Chin. J. Astron. Astrophys. Vol. 7 (2007), No. 1, 120–128
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

A Kinematical Calibration of the Galactocentric Distance *

Ming Shen and Zi Zhu

Department of Astronomy, Nanjing University, Nanjing 210093; *shenming@nju.org.cn*

Received 2006 April 14; accepted 2006 June 28

Abstract We present a new determination of the Galactocentric distance by a pure kinematical model. Two subgroups of components from the Galactic thin disk, the O-B5 stars and the Galactic open clusters, were selected for our analysis. On the basis of kinematical data of around 1200 O-B5 stars, we obtained an estimated value of R_0=8.25±0.79 kpc, while a similar evaluation from 270 Galactic open clusters gives R_0=7.95±0.62 kpc. Considering the scatter of R_0 given by individual investigators with different methods, our present determinations agree well with the best value proposed by Reid.

Key words: Galaxy: kinematics and dynamics — stars: early-type — open clusters and associations

1 INTRODUCTION

The distance to the Galactic center R_0 is a fundamental constant for astronomy and astrophysics. Most determinations of astronomical quantities are directly connected with the Galactic distance scale, e.g., the rotational speed of our Galaxy, the kinematical distances derived from radial velocities, the dynamic and luminous mass of the Galaxy, the mass and luminosity of the Galactic objects, etc. R_0 can also be used as a distance standard indirectly when evaluating extragalactic distance scales.

A pioneer work to find the center of the Galaxy was carried out by Shapley (1918), who suggested that the globular clusters have a symmetric distribution concentrated towards the center of the Galaxy, and he estimated a distance from the observer (the Sun) to the center $R_0 \approx 13\,\mathrm{kpc}$. Following Shapley's work, great efforts have been expended in deriving the constant of the Galactocentric distance via various techniques and observations. However, a serious problem is the effect of the large and variable extinction, especially in the central region of the Galaxy. One of the efficient methods is to observe the horizontal branch RR Lyrae variables in the infrared band through the Baade's window. It is known that RR Lyrae stars are well distributed all over the sky, and have a fairly well-determined distance scale. The distance to the Galactic center R_0 can be estimated from the distance corresponding to the peak of distribution of RR Lyraes, similar to the method used for globular clusters.

VLBI observations of water vapor $(\mathrm{H_2O})$ in star-forming regions provide highly precise positions and proper motions of the water masers. Proper-motion studies of the water masers in the Galactic center region give a significant measurement of the kinematical distance to this region. The proper motions of $\mathrm{H_2O}$ masers were first observed by Genzel et al. (1981). Distance estimates from Sgr B2 and other star-forming regions yielded Galactocentric distances ranging from $R_0 = 6.5$ kpc to $R_0 = 8.1$ kpc (Binney & Merrifield 1998).

Compared with the VLBI observations of water masers in Galactic center regions, observations of stars in the solar neighborhood provide crucial information of local kinematics. For the population I stars in the disk, e.g., the classical Cepheids, one can combine the radial velocity data and the well-calibrated distances from the PL relation of Galactic Cepheids, to fit with the Galactic rotation model. As an independent

---

* Supported by the National Natural Science Foundation of China.

parameter, the Galactocentric distance R_0 can be determined from a kinematical model. An initial work was given by Joy (1939), who fitted a rotation model to the Cepheid velocities and yielded $R_0 = 10$ kpc. Using much more recent observations of classical Cepheids, Caldwell & Coulson (1987), Pont et al. (1994) and Metzger et al. (1998) obtained values of R_0 that are even closer to the best value proposed by Reid (1993). The direct fitting of rotation model via radial velocity data gives the combined kinematical parameters of $2AR_0$ and R_0. As argued by Metzger et al. (1998), these parameters are strongly correlated; especially the determination of R_0 is highly correlated with the individual distances of stars derived from adopted PL relation.

