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Weak Elliptical Distortion of the Milky Way Potential traced by Open Clusters *

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Abstract From photometric observations and star counts, the existence of a bar in the central few kpc of the Galaxy is suggested. It is generally thought that our Galaxy is surrounded by a massive invisible halo. The gravitational potential of the Galaxy is therefore made non-axisymmetric generated by the central triaxial bar, by the outer triaxial halo, and/or by the spiral structures. Selecting nearly 300 open clusters with complete spatial velocity measurements and ages, we were able to construct the rotation curve of the Milky Way within a range of 3 kpc of the Sun. 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, displaced by $30^\circ \pm 3^\circ$. The motion of the clusters is suggested to be on an oval orbit rather than on a circular one.

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

1 INTRODUCTION

Various observations provide evidence that the Milky Way exhibits a non-axisymmetric structure similar to many other disk galaxies. The existence of a bar, a halo, a warp, and spirals, causes the distribution and potential of the Galaxy to deviate from axisymmetry.

Based on the photometric and kinematical studies on the Galaxy in the last decades, many investigators suggested that a triaxial bulge or a bar may exist in the central few kpc of the Galaxy. The early evidence for the barred Galaxy relied on a morphological comparison of our Galaxy with other spiral galaxies proposed by de Vaucouleurs (1970). From the survey of the Diffuse Infrared Background Experiment (DIRBE) of the Cosmic Background Explorer (COBE), Dwek (1995) declared that the near side of the bar is in the first Galactic quadrant, its major axis making an angle of $20^\circ \pm 10^\circ$ to the direction of the Galactic center. A photometric search of red clump giants with the Optical Gravitational Lensing Experiment (OGLE) led to a similar result by Stanek (1997). From the near infrared data of COBE, Gerhard (1999) pointed out that the corotation radius of the bar is in the range of 3–4.5 kpc, and that the Milky Way has a disk with a short scale length and a dark halo with a large core radius of ~15 kpc.

The prolate, triaxial objects in the Galaxy (the bar in the inner and the halo in the outer-shell) may dominate the distortion of the gravitational potential of the Milky Way, even though their structures and formation are not yet clearly recognized. The stellar orbits of the Galactic rotation under the barred disk potential will therefore deviate from the circular rotation defined by the standard Oort-Lindblad model. Thus the kinematical behavior of the disk objects may be used as an efficient tracer of the distortion.

As an approximation, we will restrict ourselves to planar distortions in a stationary potential in the following discussion. A prominent work was carried out by Kuijken & Tremaine (1994, hereafter KT),

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who applied both local and global kinematical constraints to trace the elliptical parameters of the Galactic disk, and suggested that the Sun is located close to the minor axis of the potential of an elliptical Galactic disk with equipotential axis ratio 0.9. Based on radial velocity measurements of Cepheid variables and using the non-axisymmetric model proposed by KT, Metzger et al. (1998) derived the component of the potential ellipticity $s(R_0) = 0.043 \pm 0.016$, while the other component $c(R_0)$ was not determined from the Cepheid radial velocities. In a similar work to Metzger's, with a kinematical analysis of the Hipparcos proper motions of Cepheids, Feast & Whitelock (1997) did not obtain a significant estimate of the Galactic ellipticity term $s(R_0)$.

The young open clusters have a marked superiority over other populations as probes and tracers of the disk structure of the Milky Way, providing crucial information and constraints for the understanding of Galactic kinematics and dynamics. Individual measurements of the member stars in a cluster supply precise and reliable astrophysical parameters in a statistical sense. With the increasing available data of open clusters in recent years, we can now refine our study of the Galactic structure and extend it to a larger scale. In the present paper, we concentrate on a kinematical analysis based on the proper motions, distances, radial velocities, and ages of open clusters. Because of the systematic consistency of its kinematical data, we decided to use the internally homogeneous Catalogue of Open Cluster Data (COCD) compiled by Kharchenko et al. (2005). It contains 520 open clusters identified from the astrometric and photometric data of the ASCC-2.5 catalog (Kharchenko 2001). In order to increase the number of clusters, we also used a secondary catalogue of the New Catalog of Optically Visible Open Clusters and Candidates compiled by Dias et al. (2002, hereafter DAML02) which includes 1689 clusters collected from the literature (Dias et al. 2006).

