THE DISTANCE TO A STAR-FORMING REGION IN THE OUTER ARM OF THE GALAXY

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ABSTRACT

We performed astrometric observations with the Very Long Baseline Army of WB89−437, an H2O maser source in the Outer spiral arm of the Galaxy. We measure an annual parallax of 0.167 ± 0.006 mas, corresponding to a heliocentric distance of 6.0 ± 0.2 kpc or a Galactocentric distance of 13.4 ± 0.2 kpc. This value for the heliocentric distance is considerably smaller than the kinematic distance of 8.6 kpc. This confirms the presence of a faint Outer arm toward l = 135°. We also measured the full space motion of the object and find a large peculiar motion of ~20 km s−1 toward the Galactic center. This peculiar motion explains the large error in the kinematic distance estimate. We also find that WB89−437 has the same rotation speed as the LSR, providing more evidence for a flat rotation curve and thus the presence of dark matter in the outer Galaxy.

Key words: astrometry – Galaxy: kinematics and dynamics – Galaxy: structure – masers – stars: distances

Online-only material: color figures

1. INTRODUCTION

The Outer spiral arm of the Milky Way (also called the Cygnus arm) is located beyond the Perseus arm and may be the outermost arm of the Galaxy’s stellar disc (see Figure 1). It is traceable across portions of the first and fourth quadrants of the Galaxy and it can be detected through the emission of H α and molecular gas (Nakanishi & Sofue 2003, 2006). The arm may continue through the second and third quadrants, as shown by spectroscopic and photometric observations of open clusters (Pandey et al. 2006) and H ii regions (Russel et al. 2007). Indeed, Honma et al. (2007) used the VERA array and measured the annual parallax and proper motion of H2O masers in S 269, a star-forming region at a Galactic longitude of 196°. They found a Galactocentric distance of 13.6 kpc (for R0 = 8.5 kpc), consistent with it being in the Outer arm.

The size and structure of our Galaxy have been mainly determined by kinematic distances, which involve comparing measured radial velocities with a kinematic model (e.g., Gómez 2006). However, kinematic distances depend strongly on the Galactic rotation model chosen and peculiar motions render them questionable (e.g., Xu et al. 2006). This is particularly true for the outer Galaxy, since the Galactic rotation speed is quite uncertain (e.g., Brand & Blitz 1993).

Recently, distances of Galactic maser sources have been directly determined by annual parallax measurements that use phase-referencing VLBI techniques (e.g., Hachisuka et al. 2006; Xu et al. 2006; Honma et al. 2007). Such parallax measurements can yield distances of many kiloparsecs with errors less than 10%, allowing direct distance determinations for objects located near the edge of the stellar disk of our Galaxy.

Wouterloot et al. (1993) searched for H2O maser sources toward IRAS sources with 12CO emission and found several for which their kinematic distances indicated large distances from the Galactic center. Most of these maser sources seem to be located in the Perseus arm, but several sources have large negative LSR velocities and are probably in the Outer arm (Wouterloot et al. 1995).

One of these sources, WB89−437 (IRAS 02395+6244), is located at a Galactic longitude of l = 135° and has a kinematic distance of 8.6 kpc, which would place it beyond the Outer arm. It is one of the most luminous far-infrared (FIR) source with the strongest H2O maser emission in the outer part of the Galaxy. Since radio continuum emission has not been detected, the spectral type of the exciting star is thought to be B1 (Rudolph et al. 1996) or later (Brand et al. 2001). The young stellar object WB89−437 itself is deeply embedded and, testifying for its youth, derives an outflow traced by high-velocity CO and H2O masers. The latter are found offset by roughly 3 arcseconds from the position of the peak of CO and CS emission.

Because of its size and location in the outer part of the Galaxy, we selected this maser as the target for an annual parallax measurement. Here, we report the results of these measurements, which yield the distance and proper motion of this star-forming region in the outer part of the Galaxy.

