Astrometry of Galactic Star-Forming Region Sharpless 269 with VERA: Parallactic Measurements and Constraint on Outer Rotation Curve

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Abstract

We have performed high-precision astrometry of H2O maser sources in the Galactic star-forming region Sharpless 269 (S269) with VERA. We successfully detected a trigonometric parallax of 189 ± 8 μas, corresponding to a source distance of 5.28 ± 0.22 kpc. This is the smallest parallax ever measured, and the first one detected beyond 5 kpc. The source distance as well as the proper motions were used to constrain the outer rotation curve of the Galaxy, demonstrating that the difference of rotation velocities at the Sun and at S269 (which is 13.1 kpc away from the Galaxy’s center) is less than 3%. This gives the strongest constraint on the flatness of the outer rotation curve, and provides a direct confirmation of the existence of a large amount of dark matter in the Galaxy’s outer disk.

Key words: ISM: star forming regions — ISM: individual (Sharpless 269) — masers (H2O) — VERA

1. Introduction

Rotation curves, which are plots of rotation velocities as functions of distance from galaxy centers, are important tools to study the mass distributions in disk galaxies. Assuming that the centripetal force balances with gravity, one can determine the mass distribution in a galaxy using the rotation curve. Observations of rotation curves in external galaxies revealed that they are basically flat within (and often beyond) optical disks of spiral galaxies (e.g., Rubin et al. 1980; Rubin 1983; Sofue & Rubin 2001). Flat rotation curves observed in external galaxies have provided strong evidence for the dark matter in the outer regions of galaxies (e.g., Kent 1986, 1987).

In contrast, the rotation curve of the Milky Way Galaxy remains highly uncertain, particularly in the outer region, although a large number of efforts have been made to determine it (e.g., Clemens 1985; Merrifield 1992; Brand & Blitz 1993; Honma & Sofue 1997, and references therein). The reason for this is twofold: 1) it has been difficult to measure accurate distances of the Galactic objects that are used to trace the rotation curve, such as OB stars and molecular clouds, and 2) in most cases it has been difficult to measure the proper motions of Galactic objects, and thus only the radial velocity (out of the three components of spatial velocity) could be used to constrain the Galactic rotation. Therefore, the outer rotation curve, and hence the dark-matter distribution, in the Galaxy’s disk is still highly uncertain, although it is widely believed that the Galaxy’s outer rotation curve is flat, just like those of extra-galaxies.

In order to determine a precise rotation curve of the Galaxy, high-precision astrometry is essential. By measuring the accurate position of a star, one can determine a trigonometric parallax, π, and thus the source distance, as D = 1/π. In addition, high-precision astrometry also allows us to determine source proper motions (source motions projected onto the sky plane), and thus the 3-dimensional space velocity of the source. Still, accurate astrometric measurements have been made only for sources that are located fairly close to the Sun compared to the Galaxy’s size. For instance, the HIPPARCOS mission (Perryman et al. 1997), the most modern satellite dedicated to optical astrometry, has reached distances of ~300 pc by parallax measurements, which is much smaller than the size of the Galaxy (e.g., ~15 kpc for the radius of the Galaxy’s disk). Hence, at present the astrometry of the Galaxy still remains an unexplored issue.

Over the next decades, there will be new missions for the
astrometry of the Galaxy that will aim at 10 $\mu$as accuracy (e.g., SIM\(^1\), GAIA\(^2\), JASMINE\(^3\)). These will be satellite-type missions with optical/infrared telescopes orbiting the Earth, where the observations can be made free from any disturbance of the atmosphere. At radio wavelengths, high-precision astrometry has been performed with ground-based VLBI (Very Long Baseline Interferometry), a radio interferometer with telescopes separated by ~1000 to ~10000 km. The advantage of VLBI is that it provides the highest angular resolution among the existing telescopes at any wavelength. While normal VLBI observations directly suffer from fluctuation of the atmosphere (mainly due to the water vapor content in the troposphere), a noble way, which is called ‘phase-referencing’, has been developed to cancel out the tropospheric fluctuations. In phase-referencing observations, a few sources (one target and one or more reference sources) are observed at nearly the same time by rapidly switching the telescope, and then the relative positions of the target with respect to the reference sources can be measured after correcting for any influence of the troposphere. In fact, recently, the distance of the Galactic star-forming region W3OH was determined with VLBA (Xu et al. 2006, Hachisuka et al. 2006) to solve the long-standing ambiguity of the Perseus arm distance by measuring the source distance at 2 kpc. It has also been shown that the maser emissions from late-type stars (such as Mira variables) can be used to perform kpc-scale astrometry with VLBI (Kurayama et al. 2005). These results strongly demonstrate the promising future of ground-based VLBI for the Galaxy-scale astrometry.

