# Distance to G14.33-0.64 in the Sagittarius Spiral Arm: $\mathrm{H}_{2} \mathrm{O}$ Maser Trigonometric Parallax with VERA 

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#### Abstract

We report on trigonometric parallax measurements for the Galactic star-forming region G14.33-0.64 toward the Sagittarius spiral arm. We conducted multi-epoch phase-referencing observations of an $\mathrm{H}_{2} \mathrm{O}$ maser source in G14.33-0.64 with the Japanese VLBI array VERA. We successfully detected a parallax of $\pi=0.893 \pm 0.101 \mathrm{mas}$, corresponding to a source distance of $d=1.12 \pm 0.13 \mathrm{kpc}$, which is less than half of the kinematic distance for G14.33-0.64. Our new distance measurement demonstrates that the Sagittarius arm lies at a closer distance of $\sim 1 \mathrm{kpc}$, instead of the previously assumed $\sim 2-3 \mathrm{kpc}$ from the kinematic distances. The previously suggested deviation of the Sagittarius arm toward the Galactic center from the symmetrically fitted model (Taylor \& Cordes 1993, ApJ, 411, 674) is likely due to large errors of the kinematic distances at low galactic longitudes. G14.33-0.64 most likely traces the near side of the Sagittarius arm. We attempted to fit the pitch angle of the arm with other parallax measurements along the arm, which yielded two possible pitch angles of $i=34.7 \pm 2.7$ and $i=11.2 \pm 10.5$. Our proper-motion measurements suggest that G14.33-0.64 has no significant peculiar motion relative to the differential rotation of the Galaxy (assumed to be in a circular orbit), indicating that the source motion is in good agreement with the Galactic rotation.


Key words: Galaxy: kinematics and dynamics - Galaxy: structure - ISM: H if regions - ISM: individual (G14.33-0.64) - masers $\left(\mathrm{H}_{2} \mathrm{O}\right)$

## 1. Introduction

The Milky Way is known to be a spiral galaxy, and its structure has been intensively studied for many decades (e.g., Oort et al. 1958; Dame et al. 1987, 2001). However, there is still little agreement on the detailed spiral pattern, including the number of spiral arms (e.g., Cohen et al. 1980; Drimmel 2000; Russeil 2003; Benjamin et al. 2005; Dame \& Thaddeus 2008; Hou et al. 2009). Spiral arms are regions of active star formation, and traced primarily by $\mathrm{H}_{\text {II }}$ regions, where young stellar populations (hot OB stars) ionize surrounding gas. The major difficulty in revealing the precise spiral structure of the Galaxy arises from a lack of accurate distances to the $\mathrm{H}_{\text {II }}$ regions.

Optical distance measurements, such as can be obtained from photometric studies, are limited in the Galactic disk by a large opacity due to dust. Instead, the most widely used method to map the Galaxy is to adopt kinematic distances, which are derived by matching the observed radial velocities (obtained from the Doppler shift in observed frequencies) with respect to the local standard of rest (LSR) with line-of-sight velocities expected from a Galactic rotation model (e.g., Schmidt 1965; Brand \& Blitz 1993). The famous work done by Georgelin and Georgelin (1976) adopts this method (with the help of optical observations where available) to map H II regions in the Galaxy. However, significant unmodelled deviations from circular motions can cause large distance errors (Burton \&

Bania 1974). Accurate and direct distance measurements without any assumption on the Galactic rotation are thus of the greatest importance to delineate the true Galactic structure.

It has become feasible to map the Galactic structure with VLBI (Very Long Baseline Interferometry) techniques, notably with the phase-referencing VLBI technique, by directly measuring trigonometric parallaxes of strong maser sources in star-forming regions associated with $\mathrm{H}_{\text {II }}$ regions throughout the Galaxy. In addition to precise distances and absolute sky positions that locate the source in 3 dimensions in the Galaxy, measurements of the absolute proper motions yield the full 3-dimensional space motions (i.e., secular proper motions and source distances together give tangential velocities), which enables one to obtain full source information for the Galactic structure and dynamics. Reid et al. (2009b) recently refined our knowledge of the Galactic spiral structure and kinematics by integrating early results from VLBI astrometry of the Galaxy for a total of 18 high-mass starforming regions (HMSFRs) with methanol, $\mathrm{H}_{2} \mathrm{O}, \mathrm{SiO}$ maser, and continuum emission, carried out with the NRAO Very Long Baseline Array (VLBA) and with the Japanese VERA project. VERA (VLBI Exploration of Radio Astrometry) is the first VLBI array dedicated to phase-referencing VLBI for Galactic astrometry, consisting of 4 antennas ( 20 m each in diameter) across Japan (e.g., Honma et al. 2000). The recent VERA results for Galactic astrometry through maser parallax

Table 1. VERA observations of G14.33-0.64.

| Epoch <br> $(1)$ | Date <br> $(2)$ | Day of year <br> $(3)$ | Time range (UT) <br> $(4)$ | Beam (mas) <br> $(5)$ | Beam <br> EL $>35^{\circ}$ <br> $(6)$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 2006 Oct 27 | $2006 / 300$ | $03: 00-12: 00$ | $1.87 \times 0.89 @-25^{\circ} .5$ | $2.70 \times 0.75 @-7.3$ |
| 2 | 2006 Nov 26 | $2006 / 330$ | $01: 00-08: 45$ | $1.81 \times 0.83 @-26.7$ | $2.78 \times 0.73 @-5.9$ |
| 3 | 2007 Jan 7 | $2007 / 007$ | $22: 00-05: 45$ | $1.87 \times 0.86 @-26.1$ | - |
| 4 | 2007 Feb 14 | $2007 / 045$ | $20: 00-03: 43$ | $1.92 \times 0.86 @-24.2$ | $2.48 \times 0.81 @-4.5$ |
| 5 | 2007 Mar 27 | $2007 / 086$ | $17: 00-00: 43$ | $2.10 \times 0.82 @-28^{\circ} .3$ | $2.67 \times 0.76 @-5.8$ |
| 6 | 2007 May 6 | $2007 / 126$ | $14: 00-21: 43$ | $2.24 \times 0.82 @-26.0$ | $2.49 \times 0.82 @-8.1$ |
| 7 | 2007 Aug 8 | $2007 / 220$ | $08: 00-15: 50$ | $(1.82 \times 0.92 @-22.0)$ | $2.64 \times 0.77 @-1.6$ |
| 8 | 2007 Oct 10 | $2007 / 283$ | $04: 00-11: 55$ | $(1.72 \times 0.92 @-24.6)$ | $2.72 \times 0.75 @-3.5$ |
| 9 | 2008 Jan 16 | $2008 / 016$ | $21: 00-04: 55$ | $\left(1.79 \times 0.92 @-27^{\circ} .5\right)$ | $2.49 \times 0.81 @-6.4$ |
| 10 | 2008 Apr 14 | $2008 / 105$ | $15: 00-22: 55$ | $\left(2.00 \times 0.85 @-30^{\circ} 9\right)$ | $2.69 \times 0.75 @-8.6$ |
| 11 | 2008 Jul 21 | $2008 / 203$ | $08: 30-16: 15$ | $(1.89 \times 0.84 @-24.5)$ | $3.03 \times 0.70 @-8.1$ |

* (1) Epoch number. (2) The date of observation start time in universal time (UT). (3) Day of year of observation. (4) Start time and end time in UT. (5) Beam size (major and minor axes) and its position angle (PA) east of north in single-beam images (with no data flagged). Parentheses indicate epochs not used in relative proper-motion measurements since the reference spot 4 b and feature 4 were not detected. (6) Beam size and its PA east of north in dual-beam phase-referenced images, where data with antenna elevations below $35^{\circ}$ were flagged.
measurements are reported by Honma et al. (2007), Hirota et al. (2007, 2008a, 2008b), Imai et al. (2007), Sato et al. (2008), Kim et al. (2008), Choi et al. (2008), Nakagawa et al. (2008), and Oh et al. (2010).

The object of this study, G14.33-0.64 (IRAS 18159-1648), is a Galactic star-forming region and is VERA's first target source toward the Sagittarius spiral arm in the inner Galaxy, which is an important step toward our goal of mapping the structure of the Galaxy.

In particular, located at a low galactic longitude of $l=14.33$ (with a latitude of $b=-0.64$ within the Galactic plane), G14.33-0.64 is expected to trace the closest part of the Sagittarius arm to the Sun, and thus is an important target to determine the direct distance to the arm.