From the COCD, we have 253 clusters complete with distances, proper motions, radial velocities, and ages. In addition, 29 radial velocities taken from DAML02 are supplemented to the COCD, 19 clusters are selected direct from DAML02 that are not contained in COCD. Thus, we gathered a total of 301 clusters that provide the entire spatial velocity data and ages.

2 COORDINATE SYSTEMS AND POTENTIAL MODEL

Several coordinate systems are used throughout this paper. The heliocentric rectangular system (x, y, z) has the conventional Galactic coordinates in the directions of the Galactic center, the Galactic rotation, and the north Galactic pole. Similarly, we define a Galactocentric rectangular system (X, Y, Z) by simply moving the origin of (x, y, z) to the Galactic center. Finally, a Galactocentric polar coordinates (R, ϕ) is defined with the azimuthal angle ϕ reckoned in the direction of the Galactic rotation.

In order to understand the nature of the local Galactic disk defined by the open clusters, we divide the whole sample into two groups: clusters younger than 50 Myr (151 clusters, average 16.8 Myr), and clusters older than 50 Myr (150 clusters, average 414 Myr). We show distributions of all clusters projected on the Galactic plane in Figure 1. Most of the clusters are concentrated near the Sun, within a heliocentric distance of 2 kpc, with only 56 clusters further than 2 kpc, and 18 further than 3 kpc. The right panel of this figure indicates clearly the curling spiral arms, the local Orion-Cygnus arm, the inner Sagittarius-Carina arm, and fragment of the outer Perseus arm. Different symbols mark clusters of different age groups: small dots (50 clusters) for ages less than 8 Myr (average 6.0 Myr), circles (49 clusters) for ages in the range 8–18 Myr (average 12.1 Myr), and triangles (52 clusters) for the age range 18–50 Myr (average 31.5 Myr). The clusters tend to be more inter-mixed with increasing age, and the spiral structures become indistinct for clusters older than 50 Myr (Fig. 1, left panel). A detailed study on the spiral structure traced by the young open clusters was made by Dias & Lépine (2005). The scale height of the disk is typically about 50 pc, given respectively by Piskunov et al. (2005) and Bonatto et al. (2006), derived from open cluster data.

From the kinematical behaviors of the young thin-disk population objects, e.g. the H I gas, classical Cepheids, and O-B stars, the existence of a K-term in the solar neighborhood has long been recognized by astronomers (Feast 1967; Humphreys 1972). It was generally thought that this fact could be interpreted either as a systematic error in radial velocity measurements or as evidence for non-axisymmetric motion of stars. Pont et al. (1994) from an N-body simulation suggested that an observed K-term is a local dynamic effect of non-axisymmetric motion in the barred Galaxy. On the other hand, stellar motions driven by a barred potential could be on oval orbits rather than on circular orbits. Suppose the kinematical behavior of the open clusters are dominated by an axisymmetric gravitational potential with a small perturbation