VERA (VLBI Exploration of Radio Astrometry) is a new Japanese VLBI array dedicated to VLBI astrometry (Honma et al. 2000; Kobayashi et al. 2003). A unique feature of the VERA telescopes is the dual-beam receiving system, which allows us to observe simultaneously a target and a reference source within 2.2$^\circ$. This dual-beam system enables one to cancel out tropospheric fluctuations much more effectively than switching observations with normal, single-beam telescopes (Honma et al. 2003). With a target astrometric accuracy of 10 $\mu$as, VERA aims to precisely locate hundreds of maser sources in the Galaxy and to explore their 3D structure and dynamics. The VERA array was constructed by 2002, and regular observations started in the fall of 2003. Here, we present some initial results of high-precision astrometry with VERA toward the Galactic star-forming region S269, which is located in the outer regions ($l = 196^\circ.45$). We report on the determination of the smallest parallax in human history. Our results provide a strong constraint on the flatness of the rotation curve in the outer Galaxy.

2. Observations and Reductions

We observed H$_2$O masers in the Galactic star-forming region Sharpless 269 (S269) with VERA since 2004 November, and here we present the data of 6 epochs that were obtained with the full 4-station array (Mizusawa, Iriki, Ogasawara, and Ishigaki-jima) under relatively good conditions. The epochs are day of year (DOY) 323 in 2004, DOY 026, 073, 134, 266, and 326 in 2005 (2004 November 18, 2005 January 26, March 14, May 14, September 23, and November 21), spanning ~1 year. At each epoch, the H$_2$O $616_{-53}^{+53}$ maser line at a rest frequency of 22.235080 GHz in S269 and a position reference source J0613+1306 were simultaneously observed in a dual-beam mode for nearly 9 hours. The typical on-source integration time was 5 hours for both the target maser and the reference. The reference source, J0613+1306, is one of the ICRF sources (Ma et al. 1998) with a correlated flux density of ~300 mJy. The separation angle between the maser and the reference sources is 0.73$^\circ$. Left-hand circular polarization signals were received for both S269 and J0613+1306, and digitally recorded onto magnetic tapes with the VERA-terminal system at the total data rate of 1024 Mbps. With 2-bit quantization, this data rate provides a total bandwidth of 256 MHz. The signals from the two sources were filtered with VERA Digital Filter (Iguchi et al. 2005) to obtain 1 IF (Intermediate Frequency) channel of 16 MHz for the S269 maser line and 15 IF channels of 16 MHz (240 MHz in total) for J0613+1306. Correlation processings were made with the Mitaka FX correlator. For the reference, which is a continuum source, the spectral resolution was 64 points per each 16 MHz channel, which corresponds to a velocity resolution of 3.4 km s$^{-1}$. For the maser source, the frequency and velocity resolutions were 15.625 kHz and 0.21 km s$^{-1}$, respectively.

Since the correlator’s a priori delay model is not accurate enough for high-precision astrometry, recalculations of the precise delay were made after the correlation, and the correlated visibilities were corrected for any difference between the first (rather crude) a priori model and the second (more accurate) delay model. The delay recalculation code is based on the geodynamics models described in IERS convention 1996 (McCarthy 1996), and Earth orientation parameters (EOP) were taken from IERS bulletin B final values,\(^4\) which currently provides the best estimates. Also, ionospheric delays were corrected based on the global ionosphere map (GIM), which is produced by the University of Bern every day.\(^5\)

In the data analysis of each epoch, at first fringes were searched for the reference source, J0613+130. With a 240 MHz bandwidth and a typical system noise temperature of 200 K, the reference source, having a flux of ~300 mJy, was easily detected within 1 minute integration, which is much shorter than the typical coherence time at 22 GHz (2 to 3 minutes). Since its position is accurately known, the fringe parameters of J0613+1306 were also used to calibrate the clock offset parameters (such as delay and delay-rate offset). The phase solutions for J0613+1306 were converted into the phase at the observed maser frequency, and applied to the visibilities of S269 together with the dual-beam phase calibration data. This dual-beam phase calibration data was taken in real-time during the observations, and are based on the correlation of artificial noise sources injected into two beams at each station (Kawaguchi et al. 2000). After those calibrations, the visibilities of the S269 masers were Fourier calibrated.