G14.33-0.64 was initially discovered as a far-infrared (FIR) source in a $70-\mu \mathrm{m}$ survey of the Galactic plane by Jaffe, Stier, and Fazio (1982). It was soon followed by the first detection of $\mathrm{H}_{2} \mathrm{O}$ maser emission at 22 GHz , associated with the FIR source by Jaffe, Güsten, and Downes (1981). Later, $\mathrm{H}_{2} \mathrm{O}$ maser emission was identified with an IRAS point source by Scalise, Rodriguez, and Mendoza-Torres (1989). Both class I and II methanol $\left(\mathrm{CH}_{3} \mathrm{OH}\right)$ maser sources were also found in the region: class II emission at 6.7 GHz (Walsh et al. 1995, 1997) and class I emission at 36 GHz , at 44 GHz (Slysh et al. 1994, 1999), at 84 GHz (Kalenskiĭ et al. 2001), and at 95 GHz (Val'tts et al. 2000). G14.33-0.64 has been observed to display an OH thermal absorption line at 1665 MHz (Wouterloot et al. 1993), $\mathrm{NH}_{3}(1,1)$ and $(2,2)$ inversion transition lines at 23.7 GHz (Molinari et al. 1996), CS $(J=2 \rightarrow 1)$ and CS $(J=5 \rightarrow 4)$ rotational transition lines at 98.0 GHz (Bronfman et al. 1996) and at 244.9 GHz (Shirley et al. 2003), respectively, and $1.2-\mathrm{mm}$ continuum emission (Faúndez et al. 2004). The radial velocities observed for many molecular lines of G14.33-0.64 are in good agreement at $V_{\mathrm{LSR}} \simeq 22 \mathrm{~km} \mathrm{~s}^{-1}$.

In the present paper, we report on our successful determination of the parallax of G14.33-0.64 with VERA as a step toward revealing the structure of the Sagittarius spiral arm in the inner Galaxy.

## 2. VERA Observations

VERA observations of the $22-\mathrm{GHz} \mathrm{H}_{2} \mathrm{O}$ maser source (the $6_{16} \rightarrow 5_{23}$ rotational transition) in G14.33-0.64 were carried out at 11 epochs between 2006 October and 2008 July, as listed in table 1. Using VERA's dual-beam mode for phase referencing (e.g., Honma et al. 2003, 2008a), we simultaneously observed the $\mathrm{H}_{2} \mathrm{O}$ maser source in G14.33-0.64 and the extragalactic position-reference quasar (phase calibrator) J1825-1718 with an angular separation of 1.7 at a position angle (PA) of $108^{\circ}$ east of north relative to G14.33-0.64. The flux density of the phase calibrator J1825-1718 was up to $\sim 140 \mathrm{mJy}$. A nominal $\mathrm{H}_{2} \mathrm{O}$ maser position for G14.33-0.64 was used as a reference center both for the observation and for correlation: $\alpha_{2000}=18^{\mathrm{h}} 18^{\mathrm{m}} 53.8$ and $\delta_{2000}=-16^{\circ} 47^{\prime} 50 .^{\prime \prime} 0($ Comoretto et al. 1990). The position of J1825-1718 was adopted from the second VLBA Calibrator Survey by Fomalont et al. (2003): $\alpha_{2000}=18^{\mathrm{h}} 25^{\mathrm{m}} 36.532283$ and $\delta_{2000}=-17^{\circ} 18^{\prime} 49 . \prime 84781$. The ICRF source NRAO 530 (J1733-1304: Ma et al. 1998) was also observed as a bright calibrator source (fringe finder) for 7-min scans hourly in each beam.

The instrumental phase difference between the two beams was calibrated by recording real-time phase data with an artificial noise source in each beam (Kawaguchi et al. 2000; Honma et al. 2008a). Left-hand circularly polarized signals were digitized at 2-bit sampling, and recorded at a data rate of 1024 Mbps . In the total bandwidth of $256 \mathrm{MHz}(16 \times 16 \mathrm{MHz})$, one of the sixteen $16-\mathrm{MHz}$ IF channels was assigned to the $\mathrm{H}_{2} \mathrm{O}$ maser lines in G14.33-0.64. The other 15 IF channels were for continuum emission in the phase calibrator J1825-1718, with the central IF channel set at the maser frequency, using the VERA digital filter unit (Iguchi et al. 2005).

Data correlation was performed with the Mitaka FX correlator (Chikada et al. 1991). In order to obtain sufficient resolution for the $\mathrm{H}_{2} \mathrm{O}$ maser lines, only the central 8 MHz (of the $16-\mathrm{MHz}$ IF channel) for the maser lines was split into

512 spectral points, yielding frequency and velocity resolutions of 15.625 kHz and $0.21 \mathrm{~km} \mathrm{~s}^{-1}$, respectively. Due to the spectral splitting method, one of the other 15 IF channels for J1825-1718 was also split into 512 spectral points (with the maser channel), which was not used for data reduction. The other 14 IF channels were split into 64 spectral points each, and used in data reduction.

The system noise temperatures at the zenith were typically $T_{\text {sys }}=150-300 \mathrm{~K}$ for the first 5 epochs. For the last 6 epochs, one or two antennas showed higher system noise temperatures of $T_{\text {sys }}=300-800 \mathrm{~K}$ due to bad weather, while the other antennas remained at $T_{\text {sys }}=150-300 \mathrm{~K}$.

## 3. Data Reduction

Visibility calibration and imaging were performed in a standard manner with the NRAO Astronomical Image Processing System (AIPS) package (Greisen 2003). The observed frequencies of the maser lines were converted to radial (line-of-sight) velocities with respect to the LSR, $V_{\mathrm{LSR}}$, using a rest frequency of 22.235080 GHz (Pickett et al. 1998) for the $\mathrm{H}_{2} \mathrm{O}$ $6_{16} \rightarrow 5_{23}$ transition.

We first searched for the relative positions of all $\mathrm{H}_{2} \mathrm{O}$ maser spots in the single-beam data (i.e., without phase-referencing to the calibrator J1825-1718 in the other beam) of the third epoch, and found maser emission over several spectral components (see figure 1). At this epoch, the brightest $\mathrm{H}_{2} \mathrm{O}$ maser channel was at $V_{\mathrm{LSR}}=26.6 \mathrm{~km} \mathrm{~s}^{-1}$ (feature 7 in table 3), and the visibilities of all maser channels were firstly phasereferenced to this channel by fringe fitting (AIPS task FRING) using the channel and by applying the phase solutions to all of the maser channels. In order to find the maser spot distribution, we imaged all channels with the AIPS task IMAGR with a wide field of view of $\sim 2^{\prime \prime} \times 2^{\prime \prime}$ around the reference maser spot (feature 7), with 2048 pixels $\times 2048$ pixels of size 1 mas. Many of the maser spots were outside this field ( $\sim 5^{\prime \prime}$ offset from feature 7 as seen in table 3), and were found by fringe rate mapping with the AIPS task FRMAP and by shifting the image center accordingly.

### 3.1. Phase Referencing for Parallax Measurements

Next, we obtained absolute-position maps of bright maser spots by phase-referencing visibilities of G14.33-0.64 to those of J1825-1718. For each epoch, phase solutions from fringe fitting with J1825-1718 were applied to the $\mathrm{H}_{2} \mathrm{O}$ maser channels of G14.33-0.64 for the corresponding frequencies. The instrumental phase difference between the two beams was also corrected using the real-time phase-calibration data recorded during each observation. Visibility phase errors caused by the Earth's atmosphere were calibrated based on GPS measurements of the atmospheric zenith delay which occurs due to tropospheric water vapor (Honma et al. 2008b).

Since a nominal reference center of G14.33-0.64 was used for a correlation, we first imaged the phase-referenced maser data to find the positional offset of each maser "feature" (i.e., a group of maser spots in the same position over adjacent velocity channels) from the reference center, and then recalculated and corrected the delays for the obtained absolute positions of the maser features until the features came at the map


Fig. 1. Spectral evolution of $\mathrm{H}_{2} \mathrm{O}$ maser emission in G14.33-0.64. Numbers show the observed year and day of year. Scalar-averaged cross-power spectra are shown between the VERA Mizusawa and Iriki stations. The radial velocities for many molecular lines of G14.33-0.64 are at $V_{\mathrm{LSR}} \simeq 22 \mathrm{~km} \mathrm{~s}^{-1}$.
center within 10 mas. After correcting the absolute position of the reference center for each maser feature, we used the same map center at all epochs for the same maser feature. We imaged the detected maser spots with the AIPS task IMAGR for a field of view of 25.6 mas $\times 25.6$ mas around each map center, with 512 pixels $\times 512$ pixels of size 0.05 mas. The maser positions were fitted with elliptical Gaussian distributions with the task JMFIT. The RMS noise levels in each image per channel were typically 200-600 mJy/beam.