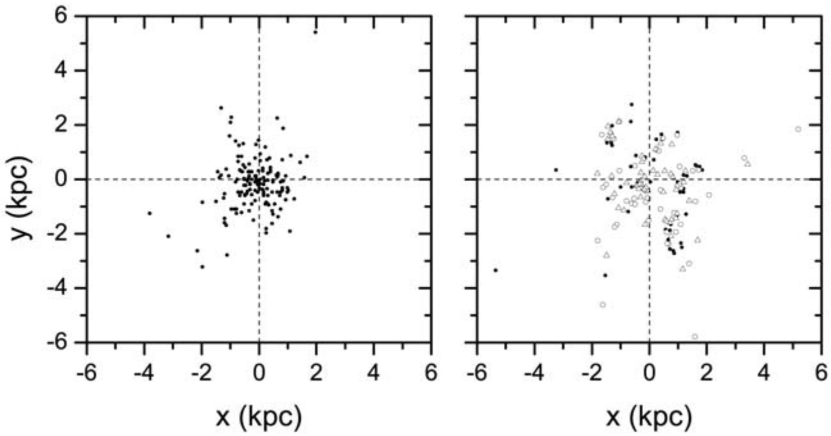

Fig. 1 Distributions of open clusters projected on the Galactic plane. Right panel for 151 clusters younger than 50 Myr (Small dots: younger than 8 Myr, circles: ages between 8 and 18 Myr, triangles: ages between 18 and 50 Myr). Left panel for 150 older clusters, older than 50 Myr.

($m = 2$), and the corresponding non-axisymmetric model is based on KT, then we have

$$\Phi(R, \phi) = \Phi_0(R) + \Phi_1(R) \cos 2(\phi - \phi_{\rm b}) \,, \tag{1}$$

where $\Phi_0(R)$ is the primary axisymmetric potential. The second part of the right hand in Equation (1) is a supposed small perturbation arisen from a bar or a triaxial halo. Then, the equal potential contours will be approximately elliptical, with minor axis in the direction $\phi_{\rm b}$.

Accepting the potential with power-law dependence on the radius, proposed by KT :

$$\Phi_0(R) \;=\; \frac{V_0^2}{2\alpha} \left(\frac{R}{R_0} \right)^{2\alpha}, \quad \alpha \neq 0, \tag{2}$$

$$\Phi_1(R) \;=\; \Psi_0 \left(\frac{R}{R_0} \right)^{p}, \qquad \Psi_0 \geq 0, \tag{3}$$

where V_0 is the circular velocity at the Sun, and R_0, the Galactocentric distance of the Sun. The circular speed and the potential ellipticity have also power-law expressions:

$$V_c(R) = V_0 \left(\frac{R}{R_0} \right)^{\alpha}, \quad \epsilon(R) = \epsilon_0 \left(\frac{R}{R_0} \right)^{p-2\alpha} . \tag{4}$$

The parameter α expresses the shape of the rotation curve, p characterizes the configuration of the barred potential. The mean radial and tangential velocities in this potential are given by KT and by Metzger et al. (1998):

$$V_R(R, \phi) \;=\; \beta_1 V_c(R) [s(R) \cos 2\phi - c(R) \sin 2\phi], \tag{5}$$

$$V_\phi(R, \phi) \;=\; V_c(R) [1 - \beta_2 c(R) \cos 2\phi + \beta_2 s(R) \sin 2\phi] \,, \tag{6}$$

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 the two orthogonal components,

$$c(R) = \epsilon(R) \cos 2\phi_{\rm b} \,, \qquad s(R) = \epsilon(R) \sin 2\phi_{\rm b} \,. \tag{7}$$

According to Equations (5) and (6), the ellipticity components may be detected directly from the spatial velocities of a disk population of objects. Obviously, large scale data (with sufficient large azimuthal angles ϕ) are needed to constrain the modeling velocities, and to yield a valid estimate of $c(R)$ and $s(R)$.

