Outer Rotation Curve of the Galaxy with VERA I: 
Trigonometric Parallax of IRAS 05168+3634

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(Received 2012 March 12; accepted 2012 April 15)

Abstract

We report on a measurement of the trigonometric parallax of IRAS 05168+3634 with VERA. The parallax is 0.532 ± 0.053 mas, corresponding to a distance of 1.88 ± 0.13 kpc. This result is significantly smaller than the previous distance estimate of 6 kpc, based on the kinematic distance. This drastic change in the source distance revises not only the physical parameters of IRAS 05168+3634, but also its location of the source, placing it in the Perseus arm, rather than the Outer arm. We also measured the proper motions of the source. A combination of the distance and the proper motions with the systemic velocity yields a rotation velocity (Θ) of 227 ± 9 km s⁻¹ at the source, assuming Θ₀ = 240 km s⁻¹. Our result combined with previous VLBI results for six sources in the Perseus arm indicates that the sources rotate systematically slower than the Galactic rotation velocity at the LSR. In fact, we show observed disk peculiar motions averaged over the seven sources in the Perseus arm as (U_{mean}, V_{mean}) = (11 ± 3, −17 ± 3) km s⁻¹, indicating that these seven sources are systematically moving toward the Galactic center, and lag behind the Galactic rotation.

Key words: Galaxy: rotation — ISM: individual (IRAS 05168+3634) — techniques: interferometric — VERA

1. Introduction

The rotation curve can be used to determine the mass distribution in spiral galaxies through equilibrium between the gravity and the centrifugal force. It has been revealed that there exist plenty of flat rotation curves beyond optical disks in external spiral galaxies. This indicates the existence of large quantities of dark matter in the outer regions of galaxies (e.g., Sofue et al. 1999). In contrast, the rotation curve of the Milky Way has a relatively large ambiguity, although it is believed to be almost flat, being similar to external spiral galaxies (e.g., Sofue et al. 2009). This uncertainty is mainly due to difficulties in measuring distance, since we are within the Milky Way. To precisely measure the distance and proper motions of Galactic objects based on astrometry, the Hipparcos satellite was launched in 1989 (Perryman 1989). However, parallax measurements with Hipparcos were limited to within 100 pc from the solar position, in contrast to the Milky Way’s disk size of ~20 kpc. Today, well-developed interferometer techniques in radio wavelength can be used to conduct Galactic astrometry over a kilo-parsec scale. In fact, VERAs (VLBI Exploration of Radio Astrometry) and VLBA (Very Long Baseline Array) have succeeded in making distance measurements over 5 kpc (e.g., Nagayama et al. 2011b; Sanna et al. 2012). To construct a rotation curve of the Milky Way in the outer region with high accuracy, we have been using VERA to observe Galactic objects with H₂O maser emissions in the Galactic-outer region. In this paper, we report on observation results for IRAS 05168+3634.

IRAS 05168+3634 is a high-mass star-forming region in the pre-UC HII phase (Wang et al. 2009). According to Wang et al. (2009), the source has a ¹³CO (J = 2–1) core, which is positioned ~1.3 toward the northeast of IRAS 05168+3634 and has an active outflow. An H₂O maser is detected in this region where the CO outflow occurs (Palla et al. 1991). The maser position coincides with a bright red source detected with the Spitzer IRAC at 4.5 μm (figure 1a). Figure 1b represents the MSX A-band image (8.28 μm, Price et al. 2001) on which CO (J = 2–1) emissions (Zhang et al. 2005), a 6 cm continuum emission peak (Molinari et al. 1998), and the IRAS source position are superposed. Although no radio continuum (6 cm) was detected in IRAS 05168+3634 by McCutcheon et al. (1991), Molinari et al. (1998) have detected a 6 cm continuum emission peak with 4.23 mJy at the triangle position in figure 1b (Zhang et al. 2005). In this region, there are several sources with different evolutionary phases of star-formation. Molinari et al. (1998) interpreted the lack of radio emission in this star-forming region as being due to accreting matter that choking off the expansion of ionized gas. As for the distance-estimate of IRAS 05168+3634, a kinematic distance of ~6 kpc was obtained (Molinari et al. 1996) based on the systemic LSR velocity (V_{LSR}) of ~15.5 ± 1.9 km s⁻¹, traced by CS (2–1) emission (Bronfman et al. 1996). However, this source is located at a Galactic longitude (ℓ) of ~171°, where the kinematic distance has a large error (Sofue 2011). In fact, kinematic distances along the Sun-Galactic Center (G.C.) line are not determined precisely, since the V_{LSR} is degenerated at around...
0 km s\(^{-1}\). To estimate the error of the kinematic distance at the source, we consider \(\Delta V_{\text{LSR}} = \pm 1.9 \text{ km s}^{-1}\) with the flat rotation model. The obtained error is significantly large, \(\sim 1.2 \text{ kpc or } \sim 22\%\) at the source. Thus, VLBI observations for IRAS 05168+3634 are necessary, not only to precisely measure distance, but also to construct a precise Outer Rotation Curve of the Galaxy. In the present paper we report on astrometric observations of IRAS 05168+3634 with VERA.