We performed a least-squares fitting to simultaneously solve for the sinusoidal parallax curve and linear proper motion in
right ascension (RA) for maser spots at consecutive velocity channels for two features that were persistent over more than a year. We did not solve for the parallax in declination because positional errors due to tropospheric zenith delay residuals were larger in declination as in other measurements (e.g., Sato et al. 2007, 2008) and also because the angular resolution was lower in declination than in RA for G14.33-0.64 (see table 1 for beam size), and the parallax ellipse was smaller in declination. Instead, we removed the parallax obtained from RA fits to fit the linear proper motion in declination.

Since image distortion and positional errors due to tropospheric zenith delay residuals are severe for sources at low elevation angles associated with low source declinations, including G14.33-0.64 (e.g., Honma et al. 2008b), we attempted 4 different elevation cutoff values of $25^{\circ}, 30^{\circ}, 35^{\circ}$, $39^{\circ}$, below which we flagged the data with the AIPS task UVFLG. For cutoffs above $39^{\circ}$, imaging became difficult with high sidelobes due to insufficient data. We adopted an elevation cutoff of $35^{\circ}$ to obtain the best fitting result. For example, a typical error in the position measurement with one maser spot was reduced from 0.18 mas to 0.14 mas by changing the elevation cutoff from $30^{\circ}$ to $35^{\circ}$. Flagging low-elevation data changed the beam size of antennas to be elongated in declination; however, the beam size in RA was kept almost unchanged or slightly better (smaller) (see table 1).

### 3.2. Single-Beam Analysis for Relative Proper Motions

We also measured the relative proper motions from the single-beam data to study the internal motions of $\mathrm{H}_{2} \mathrm{O}$ maser spots. Since the $\mathrm{H}_{2} \mathrm{O}$ maser emission in G14.33-0.64 was variable over the observing period (figure 1), the phasereference maser channel used for fringe fitting differed epoch to epoch; we used the brightest velocity channel at each epoch as the phase reference, excluding the channels around $V_{\mathrm{LSR}} \sim 26 \mathrm{~km} \mathrm{~s}^{-1}$ (feature 7 in table 3), because the maser spots in this velocity range were $5^{\prime \prime}$ away from the other spots. We imaged each maser spot with the AIPS task IMAGR for a field of view of 25.6 mas $\times 25.6$ mas ( 512 pixels $\times 512$ pixels of size 0.05 mas) by shifting the map center. The FWHM beam size of each epoch is given in table 1. RMS noise levels in each image per channel were typically $50-110 \mathrm{mJy} /$ beam.

Maser positions were fitted with elliptical Gaussian distributions with the task JMFIT, and were measured relative to the reference spot chosen at each epoch. In order to obtain relative proper motions of all spots, we calculated all maser positions relative to the maser spot at $V_{\mathrm{LSR}} \sim 21.6 \mathrm{~km} \mathrm{~s}^{-1}$ (spot 4 b in table 3) by subtracting the position of this spot from the maser positions at each epoch. Since feature 4 (including spot 4b) was only persistent over the first 6 epochs, the relative proper motions were measured over the first 6 epochs.

Our criteria for the detection of a maser feature are: (1) a signal-to-noise ratio higher than 7 is obtained in the map at more than two consecutive velocity channels, (2) the spots are identified at three or more epochs for detecting relative proper motions, and (3) their positions agree with those expected from the fitted proper motions within 1 mas. In table 3, we also list the strong feature at $V_{\mathrm{LSR}} \sim 26 \mathrm{~km} \mathrm{~s}^{-1}$, even though it has no measured proper motion.

## 4. Results

Figure 1 shows the spectral evolution of $\mathrm{H}_{2} \mathrm{O}$ maser emission in G14.33-0.64 over the observing period; scalaraveraged spectra are shown for the baseline between the VERA Mizusawa and Iriki stations.

### 4.1. Parallax Measurements

Table 2 summarizes the results from measurements of parallax $\pi$ in RA ( $X$ ) and the absolute proper motions $\mu_{X}$ and $\mu_{Y}$ in RA $(X)$ and declination $(Y)$. We used a total of seven maser spots of two maser features (features 1 and 4; feature IDs in table 2 correspond to those in table 3 ). The absolute maser positions used for the measurements were: $\alpha_{2000}=$ $18^{\mathrm{h}} 18^{\mathrm{m}} 54 . \mathrm{s}^{\mathrm{s}} 67444$ and $\delta_{2000}=-16^{\circ} 47^{\prime} 500^{\prime \prime} 2640$ for feature 1 ; $\alpha_{2000}=18^{\mathrm{h}} 18^{\mathrm{m}} 54 . \mathrm{s}^{\mathrm{s}} 65341$ and $\delta_{2000}=-16^{\circ} 47^{\prime} 500^{\prime \prime} 0650$ for feature 4.

Errors in the measurements are indicated in parentheses in table 2. For single-spot measurements, errors were estimated from the residuals by a least-squares fitting with uniform weights for all epochs. For combined fits, where different spots or features were simultaneously fitted with a single parallax and with different proper motions, we estimated the upper limit of the errors. We discuss error estimates further in detail in subsection 5.1.
The final value of the parallax (from the combined fit with all seven spots) is $\pi=0.893 \pm 0.101$ mas. This corresponds to a source distance of $d=1.12 \pm 0.13 \mathrm{kpc}$. The absolute proper motions, $\mu_{X}$ and $\mu_{Y}$, of the seven spots listed in table 2 were derived using this final value of $\pi$, instead of using different $\pi$ values from single-spot measurements.

Figures 2 and 3 show the position measurements of the seven spots used for parallax and absolute proper motion fittings. The numbers indicate the feature IDs corresponding to those in table 2 . Figures 2 a and 2 b show the eastward $(X)$ and northward $(Y)$ positional offsets versus time, respectively, for seven maser spots. Additional constant offsets are added to each maser spot in the figures for clarity. The best-fit models for the single parallax (solid curves) and different proper motions (gray lines) are plotted for the seven spots from the combined fit. Error bars are plotted for the standard deviation $(\sigma)$ of the post-fit residuals from the least-squares fitting. Figure 3 shows the trajectory on the sky.

### 4.2. Proper Motions

Table 3 lists the results from the relative position and propermotion measurements from the first 6 epochs. A total of 6 maser features are presented here with proper motions detected over 3 or more epochs.

Errors of the relative proper motions (shown in parentheses for $\mu_{x}$ and $\mu_{y}$ in table 3) for each spot were estimated from formal fitting uncertainties scaled by the RMS residuals of the spot positions. For each feature ( $\# 1$ through 6 ), the relative position and proper motion were calculated as error-weighted means of those for all detected spots of the feature, as notated by "w-mean" in table 3 .

Figure 4 shows the maser distribution and proper motion for G14.33-0.64. Figures 4 a and 4 b are radio maps of the region with contours showing the continuum emission at $6-\mathrm{cm}$

Table 2. Parallax fitting for G14.33-0.64 with elevation cutoff $35^{\circ}$.*

| Feature ID \# <br> (1) | $\begin{gathered} V_{\mathrm{LSR}} \\ \left(\mathrm{~km} \mathrm{~s}^{-1}\right) \\ (2) \end{gathered}$ | $N_{\text {epochs }}$ (3) | Detected epochs <br> (4) | RA parallax, $\pi$ (mas) <br> (5) | $\begin{gathered} \mu_{X} \\ \left(\operatorname{mas}_{y r^{-1}}\right) \\ (6) \end{gathered}$ | $\begin{gathered} \mu_{Y} \\ \left(\operatorname{mas}_{\left.\mathrm{yr}^{-1}\right)}\right) \\ (7) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1a | 14.6 | 6 | ---45678-10- | 0.931 (0.124) | 6.13 (0.27) | -4.50 (0.37) |
| 1 b | 14.8 | 8 | ---4567891011 | 0.936 (0.151) | 6.47 (0.19) | -4.15 (0.26) |
| 1 c | 15.0 | 8 | ---4567891011 | 0.950 (0.141) | 6.49 (0.19) | -4.12 (0.26) |
| 1 d | 15.2 | 6 | ---45-78910- | 1.004 (0.135) | 6.28 (0.26) | -4.23 (0.35) |
| 1 combined |  |  |  | 0.954 (0.130) |  |  |
| 4 a | 21.4 | 6 | 12-456---10- | 0.629 (0.171) | -1.60 (0.23) | -0.26 (0.30) |
| 4b | 21.6 | 6 | 12-456---10- | 0.631 (0.162) | -1.58 (0.23) | -0.42 (0.30) |
| 4 c | 21.8 | 6 | 12-45--8-10- | 0.900 (0.151) | -1.70 (0.21) | -0.12 (0.28) |
| 4 combined |  |  |  | 0.768 (0.160) |  |  |
| 1\&4 combined |  |  |  | 0.893 (0.101) |  |  |
| * (1) Feature/spot ID, corresponding to table 3. (2) LSR velocity of the maser spot. (3) Total number of detected epochs. (4) Detected epochs. (5) Measured parallax in right ascension in mas (with estimated errors in parentheses). (6) (7) Proper motions in right ascention and in declination, respectively. The results presented here were obtained by fitting with a single parallax of 0.893 mas (the final result from the combined RA parallax fit). |  |  |  |  |  |  |