3 PARAMETERS OF THE ELLIPTICAL POTENTIAL

We now consider the rotation curve defined by the spatial velocities of the open clusters. To start, we accept the circular speed $V_0 = 220\ \mathrm{km\ s^{-1}}$ (Kerr & Lynden-Bell 1986), and the best value of R_0 =8 kpc, proposed by Reid (1993). The peculiar velocity of the Sun ($U_\odot = 10.00, V_\odot = 5.25$ and $W_\odot = 7.17$) in $\mathrm{km\ s^{-1}}$ is taken from Dehnen & Binney (1998). The rotation curves are illustrated in Figure 2. The upper panel shows the tangential velocities as function of the Galactocentric distance, the bottom panel displays the rotational speed as a function of the azimuthal angle. The small dots or circles show clusters older or younger than 50 Myr. The top panel of Figure 2, for both the older and younger clusters, exhibits a flat rotation of the Milky Way with a slight decline in the solar vicinity, similar to the CO- and H I-based rotation curve derived by Clemens (1985). The bottom panel demonstrates a left-right asymmetric distribution of the velocities. The tangential velocities of clusters with negative ℓ ($\phi < 0$) are apparently larger than those with positive ℓ ($\phi > 0$). Using a linear fit to all data, we obtain the average slope $\partial V_\phi/\partial\phi = -16.7 \pm 5.2\ \mathrm{km\ s^{-1}\ rad^{-1}}$. Note that, throughout this paper, we always use iterative processing methods to eliminate clusters with extremely large residual velocities (2.6σ). The above behavior of the kinematical asymmetry may be dominated by a non-axisymmetric potential, so awakening our interest for a further analysis.

Assume the orbits of clusters are nearly circular, or more reasonably, are isomorphic with approximately the same direction of the major axis, then the circular speeds and the parameter α of Equation (4) can be easily derived from a least-squares fit to the rotation curve of the top panel of Figure 2. Considering Equation (6) and the bottom panel of Figure 2, we are able to derive the two elliptical parameters via a least-squares solution.

From a least-squares fit we obtain $\alpha = -0.167 \pm 0.029$, assuming $V_0 = 220\ \mathrm{km\ s^{-1}}$ and $R_0 = 8$ kpc. Then, $c(R_0)$ and $s(R_0)$ are solved from Equation (6) for all 301 clusters. The results are listed in Table 1. Note that, an undetermined multiplier β_2 is involved in the elliptical parameters. Because the coefficient p is unknown which may be related to the shape, size, and distribution of the bar or halo, we simply set $\beta_2 = 1$

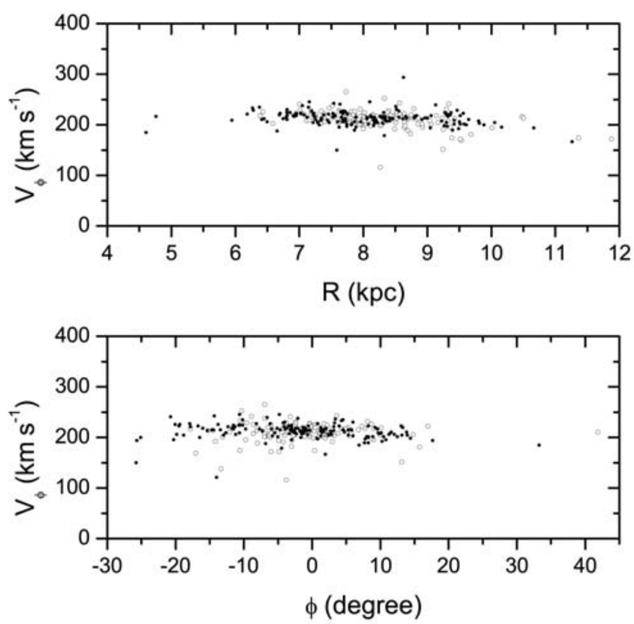

Fig. 2 Tangential velocities of open clusters, assuming $V_0 = 220\ \mathrm{km\ s^{-1}}$ and R_0 =8 kpc. Small dots for clusters younger than 50 Myr, circles, clusters older than 50 Myr. The top panel plots the speed against the Galactocentric distance, the bottom panel the same against the Galactocentric azimuthal angle.

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

for the convenience of discussion, similar to that by KT (called 'standard model' by KT in which they set $\alpha = p = 0$).