\(^1\) SIM: http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm
\(^2\) GAIA: http://sci.esa.int/science-e/www/area/index.cfm?fareaid=26
\(^3\) JASMINE: http://www.jasmine-galaxy.org/index.html
\(^4\) http://hpiers.obspm.fr/eop-pc/
\(^5\) http://www.aiub.unibe.ch/ionosphere.html
transformed to synthesize images, and the positions of the
brightness peaks were determined with respect to the reference
spot. In some epochs (especially in summer), the qualities
of phase-referenced maps were not high due to residuals
in tropospheric delay. To calibrate them, residual zenith
delays were estimated as a constant offset that maximizes
the coherence of the phase-referenced map. Typical residuals
of zenith delay are 1 to 5 cm, but in the worst case (during the
summer at Ishigaki-jima station) it was as large as 20 cm.

3. Results

The total-power spectrum of S269 taken on DOY 073
in 2005 is shown in figure 1a. Basically, it consists of
a single feature at $V_{\text{LSR}}$ of $\sim 19.6$ km s$^{-1}$ with a peak
intensity of 480 Jy, being consistent with a previous single-dish
monitoring study (Lekht 2000). This main feature was
always bright and observable for all of the epochs presented
here. Figure 1b is the maser spot map of the main feature
around $V_{\text{LSR}}$ of $\sim 19.6$ km s$^{-1}$ (for DOY 2006/073). Six
maser spots were detected in the velocity range from 19.0
to 20.1 km s$^{-1}$, and these maser spots are aligned in the
east-west direction on a scale of 0.4 mas. It is remarkable
that the thickness of the feature (spots distribution in the
north-south direction) is $\sim 50$ mas, 10-times smaller than the
width in the east-west direction. The maser distribution also
shows a velocity gradient from east to west. This kind of
structure is rather unusual for H$_2$O masers in star-forming
regions (which mostly show a bipolar structure with discrete
blue/red-shifted clusters of maser spots) but, instead, similar
to those of CH$_3$OH (methanol) masers at 6.7 GHz and
12.2 GHz in terms of the spot distribution as well as the
velocity width (e.g., Minner et al. 2000). Note that the positions
in figure 1b are the residuals to the tracking center
positions of the maser and the reference sources, which were
taken to be $(\alpha, \delta) = (06^h14^m37^s08, +13^d49^m36^s7)$ for S269,
and $(06^h13^m57^s692764, +13^d06^m45^s40116)$ for J0613+1306,
both in the J2000 coordinates. Thus, the absolute position
of the brightest 19.6 km s$^{-1}$ spot at DOY 073 of 2005 were
obtained as $(06^h14^m37^s07933, +13^d49^m36^s6945)$ with an
uncertainty of 1 mas, which mainly comes from the uncertainty
of the absolute position of the reference source, J0613+1306.
The absolute position of the maser feature shown in figure 1b
agrees well with the position of S269 IRS2w, which is the
most luminous infrared source in the S269 regions (Jiang et al.
2003).