Similar to the Galactic Cepheids, the open clusters are one of the best populations of objects to trace kinematical structure of the Galaxy. Recently, several works were concentrated on the kinematical analysis from data of open clusters, including studies by Zhao et al. (2006) and by Gerasimenko (2004). Using the radial velocity data of open clusters, two different methods were considered by Gerasimenko for deriving the Galactocentric distance R_0. Suppose a linear variation of the rotational angular velocity with the distance to the Galactic center, the modeling angular-velocity gradient was defined by a preliminary accepted R_0. The final solution of R_0 was obtained from a common angular-velocity gradient defined separately by a group of clusters exterior to the solar circle and by clusters interior to the solar circle. Inspecting the value of the angular-velocity gradient given at the estimated R_0 (see figure 3 in Gerasimenko's paper), we found that this value to be too large to accord with our present understanding of the Galactic rotation. This fact must have be arisen from the linear model of the angular velocity. It is well known that the rotation curve is nearly flat with a slight decline at the Sun. Thus, the angular velocity varies very differently from the linear model. In principle, the second method the authors used was similar to that applied by Pont et al. (1994) and by Metzger et al. (1998) for the analysis of the Galactic Cepheids, but we are doubtful about the processing the authors used.

Various methods and measurements of R_0 have been reviewed by Reid (1993): while the value of the constant $R_0 = 8.0 \pm 0.5$ kpc is currently considered as the best one, and the individual determinations are still rather discrepant. The 1985 IAU standard value of R_0 was 8.5 kpc, while the adopted value in 1964 IAU General Assembly was 10 kpc (Kerr & Lynden-Bell 1986). The errors of current measurements of R_0 are still too large, even if some published values are close to the best estimate of $R_0 \sim 8.0$ kpc.

O-B5 stars and the young open clusters, which belong to the thin disk population of the Galaxy, usually have low velocity dispersion. Analysis of the velocity field of these objects is a usual way to obtain the kinematical constants of the Galaxy. In a previous work, Zhu (2006) used about 2000 Hipparcos O-B5 stars to determine the local kinematical parameters of the Galaxy. Recently, Kharchenko et al. (2005a, b) published 650 open clusters with astrophysical parameters derived from astrometric and photometric measurements. The homogeneous data set of these open clusters provides a good opportunity to re-examine the local kinematics of the Galaxy, and invites us to take a new determination of the Galactocentric distance.

Due to its fundamental importance, the calibration of the Galactocentric distance R_0, is an on-going task for astronomers. The uncertainties and discrepancies are still too large, even if among the various methods, we have found the most efficient way of estimating R_0. The Galactocentric distance is derived usually from radial velocities on the basis of some kinematical model, but the strong couplings between the observed heliocentric distances of stars and the parameter of R_0, and between the Oort constant A and R_0, represent the most serious factors that might lead to a biased estimation of R_0. In the following, we mainly focus on estimating the Galactocentric distance by analyzing the proper motions and radial velocities of O-B5 stars and young open clusters. In contrast to the previous analyses of the radial velocities of Galactic Cepheids or open clusters, we are able to derive the Oort constant A from the proper motions and the parameter $2AR_0$ from the radial velocities independently. Our new method is an effort of minimizing the above mentioned couplings, thereby enabling us to obtain a more reliable estimate of R_0. The reductions are based on homogeneous data sets of both O-B5 stars and open clusters. The final results agree very well with the present best determination of R_0.

2 OBSERVATION DATA

As mentioned above, we will use two separate data sets, the O-B5 stars and the Galactic open clusters, for our analysis of the local kinematical structure and for deriving the constant of the Galactocentric distance.

2.1 O-B5 Stars

The astrometric data are taken from the Hipparcos Catalogue, including proper motions and trigonometric parallaxes. The radial velocities are taken from the General Catalogue of mean Radial Velocities (Barbier-Brossat & Figon 2000) which contains radial velocity measurements for 36145 stars. In the same way as we did before (Zhu 2006), we have selected 1190 O-B5 stars. All of these are single stars given in the Hipparcos Catalogue, and stars belonging to the Gould-belt have been individually excluded.

2.2 Open Clusters

Based on the All-Sky Compiled Catalogue of 2.5 million stars (ASCC-2.5) (Kharchenko 2001), Kharchenko et al. (2005a) identified 520 Galactic open clusters and compact associations using a homogeneous method and algorithms. Subsequently, an additional list of 130 open clusters was published by Kharchenko et al. (2005b), including 109 new identifications. A recent study by Piskunov et al. (2006) showed that the completeness area of those clusters reaches up to 0.85 kpc from the Sun. Dias et al. (2002a, b) collected all the published data of open clusters from the literature, 1637 clusters in all, in their DAML02 catalogue.

Our following work is based on the 520 open cluster data given by Kharchenko et al. (2005a). For the second part of the catalogue (130 clusters), we have checked their kinematical data, and found them to be inconsistent with the first part of 520 clusters, so we decided to exclude them for this study.

