PARALLAXES FOR W49N AND G048.60+0.02: DISTANT STAR FORMING REGIONS IN THE PERSEUS SPIRAL ARM

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ABSTRACT

We report trigonometric parallax measurements of 22 GHz H2O masers in two massive star-forming regions from Very Long Baseline Array observations as part of the Bar and Spiral Structure Legacy Survey. The distances of 11.11±0.69 kpc to W49N (G043.16+0.01) and 10.75±0.51 kpc to G048.60+0.02 locate them in a distant section of the Perseus arm near the solar circle in the first Galactic quadrant. This allows us to locate accurately the inner portion of the Perseus arm for the first time. Combining the present results with sources measured in the outer portion of the arm in the second and third quadrants yields a global pitch angle of 9.5 ± 1.3 for the Perseus arm. We have found almost no H2O maser sources in the Perseus arm for 50° < ℓ < 80°, suggesting that this ≈6 kpc section of the arm has little massive star formation activity.

Key words: astrometry – Galaxy: fundamental parameters – Galaxy: kinematics and dynamics – masers – stars: formation – techniques: high angular resolution

Online-only material: color figures

1. INTRODUCTION

While the nature and even the number of spiral arms in the Milky Way is still debated, mounting evidence suggests that the Perseus arm is one of two major spiral arms (Drimmel 2000; Benjamin et al. 2005; Churchwell et al. 2009). It may emerge from the far end of the bar and wrap through the inner Galaxy in the first quadrant (inner portion of the Perseus arm) and the outer Galaxy in the second and third quadrants (outer portion of the Perseus arm). Since the inner portion of the Perseus arm lies at a smaller Galactic radius and closer to the bar than the outer portion of the arm, one would expect it to be more prominent in molecular gas and star formation, yet very little is known about its signals, the center 6 kpc section of the Perseus arm for the first time. Combining the present results with sources measured in the outer portion of the arm in the second and third quadrants yields a global pitch angle of 9.5 ± 1.3 for the Perseus arm. We have found almost no H2O maser sources in the Perseus arm for 50° < ℓ < 80°, suggesting that this ≈6 kpc section of the arm has little massive star formation activity.

Recent improvements in radio astrometry with Very Long Baseline Interferometry (VLBI) techniques have yielded parallaxes and proper motions to star-forming regions in the Galaxy with accuracies of ~10 μas and ~0.1 mas yr−1, respectively (e.g., Reid et al. 2009b; Honma et al. 2012). Parallax measurements for a reasonably dense sampling of sources in spiral arms will help us to fully trace the spiral structure of the Galaxy. To reach this goal, we are using the NRAO9 Very Long Baseline Array (VLBA) to conduct a key science project, the Bar and Spiral Structure Legacy (BeSSeL) Survey, to study the structure and kinematics of the Galaxy by measuring trigonometric parallaxes and proper motions for hundreds of 22 GHz H2O and 6.7/12.2 GHz CH3OH maser sources associated with massive star-forming regions.

In this paper, we present trigonometric parallax measurements of 22 GHz H2O masers toward two high-mass star-forming regions, W49N (G043.16+0.01) and G048.60+0.02, in the inner portion of the Perseus arm.

