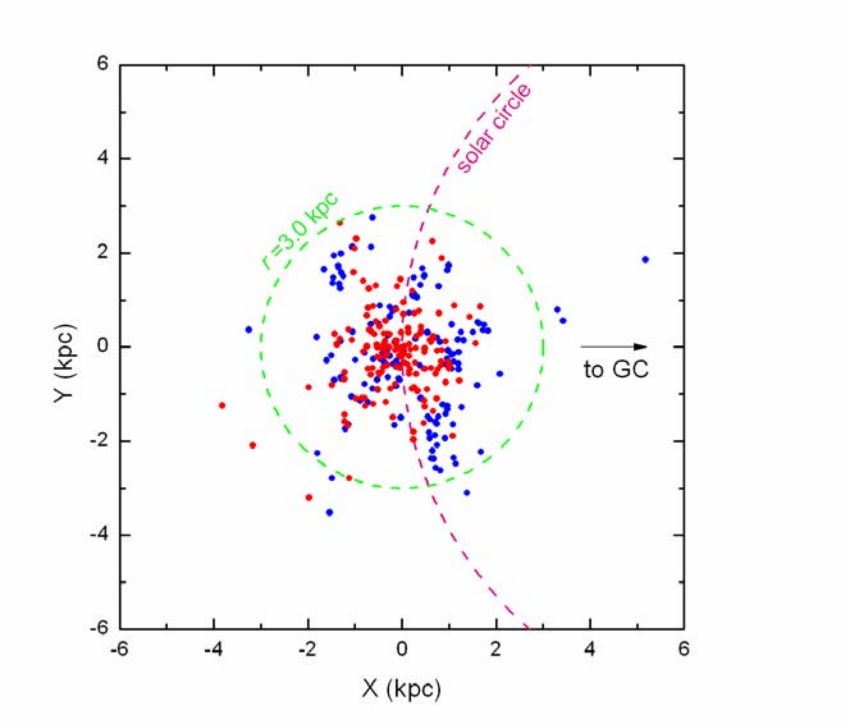


Fig. 1. The distribution of our sample of 301 open clusters on the Galactic plane. The bold dots indicate clusters younger than 50 Myr, and the open circles represent clusters older than 50 Myr.

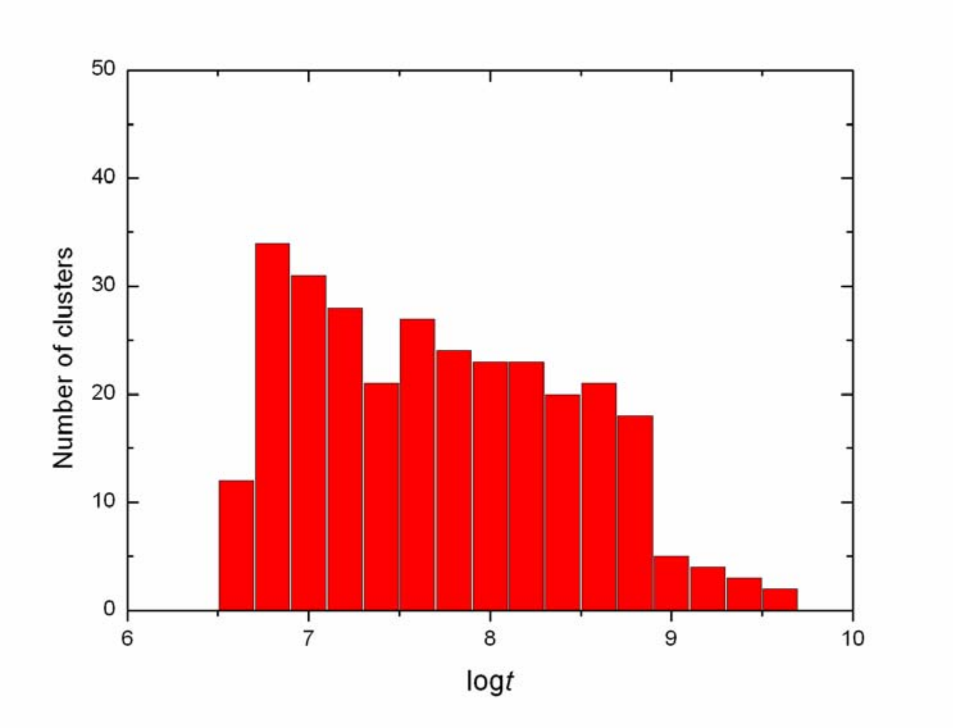


Fig. 2. The age histogram of our sample. The logarithm of ages ranges approximately from 6.6 to 9.0, corresponding to 4 Myr ~ 1 Gyr.