From the list of 520 clusters we found 253 open clusters supplied with heliocentric distances, mean proper motions, mean radial velocities and ages. For the remaining clusters, 29 mean radial velocity measurements were taken from DAML02 catalogue. In addition, 19 clusters listed in DAML02 have complete kinematical data, which were not included in the list of 520 clusters. Supplementing these data and clusters we found complete spatial velocities for 301 clusters of our sample.

In order to inspect the velocity field defined by the present sample of 301 clusters, we have examined the peculiar motion for individual clusters, and found that 10 of them have extremely large peculiar motions, they are NGC 2527, Ruprecht 55, Ruprecht 90, Trumpler 16, Pismis 17, Dolidze 25, Berkeley 31, Lynga 6, NGC 6791 and NGC 2506. Almost all of them are distant clusters, more than 3 kpc from the Sun. Thus, the calibrated distances for those clusters might be suspect, and we excluded them in our analysis.

Figure 1 displays their distribution on the Galactic plane. The X-axis points to the Galactic center, and the Y-axis to the direction of the Galactic rotation. The clusters are located within a range of $r \leq 3.0$ kpc.

3 MODELS

3.1 Proper Motions

Assume that the rotation is axisymmetric, the observed proper motions of stars should represent the Oort-differential rotation of the Galaxy. In the first-order approximation we have

$$\kappa\mu_\ell \cos b = (u_0 \sin\ell - v_0 \cos\ell)/r + A\cos 2\ell \cos b + B\cos b, \tag{1}$$

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

where constant $\kappa = 4.74047$, when proper motions are in $\mathrm{mas\,yr}^{-1}$ and the heliocentric distances r are in kpc. The parameters u_0, v_0 and w_0 are the components of solar motion in the directions of the Galactic center, the Galactic rotation and the north Galactic pole, respectively. The Oort Constants A and B are defined by

$$A = -\frac{1}{2} R_0 (\mathrm{d}\Omega/\mathrm{d}R)_0, \tag{3}$$

$$B = -\Omega_0 - \frac{1}{2} R_0 (\mathrm{d}\Omega/\mathrm{d}R)_0, \tag{4}$$

where Ω is the angular velocity, the subscript '0' stands for the location of the Sun, and r is the distance of the observed object to the Sun. For the open clusters, the heliocentric distance can be found in the catalogue directly, while for the O-B5 stars r is taken from the Hipparcos parallax.

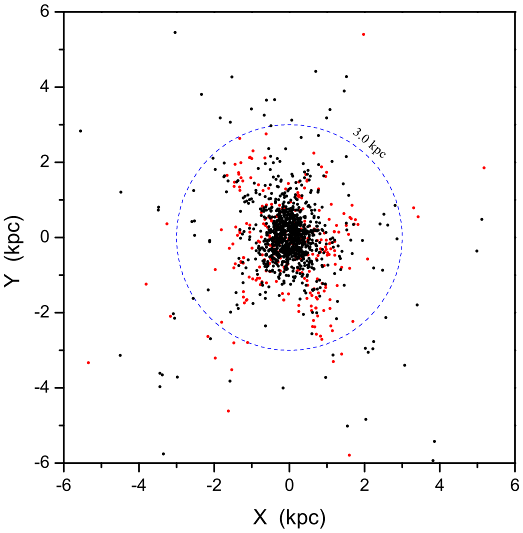

Fig. 1 Distributions of 1190 O-B5 stars and 301 open clusters on the Galactic plane. Black dots mark the O-B5 stars, red dots, the open clusters. The blue dash circle marks the area within heliocentric distance 3.0 kpc.

3.2 Radial Velocities

For a star at Galactic coordinates (ℓ, b) and Galactocentric radius R, its radial velocity can be written as (Pont et al. 1994),

$$v_r = 2AR_0\left(\frac{R_0}{R} - 1\right)\sin\ell\cos b - u_0\cos\ell\cos b - v_0\sin\ell\cos b - w_0\sin b - \delta v_r\,. \tag{5}$$

Here δv_r expresses a possible systematic offset of the zero-point of radial velocities, which has been recognized for a long time. More detailed explanation for the δv_r term will be given later. Because the O-B5 stars and open clusters of our sample are located in a thin disk, the component of the solar motion in the direction towards the north Galactic pole is cannot be determined from their radial velocities. In fact, the typical scale height of O-B stars is about 0.1 kpc, and is only 56 pc for the open clusters, as given recently by Piskunov et al. (2006). Analyzing the Hipparcos main sequence stars, Dehnen & Binney (1998) found $w_0 = 7.2 \pm 0.4$ km s^{-1}. Thus, in the following analysis for radial velocity data, w_0 will be fixed at the value of Dehnen & Binney (1998).