2. OBSERVATION AND DATA REDUCTION

We used the NRAO Very Long Baseline Array (VLBA) to observe WB89−437 under program BH136. The observations involved rapid switching between an extragalactic background continuum radio source and the H2O maser. The observations were performed at five epochs spread over about 10 months in 2006 (see Table 1 for details). The separations between adjacent epochs were typically three months and the observations were performed close to the dates of the maximum and minimum of the annual parallax signature in right ascension and declination. We limited the observing time span to 10 months, instead of one year, to minimize the effects of maser variability.

We observed two 16 MHz wide bands with one band centered on the maser’s centroid LSR velocity of −70.0 km s−1. The data were correlated with 1024 spectral channels in each band.
resulting in a channel spacing of 0.21 km s\(^{-1}\). We used the ICRF extragalactic radio source J0244+6228 at R.A. = \(02^h44^m57.696849\) ± 0.000168 and decl. = \(-62^\circ28'06.51470\) ± 0.00097 (J2000) (Fey et al. 2004) as the phase-reference source. This source had already been used for the parallax observation of the H\(_2\)O maser in W3OH (Hachisuka et al. 2006). J0244+6228 had no detectable extended structure and its high flux density, near 1 Jy at 22 GHz, makes it an excellent source for phase-referencing VLBI. Moreover, its angular separation from WB89–437 is only 0.5, promising high-quality relative astrometry. We switched between maser and reference source every 30 s, yielding \(\approx 22\) s on-source time per scan. At each epoch, we obtained total on-source integration times of \(\approx 50\) minutes for each source. The total observing time was spread over 6 hr, including the calibrator observations, the slewing time of the telescopes, and observations of a second maser which will be presented elsewhere.

In order to correct for small zenith delay errors in the atmospheric model of the VLBA correlator (see Reid & Brunthaler 2004), we performed geodetic-like observations at 22 GHz (Brunthaler et al. 2005) at the beginning and end of each VLBA observation. These observations involved 22 ICRF sources with positions accurate to better than 1 mas and sampled a wide range of source elevations with a frequency setup involving eight 4 MHz bands at left circular polarization that spanned a frequency range of 450 MHz. The multi-band delays and rates from a fringe fit to these quasars were then fitted with a model that consisted of a zenith delay offset at all antennas as well as a clock offset at all antennas except the reference antenna.

Most of the calibration and data reduction were carried out with standard procedures for spectral-line observations using the NRAO’s Astronomical Image Processing System (AIPS). First, we applied the latest values of the Earth’s orientation parameters and corrected for effects of the changing feed parallactic angles. Next, we removed atmospheric zenith delay errors, corrected for voltage offset in the samplers, and applied antenna gains and rates from a fringe fit to these quasars were then fitted with a model that consisted of a zenith delay offset at all antennas as well as a clock offset at all antennas except the reference antenna.

### Table 1

Details of the VLBA Observations

| Date          | J0244+6228 Flux Density (mJy) | Beam HPBW; P.A. (mas\(^2\); \(^\circ\)) | Image rms per Channel (mJy beam\(^{-1}\)) |
|---------------|-------------------------------|--------------------------------------|-----------------------------------------|
| 2006 Feb 9    | 445                           | 0.79 × 0.28; 11                      | 12                                      |
| 2006 Apr 17   | 758                           | 0.80 × 0.27; 12                      | 12                                      |
| 2006 Jun 24   | 852                           | 0.80 × 0.28; 11                      | 16                                      |
| 2006 Sep 20   | 1244                          | 0.80 × 0.28; 10                      | 17                                      |
| 2006 Nov 29   | 1116                          | 0.81 × 0.28; 12                      | 13                                      |

Each H\(_2\)O maser feature was detected in the LSR velocity range \(-62\) to \(-76\) km s\(^{-1}\), distributed over an area of \(0.8 \times 1.6\) (Figure 2). Sixteen of the 20 H\(_2\)O maser features were detected at two or more epochs and four of them were detected at all five epochs. We used three of the four H\(_2\)O maser features that...
were detected at all five epochs for the parallax fitting. The last feature was located at a distance of $\sim 1.4$ pc from the phase center, which is larger than our nominal field of view ($\sim 0.7$). Hence, it was heavily affected by fringe-rate smearing and was not used for the parallax estimate.