2. OBSERVATIONS AND CALIBRATION PROCEDURES

Our observations of 22 GHz H2O masers toward G043.16+0.01 and G048.60+0.02, together with several compact extragalactic radio sources, were carried out under VLBA program BR145B with 12 epochs spanning about one year. For these sources, the parallax signature in Declination was considerably smaller than for Right Ascension, and we scheduled the observations so as to maximize the Right Ascension parallax offsets as well as to minimize correlations among the parallax and proper motion parameters. The observations near each Right Ascension parallax peak were grouped as listed in Table 1. At each epoch, the observations consisted of four ...
observed three International Celestial Reference Frame sources: 3C345 (J2253+1608), 3C454 (J1642+3948), and J1925+2106 (Ma et al. 1998), near the beginning, middle, and end of the phase-referencing observations in order to monitor delay and interferometer phase reference. This is necessary to extend the interferometric phase difference among the observing bands. The phase-referencing observations were performed with the DiFX8 software correlator (Deller et al. 2007) in Socorro, NM. The data reduction task SAD or JMFIT. For the masers, we also formed Stokes I and then imaged the emission in each spectral channel. Then, we fit elliptical Gaussian brightness distributions to the images of the reference maser spots and the background sources, structure in the reference spot cancels and as such does not affect parallax measurements. After we performed the calibration for the polarized bands separately, we combined the RCP and LCP bands to form Stokes I and imaged the continuum emission of the background sources from the frequency bands simultaneously using the AIPS task IMAGR. For the masers, we also formed Stokes I and then imaged the emission in each spectral channel. Then, we fitted elliptical Gaussian brightness distributions to the images of strong maser spots and the background sources using the AIPS task SAD or JMFIT.

3. ASTROMETRIC PROCEDURES

Data used for parallax and proper motion fits were residual position differences between maser spots and background sources in eastward (Δx = Δα cos δ) and northward (Δy = Δδ) directions. These residual position differences are relative to the coordinates used to correlate the VLBA data and shifts applied in calibration. The data were modeled by the parallax sinusoid in both coordinates (determined by a single parameter, the parallax) and a linear proper motion in each coordinate. Because systematic errors (owing to small uncompensated atmospheric

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8 DiFX, a software Correlator for VLBI using Multiprocessor Computing Environments, is developed as part of the Australian Major National Research Facilities Programme by the Swinburne University of Technology and operated under licence.
residuals with reduced $\chi$ floors for the ture to the formal position uncertainties. We used different error
floors for the $\Delta x$ and $\Delta y$ data and adjusted them to yield post-fit residuals with reduced $\chi^2$ near unity for both coordinates.

As discussed in Zhang et al. (2012), the apparent motions of the maser spots can be complicated by a combination of spectral and spatial blending and changes in intensity. Thus, for parallax fitting, one needs to find stable, unblended spots and preferably use many maser spots to average out these effects. We selected maser spots brighter than 50 and 1 Jy beam$^{-1}$, which are $\approx$1/200 of the peak brightness, for G043.16+0.01 and G048.60+0.02, respectively. We considered maser spots at different epochs as being from the same feature if their separation from the middle-epoch position was less than 5 mas (a $< 5$ mas shift over 0.5 yr corresponds to a maser spot motion of $<260$ km s$^{-1}$ at a distance of 11 kpc).

H$_2$O masers can be time-variable with lifetimes of months to years. For solid parallax fits, we selected only maser spots persisting over all epochs to avoid large correlations between parallax and proper motion. We first fitted a parallax and proper motion to each H$_2$O maser spot relative to each background source separately. Since one expects the same parallax for all maser spots, we did a combined solution (fitting with a single parallax parameter for all maser spots, but allowing for different proper motions for each maser spot) using all maser spots and background sources.

In general, H$_2$O maser spots usually are not distributed uniformly around the exciting star and their kinematics can be complicated by a combination of expansion and rotation (Gwinn et al. 1992); this limits the accuracy of estimates of the absolute proper motion of the exciting star(s). Therefore, we modeled the relative motions of maser spots distributed across the source in order to solve for the motion of the phase-reference spot relative to the central star. Owing to the large field of view of the maser spots, especially in G043.16+0.01, for measuring relative motions we used only the inner-five antennas of the VLBA (to allow a wide field of view and to limit the number of pixels needed to map the sources).