The Galactocentric radius R of a star is given by

$$R = (R_0^2 + r^2\cos^2 b - 2rR_0\cos\ell\cos b)^{\frac{1}{2}}. \tag{6}$$

3.3 Fitting Models

As we discussed in Section 2, most O-B5 stars and open clusters are located within a heliocentric distances $r = 3.0$ kpc. For the 1190 O-B5 stars, nearly 7 percent (87 stars) have heliocentric distances larger than 3.0 kpc, while for the 301 open clusters about 6 percent (18 clusters) are beyond 3.0 kpc. Inspecting the peculiar velocities, we found that a majority of those distant objects have large peculiar motions, and almost half of them are extremely large. It is well known that the rotation curve is nearly flat over a wide range, with a slight decline at the Sun. For stars and/or clusters further than 3.0 kpc from the Sun, they are randomly distributed on the Galactic plane (see Fig. 1). Therefore, we do not think that the large peculiar motions of these distant objects are intrinsic kinematics. One of the most probable reasons could be errors in their distance measurements and calibrations. Further, we have checked the Galactic height of our samples. Adopting the Galactic height of the thin disk of $|z| = 0.35$ kpc, we found from our samples that 68 O-B5 stars and 9 open clusters have a Galactic height larger than 0.35 kpc. Among them more than 60% are the distant objects ($r > 3.0$ kpc), and almost all of them have a heliocentric distance larger than 2.0 kpc. It points again that the distance measurements and calibrations of those 'distant' objects may be problematic and will introduce enormous errors in the space velocities, which would be extremely harmful on our kinematical solutions. To avoid this trouble, the easiest way is to limit our samples to $r \leq 3.0$ kpc and $|z| \leq 0.35$ kpc in the following analysis.

As we did before (Zhu 2000, 2006), a numerical filter was used to reject stars or clusters when their residual velocities from the model are greater than $50\ \mathrm{km\,s^{-1}}$. This value is based on both random errors in the velocity ellipsoids and measuring errors in the proper motions and radial velocities. We have noticed that O-B5 stars and open clusters shared a similar velocity dispersion of $17\ \mathrm{km\,s^{-1}}$ (Binney & Merrifield 1998; Piskunov et al. 2006).

4 RESULTS

Equations (1) and (2) for the proper motion, and Equation (5) for the radial velocity, were solved separately by least squares. Considering the large dispersion in the tangential velocity of nearby stars (Zhu 2006), we considered several subsamples with different lower cutoffs on the heliocentric distance.

Solutions of the proper motions of O-B5 stars and open clusters are given in Tables 1 and 2, respectively. Here solution S1 is for stars within the range 0.1 kpc $\leq\ r \leq 3.0$ kpc, S2 is for 0.2 kpc $\leq\ r \leq 3.0$ kpc, etc. Within the range of $r < 0.1$ kpc there are only four O-B stars and no clusters. Thus we start our calculations with S1. In both tables the second line gives the total number of stars or clusters used in the solution, and the number of stars rejected by our numerical filter is given in the last line. Note that the numerical filter defined in the last section was always in operation. Using an iterative procedure the kinematical parameters and their standard errors were derived after a few loops.

Tables 1 and 2 show that solution S1 gives the worst estimates for Oort constants A and B, while S2 or S3 provides the best estimates. This fact can be explained by the strong tangential velocity dispersions for nearby stars within $r < 0.2$ kpc, because the components of velocity dispersions on the tangential plane, derived from proper motions, are statistically proportional to the reciprocal of the heliocentric distances. On the other hand, inspecting the number of stars rejected by the numerical filter, we find that the number in the solution S1 for open clusters seems too large, and that can be caused by the same reason of velocity dispersion. Note that for open clusters, the astrophysical data are derived from the statistical averages of the individual member stars. Thus, the kinematical data of the open clusters should be more reliable than those of the O-B5 stars. For the components (u_0, v_0, w_0) of the solar motion, we refer the reader to discussions in the literature for details (Dehnen & Binney 1998; Miyamoto & Zhu 1998; Piskunov et al. 2006).