Fig. 2. Parallax and absolute proper-motion measurements for G14.33-0.64. Filled and open circles show positional evolution of maser features 1 and 4 , respectively, with respect to the reference positions at origin. (a) East offset ( $X$ ) in mas from the reference positions of RA $(\mathrm{J} 2000)=18^{\mathrm{h}} 18^{\mathrm{m}} 54.674440$ for maser feature 1 and $\mathrm{RA}(\mathrm{J} 2000)=18^{\mathrm{h}} 18^{\mathrm{m}} 54 . \mathrm{s} 653410$ for feature 4 , as a function of time in days since the first epoch. Best-fitting models for parallax and proper motion are shown in solid curves and gray lines, respectively. Additional shifts are given for clarity: $\Delta X=+6,3.5,1,-1.5 \mathrm{mas}$ for $1 \mathrm{a}, 1 \mathrm{~b}$, $1 \mathrm{c}, 1 \mathrm{~d} ;-5,-7,-9$ mas for $4 \mathrm{a}, 4 \mathrm{~b}, 4 \mathrm{c}$, respectively. (b) North offset $(Y)$ in mas from the reference positions of $\operatorname{Dec}(\mathrm{J} 2000)=-16^{\circ} 47^{\prime} 50{ }^{\prime \prime} 26400$ for feature 1 and $\operatorname{Dec}(\mathrm{J} 2000)=-16^{\circ} 47^{\prime} 50^{\prime \prime} 06500$ for feature 4 , as a function of time in days since the first epoch. Additional shifts are given for clarity: $\Delta Y=+9,6.5,4,1.5$ mas for $1 \mathrm{a}, 1 \mathrm{~b}, 1 \mathrm{c}, 1 \mathrm{~d} ;-9,-11.5,-14$ mas for $4 \mathrm{a}, 4 \mathrm{~b}, 4 \mathrm{c}$, respectively.

Table 3. Relative proper motions.*

| $\begin{gathered} \text { Feature ID } \\ \# \\ (1) \end{gathered}$ | $\begin{gathered} V_{\mathrm{LSR}} \\ \left(\mathrm{~km} \mathrm{~s}^{-1}\right) \end{gathered}$ <br> (2) | $N_{\text {epochs }}$ <br> (3) | Epochs <br> (4) | $\begin{gathered} x_{1} \\ (\mathrm{mas}) \\ (5) \end{gathered}$ | $\begin{gathered} y_{1} \\ (\mathrm{mas}) \\ (6) \end{gathered}$ | $\begin{gathered} \mu_{x} \\ \left(\mathrm{mas}_{\mathrm{yr}} \mathrm{yr}^{-1}\right) \end{gathered}$ <br> (7) | $\begin{gathered} \mu_{y} \\ \left(\mathrm{mas} \mathrm{yr}^{-1}\right) \\ (8) \\ \hline \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 12.5 | 3 | --345- | 302.7 | -199.2 | 7.05 (0.16) | -3.69 (0.39) |
| 1 | 12.7 | 3 | --345- | 302.8 | -199.3 | 7.08 (0.19) | -3.59 (0.11) |
| 1 | 12.9 | 3 | --345- | 302.9 | -199.1 | 6.63 (0.10) | -3.70 (0.38) |
| 1 | 13.2 | 3 | --345- | 302.8 | -199.0 | 7.04 (0.23) | -4.15 (0.14) |
| 1 | 13.4 | 3 | --345- | 303.0 | -199.0 | 6.53 (0.02) | -3.86 (0.03) |
| 1 | 14.2 | 3 | ---456 | 303.2 | -198.1 | 6.31 (0.41) | -6.46 (1.93) |
| 1 | 14.4 | 3 | ---456 | 303.2 | -198.1 | 6.22 (0.29) | -6.65 (1.83) |
| 1 a | 14.6 | 4 | --3456 | 303.0 | -198.8 | 6.70 (0.53) | -5.11 (2.01) |
| 1 b | 14.8 | 4 | --3456 | 303.1 | -198.8 | 6.66 (0.23) | -4.22 (0.85) |
| 1 c | 15.0 | 3 | --345- | 302.9 | -199.3 | 7.33 (0.06) | -2.14 (0.13) |
| 1 w-mean |  |  |  | 303.0 | -199.0 | 6.64 (0.02) | -3.79 (0.03) |
| 2 | 17.6 | 4 | -23-56 | 187.3 | -134.1 | 2.23 (0.23) | -3.69 (0.19) |
| 2 | 17.8 | 5 | 123-56 | 187.3 | -134.2 | 2.12 (0.09) | -3.64 (0.10) |
| 2 | 18.0 | 4 | 123--6 | 187.4 | -134.2 | 2.05 (0.19) | -4.06 (0.26) |
| 2 | 18.2 | 3 | 123--- | 187.4 | -134.2 | 1.41 (0.46) | -3.43 (0.28) |
| 2 w-mean |  |  |  | 187.3 | -134.1 | 2.10 (0.08) | -3.67 (0.08) |
| 3 | 18.0 | 4 | --3456 | 183.7 | -129.4 | -0.14 (0.39) | -1.57 (0.45) |
| 3 | 18.2 | 4 | --3456 | 183.7 | -129.5 | -0.35 (0.23) | -0.75 (0.18) |
| 3 | 18.4 | 3 | --345- | 183.8 | -129.6 | -0.57 (0.47) | -0.42 (0.69) |
| 3 | 18.6 | 3 | --345- | 183.9 | -129.8 | -0.90 (0.28) | 0.18 (0.80) |
| 3 w-mean |  |  |  | 183.8 | -129.5 | -0.50 (0.15) | -0.80 (0.16) |
| 4 | 20.9 | 6 | 123456 | 0.1 | -0.1 | -0.07 (0.05) | -0.17 (0.16) |
| 4 | 21.2 | 6 | 123456 | 0.0 | -0.1 | -0.03 (0.02) | -0.14 (0.07) |
| 4 a | 21.4 | 6 | 123456 | 0.0 | 0.0 | 0.07 (0.03) | 0.02 (0.05) |
| 4b | 21.6 | 6 | 123456 | - | - | - | - |
| 4 c | 21.8 | 5 | 12345- | 0.0 | 0.0 | -0.01 (0.01) | 0.03 (0.07) |
| 4 | 22.0 | 5 | 12345- | -0.1 | 0.0 | 0.09 (0.07) | 0.04 (0.07) |
| 4 | 22.2 | 4 | 1234-- | -0.1 | 0.1 | 0.33 (0.19) | -0.27 (0.27) |
| 4 w-mean |  |  |  | 0.0 | 0.0 | -0.01 (0.01) | -0.02 (0.03) |
| 5 | 21.6 | 5 | 12345- | -0.3 | 3.1 | 0.50 (0.16) | 0.61 (0.25) |
| 5 | 21.8 | 5 | 12345- | -0.2 | 3.0 | 0.22 (0.03) | 0.75 (0.08) |
| 5 | 22.0 | 5 | 12345- | -0.3 | 3.1 | 0.32 (0.10) | 0.63 (0.08) |
| 5 | 22.2 | 5 | 12345- | -0.1 | 3.2 | -0.11 (0.19) | 0.61 (0.14) |
| 5 | 22.4 | 5 | 12345- | 0.0 | 3.4 | 0.11 (0.12) | -0.13 (0.64) |
| 5 w-mean |  |  |  | -0.2 | 3.1 | 0.23 (0.03) | 0.67 (0.05) |
| 6 | 22.6 | 3 | 123--- | 0.0 | -16.0 | 0.73 (0.14) | -1.33 (0.01) |
| 6 | 22.8 | 6 | 123456 | 0.1 | -16.0 | 0.10 (0.09) | -1.44 (0.08) |
| 6 | 23.1 | 6 | 123456 | 0.0 | -16.0 | 0.19 (0.02) | -1.26 (0.05) |
| 6 | 23.3 | 6 | 123456 | 0.0 | -15.9 | 0.25 (0.01) | -1.43 (0.12) |
| 6 | 23.5 | 6 | 123456 | 0.0 | -15.9 | 0.17 (0.05) | -1.24 (0.07) |
| 6 | 23.7 | 6 | 12345- | 0.0 | -15.8 | 0.30 (0.12) | -1.45 (0.10) |
| 6 w-mean |  |  |  | 0.0 | $-16.0$ | 0.23 (0.01) | -1.32 (0.01) |
| 7 | 25.4-27.7 |  |  | -4810 | 319 |  |  |
| 1,23,456 u-mean |  |  |  |  |  | 2.53 | -2.08 |