Peculiar motions of OCs

$$\kappa r \Delta\mu_\ell \cos b = \kappa r \mu_\ell^{obs} \cos b - Ar \cos 2\ell \cos b - Br \cos b$$
$$+ Cr \sin 2\ell \cos b - u_0 \sin \ell + v_0 \cos \ell$$

$$\kappa r \Delta\mu_b = \kappa r \mu_b^{obs} + Ar \sin 2\ell \sin b \cos b + Cr \cos 2\ell \sin b \cos b$$
$$+ Kr \sin b \cos b - u_0 \cos \ell \sin b - v_0 \sin \ell \sin b + w_0 \cos b$$

$$\Delta V_r = V_r^{obs} - Ar \sin 2\ell \cos^2 b - Cr \cos 2\ell \cos^2 b - Kr \cos^2 b$$
$$+ u_0 \cos \ell \cos b + v_0 \sin \ell \cos b + w_0 \sin b$$

Accepted Oort constants and solar motion:

$A = 16.44\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ $B = -12.91\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ $C = 0.50\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ $K = -2.60\ \mathrm{km\,s^{-1}\,kpc^{-1}}$

$u_0 = 11.76\ \mathrm{km\,s^{-1}}$ $\mathrm{v}_0 = 13.33\ \mathrm{km\,s^{-1}}$ $w_0 = \ \mathrm{km\,s^{-1}}$

Clusters with peculiar velocities larger than 50 km s^{-1}

No	Name of OC	r (kpc)	Z (kpc)	ΔV (km s^{-1})
1	NGC 1664	1.20	-0.01	50.38
2	NGC 2354	3.79	-0.45	114.15
3	Haffner 16	3.17	0.03	64.95
4	NGC 2506	3.46	0.60	61.69
5	Ruprecht 47	3.01	-0.01	78.60
6	NGC 2527	0.60	0.02	113.10
7	Ruprecht 55	4.89	0.07	95.13
8	Ruprecht 79	1.98	-0.03	60.74
9	Trumpler 16	2.84	-0.03	69.54
10	Bochum 12	2.22	-0.07	61.65
11	Pismis 17	3.50	0.01	101.22
12	Ruprecht 94	3.40	-0.12	53.61
13	Ruprecht 141	5.50	-0.12	57.74
14	NGC 6705	1.88	-0.09	64.83
15	Ruprecht 147	0.18	-0.04	54.62
16	NGC 7789	2.34	-0.22	71.61
17	vdBergh 1	1.69	-0.05	54.53
18	Dolidze 25	6.30	-0.14	116.72
19	Berkeley 31	8.27	0.74	223.96
20	NGC 2324	3.81	0.22	68.67
21	Lynga 6	1.60	0.01	95.64
22	NGC 6791	5.85	1.11	121.71

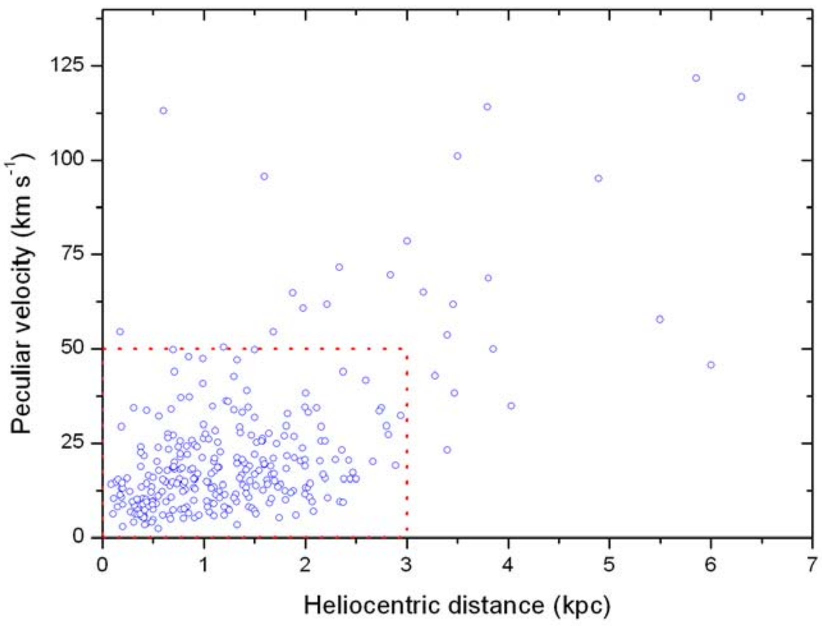
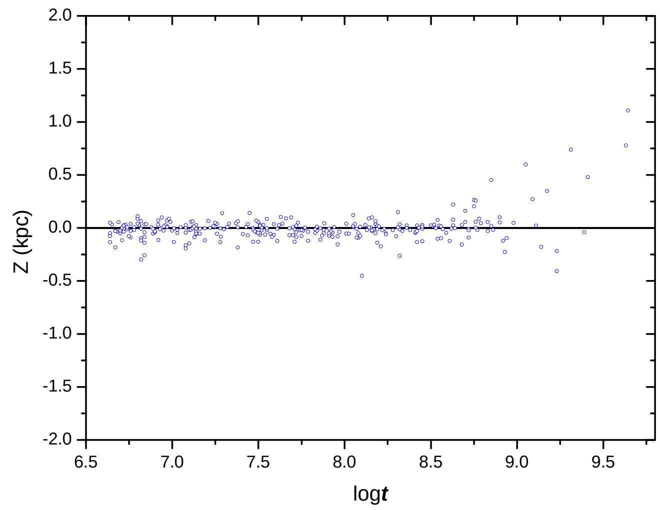
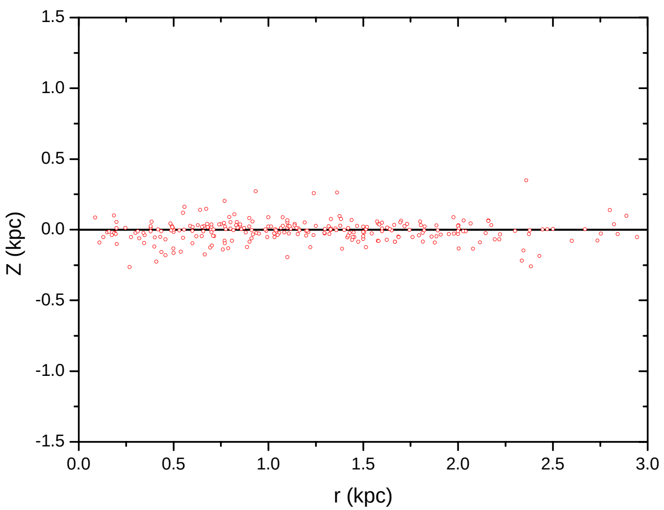