The present evaluation of ellipticity depended on the spatial velocities of clusters. Uncertainties of the modeling parameters (α, V_0 and R_0) may infect the determination. Although the coefficient α is obtained from a fit of the rotation curve, its value differs little from the Oort constants $(B - A)$ (see below). The measured values of V_0 and R_0 are more uncertain. From a comparative study of the different R_0 calibrations, Reid (1993) proposed a measurement error $\Delta R_0 = \pm 0.5\,\mathrm{kpc}$. In order to see the impact of the adopted parameters, we calculated for various values (of α, V_0 and R_0) different from the initial one. The resulting estimates of ellipticity are given in Table 1.

From the results tabulated, we find that $c(R_0)$ and $s(R_0)$ are well determined with a low correlation coefficient. Considering the errors, all the solutions are mutually consistent, especially for the parameter $c(R_0)$. The coefficient α has no strong impact on the ellipticity parameter, even if we consider the extreme cases of $\alpha = 0$ (a flat rotation) and $\alpha = -0.5$ (a rapid drop-off). Referring to Equation (7), we recall that $c(R)$ and $s(R)$ correspond to the symmetric and antisymmetric parts of the ellipticity about $\phi = \phi_{\mathrm{b}}$. Possible measurement errors in V_0 and R_0 will introduce an additional bias in the velocity:

$$\Delta V_\phi^2 = \cos^2\phi \Delta V_0^2 + V_R^2 \sin^2\phi \Delta R_0^2 / R^2 \,, \tag{8}$$

$$\Delta V_R^2 = \sin^2\phi \Delta V_0^2 + V_\phi^2 \sin^2\phi \Delta R_0^2 / R^2 \,. \tag{9}$$

The majority of clusters are located within ($6 < R < 10\,\mathrm{kpc}$, $-20^\circ < \phi < 20^\circ$; assuming $R_0 = 8\,\mathrm{kpc}$). See Figure 2. Errors of ΔV_0 and ΔR_0 will contribute primarily a constant shift plus a small fluctuation to the velocities V_ϕ. The maximum fluctuation is $|(V_\phi)_{\phi=\pm 20^\circ} - (V_\phi)_{\phi=0}| \approx 1.2\ \mathrm{km\,s^{-1}}$, on supposing $\Delta V_0 = \pm 20\ \mathrm{km\,s^{-1}}$, $\Delta R_0 = \pm 1\,\mathrm{kpc}$, and $V_R = V_0/10 = 22\ \mathrm{km\,s^{-1}}$. On the other hand, the radial motion V_R is strongly affected by the uncertainties in R_0 and V_0. That is why we do not use Equation (5) to constrain the velocity field. From an analysis of correlations within this range, between the parameters $c(R)$ and $s(R)$, and the errors ΔV_0 and ΔR_0, we find that the measurement errors in V_0 and R_0 have a weaker influence on $c(R)$ than on $s(R)$.

Based on the circular model of the Galactic rotation, the Oort constants A and B are obtained from the kinematical data of clusters in the range $r \leq 3.0\,\mathrm{kpc}$:

$A = 16.44 \pm 0.94,\ B = -12.91 \pm 0.89$, for all clusters,
$A = 16.50 \pm 0.85,\ B = -14.56 \pm 0.83$, for ages $\leq$ 50 Myr,
$A = 16.38 \pm 1.68,\ B = -10.93 \pm 1.61$, for ages $>$ 50 Myr,

in units of $\mathrm{km\,s^{-1}\,kpc^{-1}}$. The Oort constants combination, $A - B$, for all the clusters is in excellent agreement with that given by Reid & Brunthaler (2004), obtained from the Sgr A * proper motion, and the value for clusters with ages less than 50 Myr is perfectly consistent with that determined from the Hipparcos proper motions of young O-B5 stars in our previous work (Miyamoto & Zhu 1998). The corresponding circular speeds at the Sun ($R_0 = 8\,\mathrm{kpc}$) are, respectively, $V_0 = 235 \pm 10\,\mathrm{km\,s^{-1}}$, $V_0 = 248 \pm 10\,\mathrm{km\,s^{-1}}$, and $V_0 = 218 \pm 19\,\mathrm{km\ s^{-1}}$. Using these circular velocities, we finally obtain the ellipticity parameters listed Table 1. The listed coefficients α are derived from the rotation curves.