* (1) Feature/spot ID. "w-mean" notates error-weighted mean of all spots of each feature and "u-mean" refers to unweighted-mean of all features (see text). (2) LSR velocity of the maser spot. (3) Number of detected epochs. (4) Detected epochs. (5) (6) Positional offset in mas toward east $(X)$ and north $(Y)$, respectively, from the reference spot 4 b expected from the linear fit at the first epoch. (7) (8) Relative proper motion of the spot in $X$ and $Y$, respectively, with respect to spot 4b. Estimated errors are shown in parentheses.


Fig. 3. Trajectory of maser positions on the sky. Reference positions are the same as in figure 2 for each feature. Additional shifts are given for clarity: $\Delta Y=+9,5,1,-3$ mas for $1 \mathrm{a}, 1 \mathrm{~b}, 1 \mathrm{c}, 1 \mathrm{~d} ;-7,-9.5$, -12 mas for $4 \mathrm{a}, 4 \mathrm{~b}, 4 \mathrm{c}$, respectively.
wavelength (C-band) from VLA archive data (program AH361) observed in the "C" configuration at an angular resolution of $3^{\prime \prime}$ (Hughes \& MacLeod 1994). Our VLBI absolute positions of $\mathrm{H}_{2} \mathrm{O}$ maser features are also shown. Our absolute position accuracy is essentially limited by the position errors of the position-reference quasar $\mathrm{J} 1825-1718$, which are 1.23 mas in RA and 1.97 mas in declination (Fomalont et al. 2003).

Hughes and MacLeod (1994) originally associated the $\mathrm{H}_{2} \mathrm{O}$ maser emission in G14.33-0.64 with brighter radio continuum emission, offset 1.16 toward northeast from the IRAS position (at the origin) as seen in figure 4a. Our new VLBI map finds the $\mathrm{H}_{2} \mathrm{O}$ maser emission (feature 7 in particular) associated (within $5^{\prime \prime}$ ) with a different and closer radio continuum source and yields the first precise distribution of $\mathrm{H}_{2} \mathrm{O}$ maser spots in G14.33-0.64.

Figure 4 c shows the absolute proper motions of maser features 1 to 6 , which were obtained by adding the relative proper motions (in table 3) to the absolute proper motion of the reference spot 4 b (in table 2). These absolute proper motions were not corrected for apparent motions due to the solar motion and the Galactic rotation, in addition to the peculiar motion of the source. The map origin is the position of the reference spot 4 b at the first epoch: $\alpha_{2000}=18^{\mathrm{h}} 18^{\mathrm{m}} 54.653181$ and $\delta_{2000}=-16^{\circ} 47^{\prime} 500^{\prime \prime} 07668$.

Figure 4 d shows the internal motions of the maser features relative to the mean motion of the features. The mean motion
of all features 1 to 6 was obtained by averaging the obtained proper motions over the 3 distinct regions: (1) feature 1 ; (2) features 2 and 3 ; and (3) features 4,5 , and 6 . We took an unweighted mean of the relative motions of the maser features in each region, and then took an unweighted mean of the 3 regions, as listed in table 3 by "1,23,456 u-mean". We obtained the mean relative motion of $\left(\overline{\mu_{x}}, \overline{\mu_{y}}\right)=$ $(2.53,-2.08)$ mas $^{-1}{ }^{-1}$ (the bar symbols indicate mean values). By adding the absolute proper motion of the reference spot 4 b , $\left(\mu_{X}, \mu_{Y}\right)_{4 \mathrm{~b}}=(-1.58,-0.42){\text { mas } \mathrm{yr}^{-1} \text {, we obtained the abso- }}$ lute mean motion $\left(\overline{\mu_{X}}, \overline{\mu_{Y}}\right)=(0.95,-2.50) \mathrm{mas} \mathrm{yr}^{-1}$. Note a proper motion of $1.00 \mathrm{mas} \mathrm{yr}^{-1}$ corresponds to a linear velocity of $5.31 \mathrm{~km} \mathrm{~s}^{-1}$ at a source distance of 1.12 kpc . In subsection 5.5 , we will adopt this mean motion to discuss the systemic motion of G14.33-0.64, by taking errors into account to allow for the possibility that the mean maser motion does not trace the systemic motion.

## 5. Discussion

### 5.1. Astrometric Error Sources

In this section, we discuss possible error sources in our parallax and proper-motion measurements and how we estimated the errors.
The first possible error source in individual position measurements is thermal errors due to noise, which can be approximated by the halfwidth (HWHM) of the beam size divided by the signal-to-noise ratio of the maser map. We find that thermal errors can account for the errors of the relative position measurements in the single-beam data. The thermal errors are $\sim 0.01-0.1$ mas (i.e., beam size $\sim 1$ mas, signal $\sim 1-10 \mathrm{Jy} /$ beam, and noise $\sim 0.1 \mathrm{Jy} /$ beam ), which agree well with errors in the relative proper motions, as listed in table 3, which were estimated from standard deviations from the post-fit residual from the least-squares fits (see subsections 3.2 and 4.2).
However, for parallax and proper-motion measurements in the dual-beam data, errors in the measurements are larger than expected from thermal errors of $\sim 0.1$ mas (i.e., beam size $\sim 1 \mathrm{mas}$, signal $\gtrsim 3 \mathrm{Jy} /$ beam, and noise $\sim 0.3 \mathrm{Jy} /$ beam $)$. The standard deviations from the fits were $\sigma=0.26 \mathrm{mas}$, and thus are larger than the thermal noise errors.
Here, we do not consider the reference quasar as a predominant error source, since it did not show any resolved structure. Also, even though the accuracy of the maser absolute position is limited by the uncertainties of the reference quasar position, the positional error of the reference quasar only adds as a constant offset to the maser spot position at each epoch, and do not contribute to uncertainties in the parallax and proper-motion measurements.

One of the likely sources that would cause large errors in the parallax and proper-motion measurements is errors in modeling the tropospheric zenith delay (see Sato et al. 2008 and references therein). Indeed, the fact that a high elevation cutoff of $35^{\circ}$ yielded the best-fit result for the parallax fitting for G14.33-0.34 indicates that this low-declination source is subject to tropospheric delay errors. However, if errors in modeling the tropospheric zenith delay are the predominant error source, then all maser features at the same epoch should