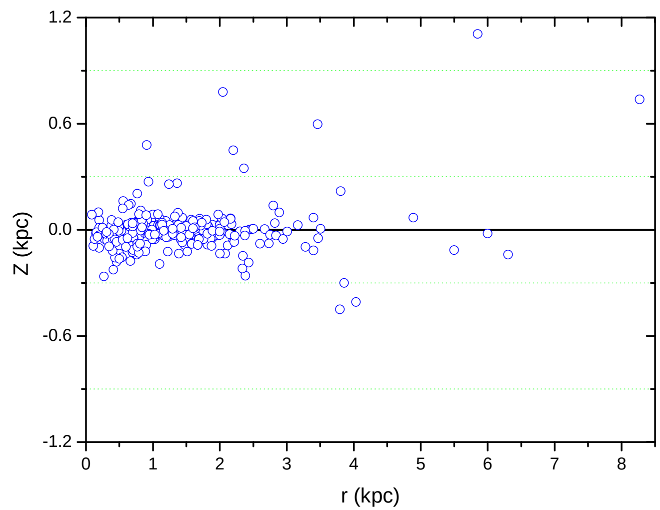
Fig. 3. Distribution of the determined peculiar velocities for 301 open clusters, among them, there are 283 clusters with the heliocentric distance less than 3.0 kpc, and 269 clusters are located in the doted rectangle with velocity dispersion less than 50 km s^{-1}.

Disk heights vs ages

Bonnatto et al. (2006)	48±3 pc for *t*⩽200Myr	150±26 pc for 200Myr <*t*⩽1Gyr	57±3 pc for all age
Our present values	50±4 pc for *t*⩽50Myr	67±6 pc for *t*>50Myr	57±4 pc for all ages







3. Kinematics

- The scale height of the OCs is sufficiently small (~60 pc), a 2D asymmetric kinematical model should be satisfactory
- 7 kinematical parameters are to be solved solar motion wrt to the LSR (u_0, v_0, w_0), and the Oort constants:

$$A = \frac{1}{2}\left(\frac{\partial V_\theta}{\partial R} - \frac{V_\theta}{R} + \frac{1}{R}\frac{\partial V_R}{\partial \theta}\right)_{R=R_0},$$

$$B = \frac{1}{2}\left(\frac{\partial V_\theta}{\partial R} + \frac{V_\theta}{R} - \frac{1}{R}\frac{\partial V_R}{\partial \theta}\right)_{R=R_0},$$

$$C = \frac{1}{2}\left(\frac{\partial V_R}{\partial R} - \frac{V_R}{R} - \frac{1}{R}\frac{\partial V_\theta}{\partial \theta}\right)_{R=R_0},$$

$$K = \frac{1}{2}\left(\frac{\partial V_R}{\partial R} + \frac{V_R}{R} + \frac{1}{R}\frac{\partial V_\theta}{\partial \theta}\right)_{R=R_0}.$$

The parameters A and C denote the azimuthal and radial strain (shear) of the velocity field, B characterizes the vorticity (rotation), and K implies the local contraction (or expansion).

Circular rotation of the Galaxy

IAU1985:	$A = 14.4 \pm 1.2, \quad B = -12.0 \pm 2.8$	
Cepheids:	$A = 14.8 \pm 0.8, \quad B = -12.4 \pm 0.6$	Feast & Whitelock 1998
Sgr A^*:	$A - B = 28.5 \pm 0.9 \ \text{km s}^{-1}\ \text{kpc}^{-1}$	Backer & Sramek 1999
SPM:	$V_0 = 270 \ \text{km s}^{-1}$	Mendez 2000
Red giants:	$A - B \approx 32.8 \ \text{km s}^{-1}\ \text{kpc}^{-1}$	Olling & Dehnen 2003
O-B5:	$A = 16.1 \pm 1.1, \quad B = -15.6 \pm 0.8$	Miyamoto & Zhu 1998

R_0=8.5 kpc (IAU1985)

V_0=220 km s^{-1} (IAU1985)

V_0=270 km s^{-1} (O-B5 stars)

Kinematical parameters derived from proper motions and radial velocities of 269 open clusters.