### 3.1. Annual Parallax and Distance

One maser feature was detected in 30 channels, and two features were detected over seven frequency channels. First, we fitted the parallaxes and proper motions to data from each spectral channel individually. The residuals to the fits showed reduced $\chi^2$ values that were relatively large ($\sim 2$–8), since the formal position errors from the Gaussian fits to the maps underestimate the true position uncertainty. The true position error of a maser spot relative to a background source is usually dominated by systematics, owing to uncalibrated residual atmospheric delays and/or maser spot structural variations. Hence, we added “error floors” in quadrature to the formal position uncertainties until we achieved $\chi^2$ per degree of freedom values of near unity for the data from each coordinate. For this data set, we needed error floors of 10 and 60 $\mu$as for different maser features. The individual parallaxes and proper motions for each feature are shown in Table 2 together with their formal errors from the fit. Also given are the average parallaxes and proper motions for each feature together with the standard error of the mean and the standard deviation (in parentheses).

Next, we fitted all channels from any given maser feature simultaneously with one parallax but different proper motions and position offsets for each channel. The resulting parallaxes for each maser feature are also given in Table 2. All three features have consistent parallaxes of 0.164 $\pm$ 0.0014, 0.163 $\pm$ 0.004, and 0.164 $\pm$ 0.007 mas. We also performed a combined parallax fit with all channels from the three features. The resulting parallax is 0.164 $\pm$ 0.0016 mas. For this fit, we used error floors of 17 and 12 $\mu$as in right ascension and declination, respectively. Figure 3 (top) shows the parallax signal for one channel (i.e., the first channel) from each feature and the combined fit to all channels. The individual proper motions and position offsets were removed before plotting.

Combining the results of several maser spots can lead to underestimation of the parallax uncertainty, since the measurements may not be statistically independent. Random-like errors (e.g., from map noise and possibly maser spot structure variations) will not be correlated among different maser spots. However, systematic errors (e.g., caused by residual atmospheric delay errors) will affect all maser spots in one epoch in a very similar way. The most conservative approach would be to assume 100% correlation and multiply the formal error by $\sqrt{N}$, where $N$ is the number of individual data sets used in the fit. This would give an error of $\sqrt{44} \times 0.0016$ mas $= 0.011$ mas.

To estimate the effect of the systematic errors on our parallax measurement, we examined position residuals after removing the proper motions and position offsets (e.g., the data plotted in Figure 3, top) and calculated the average maser position of all features from all three fields in each epoch. The averaging should reduce the random error, but leave the systematic error unaffected. A parallax fit to the averaged data points (Figure 3, bottom) yielded a value of 0.167 $\pm$ 0.003 mas, which is consistent with the value from the combined fit. Here, we used error floors of 12 and 5 $\mu$as in right ascension and declination, respectively, to achieve $\chi^2$ values of $\sim 1$. This suggests that the systematic errors are larger in right ascension, contrary to our previous experience, where systematic errors in declination dominate. However, because the source is at high declination, systematic errors in right ascension may dominate in such a case for some geometrical configurations (Pradel et al. 2006). Furthermore, the 8.6 GHz image of the calibrator J0244+6228 in the VLBI calibration tool shows a weak jet mainly directed toward the east. Thus, small changes in this jet could introduce larger systematic errors in right ascension than in declination. The different error floors are also the reason why the parallax fit to the averaged data is slightly larger than the parallax fits to the individual features.