In order to model the expansion and rotation of the entire maser source, we adopted a Bayesian fitting procedure using a Markov chain Monte Carlo method to explore parameter space, assuming the probability distribution for the data uncertainties follows the “Conservative Formulation” of Sivia & Skilling (2006), which does not have a large penalty for out-lying data points (i.e., maser spots whose motions do not follow the simple expanding model). The details on the maser kinematics model and the Bayesian fitting procedure are described in Gwinn et al. (1992) and Sato et al. (2010), respectively. We first used a simple radial expanding outflow model (model A) and then an expanding outflow with rotation (model B). The global parameters we estimated include the position ($x_0$, $y_0$) and motion ($V_0$, $V_0$) of the expansion center (relative to the reference maser spot); the $V_{LSR}$ of the expansion center $V_0$; an expansion speed $V_{exp}$ at 1” radius from the expansion center and the exponent $\gamma$ that allows for acceleration as a power law for velocity as a function of distance from the expansion center; and the rotation speed at 1” radius from the spin axis with two orientation angles of $\theta$ and $\phi$, the azimuth and elevation of the spin axis in the reference frame of the model, respectively. In addition to the global parameters, for each maser spot we estimated its offset along the line of sight from the reference maser spot.

4. RESULTS

4.1. W49N

W49N (G043.16+0.01) is a complex region of recent star formation containing the most luminous H$_2$O maser site in the Galaxy (Cheung et al. 1969; Burke et al. 1970). For the parallax measurement of W49N we phase-referenced to the maser spot at $V_{LSR}$ of $-4.75$ km s$^{-1}$. Both background sources were detected at all epochs, except for J1922+0841 at the second epoch. Figure 1 shows images of the reference maser spot and the two background sources at the last epoch (BR145BC). We found 11 maser spots detected at all 12 epochs that could be used for precision astrometry. These maser spots cluster in six locations identified with letters A through F in Figure 2. Table 3 shows the independent and combined parallax fits for those maser spots. Figure 3 shows the independent parallax fit of the maser spot at $V_{LSR}$ of $-44.77$ km s$^{-1}$ with each background source as an example. The combined parallax estimate is $0.909 \pm 0.006$ mas, corresponding to a distance of $11.11^{+0.79}_{-0.69}$ kpc. The quoted parallax uncertainty is the formal fitting error multiplied by $\sqrt{11}$, assuming conservatively 100% correlated position uncertainties among the spots.
Our distance to W49N is consistent with that of 11.4 ± 1.2 kpc obtained by Gwinn et al. (1992) by modeling the expansion (basically comparing maser Doppler velocities and proper motions). Combining the data for the two background sources, we measured the absolute proper motion of the reference maser spot to be $\mu_x = -4.49 \pm 0.13 \text{ mas yr}^{-1}$ and $\mu_y = -6.42 \pm 0.12 \text{ mas yr}^{-1}$, where $\mu_x = \mu_{\alpha}\cos\delta$ and $\mu_y = \mu_\delta$.

In order to model the internal motions of the masers to obtain the motion of the exciting star(s), we used 345 maser spots that appeared at four or more epochs within one year, and estimated their motions with respect to the reference maser spot.
Figure 3. Parallax and proper motion data (markers) and best-fitting model (dotted line) for the maser spot at the V_{LSR} of −44.77 km s^{-1} in W49N. Plotted are positions of the maser spots relative to the extragalactic radio sources J1905+0952 (circles), J1922+0841 (squares). Left panel: eastward (upper panel) and northward (lower panel) offsets vs. time. Right panel: same as the left panel, except the best-fitting proper motion has been removed, displaying only the parallax signature. (A color version of this figure is available in the online journal.)

Figure 4. Averaged positions (circles) and relative motions (arrows) with mean value removed of maser spots respective to reference maser spot located at (0, 0) mas in W49N. The color bar denotes the V_{LSR} range from −98 to 68 km s^{-1} of the maser features. The length and the direction of an arrow indicate the speed (given by the scale arrow in the upper right of the panel), the size of the arrow head is proportional to the uncertainty of the motion. (A color version of this figure is available in the online journal.)

Figure 4 shows the motions with their mean value removed, which indicates an expansion originating from a small region that might include one (or more) young stellar object(s), as suggested by Gwinn et al. (1992). We fitted the data to models of expansion, with and without rotation. The estimated parameters from a Bayesian fitting procedure described by Sato et al. (2010) are listed in Table 4.