2. Observations and Data Reduction

2.1. VLBI Observations with VERA

Between 2009 October and 2011 May, we carried out 11-epoch observations of the H\(_2\)O maser line at a rest frequency of 22.235080 GHz to measure both parallax and proper motions of IRAS 05168+3634. Details of the dates for 11 observations are listed in Table 1. Note that system problems prevented Mizusawa station from participating in the observation on DOY (day of year) 101 of 2011. Except for the observation, the average synthesized beam was 1.1 \( \times \) 0.7 mas with a position angle of 135\(^\circ\), as listed in Table 1. In contrast, the synthesized beam was 1.4 \( \times \) 0.8 mas with a position angle of 169\(^\circ\) in the observation on DOY 101, 2011. We also observed two pairs, both including a target source and a reference source from DOY 80, 2010 for the phase referencing observation. One of these was the target source, IRAS 05168+3634, and...
a velocity resolution of 0.42 km s\(^{-1}\). In contrast, each 15-IFs was composed of 64 channels for the continuum sources.

2.2. Data Reduction

The Astronomical Image Processing System (AIPS, NRAO) was used for data calibration, and general phase referencing analysis was applied to determine the absolute maser positions (e.g., see the Appendix in Kurayama et al. 2011 for the phase referencing analysis with VERA). Before a fringe search was made in AIPS to determine the clock offset and the clock rate offset, we corrected the delay model that was used in the correlation processing, since the delay model used in the correlation was not accurate enough for precise astrometry. To correct for the delay model, we applied a precise geodetic model, the most-updated Earth-rotation parameters provided by IERS, tropospheric delays measured with GPS receivers at each VERA station (Honma et al. 2008a), and ionospheric delays based on the Global Ionosphere Map (GIM), which was produced every two hours by the University of Bern. At the beginning of fringe searches with the corrected visibilities, fringes were searched for the fringe finder J0555+3948 or DA193 to determine the clock offset. Next, fringes were searched for the position reference J0530+3723 by referring to DA193. Then, the position reference was imaged with self calibration, and the complex gain solved for the position reference J0555+3948 or DA193 to determine the clock offset. Next, fringes were searched for the position reference J0530+3723 by referring to the clock offset determined with J0555+3948 or DA193. Then, the position reference was imaged with self calibration, and the complex gain solved for the position reference was transferred to the maser source IRAS 05168+3634 for phase-referencing. When transferring the complex gain from J0530+3723 to IRAS 05168+3634, the instrumental phase difference between the dual-beam system with VERA was corrected based on the phase difference between the dual-beam system measured in real time during the observations (Honma et al. 2008b). At the next step, the corrected visibilities for the maser source were Fourier-transformed to create dirty images of each maser channel. Finally, to obtain final CLEANed maps, we used

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### Table 1. Observations.

| Epoch | Date       | Time range (UTC) | Beam (mas) | Note                                      |
|-------|------------|------------------|------------|-------------------------------------------|
| A     | 2009 Oct 03| 15:35-00:40      | 1.15 × 0.72@139′0" |                                      |
| B     | 2009 Oct 30| 13:50-22:15      | 1.16 × 0.72@135′0" |                                      |
| C     | 2010 Jan 25| 08:05-16:30      | 1.04 × 0.69@131′5" |                                      |
| D     | 2010 Mar 21| 04:30-12:55      | 1.15 × 0.70@133′5" | Two maser sources were alternately observed in the same epoch. |
| E     | 2010 May 22| 00:25-08:50      | 1.21 × 0.68@149′1" |                                      |
| F     | 2010 Aug 22| 18:20-02:45      | 1.12 × 0.72@132′7" |                                      |
| G     | 2010 Oct 24| 14:15-22:40      | 1.09 × 0.73@135′2" |                                      |
| H     | 2010 Dec 02| 11:40-20:05      | 1.18 × 0.69@131′2" |                                      |
| I     | 2011 Jan 28| 07:55-16:20      | 1.10 × 0.74@132′9" |                                      |
| J     | 2011 Apr 11| 03:10-11:35      | 1.39 × 0.76@168′6" | Mizusawa station did not participate due to system trouble. |
| K     | 2011 May 06| 01:30-11:35      | 1.14 × 0.66@132′6" | Two maser sources were alternately observed in the same epoch. |

### Table 2. Source data.

| Source name       | RA (J2000.0) | Dec (J2000.0) | S.A.+ | Flux density (Jy) | Note                  |
|-------------------|--------------|--------------|-------|-------------------|-----------------------|
| IRAS 05168+3634   | 05h20m22s07′ | 36°37′56″63′ | 10.0 – 255.6 | H₂O masers        |                       |
| J0530+3723        | 05h30m12s5493′ | 37°23′32″6197′ | 2.128 | 0.10– 0.18 | Phase-reference calibrator |