In order to allow for errors induced by the VLBI structure of the reference quasar, we multiply our final error by a factor of 2 and obtain 0.167 $\pm$ 0.006 mas, which we adopt for the parallax of WB89–437. This parallax corresponds to a distance of 6.0 $\pm$ 0.2 kpc from the Sun or a Galactocentric distance of 13.4 $\pm$ 0.2 kpc (assuming $R_0 = 8.5$ kpc).

### 3.2. Proper Motion and Full Space Motion in the Galaxy

Since we have a distance, proper motion, and radial velocity, we can determine the three-dimensional motion of WB89–437 in the Galaxy. The absolute proper motion of a Galactic object relative to an extragalactic source depends not only on the annual parallax but also on differential Galactic rotation, the solar motion, and the peculiar motion (relative to Galactic rotation) of the object. In addition, H$_2$O masers in star-forming regions usually participate in outflows with typical velocities of a few tens of km s$^{-1}$. Therefore, the absolute proper motions and radial velocities of maser spots can contain a significant component from internal motions.

The absolute proper motions of the three maser features range from $-1.18$ to $-1.35$ mas yr$^{-1}$ in right ascension and from 0.59 to 1.05 mas yr$^{-1}$ in declination. The average motion of these features is $-1.27 \pm 0.05$ mas yr$^{-1}$ in right ascension and $0.82 \pm 0.13$ mas yr$^{-1}$ in declination. However, it is not clear that the average proper motion of the three maser spots represent the true motion of the whole object.

To evaluate the effect of relative internal motions, we calculated the average motion of 11 maser features relative to a reference feature (maser spot 2 with an LSR velocity of $-73.16$ km s$^{-1}$). Here, we used all maser spots which were detected in at least two epochs and not affected by fringe-rate smearing. The results are shown in Figure 2 and Table 3. Also given is the average proper motion together with the standard error of the mean and the standard deviation (in parentheses). The average motion is $-0.02 \pm 0.15$ mas yr$^{-1}$ in right ascension and $-0.35 \pm 0.18$ mas yr$^{-1}$ in declination. The true proper motion of the whole source can then be estimated by the sum of the average motion and the absolute proper motion of the reference feature. This gives a total motion of $-1.22 \pm 0.30$ mas yr$^{-1}$ in right ascension and $0.46 \pm 0.36$ mas yr$^{-1}$ in declination. Here, we also multiplied the final error by a factor of 2 to allow for errors induced by the background quasar.

We assume IAU values for the distance of the Sun from the Galactic center of $R_0 = 8.5$ kpc and the circular rotation speed of the LSR of $\Theta_0 = 220$ km s$^{-1}$. We also adopt the solar motion with respect to the LSR in km s$^{-1}$ from Hipparcos data ($U, V, W = 10.00 \pm 0.36, 5.25 \pm 0.62, 7.17 \pm 0.38$; Dehnen & Binney 1998). Then, our distance measurement of 6.0 $\pm$ 0.2 kpc, the proper motion of $-1.22 \pm 0.30$ mas yr$^{-1}$ in right ascension and $0.46 \pm 0.36$ mas yr$^{-1}$ in declination, and a radial velocity of $-72 \pm 2$ km s$^{-1}$ from CO and CS measurements (Brand et al. 2001), which should be close to the stellar velocity, imply a
Table 2  
Annual Parallax and Absolute Proper Motion of the Spots which Appeared in All Five Epochs