The motions of the expansion center relative to the reference maser spot from the two models are in good agreement within their joint uncertainties. We adopt the results from the simpler model A as the best estimate of the systematic motion. Converting the (V_0_x, V_0_y) to angular motions yields μ_x = 2.01 ± 0.08 and μ_y = 1.16 ± 0.06 mas yr^{-1} at the parallax distance of 11.1 kpc to W49N. Adding this motion to the absolute motion of the reference maser spot, we estimate an absolute proper motion of the exciting star(s) of W49N to be μ_x = −2.48 ± 0.15 mas yr^{-1} and μ_y = −5.27 ± 0.13 mas yr^{-1}. We note that the differences in the proper motions of a maser spot provided by different background sources are larger than their formal errors for the individual fits. These differences could result from small structural variations such as jet motions in the background source or from unmodeled atmospheric delays.

4.2. G048.60+0.02

For the parallax measurement of G048.60+0.02, all the background sources were detected at all epochs after phase-referencing to the maser spot at V_{LSR} of +25.58 km s^{-1}.
Figure 5. Images of the H$_2$O maser reference spot at V$_{LSR}$ of +25.58 km s$^{-1}$ and the extragalactic radio sources used for the parallax measurements of G048.60+0.02 at the first epoch (2010 March 13). The source names are in the upper left corner and the restoring beam (dotted ellipse) is in the lower left corner of each panel. The contour levels for G048.60+0.02 maser emission are 5 Jy beam$^{-1} \times 2^n$, $n = 0, \ldots, 5$, and for the background sources (J1913+1307, J1917+1405 and J1924+1540) are spaced linearly at 0.01, 0.01, and 0.05 Jy beam$^{-1}$, respectively.

Figure 5 shows images of the reference maser spot and the background sources at epoch 1. Figure 6 shows the spatial distribution of H$_2$O maser spots and regions with maser spots used for the parallax fit. We found nine maser spots that appeared at all epochs, which could be used for astrometric measurements. Table 5 shows the independent and combined solution for those maser spots. Figure 7 shows the parallax fit of the maser spot at V$_{LSR}$ of +24.31 km s$^{-1}$ with each background source as an example. The combined parallax estimate is 0.093 ± 0.005 mas, corresponding to a distance of 10.75$^{+0.61}_{-0.55}$ kpc. The quoted parallax uncertainty is the formal fitting error multiplied by $\sqrt{9}$, allowing for the possibility that position uncertainties of maser spots are entirely correlated. The absolute proper motion of the reference maser spot is estimated to be $\mu_x = -3.19 \pm 0.01$ mas yr$^{-1}$ and $\mu_y = -5.61 \pm 0.03$ mas yr$^{-1}$.

We found 55 maser spots that were detected in at least four epochs over one year and estimated their relative motions with respect to the reference maser spot. Figure 8 shows these motions with their mean value removed. Similar to the kinematic modeling of W49N, we fitted the data to expansion models with and without rotation. The estimated parameters are listed in Table 6. Owing to the large uncertainty of the parameters for rotation, we adopted the results from model A. The proper motion of the expansion center relative to the reference maser

Table 4

| Parameter | Unit | Model A | Model B |
|-----------|------|---------|---------|
| Velocity  | V$_0$ km s$^{-1}$ | 101.34 ± 4.02 | 106.27 ± 4.28 |
|           | V$_{CV}$ km s$^{-1}$ | 61.30 ± 2.58 | 57.92 ± 3.13 |
|           | V$_{0z}$ km s$^{-1}$ | 10.73 ± 1.40 | 10.55 ± 1.28 |
| Position  | $x_0$ arcsec | 0.37 ± 0.08 | 0.23 ± 0.08 |
|           | $y_0$ arcsec | 0.06 ± 0.08 | −0.11 ± 0.13 |
| Expansion | V$_{exp}$ km s$^{-1}$ | 16.77 ± 1.80 | 10.99 ± 1.33 |
| Rotation  | $\gamma$ | 0.60 ± 0.06 | 0.81 ± 0.06 |
|           | V$_{rot}$ km s$^{-1}$ | 0 | 5.28 ± 0.80 |
|           | $\theta$ radian | 0 | 0.48 ± 0.72 |
|           | $\phi$ radian | 0 | 1.68 ± 0.30 |

Notes. Model A includes only radial motions. Model B includes radial and rotation motions.