$$
V_{\text {LSR }}\left(\mathrm{km} \mathrm{~s}^{-1}\right)
$$



Fig. 4. (a) (b) Radio maps of G14.33-0.64 showing $\mathrm{H}_{2} \mathrm{O}$ (dot) and methanol (triangle) maser positions superimposed on contours for 6-cm continuum emission obtained from VLA archive data (program AH361). The angular resolution is $3^{\prime \prime}$ for the VLA observation (Hughes \& MacLeod 1994) and the beam size is shown in gray at the left corner of each panel. Image noise level is $\sigma=0.07 \mathrm{mJy} / \mathrm{beam}$, and contours are linearly spaced and correspond to $4 \sigma, 6 \sigma, 8 \sigma, \cdots, 22 \sigma$. Peak intensity is $1.6 \mathrm{mJy} /$ beam. Map origin is at the IRAS source position of $\alpha_{2000}=18^{\mathrm{h}} 18^{\mathrm{m}} 53.9, \delta_{2000}=-16^{\circ} 47^{\prime} 39^{\prime \prime}$. Dots represent our VLBI absolute positions of $\mathrm{H}_{2} \mathrm{O}$ maser features in table 3. Numbers correspond to feature IDs in table 3. Our absolute position errors essentially come from errors of the reference quasar position J1825-1718, which are 1.23 mas in RA and 1.97 mas in Dec (Fomalont et al. 2003). Triangles show the positions of $44-\mathrm{GHz}$ methanol masers mapped with the VLA by Slysh et al. (1999) with position errors of 0!"2. Colors indicate the LSR velocity of the spots for both methanol and $\mathrm{H}_{2} \mathrm{O}$ maser emission. (c) Absolute proper motions of $\mathrm{H}_{2} \mathrm{O}$ maser features without correction of the solar motion and Galactic rotation. Map origin (reference spot 4b) is at $\alpha_{2000}=18^{\mathrm{h}} 18^{\mathrm{m}} 54 . \mathrm{s} 653181$ and $\delta_{2000}=-16^{\circ} 47^{\prime} 500^{\prime \prime} 07668$ (i.e., the position of spot 4 b at the first epoch). ( d$)$ Internal motions of all maser features with the mean motion of the features of $\left(\overline{\mu_{X}}, \overline{\mu_{Y}}\right)=(0.95,-2.50)$ mas $\mathrm{yr}^{-1}$ removed (without correction of the solar motion and Galactic rotation). Map origin is the same as in figure 4 c . A proper motion of 1.00 mas $\mathrm{yr}^{-1}$ corresponds to a linear velocity of $5.31 \mathrm{~km} \mathrm{~s}^{-1}$ at a source distance of 1.12 kpc
show systematic errors in the position measurements. As can be seen in figure 2, the deviations from the parallax fits clearly differ for the two different maser features at each eposh (features 1 and 4), which indicate that the errors are random for different features at the same epoch. Therefore, it is likely that the errors in modeling of tropospheric zenith delay are not the
predominant error source in the remaining data after having removed as many effects of the tropospheric delay errors as possible by adopting a high elevation cutoff.

Another likely error source in the parallax measurements is a variation in the maser structure. In figure 2, the tendency of deviations from the parallax fits is similar for maser spots
in the same feature, but different between different features (features 1 and 4). This is consistent with the fact that the variation of the maser structure causes positional errors that are uncorrelated for different features, but might be correlated between maser spots in adjacent velocity channels within the same feature. In our parallax measurements, a variation of the maser structure is likely to be the predominant error source.

We estimated the errors of the parallax measurements from the post-fit residuals from the least-squares fitting. For different spots within the same maser feature (e.g., spots $1 \mathrm{a}, 1 \mathrm{~b}, 1 \mathrm{c}$, and 1 d in feature \#1), we allowed for the possibility that errors due to variations in the maser structure data may be partially correlated. As a conservative approach, we assumed that the errors of all spots within the same maser feature at the same epoch are $100 \%$ correlated (but random for different features). This means that, even though we used 7 maser spots of $1 \mathrm{a}, 1 \mathrm{~b}, 1 \mathrm{c}$, $1 \mathrm{~d}, 4 \mathrm{a}, 4 \mathrm{~b}, 4 \mathrm{c}$ for the measurements, we assumed that only 2 different maser features contribute as 2 independent spots so as to reduce the errors of the measurements. We obtained an error of $\sigma_{\pi}=0.101$ mas. Instead, if we assumed errors due to variation in maser structure are random and uncorrelated for all of the 7 spots ( $1 \mathrm{a}-1 \mathrm{~d}$ and $4 \mathrm{a}-4 \mathrm{c}$ ), the errors would reduce to $\sigma_{\pi}^{\prime}=0.060$ mas. In reality, the errors of different spots in the same feature are not likely to be $100 \%$ correlated, but only partially correlated (if not uncorrelated). Therefore, the error estimate of $\sigma_{\pi}=0.101 \mathrm{mas}$ in our parallax measurements is the upper limit of the errors, adopted as a conservative approach.

### 5.2. Distance to the Sagittarius Spiral Arm

Our parallax measurement for G14.33-0.64 reveals the source distance to be $d=1.12 \pm 0.13 \mathrm{kpc}$, which is less than half of previously derived kinematic distances. The kinematic distances for G14.33-0.64 are, for example, 2.5 kpc by Molinari et al. (1996) from the $\mathrm{NH}_{3}(1,1)$ and $(2,2)$ lines; 2.6 kpc both by Walsh et al. (1997) and Val'tts et al. (2000) from $6.7-\mathrm{GHz}$ and $95-\mathrm{GHz}$ methanol maser lines, respectively; 3.1 kpc from the $\mathrm{H} 110 \alpha$ line and 2.6 kpc from $\mathrm{H}_{2} \mathrm{CO}$ absorption lines by Sewilo et al. (2004). All of the kinematic distances above were derived using a Galactic rotation model by Brand and Blitz (1993). Palagi et al. (1993) derived 2.7 kpc from $\mathrm{H}_{2} \mathrm{O}$ maser lines with a peak at $V_{\mathrm{LSR}}=22.8 \mathrm{~km} \mathrm{~s}^{-1}$ using the rotation curve of Brand (1986). The good agreement among previous kinematic distances is a result of using the same rotation model and similar radial velocities, $V_{\mathrm{LSR}} \simeq 22 \mathrm{~km} \mathrm{~s}^{-1}$, observed at different wavelengths. The most persistent $\mathrm{H}_{2} \mathrm{O}$ maser feature in our measurements, feature 4 , also showed a radial velocity of $V_{\mathrm{LSR}} \simeq 22 \mathrm{~km} \mathrm{~s}^{-1}$, which agrees well with the systemic radial velocity of G14.33-0.64, but several other spectral components differed up to $10 \mathrm{~km} \mathrm{~s}^{-1}$ in radial velocities.

Figure 5 shows the classic model of the Galaxy by Georgelin and Georgelin (1976). Gray lines show the modified model by Taylor and Cordes (1993). Note that a shift toward the Galactic center in the position of the Sagittarius arm was introduced by Taylor and Cordes (1993), to correspond better with the kinematic distances of Downes et al. (1980). Downes et al. (1980) estimated the kinematic distances to the Galactic H II regions from radio observations of $\mathrm{H} 110 \alpha$ and $\mathrm{H}_{2} \mathrm{CO}$ lines using the Schmidt (1965) model, with typical errors of $\pm 1$ to 2 kpc for
galactic longitudes $l=20^{\circ}$ to $60^{\circ}$, which can be more than $\sim 50 \%$ errors for the Sagittarius arm at lower galactic latitudes. Although G14.33-0.64 was not in the catalog by Downes et al. (1980), it was in the catalog by Sewilo et al. (2004) in H110 $\alpha$ and $\mathrm{H}_{2} \mathrm{CO}$ line observations. It can be clearly seen in figure 5 that the kinematic distance (shown as the yellow circle) places G14.33-0.64 as well as the interpolated Sagittarius arm further toward the Galactic center, like other sources in the arm.

However, our direct parallax measurements (red square in figure 5) reveal the location of G14.33-0.64 to be closer to the Sun and outward in the Galaxy, in good agreement with the Sagittarius arm originally modeled by Georgelin and Georgelin (1976), without the "bump" toward the Galactic center. In figure 5, three other star-forming regions, G35.20-0.74 (blue diamond), G35.20-1.74 (pink triangle), and W 51 IRS2 (green hexagon), possibly in the Sagittarius spiral arm, are also plotted with parallax distances of $2.19_{-0.20}^{+0.24} \mathrm{kpc}, 3.27_{-0.42}^{+0.56} \mathrm{kpc}$, (Zhang et al. 2009) and $5.1_{-1.4}^{+2.9} \mathrm{kpc}$ (Xu et al. 2009) from the VLBA for $12-\mathrm{GHz}$ methanol maser emission.

It is most likely that the "bump" in the Sagittarius spiral arm toward the Galactic center suggested in Taylor and Cordes (1993) is due to errors of the kinematic distances. A more recent model by Cordes and Lazio (2002), which is built upon the Taylor and Cordes (1993) model, also retains the "bump" of the Sagittarius arm toward the Galactic center. Both Taylor and Cordes (1993) and Cordes and Lazio (2002) give models for the distribution of free electrons in the Galaxy, upon which most pulsar distances are determined using the observed dispersion measures (DM), i.e., the column density of electrons toward the pulsars (Frail \& Weisberg 1990). These models are built by numerically fitting predicted and observed dispersion measures for pulsars with known "independent distance estimates" (Taylor \& Cordes 1993), most of which come from uncertain kinematic distances.