	Nos	u_0 km/s	v_0 km/s	w_0 km/s	A km/s/kpc	B km/s/kpc	C km/s/kpc	K km/s/kpc
all clusters	269	11.76	13.33	8.11	16.44	-12.91	0.50	-2.60
		±0.56	±0.56	±0.55	±0.93	±0.93	±0.93	±0.93
$t \leq 50$ Myr	137	10.84	14.62	7.88	16.50	-14.56	2.86	-1.09
		±0.67	±0.67	±0.66	±0.85	±0.85	±0.85	±0.85
$t > 50$ Myr	132	12.32	12.77	8.18	16.38	-10.93	-2.73	-4.58
		±0.85	±0.84	±0.84	±1.71	±1.71	±1.71	±1.71

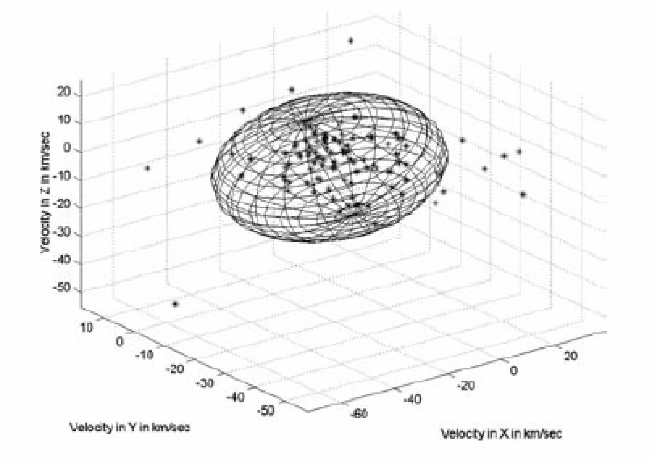
Velocity ellipsoid

Velocity ellipsoid derived from proper motions and radial velocities of 269 open clusters.

	Nos	σ_u km/s	σ_v km/s	σ_w km/s	σ km/s
all clusters	269	14.02 ±0.74	11.71 ±0.63	8.75 ±0.54	20.25 ±0.67
$t \leq 50$ Myr	137	13.14 ±0.91	11.08 ±0.75	8.71 ±0.71	19.27 ±0.82
$t > 50$ Myr	132	14.91 ±1.15	12.33 ±1.01	8.78 ±0.83	21.25 ±1.05

Piskunov et al. (2006)

$$\sigma_u = 13.86 \pm 0.81 \quad \mathrm{km\,s^{-1}}$$
$$\sigma_v = 8.75 \pm 0.51 \quad \mathrm{km\,s^{-1}}$$
$$\sigma_w = 5.05 \pm 0.30 \quad \mathrm{km\,s^{-1}}$$
$$\sigma = 17.15 \pm 0.71 \quad \mathrm{km\,s^{-1}}$$



3. Distance to the Galactic center

- Different methods of R_0 calibrations:
  - Galactic halo objects: globular clusters (shapley 1918); RR Lyrae
  - Center region of the Galaxy: Sgr A*; star S2
  - Kinematical calibration from thin-disk populations: Cepheids; OCs
- Difficulties:
  - The heavy obscuration in the center region;
  - Considerable biases and errors both from observations and models;
  - Large deviation of individual determinations ranges from 6 ~ 13 kpc (recently 7 ~ 9 kpc)
  - Strong correlated with the distance scale adopted

Typical values of R_0

- Shapley 1918: R_0 =13 kpc
- 1964 IAU: R_0 =10 kpc
- 1985 IAU: $R_0 = 8.5 \pm 1$ kpc
- “Best value”: $R_0 = 8.0 \pm 0.5$ kpc (Reid 1993)

Our models

- Oort constant *A* is derived from PMs via an axisymmetric rotation model;
- Parameter $2AR_0$ is obtained from radial velocities:

$$v_r = 2AR_0\left(\frac{R_0}{R} - 1\right)\sin\ell\cos b - u_0\cos\ell\cos b - v_0\sin\ell\cos b - w_0\sin b - \delta v_r .$$

- R_0 is finally given from the PM and RV solutions

Table 3. Galactocentric distance of the Sun and other kinematical parameters obtained from open clusters, on base of an axisymmetric rotation model.

Data	u_0 km/s	v_0 km/s	w_0 km/s	A km/s/kpc	B km/s/kpc	$2AR_0$ km/s	δv_r km/s	R_0 kpc
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	7.20 (set)	16.16 (set)		259.5 ±14.7	2.42 ±0.86	8.03 ±0.70