| Feature | $V_{LSR}$ (km s$^{-1}$) | $\Delta$R.A. (mas) | $\Delta$Decl. (mas) | $\pi$ (mas) | $\mu_{R.A.}$ (mas yr$^{-1}$) | $\mu_{Decl.}$ (mas yr$^{-1}$) |
|---------|-------------------------|---------------------|---------------------|-------------|-----------------------------|-----------------------------|
| 1       | 66.42                   | 69.34               | 203.72              | 0.168 ± 0.006 | -1.16 ± 0.02 | 0.58 ± 0.03 |
| 1       | 66.63                   | 68.43               | 203.72              | 0.180 ± 0.009 | -1.17 ± 0.02 | 0.60 ± 0.02 |
| 1       | 66.84                   | 65.35               | 203.72              | 0.156 ± 0.008 | -1.34 ± 0.02 | 0.63 ± 0.03 |
| 1       | 67.05                   | 63.36               | 203.73              | 0.160 ± 0.006 | -1.36 ± 0.02 | 0.56 ± 0.03 |
| 1       | 67.26                   | 63.36               | 203.73              | 0.176 ± 0.003 | -1.37 ± 0.03 | 0.57 ± 0.01 |
| 1       | 67.47                   | 63.37               | 203.72              | 0.162 ± 0.009 | -1.36 ± 0.02 | 0.62 ± 0.03 |
| 1       | 67.68                   | 63.38               | 203.72              | 0.170 ± 0.006 | -1.37 ± 0.02 | 0.61 ± 0.02 |
| 1       | 67.89                   | 63.39               | 203.73              | 0.166 ± 0.007 | -1.37 ± 0.02 | 0.59 ± 0.02 |
| 1       | 68.10                   | 63.40               | 203.72              | 0.161 ± 0.009 | -1.36 ± 0.02 | 0.61 ± 0.03 |
| 1       | 68.31                   | 63.40               | 203.73              | 0.165 ± 0.007 | -1.36 ± 0.02 | 0.59 ± 0.02 |
| 1       | 68.53                   | 63.41               | 203.73              | 0.170 ± 0.007 | -1.37 ± 0.02 | 0.58 ± 0.02 |
| 1       | 68.74                   | 63.41               | 203.74              | 0.166 ± 0.006 | -1.36 ± 0.02 | 0.57 ± 0.01 |
| 1       | 68.95                   | 63.42               | 203.74              | 0.168 ± 0.006 | -1.37 ± 0.02 | 0.55 ± 0.01 |
| 1       | 69.16                   | 63.43               | 203.74              | 0.164 ± 0.009 | -1.36 ± 0.03 | 0.56 ± 0.02 |
| 1       | 69.37                   | 63.43               | 203.74              | 0.164 ± 0.009 | -1.35 ± 0.03 | 0.57 ± 0.02 |
| 1       | 69.58                   | 63.43               | 203.74              | 0.176 ± 0.004 | -1.37 ± 0.03 | 0.56 ± 0.01 |
| 1       | 69.79                   | 63.44               | 203.74              | 0.170 ± 0.006 | -1.36 ± 0.02 | 0.57 ± 0.01 |
| 1       | 70.00                   | 63.44               | 203.74              | 0.170 ± 0.006 | -1.35 ± 0.02 | 0.58 ± 0.01 |
| 1       | 70.21                   | 63.45               | 203.74              | 0.173 ± 0.004 | -1.35 ± 0.03 | 0.59 ± 0.01 |
| 1       | 70.42                   | 63.45               | 203.74              | 0.163 ± 0.006 | -1.34 ± 0.02 | 0.61 ± 0.02 |
| 1       | 70.63                   | 63.45               | 203.74              | 0.167 ± 0.004 | -1.35 ± 0.02 | 0.60 ± 0.01 |
| 1       | 70.84                   | 63.45               | 203.74              | 0.166 ± 0.006 | -1.35 ± 0.02 | 0.60 ± 0.02 |
| 1       | 71.05                   | 63.45               | 203.75              | 0.166 ± 0.002 | -1.34 ± 0.02 | 0.61 ± 0.01 |
| 1       | 71.26                   | 63.46               | 203.75              | 0.160 ± 0.007 | -1.33 ± 0.02 | 0.63 ± 0.02 |
| 1       | 71.47                   | 63.46               | 203.75              | 0.156 ± 0.009 | -1.33 ± 0.02 | 0.63 ± 0.03 |
| 1       | 71.68                   | 63.47               | 203.75              | 0.156 ± 0.008 | -1.33 ± 0.02 | 0.62 ± 0.02 |
| 1       | 71.90                   | 63.47               | 203.76              | 0.153 ± 0.010 | -1.32 ± 0.02 | 0.63 ± 0.03 |
| 1       | 72.11                   | 63.48               | 203.77              | 0.148 ± 0.011 | -1.32 ± 0.03 | 0.60 ± 0.05 |
| 1       | 72.32                   | 63.49               | 203.76              | 0.176 ± 0.002 | -1.36 ± 0.03 | 0.60 ± 0.01 |
| 1       | 72.53                   | 63.49               | 203.77              | 0.168 ± 0.007 | -1.34 ± 0.03 | 0.58 ± 0.02 |