+ The separation angle between the maser and the reference sources.
+ The position is based on Fomalont et al. (2003).
the “clean” task in AIPS, and we identified masers at each velocity channel from the final maps. We used the “jimit” task in AIPS to determine the absolute maser position and the flux of the maser source by elliptical Gaussian fittings to the brightness peak of the map. We regarded a detected maser, the linear proper motion and the sinusoidal parallax motion. For astrometry, we used the following selection criteria: (1) spots or more. To identify the same maser spot in each epoch for since it achieved a high SNR (signal to noise ratio) of five brightness peak of the map. We regarded a detected maser, flux of the maser source by elliptical Gaussian fittings to the task in AIPS to determine the absolute maser position and the “clean” task in AIPS, and we identified masers at each epoch for the two features (feature-1 with V \_LSR = −20.3 km s \(^{-1}\) and feature-2 with \(V \_LSR = −20.7 \) km s \(^{-1}\)). Table 3. Parallax fits.*

| Feature | \(V \_LSR\) (km s \(^{-1}\)) | N\_epochs | Epochs | Parallax (Error) | Proper motions (Error) | Errors |
|---------|-----------------|-----------|--------|-----------------|----------------------|---------|
| 1       | −20.3           | 9         | ABDEHJIJK | 0.548(0.104) | −1.65(0.14) | −1.98(0.21) | 0.18 0.34 0.38 |
| −20.7   | 10              |           | ABCDEHJIJK | 0.533(0.087) | −1.66(0.11) | −1.94(0.19) | 0.17 0.33 0.37 |
| −21.1   | 9               |           | ABDEHJIJK | 0.561(0.109) | −1.62(0.14) | −1.97(0.20) | 0.19 0.34 0.39 |
| 2b      | −23.6           | 9         | ACDEFGHII | 0.538(0.080) | −1.59(0.13) | −4.67(0.17) | 0.17 0.23 0.29 |
| −24.1   | 9               |           | ACDEFGHJI | 0.519(0.066) | −1.57(0.11) | −4.41(0.23) | 0.15 0.30 0.34 |

Combined fit for five spots 0.537(0.038) 0.17 0.31 0.35
Combined fit for two features 0.526(0.053) 0.16 0.32 0.36

Final (mean of the two combined fittings) 0.532(0.053)

* Combined fits were done to the data set of two (see text). Final value is determined by taking the mean of the two. Error of the final parallax is estimated by combining in quadrature the scatter of the individual parallaxes around the mean (±0.006 mas) and the error bar of individual parallax (±0.053 mas).

Table 4. Determination of the systematic proper motions for IRAS 05168+3634.

| Feature | \(V \_LSR\) (km s \(^{-1}\)) | Proper motions* (Error) | Note |
|---------|-----------------|----------------------|------|
| 1 & 4   | −20.3—21.1 & −13.6—14.8 | −1.83(0.25) | −2.31(0.49) | Systematic proper motions |
| 2a & 2b | −24.5 & −23.6—24.1    | −1.28(0.43) | −3.52(1.43) |
| 3       | −21.1—22.8       | 1.30(0.24)  | −3.31(0.18) |
| 5       | −13.6            | 2.71(0.81)  | −3.42(1.62) |

Mean −19.3 0.23(1.07) −3.14(0.28)†

* We averaged the proper motion values of four representative features to determine the systematic proper motions (see text). Note that these four feature values were determined by adapting the parallax of 0.532 mas.
† The errors of the systematic proper motions were determined by dividing the standard deviations by a factor of \(\sqrt{4}\).

3. Results
3.1. Trigonometric Parallaxes of IRAS 05168+3634

The 11-epoch VLBI observations performed over about a period of one and a half years clearly showed an annual parallax and proper motions for IRAS 05168+3634 (see table 3 and figure 2). In table 3, we give the parallax results for five spots in the two features (1 and 2b) to be 0.548 ± 0.104, 0.533 ± 0.087, 0.561 ± 0.109, 0.538 ± 0.080, and 0.519 ± 0.066 mas, respectively. Note that astrometric errors in each epoch are given so that the standard deviation of \(\chi^2\) becomes unity, since a systematic error is generally larger than a thermal error estimate in the phase-referencing VLBI (e.g., Sanna et al. 2012). In addition, we conducted a combined-fitting assuming a common parallax with discrete proper motions for each spot. As a result, the parallax was determined to be 0.537 ± 0.038 mas for the five spots, corresponding to a distance of 1.86±0.14 kpc. In the same way, the other parallax was determined to be 0.526 ± 0.053 mas for the two features (feature-1 with \(V \_LSR = −20.7 \) km s \(^{-1}\) and feature-2 with \(V \_LSR = −24.1 \) km s \(^{-1}\)), corresponding to a distance of 1.90±0.17 kpc. Note that the selected two spots in the two features are brighter than the other spots, and have less parallax errors compared with the other spots. We averaged the two combined fit results to obtain a final
Fig. 2. Maser positional evolutions and the combined-fit results (see text). The error bars represent position errors resulting from the astrometric (systematic) errors, which are given so that the reduced $\chi^2$ becomes unity. (a) Maser positional evolutions in right ascension with circles. Dotted lines represent proper motions, and dashed lines show fitted lines. (b) Same as (a), but in declination. (c) Parallax motions in right ascension with the proper motions subtracted from (a). The solid lines show a line fitted to the parallax motions with the circles. (d) Same as (c), but in the declination.