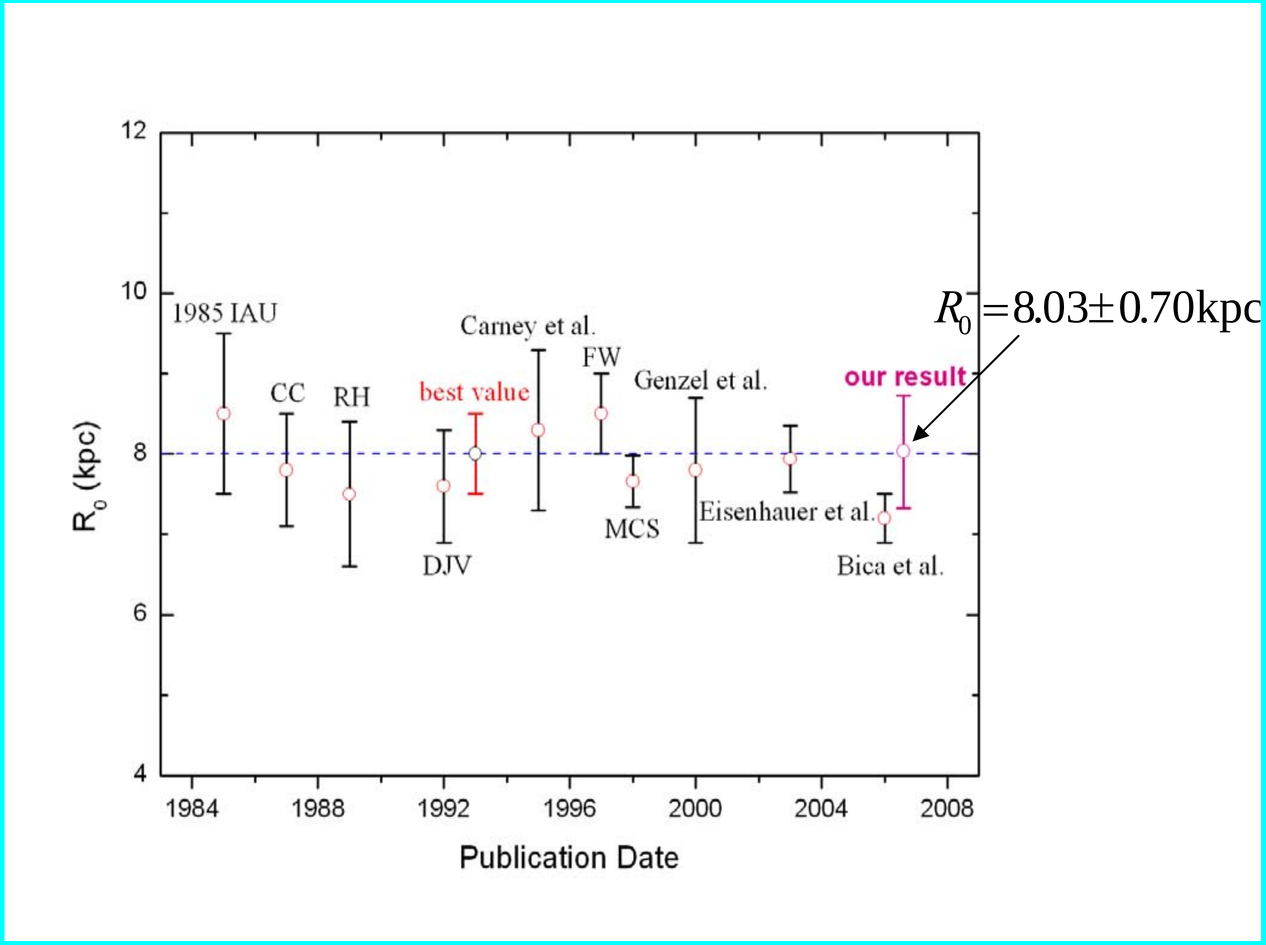
Galactic rotation V_0 =235±10 km s^{-1}, suppose R_0 =8 kpc.

from the latitude proper motion of the Sgr A* source at the Galactic center $\mu_b = -0.202 \pm 0.019$ mas yr^{-1} given by Reid & Brunthaler (2004), we get

$$R_0 = \frac{1}{\kappa} \frac{W_\odot}{\mu_b} = 7.49 \pm 0.81 \text{ kpc}, \qquad (10)$$

supposing Sgr A* is in rest. Here $W_\odot = 7.17 \pm 0.38$km s^{-1} is the component of the solar motion taken from Dehnen & Binney (1998).

Distance to the Galactic center derived from various techniques in the last decades



CC:	Cepheids
RH:	global clusters
DJV:	planetary lebulae
Carney et al:	RR Lyrae
FW:	Cepheids
MCS:	Cepheids
Genzel et al:	stars near Sgr A*
Eisenhauer et al:	star S2
Bica et al:	global clusters