In our previous study (Zhu 2006), we have used the same data set of O-B5 stars. The Oort constants were found $D^+_{12} = A = 16.18 \pm 1.06\ \mathrm{km\,s^{-1}\ kpc^{-1}}$ and $D^{-1}_{21} = B = -14.76 \pm 1.06\ \mathrm{km\,s^{-1}\ kpc^{-1}}$ (see table 2 in Zhu 2006). The present solution of the Oort constant A is different from our previous one. Note that our former work was based on a 3-D asymmetric rotation model in which rotations and shear motions on planes perpendicular to the Galactic plane, and motions of overall contractions and/or expansions were considered besides the flat axisymmetric rotation in the present model. Solutions to the asymmetric model need both proper motions and radial velocities. A possible systematic offset of the radial velocity system δv_r (see below) will introduce additional motions to the model. The difference can also be inferred from the observed equations given by Zhu (2000), since the radial velocities involve the constant A but not the constant B.

Now, we go on to treat the radial velocities on the basis of Equation (5). As we mentioned in Section 3, it is not possible to derive the component w_0 of the solar motion simply from the radial velocities. This parameter will be fixed at $w_0 = 7.2\ \mathrm{km\,s^{-1}}$, the value given by Dehnen & Binney (1998). In order to obtain a precise estimate of R_0 we used an iterative method. For a given initial value of R_0, we determined $2AR_0$ as a single parameter. Then, using the values of A given in Table 1 or 2, we derive a new estimate of R_0 from the $2AR_0$. We repeat the iteration until convergence is achieved. The final solutions are listed in Table 3 for the O-B5 stars and in Table 4 for the open clusters. To examine the effect of the fixed value of w_0 on the kinematical solution, we made a second calculation using the value of w_0 obtained directly from proper-motion analysis in Table 1 or 2. We found that there is no correlation between the adopted w_0 and the resulting kinematical parameters. This fact can be easily inferred from Equation (5) which shows

Table 1 Kinematical parameters derived from proper motions of the Hipparcos O-B5 stars. The solar motion components (u_0, v_0, w_0) are in units of $\mathrm{km\,s^{-1}}$, the Oort constants A and B are in units of $\mathrm{km\,s^{-1}\,kpc^{-1}}$.

Solutions r (kpc)	S1 $(0.1 \sim 3.0)$	S2 $(0.2 \sim 3.0)$	S3 $(0.3 \sim 3.0)$	S4 $(0.4 \sim 3.0)$	S5 $(0.5 \sim 3.0)$
Total No.	1062	1001	884	694	559
u_0	11.03 ± 0.49	10.08 ± 0.49	9.78 ± 0.59	9.52 ± 0.66	9.22 ± 0.80
v_0	11.52 ± 0.47	9.33 ± 0.46	8.29 ± 0.58	8.12 ± 0.65	8.54 ± 0.78
w_0	6.18 ± 0.43	5.74 ± 0.43	5.71 ± 0.54	6.03 ± 0.60	6.49 ± 0.71
A	14.63 ± 1.40	14.82 ± 1.16	14.84 ± 1.20	14.48 ± 1.10	14.63 ± 1.13
B	-15.37 ± 1.03	-14.80 ± 0.85	-14.77 ± 0.88	-15.20 ± 0.80	-15.24 ± 0.81
Rejected No.	15	13	12	10	9

Table 2 Kinematical Parameters Derived from Proper Motions of Galactic Open Clusters

Solutions r (kpc)	S1 $(0.1 \sim 3.0)$	S2 $(0.2 \sim 3.0)$	S3 $(0.3 \sim 3.0)$	S4 $(0.4 \sim 3.0)$	S5 $(0.5 \sim 3.0)$
Total No.	275	264	258	239	219
u_0	11.06 ± 0.53	10.40 ± 0.60	7.83 ± 0.66	8.02 ± 0.74	6.06 ± 0.89
v_0	10.88 ± 0.53	10.51 ± 0.56	10.11 ± 0.58	11.30 ± 0.68	12.08 ± 0.82
w_0	7.01 ± 0.48	7.32 ± 0.51	6.98 ± 0.53	7.16 ± 0.63	7.17 ± 0.73
A	16.09 ± 0.91	16.20 ± 0.90	16.43 ± 0.85	16.49 ± 0.85	16.74 ± 0.88
B	-13.10 ± 0.65	-13.11 ± 0.64	-13.46 ± 0.60	-13.09 ± 0.61	-12.95 ± 0.62
Rejected No.	13	4	3	1	1

Table 3 Kinematical parameters derived from radial velocities of O-B5 stars, where $u_0, v_0, w_0, \delta v_r$ and $2AR_0$ are in $\mathrm{km\,s^{-1}}$, R_0 in kpc.