In particular, kinematic distances are more severely affected by errors of the radial velocities for sources at low galactic longitudes than at high longitudes. For example, for the simplest assumption of circular Galactic rotation with a source distance $d$ in the solar neighborhood ( $d \ll R_{0}$, where $R_{0}$ is the distance to the Galactic center from the Sun), the kinematic distance $d$ can be approximated by $d_{\text {kin }} \approx V_{\mathrm{LSR}} /[A \sin (2 l)]$ using Oort's constant $A$ (see e.g., Karttunen et al. 2007). Errors in the kinematic distances $\sigma_{d_{\mathrm{kin}}}$ are thus proportional to the errors in the radial velocities divided by $\sin (2 l)$ : $\sigma_{d_{\text {kin }}} \propto \sigma_{V_{\mathrm{LSR}}} / \sin (2 l)$. Therefore the kinematic distances toward the Sagittarius arm in the inner Galaxy are expected to be particularly uncertain.

Taylor and Cordes (1993) acknowledged that pulsar distances derived from previous models generally tend to be overestimated for $|l|<30^{\circ}$ and underestimated for $l=50^{\circ}-70^{\circ}$ (although they claim their own model has no significant dependence of distance errors on $l$ ), which can account for the "bump" of the Sagittarius arm toward the Galactic center at low galactic longitudes. Our results as shown in figure 6 indicate that the previously expected "bump" in the Sagittarius arm toward the Galactic center is most likely due to errors that arise from kinematic distances.

Russeil (2003) pointed out that the nearest part of the Sagittarius arm is placed at $\sim 2 \mathrm{kpc}$ based on kinematic


Fig. 5. Model of the Galaxy by Georgelin and Georgelin (1976), overlaid with the modified model by Taylor and Cordes (1993) shown in gray. " $\odot$ " indicates the location of the Sun and "GC" the position of the Galactic center. The red square shows the new location of G14.33-0.64 based on our parallax measurements, while the yellow circle is the previously estimated position of G14.33-0.64 based on kinematic distances. Three star-forming regions, G35.20-0.74 (blue diamond), G35.20-1.74 (pink triangle), and W 51 IRS 2 (green hexagon), possibly belonging to the Sagittarius spiral arm are also indicated with parallactic distances measured by Zhang et al. (2009) and by Xu et al. (2009) with the VLBA for $12-\mathrm{GHz}$ methanol maser emission. Errors for all parallactic distances are also shown, which are within the size of dots for G14.33-0.64 and for G35.20-0.74.
distances [using the rotation curve of Brand and Blitz (1993)], while a fitted regular logarithmic arm, also based on kinematic distances, passes at $\sim 1 \mathrm{kpc}$, indicating the possibility that the Galaxy does not have a regular design. However, our parallax measurements suggest that the nearest part of the Sagittarius arm, indeed, lies at $\sim 1 \mathrm{kpc}$. The disagreement between the arm fitting and the kinematic distance is likely due to errors of kinematic distances, rather than an irregular design of the Sagittarius arm.

Direct determinations of distances are of great importance and required to obtain a true map of the Galaxy and, in particular, of the Sagittarius arm. Our parallax measurement of G14.33-0.64 with VERA reveals the location of the Sagittarius arm to be closer to the Sun than previously thought.

### 5.3. Pitch Angle of the Sagittarius Arm

We attempted to fit the pitch angle $i$ of the Sagittarius arm using our parallax measurement of G14.33-0.64 with three other parallax measurements of sources shown in figure 5, which may lie in the Sagittarius arm: G35.20-0.74, G35.20-1.74 (Zhang et al. 2009), and W 51 IRS2 (Xu et al. 2009). The pitch angle $i$ is defined as the angle between the arm and the tangent to a Galactocentric circular orbit.

For an ideal logarithmic spiral arm, it can be expressed as, $\ln \left(R_{1} / R_{2}\right)=-\left(\beta_{1}-\beta_{2}\right) \tan i$, for two sources 1 and 2 (indicated by subscripts) in the arm, where $R$ is the Galactocentric radius at a Galactocentric longitude $\beta$ ( 0 toward the Sun and increasing with galactic longitude; see Reid et al. 2009b).

Figure 6 a shows a plot of $\log _{10}(R / \mathrm{kpc})$ vs. $\beta$ (in degrees) for G14.33-0.64 (red square), G35.20-0.74 (blue diamond), G35.20-1.74 (pink triangle), and W 51 IRS2 (green hexagon). Here we adopted the Sun-center distance of $R_{0}=8.5 \mathrm{kpc}$. Errors are indicated for each source with parallax uncertainties of $\pm 1 \sigma$ from this study, Zhang et al. (2009), and Xu et al. (2009). We attempted a linear least-squares fitting to the sources with unweighted straight lines. (Note that we need to express $\ln R$ in natural logarithm and $\beta$ in radians to calculate the pitch angle.)

As can be seen in figure 6a, the four sources do not lie on a straight line, and we attempted fittings with two possible combinations of three sources, which are shown in gray lines in the figure. Line A shows a best-fit straight line for G14.33-0.64, G35.20-0.74, and G35.20-1.74 (excluding W 51 IRS2), which yields a pitch angle of $i=34.7 \pm 2.7$. Line B is a fitting result from G14.33-0.64, G35.20-0.74, and W 51 IRS2 (excluding G35.20-1.74), which yields a smaller


Fig. 6. Fits for the pitch angle of the Sagittarius spiral arm. The logarithm of Galactocentric radius $R$ (measured in kpc) is plotted against Galactocentric longitude $\beta$ (in degrees). The Sun-center distance of 8.5 kpc was adopted. (a) G14.33-0.64 (red square), G35.20-0.74 (blue diamond), G35.20-1.74 (pink triangle), and W 51 IRS2 (green hexagon) are plotted with parallaxes and associated uncertainties from this study, Zhang et al. (2009), and Xu et al. (2009). Gray lines show the best-fit straight lines from an unweighted linear least-squares fitting to the data. The pitch angle $i$ was obtained by taking the negative of the arctangent of the line slopes. (Note that we need to express $\ln R$ in natural logarithm and $\beta$ in radians to calculate the pitch angle.) Line A shows the fitting result from G14.33-0.64, G35.20-0.74, and G35.20-1.74, while line B is from G14.33-0.64, G35.20-0.74, and W 51 IRS2. (b) Same as (a), but with five sources (cyan dots) in the Local (Orion) arm (spur) also shown with precise parallax measurements. Line C is an unweighted straight line fit to W 51 IRS2 and the five sources in the Local arm (see text).
pitch angle of $i=11.2 \pm 10.5$. This pitch angle, $i \sim 11^{\circ}$, agrees well with the four-arm Milky Way model by Vallée (1995) with a best-fit pitch angle of $i=12 . .^{\circ} \pm 1^{\circ}$.

Figure 7 is a plot of the positions of the four sources superimposed on an artist's conception of the Milky Way. For a comparison, five sources in the Local (Orion) "arm" or spur are also shown with precise parallax measurements: G59.7+0.1 (Xu et al. 2009), Cep A (Moscadelli et al. 2009), Orion (Hirota et al. 2007; Menten et al. 2007; Kim et al. 2008), G232.6+1.0 (Reid et al. 2009a), and VY CMa (Choi et al. 2008). With the five sources, Reid et al. (2009b) fitted the pitch angle of the Local arm to be $27.8 \pm 4 .{ }^{\circ} 7$, which is larger than the pitch angles they fitted for another spiral arm, e.g., $16.5 \pm 3.1$ for the Perseus spiral arm.

In figure 6b, we also attempted a straight-line fitting (line C) to the five Local arm sources (marked by cyan dots) plus W 51 IRS2 (green hexagon), which yields a pitch angle of $26^{\circ} 1 \pm 12.3$, which is consistent with the pitch angle fitted with only five sources mentioned above. Thus, the Local arm/spur may branch from the Sagittarius arm near the position of W 51 IRS2, which is often considered to be at the tangent point of the Sagittarius arm. One possible interpretation is that the Sagittarius arm bifurcates near the position of W 51 IRS2 into the Local spur (line C) at a pitch angle of $i \sim 26^{\circ}$ and into the other arm traced by G14.33-0.64 and G35.20-0.74 (line B) at a pitch angle of $i \sim 11^{\circ}$. Another possibility is that the Sagittarius arm is traced by G14.33-0.64, G35.20-0.74, and G35.20-1.74 (line B) and branches from the interior (Scutum-Crux) arm at a large pitch angle of $i \sim 34^{\circ}$. However, more sources with precise parallaxes are needed to establish a clear spiral arm structure. Ongoing and future parallax measurements with VERA and with the VLBA are expected to reveal the structure of the Sagittarius arm and other spiral arms of the Galaxy further in detail.