The results in the last three lines of Table 1 are essentially indistinguishable, though the parameter $s(R_0)$ from the older clusters is a little less than from the younger clusters. Considering the relatively small velocity dispersion of a cold disk population, we prefer to accept the ellipticity of the potential obtained from the younger clusters.

The present determination of $s(R_0)$ agrees well with that given by Metzger et al. (1998), who found $s(R_0) = 0.043 \pm 0.016$ from a kinematical analysis of Galactic Cepheids. For the component $c(R_0)$, we still have not found a clear reason for the large difference between our result and that given by KT. KT obtained $c(R_0) = 0.082 \pm 0.014$ based both on local kinematical constraints and global constraints of the H I velocity field, and Metzger et al. (1998) have pointed out that a small $c(R_0) < 0.04$ may exist in their consideration of the RR Lyrae and Cepheid distance calibrations.

4 CONCLUSIONS AND DISCUSSION

We performed a kinematical analysis based on the spatial velocities of Galactic open clusters. Using the model of an asymmetric disk proposed by KT, a meaningful determination of the elliptical components $c(R_0)$ and $s(R_0)$ is given, which implies a weak elliptical distortion of the Milky Way potential. The proposed equipotential ellipticity at the Sun with its minor axis in direction is $\epsilon(R_0) = 0.054 \pm 0.013$, $\phi_b = 29.5° \pm 3°.3$, obtained from the younger clusters with ages less than 50 Myr, and assuming $\beta_2 = 1$. Because the parameter p is not determined, the value of ellipticity will be increased by a factor of 3 for $p \approx -3$, for a bar located well inside the solar circle, or, decreased by a factor of 0.8 for $p \approx +2$, for a triaxial halo with core radius much larger than the solar circle.

On the other hand, the modeling parameter $V_0 = 248\ \mathrm{km\ s^{-1}}$ is derived from the Oort constants, given for R_0=8 kpc. If V_0 is overestimated, then the ellipticity will be underestimated. If we accept $V_0 = 220$ $\mathrm{km\ s^{-1}}$ and R_0=8 kpc, then we have $\epsilon(R_0) = 0.066 \pm 0.015$ and $\phi_b = 31.5° \pm 2.7°$. Thus we suggest

$$\epsilon(R_0) = 0.060 \pm 0.012, \quad \phi_b = 30° \pm 3° . \tag{10}$$

The present finding shows that the Sun deviates from the direction of the minor axis by about $-30\,°$. Thus, observations of more remote clusters are needed for a more reliable determination, especially, distant clusters along the Galactic longitude $\ell = +90°$.

The present work is the first that has succeeded in obtaining the two elliptical components of the Milky Way potential using a consistent data set of a disk population of the open clusters, based on the simple dynamic model by KT. Using our solution from the open clusters, the motion of objects at the Sun is suggested to be on an oval orbit, rather than on a circular one. See Figure 3.

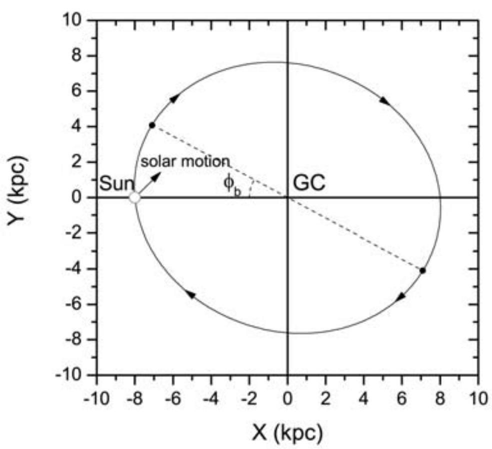

Fig. 3 A schematic orbit of the stars at the Sun.

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