Solutions r (kpc)	S1 $(0.1 \sim 3.0)$	S2 $(0.2 \sim 3.0)$	S3 $(0.3 \sim 3.0)$	S4 $(0.4 \sim 3.0)$	S5 $(0.5 \sim 3.0)$
Total No.	1062	1001	884	694	559
u_0	9.70 ± 0.54	9.78 ± 0.56	9.59 ± 0.60	9.82 ± 0.67	8.86 ± 0.78
v_0	13.76 ± 0.45	13.31 ± 0.47	13.31 ± 0.51	12.69 ± 0.58	13.03 ± 0.68
w_0(set)	7.2	7.2	7.2	7.2	7.2
δv_r	2.38 ± 0.46	2.69 ± 0.48	3.17 ± 0.52	3.68 ± 0.59	3.63 ± 0.69
$2AR_0$	243.23 ± 13.21	244.44 ± 13.43	248.23 ± 13.77	244.63 ± 14.18	237.79 ± 15.03
R_0	8.31 ± 0.91	8.25 ± 0.79	8.36 ± 0.82	8.45 ± 0.81	8.13 ± 0.81
Rejected No.	25	24	22	20	17

the velocity w_0 is orthogonal to the other kinematical components, especially for our present case of O-B5 stars and open clusters distributed in a thin sheet.

In the analysis above, we prefer to accept the simple fitting errors from our model for the weights, instead of the usual weighting system obtained from the measurement errors. It is emphasized that weights derived from the measurement errors should include both effects of errors in radial and tangential velocities, and of peculiar velocities of stars which are deviations from the LSR. Due to the lack of the measurements, errors in the radial velocities are not available for many of the stars and clusters in our sample. A statistical average of the peculiar motions yields the velocity dispersion for a given group of stars. A recent work on the kinematical analysis from the open clusters presented the velocity dispersion defined by the open clusters (Zhao et al. 2006). The peculiar motions for individual stars are hard to know, even though their statistical mean effect can be expressed as equations (20), (21) and (22) given by Zhu (2006). Thus, we decided to use the fitting errors to evaluate the measuring deviations of the kinematical parameters.

Comparing the solutions for the different subsamples, given in Tables 1 and 2, we find that all the parameters are in good agreement within their standard errors. Note that for the radial velocities the influence of velocity dispersion is independent of the heliocentric distances of the stars. This fact can be easily inferred from the standard errors for each parameter. The number of rejected stars given in the last line of

Table 4 Kinematical Parameters Derived from Radial Velocities of Open Clusters

Solutions r (kpc)	S1 $(0.1 \sim 3.0)$	S2 $(0.2 \sim 3.0)$	S3 $(0.3 \sim 3.0)$	S4 $(0.4 \sim 3.0)$	S5 $(0.5 \sim 3.0)$
Total No.	275	264	258	239	219
u_0	9.93 ± 1.04	9.78 ± 1.06	9.61 ± 1.08	9.15 ± 1.14	8.65 ± 1.22
v_0	12.27 ± 0.81	11.93 ± 0.82	12.01 ± 0.84	11.78 ± 0.89	11.51 ± 0.95
w_0(set)	7.2	7.2	7.2	7.2	7.2
δv_r	2.48 ± 0.86	2.73 ± 0.88	2.85 ± 0.89	3.05 ± 0.95	3.08 ± 1.01
$2AR_0$	261.40 ± 14.79	261.28 ± 14.89	261.23 ± 15.01	261.54 ± 15.44	261.32 ± 15.83
R_0	8.12 ± 0.65	8.06 ± 0.64	7.95 ± 0.62	7.93 ± 0.62	7.81 ± 0.63
Rejected No.	1	0	0	0	0

each table indicates a remarkable difference between the O-B5 stars and open clusters. For the open clusters almost no cluster was rejected by the filter. One reason is that we have already removed four clusters from our basic sample set, which had extremely large peculiar velocities. The persistence of a significant δv_r in radial velocities for Galactic young stars has been recognized for a long time (Feast 1967; Humphreys 1972), which is possibly a systematic offset of the zero-point of radial velocities. This can be interpreted either as a κ-term for an overall kinematical contraction or expansion on the Galactic plane, or as a systematic error in the measurements of radial velocities. On the other hand, if an axisymmetric model is not sufficient to describe the Galactic rotation defined by the young disk stars, i.e., if the young objects are along elliptical orbits on the Galactic plane, then a non-axisymmetric model should be introduced to describe their kinematical behaviors. Given some dynamic model, we should be able to model the corresponding rotation of the elliptical orbits. Further studies on this subject will be published later.