Average Combined Fit 0.164 ± 0.001 (0.007) 0.164 ± 0.0014 0.159 ± 0.004 (0.002) 0.59 ± 0.004 (0.02)

Average Combined Fit 0.164 ± 0.0004 (0.011) 0.163 ± 0.0004 0.164 ± 0.0004 (0.011) 0.164 ± 0.0004 |

Average Combined Fit 0.163 ± 0.0016 (0.015) 0.163 ± 0.0016 0.164 ± 0.0016 0.164 ± 0.0016

Notes. Coordinates are relative to the phase center (02h43m28.5s, 62°57′08″388″) at epoch 2006.5. Column 5 lists the parallax estimates. Columns 6 and 7 give the motion on the plane of the sky along the right ascension and declination, respectively. $\mu_{R.A.}$ is the true R.A. motion multiplied by $\cos(\text{Decl.})$.

peculiar motion relative to a circular Galactic rotation of

$$U' = 23.1 \pm 4.1 \text{ km s}^{-1},$$

$$V' = -3.6 \pm 7.9 \text{ km s}^{-1},$$

$$W' = 0.8 \pm 9.9 \text{ km s}^{-1}.$$  

Here, $U'$ denotes the velocity component toward the Galactic Center, $V'$ is the component in direction of Galactic rotation, and $W'$ is the component toward the north Galactic pole.

If one uses a different rotation model of the Milky Way with $R_0 = 8.0$ kpc and $\Theta_0 = 236$ km s$^{-1}$, which is consistent with
the measured proper motion of the Galactic center supermassive black hole, Sgr A* (Reid & Brunthaler 2004), we get

\[
U' = 15.2 \pm 4.1 \text{ km s}^{-1},
V' = -4.2 \pm 8.0 \text{ km s}^{-1},
W' = 0.8 \pm 9.9 \text{ km s}^{-1}.
\]

Hence, WB89–437 rotates in both cases with the approximately same velocity as the LSR but shows a large peculiar motion of \(\approx 20 \text{ km s}^{-1}\) toward the Galactic center.

4. DISCUSSION

4.1. WB89–437 in the Outer Galaxy

The Galactocentric distance of WB89–437 is 13.4 kpc (for \(R_0 = 8.5 \text{ kpc}\)), which places the source well outside the Perseus spiral arm, which is at a Galactocentric distance of \(\approx 10.0 \text{ kpc}\) in this direction (Xu et al. 2006; Hachisuka et al. 2006). While the distribution of molecular gas in the outer Galaxy shows that the Outer arm becomes much weaker near \(l = 90^\circ\) (Nakanishi & Sofue 2006), some CO clouds with high radial velocities are distributed from \(l = 131^\circ\) to \(137^\circ\) (Dígen et al. 1996). This indicates that WB89–437 (at \(l = 135^\circ\)) is located in a weak extension of the Outer arm. Potential arm objects at \(l > 137^\circ\) have been identified (Russell et al. 2007) which suggest that this faint arm continues to the third Galactic quadrant. This view is supported by Honma et al. (2007) who used the VERA array and measured the annual parallax and proper motion of an H2O maser at a Galactic longitude of 196\(^\circ\). They found a Galactocentric distance of 13.6 kpc (for \(R_0 = 8.5 \text{ kpc}\)), consistent with it being in the Outer arm. There are many maser sources at the outer Galaxy whose annual parallaxes have not been measured. With direct measurements of distances to these sources, we may understand the structure of the outer (and the Perseus) arm in more detail.