parallax result, since the five spots may not be independent of each other. As a consequence, we obtained a final parallax of $0.532 \pm 0.053$ mas, corresponding to a distance of $1.88^{+0.21}_{-0.17}$ kpc. Note that the parallax error was estimated by combining in quadrature the scatter of the individual parallaxes around the mean ($\pm 0.006$ mas) and the error bar of individual parallax ($\pm 0.053$ mas). In figures 2a and 2b, we show the combined fit results with the final parallax result, fixed for the five spots in directions of right-ascension (RA) and declination (Dec), respectively. The error bars in figure 2 represent the astrometric error described above. The astrometric errors set for the combined fitting are $0.17$ mas for $\Delta \alpha \cos \delta$ and $0.31$ mas for $\Delta \delta$. These errors mainly originated in the tropospheric zenith delay (e.g., Honma et al. 2007). Moreover, the separation angle between the maser and the phase reference sources was relatively large ($= 2\degree 1$) in our observations, which caused a large residual of tropospheric delay between the target and the reference pair. The error of $\Delta \delta$ is larger than that of $\Delta \alpha \cos \delta$, which is consistent with previous VERA results. In addition, the parallax amplitude is reduced in the declination. Hence, the parallax signal is not clear in the declination as in figure 2d.

The final parallax result of $1.88^{+0.21}_{-0.17}$ kpc is smaller than the previously estimated source distance of 6 kpc, based on the kinematic distance (Molinari et al. 1996). We discuss the consequence of this difference in distance in section 4.

3.2. Systematic Proper Motions of IRAS05168+3634

As the next step, we determined systematic proper motions from the observational data. Note that a maser source has both internal and systematic proper motions. Hence, to obtain the systematic motions, one should remove the internal motions (e.g., Hachisuka et al. 2009). Figures 1c and 1d show
the distribution of maser spots that were detected for more than two epochs. The brightest maser spot with the distribution of maser spots that were detected for IRAS 05168+3634 was associated in another massive star-forming region. Thus, here we assume random internal motions to determine the systematic proper motions. We identified six features to determine the systematic proper motions through the described criteria (figure 1c, figure 1d, and table 4). Features 1 and 4 are located in the same region with the same directed motion, meaning that these may be associated with the same gas. In the same way, features 2a and 2b may also be associated with the same gas. Thus, we reduced the number of data from six to a representative four, including features 1 & 4, 2a & 2b, 3, and 5 in table 4. The proper motions of the four representative features were derived by adapting a parallax of 0.532 mas. As a result of data averaging, we determined the systematic proper motions of the four representative features. The difference of 3.8 km s\(^{-1}\) was converted to 0.43 mas yr\(^{-1}\) by adapting a distance of 1.88 kpc for IRAS 05168+3634. This indicates that the determined systematic proper motions for IRAS 05168+3634 include an error of at least 0.4 mas yr\(^{-1}\).

4. Discussion

4.1. Location and Revised Physical Parameters for IRAS 05168+3634

Our parallax measurement revises the distance to IRAS 05168+3634 from 6 kpc to 1.88 kpc, which requires a significant reduction of the physical parameters for the source. By adapting a distance of 1.88 kpc, the source is likely to be located in the Perseus arm rather than in the Outer arm (figure 3). Figure 3a provides a schematic face-on view of the Galaxy (Georgelin & Georgelin 1976) on which the location of IRAS 05168+3634 is superposed. While the blue circle is based on the kinematic distance of the source, the red circle is based on our parallax measurement. Clearly, our result is smaller than the kinematic distance. Black circles show previous VLBI results listed in table 6. Note that \(R_0 = 8.33\) kpc was assumed from Gillessen et al. (2009). Figure 3b represents the source positions on a Galacto-centric longitude versus a Galacto-centric radius plot. The horizontal axis is the Galacto-centric longitude, \(\beta\), which is set to 0.

Fig. 3. Position of IRAS 05168+3634 based on both the kinematic distance and our parallax measurement. (a) Red circle showing our observation result, while the blue one represents the kinematic distance. The black circles show previous VLBI results for other sources in star-forming regions (see table 6). These results are superposed on the Galactic face-on image (Georgelin & Georgelin 1976). \(R_0 = 8.33\) kpc is assumed (Gillessen et al. 2009). The solar position is \((X, Y) = (0, 0)\) kpc. (b) It is the same as (a), but in polar coordinates. The horizontal axis is the Galacto-centric longitude \(\beta\), and the vertical one is the Galacto-centric distance in log scale (see text). Solid and dashed lines show fitted lines for Outer and Perseus arms through the equation of log-spiral [see equation (1)]. The dotted line also represents the fitted line for the Sagittarius-Carina arm. The pitch angles of the Outer and Perseus arms show 11°6 and 17°8 ± 1°7, respectively. The pitch angle of the Sagittarius-Carina arm was not determined precisely.
The fitted line is shown in figure 3b with the dashed line. In table 5 shows the lower limit of
M
and the peak
N
cloud with which IRAS 05168+3634 is associated is also likely to be virialized in the same way as other disk clouds.