4. Elliptical components of the potential

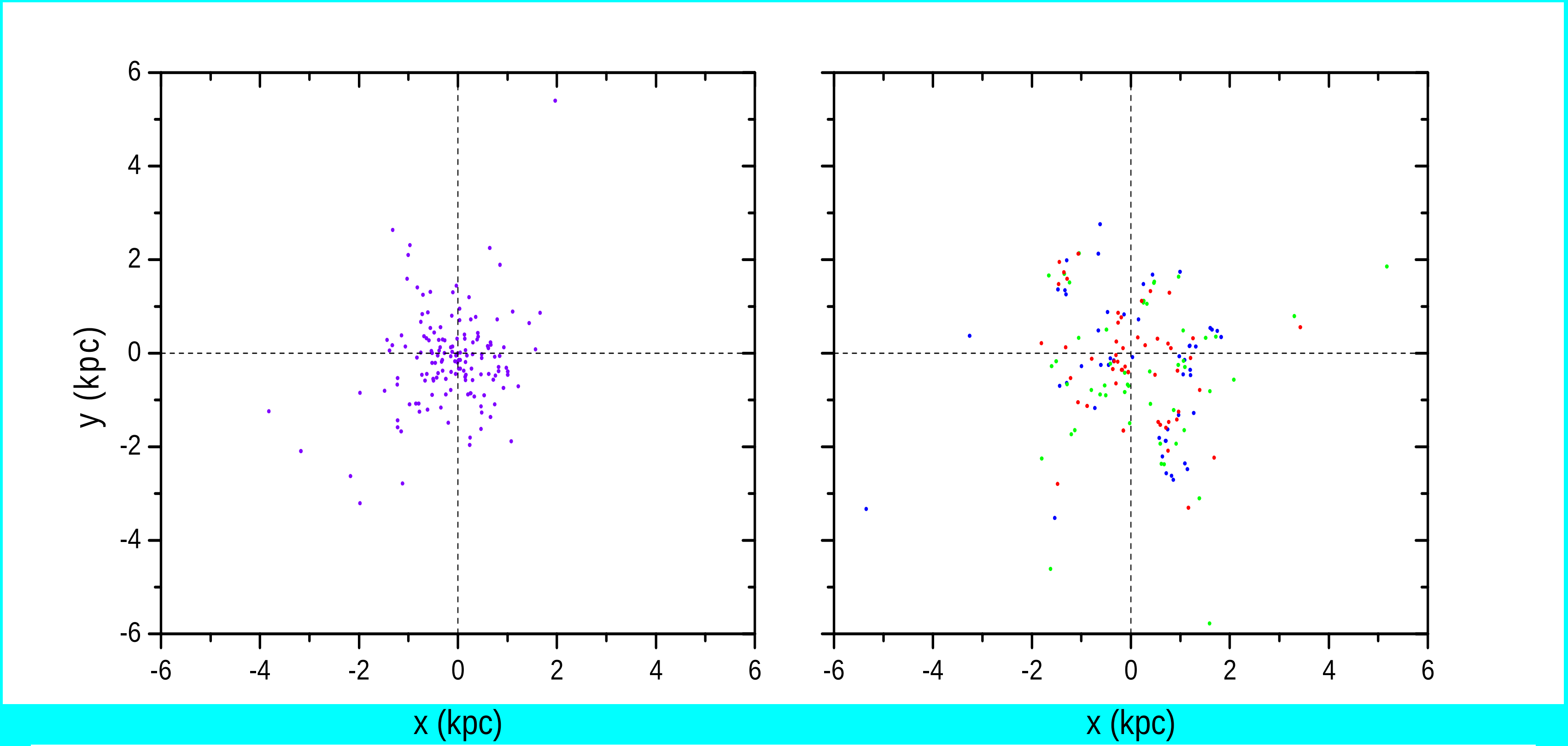
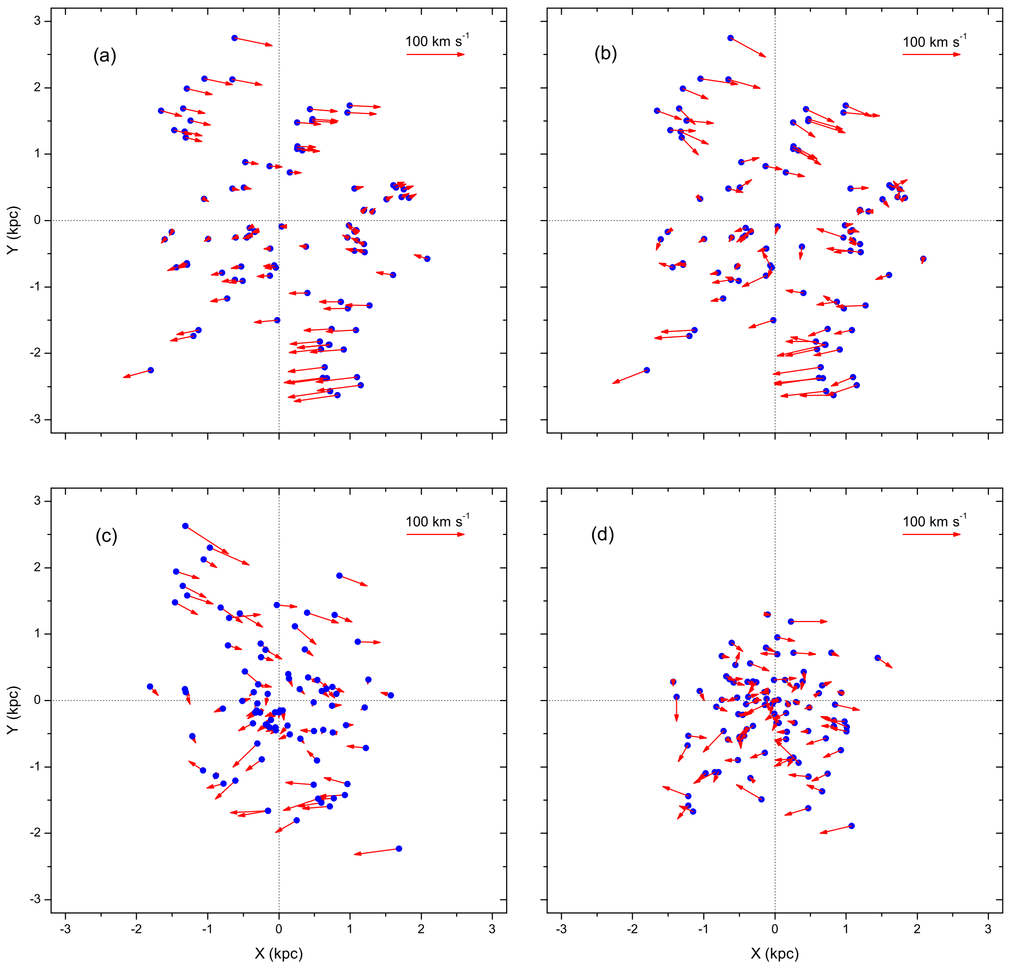


Fig. 1.— Distributions of open clusters projected on the Galactic plane. The right panel demonstrates 151 clusters younger than 50 Myr. The blue dots show the youngest clusters with age less than 8 Myr, the green corresponds to clusters of ages of $T = (8, 18]$ Myr, and the red gives clusters within ages of $T = (18, 50]$ Myr. The left panel illustrates 150 older clusters with ages larger than 50 Myr.