With a Galactic latitude of \(b = 2:8\) and a distance of 6 kpc, WB89–437 is located \(~300 \text{ pc}\) above the Galactic plane. With our upper limit of 10 km s\(^{-1}\) for the motion perpendicular to the plane, it would have needed more than 30 Myr to reach its current position. This is much larger than the age of this object. Thus, WB89–437 must have formed already far above the plane.

4.2. Galactic Dynamics in the Outer Arm

The annual parallax distance to WB89–437 (6.0 \(\pm 0.2 \text{ kpc}\)) is significantly smaller than its kinematic distance of 8.6 \(\pm 0.4 \text{ kpc}\), assuming recommended IAU values \(R_0\) and \(\Theta_0\). However, we note that our measured distance is in slightly better agreement with the kinematic distance of 7.3 \(\pm 0.3 \text{ kpc}\) that one obtains for \(R_0 = 8.0 \text{ kpc}\) and \(\Theta_0 = 236 \text{ km s}^{-1}\) (Reid & Brunthaler 2004), but there is still a significant discrepancy. The large peculiar motion of WB89–437 of \(~20 \text{ km s}^{-1}\) toward the
Galactic center has a component of $\sim 10$ km s$^{-1}$ toward the Sun and is partially responsible for this discrepancy.

This is similar to the case of W3OH (Xu et al. 2006; Hachisuka et al. 2006), which is located at a similar Galactic longitude but is in the Perseus arm. W3OH also shows a large peculiar motion and a true distance which is smaller than the kinematic distance. Anomalous motions in the Perseus arm are well known to exist (Humphreys 1978); they could be caused by spiral density waves. On the other hand, since the Outer arm in the Galaxy is a faint arm, one expects that the influence of a density wave on it is smaller than on an inner arm. In fact, spiral structure of H$\text{I}$ gas at large Galactic radii (greater than 25 kpc) is not seen (Levine et al. 2006).

A flat rotation curve of the outer Galaxy implies the existence of dark matter since the density of visible matter in the outer Galaxy is smaller than in the inner Galaxy. The measured circular orbital speed of WB89–437 is consistent with that of the LSR. This confirms the result of Honma et al. (2007) that the rotation curve of the Milky Way is constant out to $\sim 13.5$ kpc and provides more solid evidence for the existence of dark matter in the outer region of the Galaxy. However, since massive star-forming regions can have large peculiar motions, it may be possible, although unlikely, that the rotation curve falls by $\sim 20$ km s$^{-1}$ between the Sun and the Outer arm, but the source has a compensating component in the direction of Galactic rotation.

5. CONCLUSION

We performed astrometric VLBA observations toward the Galactic H$_2$O maser source WB89–437 in the Outer arm of the Galaxy. The measured annual parallax of $0.167 \pm 0.006$ mas corresponds to a heliocentric distance of $6.0 \pm 0.2$ kpc (a Galactocentric distance of $13.4 \pm 0.2$ kpc). This confirms the presence of a faint Outer arm in the direction of $l = 135^\circ$. Our measured distance is smaller than the kinematic distance of 8.6 kpc. We also estimate the three-dimensional motion of the object with respect to a Galactic reference frame and find that the discrepancy between kinematic distance and true distance is caused, in part, by a large peculiar motion of $\sim 20$ km s$^{-1}$ toward the Galactic center. We also find that WB89–437 has the same rotation speed as the LSR, confirming a flat rotation curve in the outer Galaxy.

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