Figure 2 shows the positional variations of the brightest
maser spot in the $X$ ($\equiv \cos \delta \Delta \alpha$, east-west offset) and $Y$
($\equiv \Delta \delta$, north-south offset) directions for a monitoring span
of 1 yr. As can be clearly seen from the plot (especially
in $X$ direction), the positions show systematic sinusoidal
modulation with a period of 1 yr. The phase of the observed
sinusoidal curve (i.e., the peak date) perfectly matches with
that of the expected parallax curve for S269, ensuring that the
modulation certainly originates from the parallax of S269. In
figure 2, the error bars were estimated as the standard deviation
from the best-fit with parallax plus linear proper motions. This
error estimate was made because it is difficult to predict the
observational error in VLBI astrometry; the error depends on
many factors, such as the residual phase in phase-referencing,
the error in zenith delay of the troposphere and the ionosphere,
and the error in calibration of the instrumental offset, and
so on, and is hardly predictable. The estimated error bars
are 25 $\mu$as for $X$ and 75 $\mu$as for $Y$. We note that the error
in $Y$ is three-times larger than that in $X$. This can be
explained if one assumes that the majority of the error comes
from the uncertainty in the tropospheric zenith delay, since
the tropospheric delay changes the apparent elevations of the
source. A detailed consideration of the error is discussed in
the next section. For our parallax measurements, in this paper
we consider only the $X$ component, because the $Y$ direction
error is large, and also because S269 is near the ecliptic and
the parallax ellipse is highly elongated in the $X$ direction,
making the contribution of $Y$ to the parallax determination
smaller. Here, we use the brightest three spots at the radial
velocity from 19.4 to 19.8 km s$^{-1}$, including the brightest
one at 19.6 km s$^{-1}$ to ensure a high signal-to-noise ratio; as
can be clearly seen from figure 1, the H$_2$O maser spectrum
is sharply peaked at 19.6 km s$^{-1}$, and the maser intensity
becomes weak at off-peak radial velocities. Least-squares fits
were made to positions of the three maser spot, with parallax
$\pi$ as well as proper motions $\mu_X$ (east-west direction) and $\mu_Y$
Table 1. The best-fit values of parallax $\pi$ and proper motions $\mu_X$ and $\mu_Y$ for the three brightest spots.

| $X$ (mas) | $Y$ (mas) | $V_{\text{LSR}}$ | $\pi$ (mas) | $\mu_X$ (mas/yr) | $\mu_Y$ (mas/yr) |
|---|---|---|---|---|---|
| $-8.183$ | $-5.571$ | $19.8$ | $0.208\pm0.030$ | $-0.425\pm0.032$ | $-0.123\pm0.076$ |
| $-8.365$ | $-5.591$ | $19.6$ | $0.199\pm0.012$ | $-0.388\pm0.014$ | $-0.118\pm0.071$ |
| $-8.427$ | $-5.602$ | $19.3$ | $0.176\pm0.012$ | $-0.457\pm0.015$ | $-0.123\pm0.072$ |

The last row gives the values obtained by weighted mean. Note that positions $X$ and $Y$ are those at the first epoch (DOY 323 in 2004) with respect to the tracking center position of S269, which was taken to be $(06^h 14^m 37^s 08, +13^d 49' 36'' 7')$ in J2000.0.

As can be seen in table 1, independent analyses for the three spots give results consistent with each other, from 176 $\mu$as to 208 $\mu$as. To obtain the best estimate of the parallax, $\pi$, we took a weighted mean of the parallaxes, yielding a parallax of S269 as $189\pm8$ $\mu$as, where the error bar is estimated to be $\sigma^2 = 1/\sum(1/\sigma_i^2)$. This corresponds to a source distance of $5.28^{+0.24}_{-0.22}$ kpc. This is the smallest parallax ever measured to date, demonstrating the high capability of VERA to perform Galactic-scale astrometry. The distance to S269 is found to be slightly larger than previous estimates, which claimed a distance of $\sim4$ kpc (Moffat et al. 1979).

From the fitting results in table 1, the weighted means of the proper motions were obtained as $(\mu_X, \mu_Y) = (-0.422\pm0.010, -0.121\pm0.042)$ mas yr$^{-1}$, respectively. To convert these observed (heliocentric) proper motions to the ones with respect to LSR, we used the solar motion based on the HIPPARCOS satellite data (Dehnen & Binney 1998), which is $(U, V, W) = (10.0, 5.25, 7.17)$ km s$^{-1}$. Using the galactic coordinates of S269 ($l, b$) = (196°45', $-1°96'$) and the Galactic plane’s position angle of $151.51^\circ$ there, one can calculate the proper motion projected to the direction of $l$ and $b$ as $(\mu_l, \mu_b) = (-0.184\pm0.032, -0.149\pm0.029)$ mas yr$^{-1}$. Given the source distance of $5.28$ kpc, these proper motions correspond to a velocity vector of $(v_l, v_b) = (-4.60\pm0.81, -3.72\pm0.72)$ km s$^{-1}$, respectively. These velocity components are remarkably small compared to the rotation speed of the Galaxy, which is on the order of $\approx200$ km s$^{-1}$. Given that S269 is located in the anti-center region, the small value of $v_l$ indicates that the Galactic rotation velocities at the Sun and at S269 are close to each other, and the proper motions were cancelled out in our relative proper-motion measurements. A detailed discussion of the Galactic rotation velocity is given in the next section.