4.2. Rotation Velocity of IRAS 05168+3634

Combining the distance and the systematic proper motions for IRAS 05168+3634 with the systemic velocity provides full space motion of the source, which allows us to determine not only the rotation velocity of the source, but also its peculiar motions. First, we converted \((\mu_\ell \cos \delta, \mu_\delta) = (0.23 \pm 1.07, -3.14 \pm 0.28) \text{ mas yr}^{-1}\) in the equatorial coordinate system into \((\mu_\ell \cos b, \mu_b) = (2.71 \pm 0.84, -1.61 \pm 1.04) \text{ mas yr}^{-1}\) in the Galactic coordinate one. By adapting the distance of our measurement \((d = 1.88 \pm 0.17 \text{ kpc})\), we obtained \((\mu_\ell \cos b, \mu_b) = (24.1 \pm 7.5, -14.3 \pm 9.2) \text{ km s}^{-1}\). Second, we used \(V_{\text{LSR}} = -15.5 \pm 1.9 \text{ km s}^{-1}\) of CS (2–1) emission (Bronfman et al. 1996) as the radial velocity of the source, which was converted into \(V_{\text{helio}} = -7.8 \pm 1.9 \text{ km s}^{-1}\) in the heliocentric frame. The conversion calculation was conducted based on the equations in the Appendix of Reid et al. (2009b). Third, peculiar solar motions of \((U_\odot, V_\odot, W_\odot) = (11.1 \pm 1, 12.24 \pm 2, 7.25 \pm 0.5) \text{ km s}^{-1}\) were assumed from Schönrich, Binney, and Dehnen (2010). The peculiar motions represent a deviation of the Sun from the Galactic circular orbit. The directions of the peculiar motions are towards the Galactic center \((U_\odot, V_\odot, W_\odot)\), the Galactic rotation \((V_\odot)\), and the northern Galactic pole \((W_\odot)\). Fourth, the Galactic constants, \(R_0 = 8.33 \text{ kpc}\) and \(\Theta_0 = 240 \text{ km s}^{-1}\), were assumed from Reid and Brunthaler (2004) and Gillessen et al. (2009). Reid and Brunthaler (2004) observed the proper motions of Sgr A* and Gillessen et al. (2009) determined the distance to the Galactic-center based on stellar orbits around Sgr A*. Finally, these converted and assumed values allowed us to determine a rotation velocity \(\Theta\) of \(227^{+9}_{-11} \text{ km s}^{-1}\) at the source. At the same time, we obtained the peculiar motions of the source in the Galactic plane by simple geometry (e.g., Appendix in Reid et al. 2009b). Note that the error in the rotation velocity was evaluated from errors of the parallax, the proper motions, and the systemic velocity. The rotation velocity, \(\Theta(R)\), is marginally smaller than the rotation velocity at the LSR, \(\Theta_0\). This result may indicate that the Galactic rotation at the Galacto-centric distance of 10.2 kpc is slower than the rotation velocity at the LSR. Note

| Physical parameter | Kinematic distance of 6.08 kpc | Our parallax measurement of 1.88 kpc |
|--------------------|--------------------------------|-----------------------------------|
| Virial mass \((M_\odot)\) | \(2.4 \times 10^3\) | \(7.4 \times 10^2\) |
| LTE mass \((M_\odot)\) | \(> 1.2 \times 10^4\) | \(> 1.1 \times 10^3\) |
| \(\alpha = M_{\text{vir}} / M_{\text{LTE}}\) | 0.2 | 0.7 |
| Bolometric luminosity \((L_\odot)\) | 17130 | 1638 |
| Spectral type | B0.5* | B3* |

* Panagia (1973).
that the source is located at the Galacto-centric distance of $10.19_{-0.17}^{+0.21}$ kpc. The previous six VLBI results in the Perseus arm are consistent with our result for the slower rotation (table 6 and figure 4). The previous VLBI results together with our result are also consistent with the previous one-dimensional (radial velocity) observations, called the 9-kpc dip in Sofue, Honma, and Omodaka (2009). In the next section we further discuss this slower rotation with the peculiar motions in the Perseus arm.