There are systematic deviations for the kinematical parameters A, B and $2AR_0$, between solutions from O-B5 stars (Tables 1 and 3) and those from open clusters (Tables 2 and 4). For A and B derived from the proper motions, the relative discrepancy is about 10%, when we compare the values in Table 1 for O-B5 stars and those in Table 2 for clusters. However, the relative discrepancy for R_0 is much lower (see R_0 in Tables 3 and 4). The estimate of R_0 is practically compensated by the estimates of A and $2AR_0$ both being lower (or higher). This advantage of our present method provides us a significant tool to decrease the estimated bias in R_0. As mentioned before, we select the Galactocentric distances R_0 in the Solution S2 in Table 3 and the Solution S3 in Table 4. Thus, we have

$$R_0 = 8.25 \pm 0.79 \text{ kpc from O-B5 stars, and}$$
$$R_0 = 7.95 \pm 0.62 \text{ kpc from Galactic open clusters,}$$

which have the lowest estimated errors from the two different samples.

5 DISCUSSION AND CONCLUSIONS

The heavy obscuration in the center region of our Galaxy is one of the most serious problems for deriving the distance calibration to the Galactic center, R_0. Considerable biases and errors might arise from both observations and models, despite the great efforts made since the first estimate of R_0 by Shapley in 1918. After a simple survey of the historical data of R_0 found by individual investigators using different observations, Kerr & Lynden-Bell (1986) recommended a value of $R_0 = 8.5$ kpc for 1985 IAU constant. With a careful statistical analysis, an averaged “best value” of $R_0 = 8.0 \pm 0.5$ kpc was proposed by Reid (1993), which was summarized from some data obtained during the 1970s and 1980s. During the past decade, dozens of new determinations were made, most of them lie within the range $R_0 \approx 7 \sim 9$ kpc. Avedisova (2005) summarized the estimates of R_0 derived over the last decade, and found an average value of $R_0 = 7.80 \pm 0.33$ kpc. Figure 2 is a time plot of the various determinations R_0 in recent years.

Using radial velocities of classical Cepheids, the Galactocentric distance was estimated by Caldwell & Coulson (1987) and by Metzger, Caldwell & Schechter (1998). Another estimation was by Racine & Harris (1989) from the space distribution of globular clusters. After correcting for the effects of extinction, they obtained $R_0 = 7.5 \pm 0.9$ kpc. Applying observations of luminosity functions to the bulge-population planetary nebulae, Dopita, Jacoby & Vassiliadis (1992) obtained $R_0 = 7.6 \pm 0.7$ kpc. Carney et al.(1995) derived $R_0 = 8.3 \pm 1.0$ kpc from infrared photometry of 58 RR Lyrae variables in the field of Baade’s

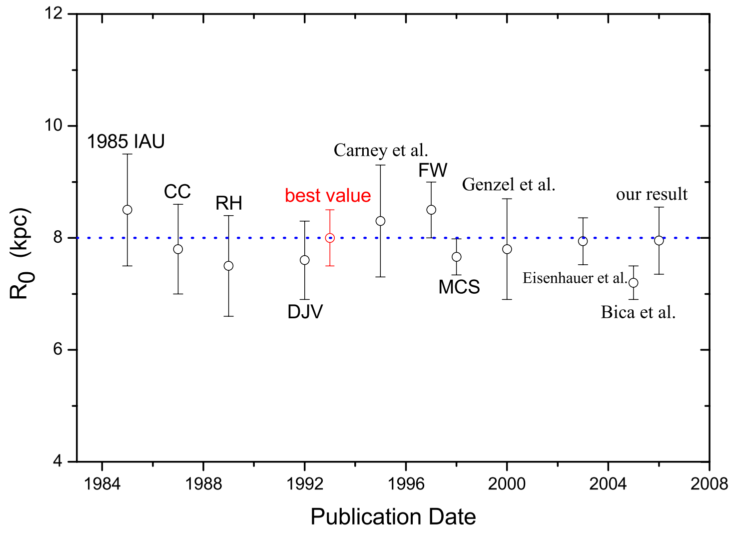

Fig. 2 Some determinations of R_0 in the last decades.