Figure 6. Left panel: spatial distribution of the H$_2$O maser spots (with brightness $\geq 1$ Jy beam$^{-1}$ for a restoring beam of $\sim 3 \times 1$ mas) toward G048.60+0.02 from VLBA observations at the first epoch (2010 March 13). Each maser spot is represented by a filled circle whose area is proportional to the logarithm of the flux density. Right panel: blow-ups of the maser spot distribution in the field indicated with a dotted box in the left panel. All the maser spots (with brightness $\geq 1$ Jy beam$^{-1}$ for a restoring beam of $\sim 0.8 \times 0.3$ mas) used for parallax fit are from this field. Each region including maser spot for parallax fit is labeled with a letter. The reference maser spot is in region A. The color bar denotes the V$_{LSR}$ range from +8 to +36 km s$^{-1}$.

(A color version of this figure is available in the online journal.)
Combined Absolute proper motions are defined as
\[ \mu_x = \mu_x \cos \nu \] and \[ \mu_y = \mu_y \nu \]
(\( \nu \) is the reduced \( \chi^2 \) of post-fit residuals, \( \sigma_x \) and \( \sigma_y \) are the error floor in \( x \) and \( y \), respectively.)
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Figure 8. Averaged positions (circles) and relative motions (arrows) with mean value removed of maser spots relative to reference maser spot located at (0, 0) mas in G048.60+0.02. The color bar denotes the $V_{\text{LSR}}$ range from 8 to 35 km s$^{-1}$ of the maser features. The length and the direction of an arrow indicate the speed (given by the scale arrow in the upper left of the panel), the size of the arrow head is proportional to the uncertainty of the motion. (A color version of this figure is available in the online journal.)

Table 6

| Parameter | Type      | Unit     | A          | B          |
|-----------|-----------|----------|------------|------------|
| Velocity  | $V_{0x}$  | km s$^{-1}$ | 15.51 ± 3.96 | 25.00 ± 4.44 |
| Velocity  | $V_{0y}$  | km s$^{-1}$ | 4.04 ± 1.83  | 6.62 ± 3.65  |
| Velocity  | $V_{0z}$  | km s$^{-1}$ | 20.65 ± 2.64 | 19.24 ± 2.73 |
| Position  | $x_0$     | arcsec   | 0.11 ± 0.09  | −0.06 ± 0.11 |
| Position  | $y_0$     | arcsec   | −0.05 ± 0.09 | 0.01 ± 0.09  |
| Expansion | $V_{\text{exp}}$ | km s$^{-1}$ | 7.78 ± 2.91  | 9.25 ± 3.30  |
| Rotation  | $\gamma$  | radian   | −0.26 ± 0.35  | −0.23 ± 0.41 |
| Rotation  | $\theta$  | radian   | 7.44 ± 8.45  | 1.48 ± 1.76  |
| Rotation  | $\phi$    | radian   | −1.46 ± 1.59 |            |

Notes. Model A includes only radial motions. Model B includes radial and rotation motions.

spot corresponds to $\mu_x = 0.30 \pm 0.08$ mas yr$^{-1}$ and $\mu_y = 0.11 \pm 0.08$ mas yr$^{-1}$ at a distance of 10.7 kpc. Adding this to the absolute motion of the reference maser spot, we obtained an absolute proper motion of the exciting star of G048.60+0.02 to be $\mu_x = -2.89 \pm 0.08$ mas yr$^{-1}$ and $\mu_y = -5.50 \pm 0.09$ mas yr$^{-1}$.