4.3. Peculiar Motions: Comparison between the Perseus Arm and Other Regions

As for the peculiar motions of IRAS 05168+3634, we derived the values of $(U, V, W) = (8.1^{+3.6}_{-3.9}, -12.5^{+9.2}_{-11.1}, -7.0^{+9.7}_{-11.9})$ through the procedure described in the previous section. The directions of the peculiar motions are towards the Galactic center ($U$), the Galactic rotation ($V$), and the northern Galactic pole ($W$) at the source position. The errors of the peculiar motions were evaluated from errors of the parallax, the proper motions, and the systemic velocity. The peculiar motions tell us the deviation of the source from the circular Galactic orbit. Note that here we assumed a flat rotation model of $\Theta(R) = \Theta_0$. To compare the peculiar motions to previous VLBI results, we list the previous VLBI results in table 6. The sources listed in table 6 were observed with VLBI in star-forming regions. In figure 4a, we plot the disk peculiar motions...
### Table 6. Peculiar motions between sources of the Perseus arm and that of other places.

| Source         | $U$ (km s$^{-1}$) | $V$ (km s$^{-1}$) | $W$ (km s$^{-1}$) | Ref.† | Note                  |
|----------------|-------------------|-------------------|-------------------|-------|-----------------------|
| G9.62+0.20     | $-39^{+15}_{-23}$ | $-52^{+15}_{-21}$ | $-10^{+5}_{-9}$   | 15    | close to 3 kpc arm    |
| G12.89+0.49    | $20^{+8}_{-9}$    | $-4^{+16}_{-17}$  | $-4^{+10}_{-9}$   | 16    | Carina-Sagittarius arm|
| G14.33–0.64    | $13^{+15}_{-15}$  | $-6^{+14}_{-17}$  | $-4^{+9}_{-8}$    | 17    | Carina-Sagittarius arm|
| G15.03–0.68    | $2^{+4}_{-3}$     | $7^{+2}_{-3}$     | $-5^{+2}_{-2}$    | 16    | Carina-Sagittarius arm|
| G23.01–0.41    | $28^{+12}_{-15}$  | $-23^{+10}_{-11}$ | $-1^{+4}_{-5}$    | 18    | Crux-Scutum arm       |
| G23.44–0.18    | $2^{+30}_{-24}$   | $-22^{+12}_{-21}$ | $2^{+3}_{-4}$     | 18    | Norma arm             |
| G23.66–0.13    | $36^{+8}_{-11}$   | $9^{+5}_{-6}$     | $4^{+1}_{-1}$     | 19    | close to the bar       |
| G35.20–0.74    | $-5^{+6}_{-7}$    | $-6^{+5}_{-6}$    | $-8^{+2}_{-3}$    | 21    | Carina-Sagittarius arm|
| G35.20–1.74    | $-10^{+11}_{-15}$ | $-10^{+9}_{-11}$  | $-9^{+4}_{-5}$    | 21    | Carina-Sagittarius arm|
| G48.61+0.02    | $-1^{+3}_{-4}$    | $-42^{+2}_{-2}$   | $6^{+2}_{-2}$     | 22    | Carina-Sagittarius arm|
| W 51 Main/South| $-8^{+8}_{-9}$    | $-1^{+5}_{-6}$    | $5^{+6}_{-6}$     | 23    | Carina-Sagittarius arm|
| IRAS 19213     | $17^{+7}_{-9}$    | $-10^{+5}_{-3}$   | $-4^{+7}_{-5}$    | 1     | Carina-Sagittarius arm|
| G59.78+0.06    | $2^{+2}_{-2}$     | $1^{+4}_{-4}$     | $-4^{+1}_{-1}$    | 25    | Local arm             |
| ON 1           | $1^{+4}_{-4}$     | $-5^{+3}_{-3}$    | $8^{+4}_{-3}$     | 26    | Local arm             |
| G75.30+1.32    | $11^{+8}_{-7}$    | $1^{+15}_{-14}$   | $-18^{+8}_{-9}$   | 13    | Outer arm             |
| ON 2N          | $-3^{+5}_{-4}$    | $-5^{+5}_{-4}$    | $1^{+4}_{-4}$     | 27    |                       |
| AFGL2789       | $5^{+6}_{-7}$     | $-28^{+8}_{-7}$   | $-11^{+6}_{-8}$   | 1     | Perseus arm           |
| L 1206         | $1^{+6}_{-4}$     | $-9^{+5}_{-4}$    | $0^{+7}_{-6}$     | 2     | Star-forming region   |
| Cep A          | $4^{+6}_{-5}$     | $-5^{+6}_{-5}$    | $-5^{+3}_{-3}$    | 3     | Local arm             |
| NGC 7538       | $19^{+3}_{-2}$    | $-23^{+4}_{-3}$   | $-10^{+2}_{-2}$   | 3     | Perseus arm           |
| L1287          | $11^{+4}_{-4}$    | $-11^{+5}_{-5}$   | $-3^{+3}_{-3}$    | 2     | SFR                   |
| IRAS 00420     | $14^{+4}_{-4}$    | $-14^{+4}_{-4}$   | $-3^{+1}_{-2}$    | 4     | SFR in the Perseus arm|
| NGC 281        | $9^{+6}_{-2}$     | $3^{+6}_{-6}$     | $-9^{+3}_{-3}$    | 2     | SFR in the Perseus arm|
| W 3(OH)        | $19^{+4}_{-4}$    | $-11^{+4}_{-4}$   | $1^{+3}_{-3}$     | 7     | Perseus arm           |
| WBB9437        | $15^{+8}_{-9}$    | $2^{+13}_{-12}$   | $1^{+13}_{-12}$   | 8     | Outer arm             |
| IRAS 05168     | $8^{+4}_{-4}$     | $-13^{+9}_{-11}$  | $-7^{+10}_{-12}$  | 9     | Perseus arm           |
| HP-Tau/G2      | $-18^{+2}_{-2}$   | $1^{+4}_{-4}$     | $0^{+1}_{-1}$     | 34    |                       |
| IRAS 06061     | $12^{+2}_{-2}$    | $-22^{+3}_{-3}$   | $-11^{+2}_{-2}$   | 35    | Perseus arm           |
| S252           | $-2^{+3}_{-3}$    | $-9^{+1}_{-1}$    | $-2^{+0.5}_{-0.5}$| 10    | Perseus arm           |
| S255           | $0^{+6}_{-6}$     | $3^{+14}_{-15}$   | $3^{+10}_{-11}$   | 2     | SFR                   |
| S269           | $5^{+5}_{-5}$     | $6^{+3}_{-3}$     | $-4^{+2}_{-2}$    | 11    | Outer arm             |
| Orion          | $-7^{+5}_{-5}$    | $-4^{+5}_{-5}$    | $3^{+4}_{-4}$     | 12    |                       |
| G232.6+1.0     | $1^{+5}_{-5}$     | $-6^{+5}_{-6}$    | $1^{+3}_{-3}$     | 10    | Local arm             |