4. Discussion

4.1. Sources of Astrometric Error

As described in the previous section, the astrometric errors estimated from the fitting deviations are 25 $\mu$as for $X$ and 75 $\mu$as for $Y$. These can be explained if the dominant error source is the uncertainty in the tropospheric zenith delay. For instance, if we take a typical uncertainty of 3 cm for the tropospheric zenith delay, then it causes a path-length difference of $0.4\text{ mm} (=30\text{ mm} \times 0.7^\circ / 57.3^\circ$/rad, where $0.7^\circ$ is the separation angle between S269 and the reference source) between the two sources. This uncertainty in the path-length difference roughly corresponds to $40\mu$as ($=0.4\text{ mm} / 2.3\times10^5\text{ mm}$, where $2.3\times10^5\text{ mm}$ is the maximum baseline length of the VERA array). In practice, observations are not done toward the zenith, but sources are at a lower elevation angle ($EL$). Because our observations were usually made for an elevation angle larger than $20^\circ$, the effect
of the zenith delay error was multiplied by a factor of 1 (corresponding to $EL = 90^\circ$) to $\sim 3$ ($EL = 20^\circ$), depending on the source elevation. If this factor is taken into account, one can expect an astrometric error of 40 to 120 $\mu$as, depending on the $EL$ distribution; the astrometric error in $Y$, obtained above (75 $\mu$as), is certainly in this possible range. On the other hand, the astrometric error in the $X$ direction can be suppressed for two reasons: first, the source pair considered here has a smaller separation in the $X$ direction than in the $Y$ direction and, second, the observational track in each epoch is roughly symmetric with respect to the meridian transit (i.e., each epoch has nearly same track before and after the transit). This symmetry can help to reduce the astrometric error in the $X$ direction caused by the tropospheric zenith delay offset.

Other possible sources of astrometric error are those in station positions, the delay model, and the ionosphere. Currently, VERA station positions are determined with an accuracy of $\sim 3$ mm based on geodetic observations at S/X (2/8 GHz) bands carried out every two weeks. Also, our delay calculation code was compared with CALC7 developed by the NASA/GSFC VLBI group, which is the international standard of delay models. It turned out that the difference between the two codes is less than 2 mm. Therefore, these errors are smaller than that of the zenith delay by an order of magnitude. Regarding the ionosphere, its contribution is small at 22 GHz, and corrections with the GPS-based Global Ionosphere Map (GIM), provided by University of Bern, are precise enough for 10 $\mu$as astrometry. We note that the trend of the larger error in the $Y$ direction was also found in other observations of VERA. Therefore, the larger error in $Y$ is not a special phenomenon of only the S269 observations, but, rather, is common to all VERA observations, and is most likely to originate from the tropospheric zenith delay error.

4.2. Constraint on Galactic Rotation

Here, we use the proper motions and parallax obtained in the previous section to constrain the Galactic rotation velocity at the position of S269. First, the small proper motion perpendicular to the Galactic plane ($v_b = -3.72 \pm 0.72$ km s$^{-1}$) indicates that S269 basically partakes in galactic rotation, and also that the H$_2$O maser proper motions truly reflect the systemic motion of S269. Radial velocity measurements support the latter idea; while the maser emission is peaked at 19.6 km s$^{-1}$, the peak velocity of HII region observed with SII lines is 16.5 km s$^{-1}$, and the systemic velocity of the associated molecular cloud observed in CO is 17.7 km s$^{-1}$ (Godbout et al. 1997), which agrees well with the maser radial velocity within 3 km s$^{-1}$. Therefore, from the radial velocity as well as the proper motions perpendicular to the Galactic plane, one can expect that the peculiar velocity of the maser source with respect to pure Galactic rotation is as small as $\sim 5$ km s$^{-1}$.
From this fact one can expect that the proper motion in the $l$ direction ($v_l$) basically reflects the difference of the galactic rotation velocities at the position of S269 and at the Sun, and also that one can constrain the outer rotation velocity at the position of S269. In fact, S269 is located near to the galactic anti-center region ($l = 196.45^\circ$), and thus the lack of a large proper motion in the $l$ direction indicates that the galactic rotation speed there is close to that at the Sun. If a source is on perfect Galactic rotation, the radial and tangential velocities with respect to LSR observers can be written as