(a) Simulation of 90 OCs younger than 18 Myr. Suppose R_0=8 kpc, V_0=220 km s^{-1}, d*V*/d*R*=-4.0 km s^{-1} kpc^{-1}.
(b) Ages less than 18 Myr, 90 OCs.
(c) Ages in a range of 18 ~ 120 Myr, 88 OCs.
(d) Ages older than 120 Myr, 91 OCs



Velocity distribution of spiral arms

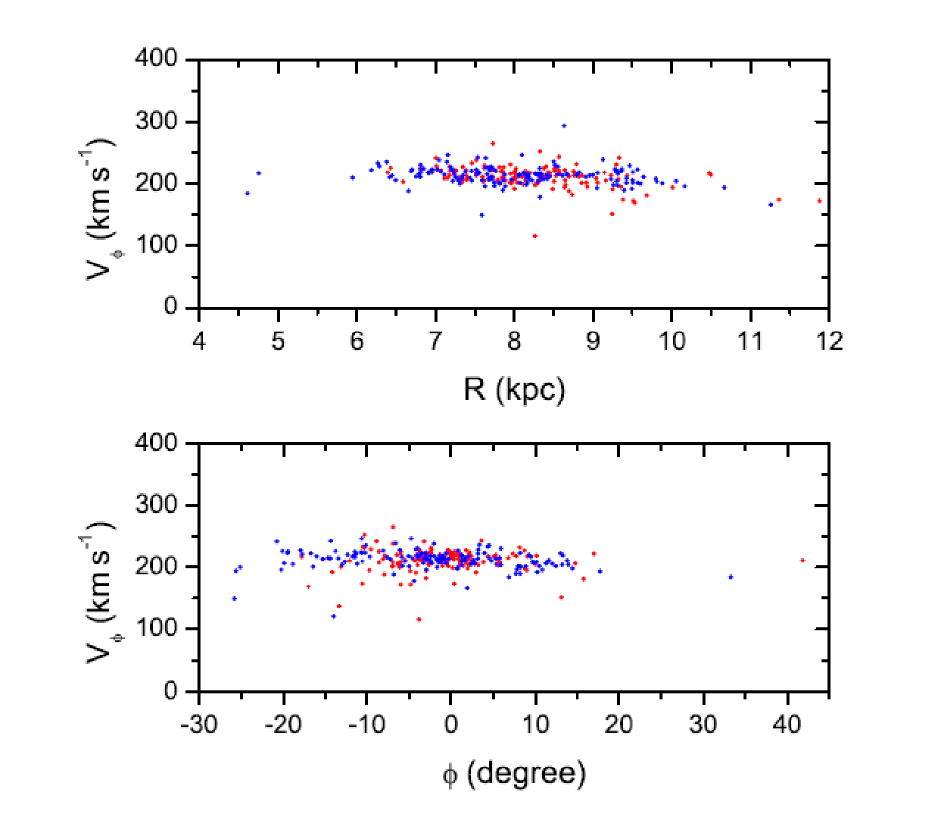


Fig. 2.— Tangential velocities of open clusters, suppose $V_0 = 220\,\mathrm{km\ s^{-1}}$ and R_0 =8 kpc. The green dots imply the younger clusters with ages less than 50 Myr. Dots in red display clusters older than 50 Myr. The top panel shows speeds against the Galactocentric distances of clusters, the bottom panel gives their variations as functions of their Galactocentric azimuthal angle from the Sun.

- Non-axisymmetric model of potential (Power-law depended)

$$\Phi(R,\phi) = \Phi_0(R) + \Phi_1(R)\cos 2(\phi - \phi_b)\,,$$

$$\begin{aligned}
\Phi_0(R) &= \frac{V_0^2}{2\alpha}\left(\frac{R}{R_0}\right)^{2\alpha}, \qquad \alpha \neq 0,\\
\Phi_1(R) &= \Psi_0\left(\frac{R}{R_0}\right)^{p}, \qquad \Psi_0 \geq 0,
\end{aligned}$$

- The circular speed and the potential ellipticity

$$V_c(R) = V_0\left(\frac{R}{R_0}\right)^{\alpha}, \qquad \epsilon(R) = \epsilon_0\left(\frac{R}{R_0}\right)^{p-2\alpha}.$$

- The mean radial and tangential velocities

$$\begin{aligned}
V_R(R,\phi) &= \beta_1 V_c(R)[s(R)\cos 2\phi - c(R)\sin 2\phi],\\
V_\phi(R,\phi) &= V_c(R)[1 - \beta_2 c(R)\cos 2\phi + \beta_2 s(R)\sin 2\phi]\,,
\end{aligned}$$

with $\beta_1 = \frac{1+p/2}{1-\alpha}$ and $\beta_2 = \frac{1+p(1+\alpha)/4}{1-\alpha}$

- The non-axisymmetric potential is specified by two orthogonal components:

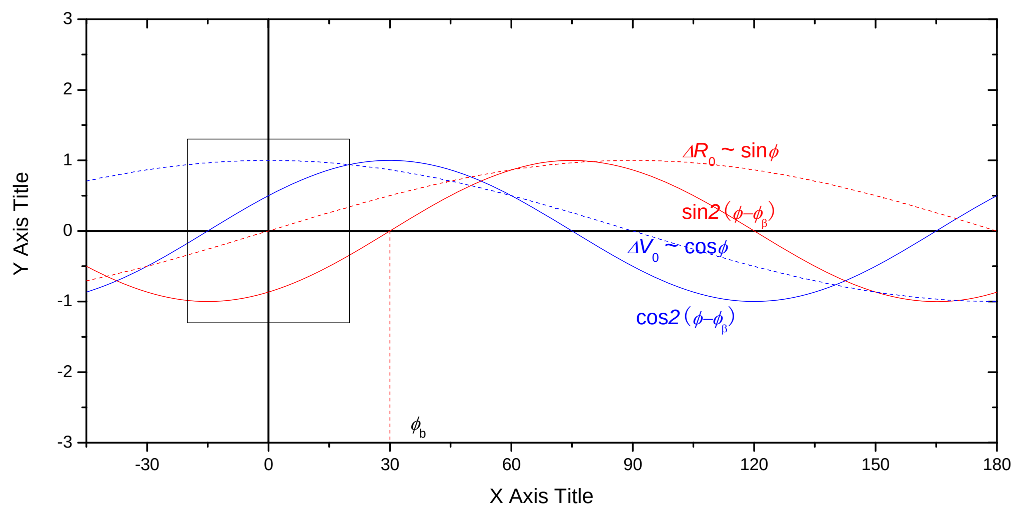
$$c(R) = \epsilon(R)\cos 2\phi_b\,, \qquad s(R) = \epsilon(R)\sin 2\phi_b\,.$$

Table 1: Parameters of non-axisymmetric potential derived from spatial velocities of open clusters, set $\beta_2 = 1$. N is the number of clusters used in the final solution. V_0 (in km s^{-1}), R_0 (in kpc), and α are the accepted values in our calculation, CC is the correlation coefficient between parameters $c(R_0)$ and $s(R_0)$.

Age range	N	α	V_0	R_0	$c(R_0)$	$s(R_0)$	CC	$\epsilon(R_0)$	ϕ_b (°)
All ages	286	-0.167	220	8.0	0.028±0.003	0.049±0.012	0.173	0.056±0.013	30.1±2.9
	288	0	220	8.0	0.029±0.004	0.051±0.012	0.171	0.059±0.013	30.0±2.9
	293	-0.5	220	8.0	0.029±0.004	0.039±0.014	0.181	0.048±0.016	26.8±5.1
	287	-0.167	240	8.0	0.026±0.003	0.043±0.011	0.173	0.050±0.012	29.2±3.2
	286	-0.167	200	8.0	0.031±0.004	0.058±0.013	0.168	0.066±0.014	31.1±2.6
	286	-0.167	220	7.5	0.029±0.003	0.047±0.011	0.166	0.055±0.012	29.2±3.1
	286	-0.167	220	8.5	0.028±0.003	0.053±0.012	0.175	0.060±0.013	31.0±2.7
All ages	286	-0.162	235	8.0	0.027±0.003	0.044±0.011	0.173	0.052±0.012	29.4±3.1
$\leq$ 50 Myr	146	-0.131	248	8.0	0.028±0.004	0.047±0.012	0.179	0.054±0.013	29.5±3.3
$>$ 50 Myr	142	-0.192	218	8.0	0.027±0.005	0.039±0.022	0.155	0.047±0.023	27.7±7.7

- Measurement errors and correlation analysis

$$\Delta V_\phi^2 = \cos^2\phi \Delta V_0^2 + V_R^2 \sin^2\phi \Delta R_0^2/R^2$$
$$\Delta V_R^2 = \sin^2\phi \Delta V_0^2 + V_\phi^2 \sin^2\phi \Delta R_0^2/R^2 \,.$$



- Result

$$\epsilon(R_0) = 0.060 \pm 0.012, \qquad \phi_b = 30^\circ \pm 3^\circ \,. \tag{10}$$

The present finding shows that the Sun deviates from the direction of the minor axis about -30°. Thus observation of more removed clusters is needed for a more reliable constraint to improve the determination, especially, the observation of the distant clusters along the Galactic longitude $\ell = +90^\circ$.

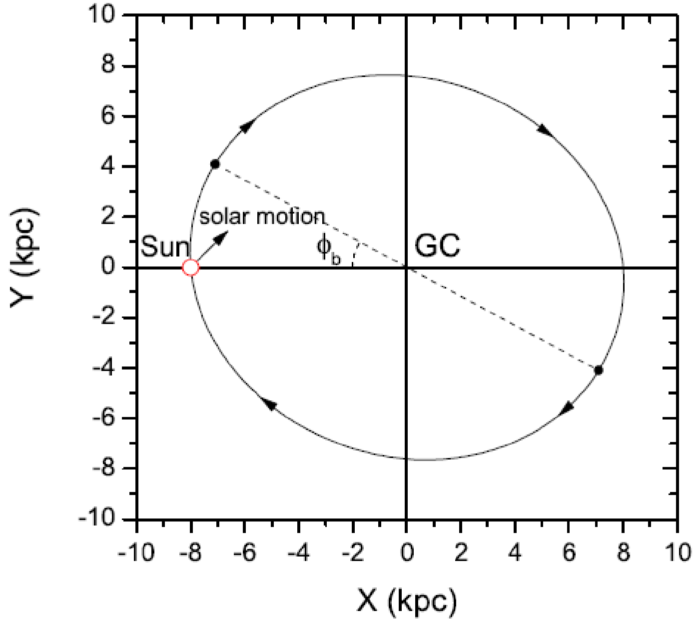


Fig. 3.— A schematic description of the motions of stars at the Sun.

Schoenen Dank!