window. Using the new value of the zero-points of the PL relation derived directly from the Hipparcos trigonometric parallaxes, Feast & Whitelock (1997) suggested $R_0 = 8.5 \pm 0.5$ kpc. Genzel et al. (2000) reported an anisotropy-independent estimate of the Sun-Galactic center distance between 7.8 and 8.2 kpc, with a formal statistical uncertainty of ± 0.9 kpc, based on analysis of radial velocities for more than 100 stars in the central few arcseconds from the black hole candidate Sgr A*. With new astrometric and spectroscopic observations at the ESO VLT for the star S2 orbiting the massive black hole in the Galactic center, Eisenhauer et al. (2003) deduced the value of $R_0 = 7.94 \pm 0.42$ kpc. Based on new updated data of 153 globular clusters, Bica et al. (2006) found $R_0 = 7.2 \pm 0.3$ kpc. Our result from open clusters, together with those mentioned above, are displayed in Figure 2.

A direct comparison shows that our results, derived both from O-B5 stars and open clusters, are in good agreement with the 'best value' suggested by Reid (1993), and with the other recent determinations of R_0. Our new derivation of R_0 was based on a simple Oort-Lindblad model of Galactic rotation. Using independent observations for proper motions and radial velocities, the bias in the estimated R_0 was favorably compensated by the kinematical parameters. Our present method provides a useful tool for obtaining more reliable determination of R_0.

Acknowledgements This work was supported by the National Natural Science Foundation of China (grant No. 10333050).

References

Avedisova A. S., 2005, Astronomy Reports, 49(6), 435
Barbier-Brossat M., Figon P., 2000, A&AS, 142, 217
Bica E., Bonatto C., Barbuy B. et al., 2006, A&A, 450, 105
Binney J., Merrifield M., 1998, Galactic Astronomy, Princeton: Princeton University Press
Caldwell J. A. R., Coulson I. M., 1987, AJ, 93, 1090
Carney B. W., Fulbright J. P., Terndrup D. M. et al., 1995, AJ, 110, 1674
Dehnen W., Binney J., 1998, MNRAS, 298, 387
Dias W. S., Alessi B. S., Motinho A. et al., 2002a, A&A, 389, 871
Dias W. S., Lépine J. R. D., Alessi B. S. et al., 2002b, http://www.astro.iag.usp.br/~wilton/

Dopita M. A., Jacoby G. H., Vassiliadis E., 1992, ApJ, 389, 27
Eisenhauer F., Schödel R., Genzel R. et al., 2003, ApJ, 597, L121
Feast M. W., 1967, MNRAS, 136, 141
Feast M. W., Whiteclock P., 1997, MNRAS, 291, 683
Genzel R., 1981, ApJ, 244, 884
Genzel R., Pichon C., Eckart A. et al., 2000, MNRAS, 317, 348
Gerasimenko T. P., 2004, Astronomy Reports, 48, 103
Humphreys R. M., 1972, A&A, 20, 29
Joy A. H., 1939, ApJ, 89, 356
Kerr F. J., Lynden-Bell D., 1986, MNRAS, 221, 1023
Kharchenko N. V., 2001, Kinematics and Physics of Celestial Bodies, 17, 409
Kharchenko N. V., Piskunov A. E., Röser S. et al., 2005a, A&A, 438, 1163
Kharchenko N. V., Piskunov A. E., Röser S. et al., 2005b, A&A, 440, 403
Metzger M. R., Caldwell J. A. R., Schechter P. L., 1998, AJ, 115, 635
Miyamoto M., Zhu Z., 1998, AJ, 115, 1483
Piskunov A. E., Kharchenko N. V., Röser S. et al., 2006, A&A, 445, 545
Pont F., Mayor M., Burki G., 1994, AJ, 285, 415
Racine R., Harris W. E., 1989, AJ, 98, 1609
Reid M. J., 1993, ARA&A, 31, 345
Shapley H., 1918, ApJ, 48, 154
Zhao J. L., Chen L., Zu Z. L., 2006, Chin. J. Astron. Astrophys. (ChJAA), 6, 287
Zhu Z., 2000, Ap&SS, 271, 353
Zhu Z., 2006, Chin. J. Astron. Astrophys. (ChJAA), 6, 363