$$v_r = \left(\frac{\Theta}{R} - \frac{\Theta_0}{R_0}\right)R_0 \sin l,$$

(1)

$$v_l = \left(\frac{\Theta}{R} - \frac{\Theta_0}{R_0}\right)R_0 \cos l - \frac{\Theta}{R} D.$$

(2)

For the component perpendicular to the Galaxy plane, obviously $v_b = 0$. These equations relate the observed velocities to the rotation velocity at the source ($\Theta$) through the Galactic constants, $R_0$ and $\Theta_0$. Figure 3 shows a plot of the expected $v_r$ and $v_l$ for S269 as a function of $\Theta = \Theta/\Theta_0$ (rather than $\Theta$ for seeing the difference of the rotation velocities at S269 and the Sun). Here, the Galactic constant, $R_0$, is assumed to be 8.0(±0.5) kpc (Reid 1993), and three cases of $\Theta_0$, 180, 200, and 220 km s$^{-1}$ are considered as recent determinations of $\Theta_0$ still vary substantially (Olling & Merrifield 1998; Miyamoto & Zhu 1998; Reid & Brunthaler 2004). As can be seen in figure 3, the tangential velocity, $v_l$, has a strong dependence on $\Theta$, and thus the observed $v_l$ can be used to constrain the rotation velocity. Considering that the velocity component perpendicular to the Galactic plane is 3.7 km s$^{-1}$, and that the radial velocity differences between the maser and other lines (such as CO and SHI) are also ~ 3 km s$^{-1}$, here we can safely assume the possible range of the true tangential velocity to be $v_l = -5 \pm 5$ km s$^{-1}$, and that of the true radial velocity is $v_r = 20 \pm 5$ km s$^{-1}$. If figure 3, this tangential velocity range is obtained if $\Theta$ lies between 0.97 and 1.03. Therefore, at the position of S269, $\Theta$ should be 1.00 ± 0.03, i.e., the rotation velocity at the S269 ($\Theta$) must be the same as $\Theta_0$ within the 3% level. This is the strongest constraint of the rotation velocity in the outer galaxy ever obtained. Note that the same argument is possible based on the radial velocity, $v_r$, but the constraint is not as strong as that from the tangential velocity, because the gradient of $v_r(\Theta)$ plot is much shallower. However, we note that the radial velocity, $v_r = 20 \pm 5$ km s$^{-1}$, can be consistently explained by a rotation velocity ratio of $\theta \sim 1$.

In previous studies, the Galactic rotation curve had an uncertainty of up to 100 km s$^{-1}$ in the outer region if one included the strong dependence on Galactic constants, $\Theta_0$ (Honma & Sofue 1997). This situation is summarized in