5. DISCUSSION

5.1. Inner Portion of the Perseus Arm Traced by H$_2$O Maser Sources

Spiral arms in the Galaxy can be identified as large-scale features in longitude–velocity ($\ell - v$) diagrams from CO surveys (e.g., Dame et al. 1986). We therefore assign our masers to arms by associating them with molecular clouds, without possible bias by using distance and a model of spiral structure. A secure arm assignment requires that the position and velocity of the maser and the molecular cloud be in agreement with the position-velocity ($\ell - v$) locus of the arm. Using the data from the $^{13}$CO Galactic Ring Survey by Jackson et al. (2006) and the APEX Telescope Large Area Survey of the GALaxy (ATLASGAL; Schuller et al. 2009), we determined that both G043.16+0.01 and G048.60+0.02 are nearly coincident on the sky with giant molecular clouds (see Figure 9). The clouds have small angular sizes ($\approx 3'$), relatively large composite line widths (FWHM 9.4 and 5.0 km s$^{-1}$, respectively), and low positive LSR velocities (11.1 and 17.7 km s$^{-1}$, respectively) which are consistent with the $\ell - v$ locus identified by Vallée (2008) for the Perseus arm.

Combining the two sources in the inner portion of the Perseus arm reported here with 22 sources with parallax measurements in the outer portion of the Perseus arm from the BeSSeL Survey, the Japanese VLBI Exploration of Radio Astrometry (VERA) project and the European VLBI Network (Y. K. Choi et al. 2013, in preparation), there are now 24 sources defining the locus of the Perseus arm. Figure 10 plots log($R$) versus $\beta$ for these sources, where $R$ and $\beta$ are Galactocentric radius and azimuth ($\beta$ is defined as $0^\circ$ toward the Sun and increasing with Galactic longitude). As shown in Figure 11, these sources are consistent with following a spiral from $\beta \approx -25^\circ$ to $90^\circ$ (corresponding to Galactic longitude $\ell \approx 240^\circ$ to $43^\circ$) and extending nearly 15 kpc in length.

Using a Bayesian fitting approach that takes into account uncertainties in distance, that maps into both $R$ and $\beta$ (M. J. Reid 2009 APEX, the Atacama Pathfinder EXperiments, is a collaboration between the Max Planck Institut für Radioastronomie, the Onsala Space Observatory, and the European Southern Observatory.}

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Figure 9. Velocity-integrated $^{13}$CO intensity for the molecular clouds apparently associated G043.16+0.01 (left panel) and G048.60+0.02 (right panel). The velocity integration ranges are indicated in the upper right of each figure. The data are from the Galactic Ring Survey (Jackson et al. 2006). The over plotted contours are for the 870 $\mu$m continuum emission from the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL; Schuller et al. 2009). The contour levels start at 2 Jy beam$^{-1}$ and increase by factors of two for G043.16+0.01; they are linearly spaced at 1 Jy beam$^{-1}$ for G048.60+0.02.

(A color version of this figure is available in the online journal.)

Figure 10. Pitch angle of Perseus arm. The logarithm of Galactocentric radius, $R$ (in kpc units) is plotted against Galactocentric longitude ($\beta$). The dashed line is a weighted fit to all the points and corresponds to a pitch angle of 9.5$^\circ$.

(A color version of this figure is available in the online journal.)

et al. 2013, in preparation), and is insensitive to outliers (Sivia & Skilling 2006, see “conservative formulation”), we estimate a global pitch angle of 9.5$\pm$1.3 for the Perseus arm, which is in good agreement with that of 9.9$\pm$2.1 determined from the 22 sources confined to the outer portion of the Perseus arm. As we can see from Figure 10, G043.16+0.01 and G048.60+0.02 at $\beta \geq 80^\circ$ are crucial constraints for fitting a global pitch angle, since most of the sources are located at $\beta \leq 25^\circ$. The preliminary pitch angle based on four sources in the Perseus arm in Reid et al. (2009b) of 16.5$\pm$3.1 employed a simpler least-squares fitting approach in which only the residual in Galactocentric radius was minimized (when fitting a straight line to log($R$) versus $\beta$). Refitting the data from the four sources available in Reid et al. (2009b) with the new Bayesian approach, which accounts for error in both log($R$) and $\beta$, yields 15.1$\pm$6.1. Thus the preliminary fit and our new fit, based on 24 sources, agree within their joint uncertainty.