Fig. 7. Galactic maser source locations in the Sagittarius and Local (Orion) arms, superimposed on artist's conception (R. Hurt: NASA/JPL-Caltech/SSC). " $\odot$ " indicates the location of the Sun and "*" the position of the Galactic center. The red square shows the new location of G14.33-0.64 based on our parallax measurements. Three star-forming regions, G35.20-0.74 (blue diamond), G35.20-1.74 (pink triangle), and W 51 IRS2 (green hexagon), possibly belonging to the Sagittarius spiral arm, are also indicated with parallactic distances. The positions of five sources in the Local (Orion) "arm" or spur are indicated by cyan dots with precise parallactic distances (see text). Errors for all parallactic distances are also shown, which are mostly smaller than the size of the symbols.

### 5.4. Magnetic Field Reversals and the Sagittarius Arm

It is of interest to compare our results for the distance to the Sagittarius arm with studies of Galactic magnetic field reversals. The Galactic magnetic field has been probed most often by Faraday rotation measure (RM) observations of linearly polarized emission from both pulsars (e.g., Han et al. 1999, 2006; Noutsos et al. 2008) and extragalactic radio sources (e.g., Brown et al. 2007). A common conclusion in many pulsar polarization studies is that the magnetic field in the Local arm is clockwise while it is counterclockwise in the first quadrant ( $0^{\circ} \leq l \leq 90^{\circ}$ ) component of the Sagittarius arm, indicating the existence of a magnetic field reversal between the arms. Weisberg et al. (2004) found from pulsar polarimetry a null in the magnetic field of a width of less than 0.5 kpc extending from near the Sun over 7 kpc toward $l \sim 60^{\circ}$ (figure 4 in Weisberg et al. 2004), located midway between the Local and Sagittarius arms, which is most likely the field reversal region.

Weisberg et al. (2004) noted a " $1-\mathrm{kpc}$ wide strip" of steady magnetic field from the local reversal (midway between the Local and Sagittarius arms) into the Sagittarius arm, based on the Sagittarius arm model by Cordes and Lazio (2002). As previously discussed, our parallax measurements demonstrate that the Sagittarius arm lies at a closer distance of $\sim 1 \mathrm{kpc}$, instead of previously estimated $\sim 2-3 \mathrm{kpc}$ from kinematic distances, and we find that G14.33-0.64 (this study) and G35.20-0.74 (Zhang et al. 2009) trace out the near side of the Sagittarius arm, which lie outside of the "bump" delineated in Taylor and Cordes (1993) as well as in Cordes and Lazio (2002). Our parallax measurements thus indicate that the strip of steady magnetic field found by Weisberg et al. (2004) is likely in the Sagittarius arm, rather than in an interarm region exterior to the arm. This lends support to the fact that the magnetic field in the Sagittarius arm is steadily and dominantly counterclockwise, and is further evidence for the conclusion of Weisberg et al. (2004) that the field maxima tend to lie along the spiral arms, while the field reversals occur between the arms.

### 5.5. Motion of G14.33-0.64 and the Galactic Rotation

As shown in figures 4 c and 4 d , the internal motions of the $\mathrm{H}_{2} \mathrm{O}$ masers in G14.33-0.64 show a bipolar jetlike motion on the sky, with deviations of $\simeq 1-2$ mas yr $^{-1}$ from the mean, which correspond to a linear velocity of $5-10 \mathrm{~km} \mathrm{~s}^{-1}$ at a distance of 1.12 kpc . The central radial velocity $V_{\mathrm{LSR}} \simeq 22 \mathrm{~km} \mathrm{~s}^{-1}$ of the maser emission agrees well with other molecular line velocities, and the deviations up to $10 \mathrm{~km} \mathrm{~s}^{-1}$ from the central radial velocity agree with the proper motions.

From the parallax, proper motion, radial velocity, and the sky position of the $\mathrm{H}_{2} \mathrm{O}$ maser source, we can now calculate the full three-dimensional position and velocity of the source in the Galaxy. By following the methods described in detail by Reid et al. (2009b) to convert from the heliocentric reference frame to a reference frame that rotates with the Galaxy,
we obtained the peculiar motion of the source with respect to the Galactic rotation.

We adopted the mean absolute proper motion (the reference frame in figure 4 d$)$ of $\left(\overline{\mu_{X}}, \overline{\mu_{Y}}\right)=(0.95,-2.50){\text { mas } \mathrm{yr}^{-1} \text { as }}^{2}$. the systemic motion of the source (before the correction of the solar motion and the Galactic rotation), with uncertainties of $\pm 2{\mathrm{mas} \mathrm{yr}^{-1} \simeq \pm 10 \mathrm{~km} \mathrm{~s}^{-1} \text { in each of the eastward }(X) \text { and }}$ northward $(Y)$ directions to allow for the possibility that the mean maser motion does not trace the systemic motion.

For the radial velocity, we adopted $V_{\mathrm{LSR}}=22 \pm 10 \mathrm{~km} \mathrm{~s}^{-1}$. Adopting the Hipparcos solar motion values of $U_{\odot}=$ $10.0 \pm 0.36 \mathrm{~km} \mathrm{~s}^{-1}$ (radially toward the Galactic center), $V_{\odot}=5.25 \pm 0.62$ (in the local direction of Galactic rotation), and $W_{\odot}=7.17 \pm 0.38 \mathrm{~km} \mathrm{~s}^{-1}$ (vertically upwards, i.e., toward the north Galactic pole perpendicularly to the Galactic plane) from Dehnen and Binney (1998) with the recent bestfit results for the Galactic constants of $R_{0}=8.4 \pm 0.6 \mathrm{kpc}$ and $\Theta_{0}=254 \pm 16 \mathrm{~km} \mathrm{~s}^{-1}$ by Reid et al. (2009b), and assuming a flat rotation of the Galaxy (i.e., rotational velocity $\Theta$ at the source location is the same as at the Sun, $\Theta \simeq \Theta_{0}$ ) the peculiar velocity components of G14.33-0.63 were obtained to be $U_{s}=11 \pm 10 \mathrm{~km} \mathrm{~s}^{-1}$ toward the Galactic center at the source position, $V_{s}=-1 \pm 11 \mathrm{~km} \mathrm{~s}^{-1}$ in the local direction of the Galactic rotation, and $W_{s}=-4 \pm 11 \mathrm{~km} \mathrm{~s}^{-1}$ vertically out of the Galactic plane toward the north Galactic pole.

Here, the uncertainties of $10-11 \mathrm{~km} \mathrm{~s}^{-1}$ in the derived peculiar motion are directly due to the uncertainties for the proper motion and the radial velocity of G14.33-0.64. The contribution from uncertainties in the Galactic constants $R_{0}$ and $\Theta_{0}$ is negligible, because the Galactic rotation term was almost canceled out in the differential calculation. If we adopt the IAU standard values of $R_{0}=8.5 \mathrm{kpc}$ and $\Theta_{0}=220 \mathrm{~km} \mathrm{~s}^{-1}$ instead, the resulting peculiar motion becomes $U_{s}=12 \pm 10 \mathrm{~km} \mathrm{~s}^{-1}$, $V_{s}=-1 \pm 11 \mathrm{~km} \mathrm{~s}^{-1}$, and $W_{s}=-4 \pm 11 \mathrm{~km} \mathrm{~s}^{-1}$. Therefore, the peculiar motion of G14.33-0.64 is not significant in the direction of Galactic rotation $\left(V_{s}\right)$ or in the direction out of the Galactic plane $\left(W_{s}\right)$. For the source location of G14.33-0.64 relative to the Sun in the Galaxy, the larger peculiar velocity component of G14.33-0.64 toward the Galactic center $\left(U_{s}\right)$ reflects a radial velocity larger than expected from the circular rotation model, which has led to the larger kinematic distances derived in previous studies. Overall, G14.33-0.64 shows no significant peculiar motion, and is consistent with the circular Galactic rotation model.

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