Note that the radial velocity considered here is slightly different from the traditionally-defined $V_{LSR}$, since the Solar motion considered here is the one recently obtained from HIPPARCOS data (Dehnen & Binney 1998). However, the difference in $V_{LSR}$ and $v_r$ is not significant, being 3.3 km s$^{-1}$ for S269.
The point for S269 determined in this study is also shown in figure 4. The coincidence of the rotation velocities at the Sun and S269 simply indicates that the rotation curve there is basically flat, as was known for the rotation curves of other spiral galaxies (Rubin et al. 1980; Rubin 1983; Sofue & Rubin 2001). In disk galaxies like the Galaxy, the optical surface brightness obeys an exponential law, i.e., $I(r) = I_0 \exp(-r/h)$, where $r$ is the radius and $h$ is the disk scale length. Assuming that the surface brightness traces the mass density (i.e., constant Mass-to-Light ratio), one can calculate the rotation curve of the optical disk, assuming no dark matter (Freeman 1970). In figure 4, we also showed such a rotation curve for the Galaxy’s disk, assuming a disk scale length of $h = 3$ kpc and a maximum rotation velocity of 200 km s$^{-1}$. As can be seen from figure 4, such a rotation curve without dark matter was not completely ruled out previously. However, the rotation velocity measurement for S269 evidently shows the discrepancy between the observed rotation curve and that expected from the optical disk without dark matter, providing a strong confirmation for the existence of dark matter in the Galaxy’s outer region. At the position of S269, the rotation curve of the exponential disk gives $V_{\exp} = 168$ km s$^{-1}$, while the astrometric measurement of S269 provides $V_{\text{obs}} = 200$ km s$^{-1}$. In the case of a spherical mass distribution, the enclosed mass, $M_r$, within radius $r$ is proportional to $r^2$, as $M_r \propto r^2$. The values of $V_{\exp}$ and $V_{\text{obs}}$ obtained above give $(V_{\exp}/V_{\text{obs}})^2 = 0.70$, and thus within the position of S269 at least ~30% of the enclosed mass must be composed of dark matter.

Although this study presents astrometric measurements for only one source, the present study demonstrates the high capability of VERA for studying Galactic rotation based on Galaxy-scale astrometry. During the next decade, VERA will continue astrometric observations of nearly one thousand Galactic maser sources, and will provide an accurate rotation curve over the whole Galaxy’s disk as well as an accurate description of the dark-matter distribution of the Galaxy.

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References

Brand, J., & Blitz, L. 1993, A&A, 275, 67
Clemens, D. P. 1985, ApJ, 295, 422
Dehnen, W., & Binney, J. 1998, MNRAS, 298, 387
Freeman, K. C. 1970, ApJ, 160, 811
Godbout, S., Joncas, G., Durand, D., & Arsenuault, R. 1997, ApJ, 478, 271
Hachisuka, K., et al. 2006, ApJ, 645, 337
Honma, M., & Sofue, Y. 1997, PASJ, 49, 453
Honma, M., Kawaguchi, N., & Sasao, T. 2000, Proc. SPIE 4015, 624
Honma, M., et al. 2003, PASJ, 55, L57
Iguchi, S., Kurayama, T., Kawaguchi, N., & Kawakami, K. 2005, PASJ, 57, 259
Jiang, Z., et al. 2003, ApJ, 596, 1064
Kawaguchi, N., Sasao, T., & Manabe, S. 2000, Proc. SPIE 4015, 54
Kent, S. M. 1986, AJ, 91, 1301
Kent, S. M. 1987, AJ, 93, 816
Kerr, F. J., & Lynden-Bell, D. 1986, MNRAS, 221, 1023
Kobayashi, H., et al. 2003, ASP Conf. Ser., 306, 367
Kurayama, T., Sasao, T., & Kobayashi, H. 2005, ApJ, 627, L49
Lekht, E. E. 2000, A&AS, 141, 185
Ma, C., et al. 1998, AJ, 116, 916
McCarthy, D. D. 1996, IERS Technical Note, No.21
Merrifield, M. R. 1992, AJ, 103, 1552
Minner, V., Booth, R. S., & Conway, J. E. 2000, A&A, 362, 1093
Miyamoto, M., & Zhu, Z. 1998, AJ, 115, 1483
Moffat, A. F. J., Fitzgerald, M. P., & Jackson, P. D. 1979, A&AS, 3, 197
Olling, R. P., & Merrifield, M. R. 1998, MNRAS, 297, 943
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Reid, M. J. 1993, ARA&A, 31, 345
Reid, M. J., & Brunthaler, A. 2004, ApJ, 616, 872
Rubin, V. C., Ford, W. K., Jr., & Thonnard, N. T. 1980, ApJ, 238, 471
Rubin, V. C. 1983, Science, 220, 1339
Sofue, Y., & Rubin, V. 2001, ARA&A, 39, 137
Xu, Y., Reid, M. J., Zheng, X. W., & Menten, K. M. 2006, Science, 311, 54