5.2. 3D Motion in the Inner Portion of the Perseus Arm

Combining the parallax and proper motion measurements with the systemic $V_{LSR}$ (as listed in Table 7) enable us to
determine the three-dimensional (3D) peculiar motions (relative to circular motion around the Galactic center) of G043.16+0.01 and G048.60+0.02. The \( V_{\text{LSR}} \) of G043.16+0.01 estimated from maser kinematics modeling (see Table 4) is about 11 km s\(^{-1}\), which is consistent with that of 11 km s\(^{-1}\) estimated for the molecular cloud. Similarly, for G048.60+0.02 we estimate a \( V_{\text{LSR}} \) of 20 km s\(^{-1}\) from kinematic modeling of masers (see Table 6), which is also close to the cloud velocity of 18 km s\(^{-1}\). To allow for a difference of \( V_{\text{LSR}} \) between H\(_2\)O and CO, we assign a \( V_{\text{LSR}} \) uncertainty of 5 km s\(^{-1}\). Similarly, there might be additional uncertainty referring those maser motions to that of the central star as reported in Section 4. To account for this, we added a proper motion error floor corresponding to 5 km s\(^{-1}\) to the measurement uncertainty in quadrature. The final adopted astrometric parameters and their uncertainties are listed in Table 7.

Assuming a flat rotation curve for the Milky Way with a rotation speed of LSR \( \Theta_0 = 239 \) km s\(^{-1}\), the distance to the Galactic center of \( R_0 = 8.3 \) kpc (Brunthaler et al. 2011), and the solar motion of \( (U_\odot = 11.1, V_\odot = 12.24, W_\odot = 7.25) \) km s\(^{-1}\) from revised Hipparcos measurements by Schönrich et al. (2010), we estimated peculiar motions for the sources using the procedure described in Reid et al. (2009b). In order to obtain realistic uncertainties for peculiar motions, we include the effects of uncertainties in parallax, proper motion, and \( V_{\text{LSR}} \). We do this by generating 10,000 random trials consistent with our measured values and (Gaussianly distributed) uncertainties. The \((U_s, V_s, W_s)\) components of peculiar motion toward the Galactic center, in the direction of Galactic rotation, and toward the north Galactic pole, respectively, are given in Table 7. All components are consistent with zero motion, albeit with fairly large uncertainties owing to the great distances of the sources.

### 5.3. Distance to G048.60+0.02

Nagayama et al. (2011) also measured an H\(_2\)O maser parallax distance for G048.60+0.02 of 5.03 ± 0.19 kpc using the VERA array. This result is significantly different from our distance of 10.75\(^{+0.61}_{-0.55}\) kpc. The Nagayama distance would place G048.60+0.02 in the Sagittarius–Carina arm and near (projected separation \( \approx 1^\circ \)) the supernova (SN) remnant G049.49−0.37 and the active star-forming region W51, which has several parallax distance measurements near 5.3 kpc (Xu et al. 2009; Sato et al. 2010; Wu et al. 2013). Note that the \( V_{\text{LSR}} \) of 18 km s\(^{-1}\)
for G048.60+0.02 is offset by \( \approx 50 \) km s\(^{-1} \) from the W51 sources. This is inconsistent with the spiral arm assignment of G048.60+0.02 to the inner portion of the Perseus arm (described in Section 5.1 and based on \(^{13}\)CO position–velocity information). Nagayama et al. (2011) suggested that the large velocity offset might be the result of the multiple SN explosions in W51. However, this is inconsistent with N-body simulations by Baba et al. (2009), which suggest that the acceleration by the SN explosion does not cause motions of that magnitude for swept-up, star-forming gas.