| Sun            | $U_\odot = 11.1^{+1}_{-1}$ | $V_\odot = 12.24^{+2}_{-2}$ | $W_\odot = 7.25^{+0.5}_{-0.5}$ | Schonrich, Binney, and Dehnen (2010) |

* $\Theta_0 = 240$ km s$^{-1}$ and $R_0 = 8.33$ kpc are assumed to determine the peculiar motions. The rotation model is flat ($\Theta(R) = \Theta_0$) assumed.

† References: (1) Oh et al. (2010); (2) Rygl et al. (2010); Sato et al. (2008); (3) Moscadelli et al. (2009); (4) Moellenbrock, Claussen, and Goss (2009); (5) Reid et al. (2009b); (6) Honma et al. (2011); (7) Xu et al. (2006); (8) Hachisuka et al. (2009); (9) this paper; (10) Reid et al. (2009a); (11) Honma et al. (2007); (12) Hirota et al. (2007); Menten et al. (2007); (13) Sanna et al. (2012); (14) Sanna et al. (2009); (15) Xu et al. (2011); (16) Sato et al. (2010b); (17) Brunthaler et al. (2005); (18) Bartkiewicz et al. (2005); (19) Zhang et al. (2009); (22) Nagayama et al. (2011a); (23) Sato et al. (2010b); (24) Xu et al. (2009); (26) Nagayama et al. (2011a); (27) Ando et al. (2011); (34) Torres et al. (2009); (35) Niinuma et al. (2011).

on the $U$ and $V$ plane from table 6 for the 33 sources. Each symbol shows Scutum-Crux (open square), Sagittarius-Carina (filled square), Perseus (circle), Outer arms (open triangle), and other regions (filled triangle). It is clear that almost all sources in the Perseus arm are systematically located in the lower right region ($U > 0$ and $V < 0$) of the $U-V$ plane. We emphasize that the sources in the Perseus arm are systematically moving toward the Galactic center ($U > 0$), and counter to the Galactic rotation ($V < 0$). We obtained disk peculiar motions averaged over the seven sources in the Perseus arm as...
$U_{\text{mean}}, V_{\text{mean}} = (11 \pm 3, -17 \pm 3)$ km s$^{-1}$ (NGC 281 excluded). Both $U_{\text{mean}}$ and $V_{\text{mean}}$ show peculiar motions of greater than 3-$\sigma$ significance in the Perseus arm. The peculiar motions there may trace the streaming motions where the Galactic shock front occurs (Roberts 1969).