Generally, there is excellent agreement between parallaxes measured by different VLBI arrays. What could explain this unusual difference? Our VLBA parallax measurement is superior to those of Nagayama et al. (2011) in several ways. First, our observations have longer interferometric baselines. Second, our observations have more and closer background sources, nearly symmetrically distributed relative to the target, as shown in Figure 12. This could be very important to reduce the systematic error due to unmodeled tropospheric delays. Note that the background sources used by Nagayama are very close together and both are offset mostly north of G048.60+0.02. Therefore, unmodeled tropospheric delays will be similar for both of their background sources. Noting this source of correlation, as well as the nearly 100% correlation among different maser spot positions, owing to nearly identical unmodeled tropospheric delays, the (formal) parallax uncertainty quoted by Nagayama of \( \pm 0.007 \) mas may be underestimated by factors of \( \sqrt{5} \) and \( \sqrt{2} \) (for 9 maser spots and 2 background sources), and more realistically is \( \pm 0.030 \) mas. However, even with this uncertainty, the difference between our and Nagayama’s parallaxes (0.103 \( \pm 0.031 \)) is still somewhat significant. Third, our observing epochs symmetrically sample the peaks of the sinusoidal parallax signature in right ascension, yielding near-zero correlation coefficients between parallax and proper motion terms. For these reasons, we suspect that our measured distance of \( 10.75^{+0.61}_{-0.55} \) kpc to G048.60+0.02 is more reliable.

5.4. A Star Formation Gap in the Perseus Arm

As shown in Figure 10, we have yet to locate a high-mass star forming region with \( \beta \) between \( \approx 30^\circ \) and \( 80^\circ \) in the Perseus arm. Although we observed sources whose sky positions and velocities suggested kinematic distances in the Perseus arm, all were found to be much closer and located in the Local arm (Xu et al. 2013). In Figure 13, we plot the Galactic plane locations (based on kinematic distances) of \( \approx 200 \) 22-GHz H\(_2\)O masers stronger than 10 Jy and associated with star-forming regions.

As shown in Figure 14, CO emission indicates that the Perseus arm can be seen from \( \ell \approx 180^\circ \) to \( 48^\circ \), where it spirals to the Solar Circle and \( V_{\text{LSR}} \) values approach zero and merge with local emission. The longitude range \( 64^\circ \) to \( 76^\circ \) is weak in CO emission (as it is from \( 160^\circ \) to \( 168^\circ \)). This suggests that the Perseus arm, at least between \( \ell \approx 64^\circ \) and \( 76^\circ \), is low in
giant molecular clouds and massive star formation. Also plotted is the Galactic distribution of Massive Young Stellar Objects (MYSOs) from the Red MSX Sources (RMS) Survey (Urquhart et al. 2007). Since MYSOs are indicators of star formation, the small numbers of MYSOs at $50^\circ < \ell < 80^\circ$ also indicates low levels of star formation in this portion of the Perseus arm.

6. SUMMARY

We measured trigonometric parallaxes and proper motions of H$_2$O masers in two star-forming regions, G043.16+0.01 and G048.60+0.02. We establish that both sources are at great distances and that G043.16+0.01 is one of the most luminous star forming regions in the Milky Way. These two sources have positions and $V_{LSR}$ that match $^{13}$CO emission from giant molecular clouds that are located in the Perseus arm. Thus, our parallax distances accurately locate the inner portion of the Perseus arm within the Milky Way. Combining our results with other parallax measurements for maser sources associated with the outer portion of the Perseus arm, we determined a global pitch angle of $9.3 \pm 1.3$ for the Perseus arm. Finally, we suggest that there is little massive-star formation in the Perseus arm between $l \approx 50^\circ$ and $80^\circ$.

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Facility: VLBA

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