As for other sources, some show significantly large peculiar motions (e.g., G9.62$+0.20$, G23.66$-0.13$, and G23.66$-0.13$). All of them are located close to the Galactic bar, which may be affected by the gravitational potential of the central bar. Roberts, Huntley, and van Albada (1979) showed that a bar-like potential can induce strong noncircular motions in a gas flow of $\sim 50$–$150$ km s$^{-1}$, which is consistent with one of the sources (G9.62$+0.20$). Of course, there are other possibilities for large peculiar motions. For instance, G48.61$+0.02$ shows a peculiar motion that is counter to the Galactic rotation, larger than 40 km s$^{-1}$. It is affected by local phenomena, multiple supernovae (Nagayama et al. 2011b). Another interesting feature of the peculiar motions is the variation of the peculiar motions as a function of the Galacto-centric distance (figures 4b and 4c). The $V$ values vary among the spiral arms in figure 4c. The Perseus and Norma arms have minus $V$ values with respect to around $V = 0$ km s$^{-1}$ values or plus values in the Outer and Carina-Sagittarius arms. In particular, this tendency of the Outer and Perseus arms was also suggested by optical (spectroscopic) observations in Russell, Adam, and Georgelin (2007). Russell, Adam, and Georgelin (2007) argued that this difference between the $V$ components of the Outer and Perseus arms may be explained by streaming motions due to the spiral density-wave. These streaming motions produce radial ($U$ component) and azimuthal ($V$ component) residual velocities. According to Mel’Nik, Dambis, and Rastorguev (1999), the difference in the peculiar motions of the Outer and Perseus arms may be explained by the location of the co-rotation (CR) radius by density-wave theory. Inside the co-rotation radius, radial and azimuthal residual velocities are directed toward the Galactic center and counter to the Galactic rotation, while outside the co-rotation, residual velocities are directed away from the Galactic center and toward the Galactic rotation; inside and outside the CR, the directions of peculiar motions are the inverse of each other. Russell, Adam, and Georgelin (2007) determined a co-rotation radius of 12.7 kpc by assuming the co-rotation as the position of $V = 0$ (see figure 7 in Russell et al. 2007). This result can explain the variation in the $V$ values between the Outer and Perseus arms in the VLBI observations (figure 4c). On the other hand, the $U$ values of both the Outer and Perseus arms have the same sign ($U > 0$), which cannot be explained by the location of the co-rotation between the two arms (figure 4b). However, the number of Outer arm sources is still small (G75.30$+1.32$, WB89$-437$, and S269). Thus, more observations of the Outer arm are necessary to confirm whether our interpretation of the peculiar motions with the density-wave theory is correct or not. In contrast, Wada, Baba, and Saito (2011) showed that the spiral features of the gas in the Galactic disk are formed by mechanisms that essentially differ from the Galactic shock in stellar density waves. They also showed that, unlike the stream motions in the Galactic shock, the interstellar matter flows into the local potential minima with irregular motions. Therefore, random irregular motions can be another candidate to explain the observed peculiar motions.

5. Conclusion

Our VLBI observations show results of the parallax and proper motions for IRAS 05168$+3634$. The parallax is $0.532 \pm 0.053$ mas, which corresponds to a distance of $1.88^{+0.21 \pm 0.17}$ kpc, and the proper motions are $(\mu_u \cos \delta, \mu_l) = (0.23 \pm 1.07, -3.14 \pm 0.28)$ mas yr$^{-1}$. The distance is significantly smaller than the previously estimated kinematic distance, being 6 kpc (Molinari et al. 1996). According to the drastic change in the source distance, the source is placed in the Perseus arm rather than in the Outer arm. The combination of distance, proper motions, and systemic velocity provides a rotation velocity of $227^{+9 \pm 11}_{-11 \pm 9}$ km s$^{-1}$ at the source, assuming $\Theta_0 = 240$ km s$^{-1}$. Our result indicates marginally slower rotation with $\sim 1$-$\sigma$ significance for the Perseus arm, but consistent with the previous VLBI results for six sources in the Perseus arm (NGC 281 excluded). We also show the disk peculiar motions averaged over the seven sources in the Perseus arm as $(U_{\text{mean}}, V_{\text{mean}}) = (11 \pm 3, -17 \pm 3)$ km s$^{-1}$. Note that here we assume the flat rotation as $\Theta(R) = \Theta_0$. This suggests that the seven sources in the Perseus arm are systematically moving toward the Galactic center, and lag behind the Galactic rotation with more than 3-$\sigma$ significance. The peculiar motions may be caused in the inner edge of the Perseus arm, where a shock front predicted by the density-wave theory occurs (Mel’Nik et al. 1999). However, the density wave with $CR = 12.7$ kpc cannot fully explain the disk peculiar motions between the Perseus and Outer arms obtained by VLBI observations. That they both share the same sign of $U$ values ($U > 0$) cannot be explained by the density wave, while the sign variation of the $V$ values between the two arms is consistent with the prediction of the density wave. However, more observations are necessary to confirm whether the density-wave theory can explain the disk peculiar motions of both $U$ and $V$ simultaneously, or not, over the entire Galactic disk. We have been observing H$_2$O maser sources located in the star-forming regions to determine any parallax and proper motions with VERA. Our observations will be used to construct a highly accurate outer rotation curve of the Galaxy. This would allow us to determine not only the mass distribution of the Galaxy, but also that of the dark matter. If characteristic phenomena are seen in individual objects, we will report these together with the outer rotation curve.

Finally, we thank the VERA project members for the support they offered during observations. We would also like to thank the referee for carefully reading the manuscript. This work was supported in part by The Graduate University for Advanced Studies (Sokendai).
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