Astrometry of H$_2$O Masers in Nearby Star-Forming Regions with VERA. IV. L 1448 C

Tomoya HIROTA,1,2 Mareki HONMA,1,2 Hiroshi IMAI,3 Kazuyoshi SUNADA,2,4 Yuji UENO,4 Hideyuki KOBASHI,1,5 and Noriyuki KAWAGUCHI2,4

1Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588
tomoya.hirota@nao.ac.jp
2Department of Astronomical Sciences, Graduate University for Advanced Studies, 2-21-1 Osawa, Mitaka, Tokyo 181-8588
3Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima, Kagoshima 890-0065
4Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, 2-12 Hoshi-ga-oka, Mizusawa-ku, Oshu-shi, Iwate 023-0861
5Department of Astronomy, Graduate University for Advanced Studies, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033

(Received 2010 June 3; accepted 2010 July 23)

Abstract

We have carried out multi-epoch VLBI observations with VERA (VLBI Exploration of Radio Astrometry) of 22 GHz H$_2$O masers associated with a Class 0 protostar, L 1448 C, in the Perseus molecular cloud. The maser features trace the base of a collimated bipolar jet driven by one of the infrared counter parts of L 1448 C, named as L 1448 C(N) or L 1448-mm A. We detected possible evidence for apparent acceleration and precession of the jet according to the three-dimensional velocity structure. Based on phase-referencing VLBI astrometry, we successfully detected an annual parallax of the H$_2$O maser in L 1448 C to be 4.31 ± 0.33 milliarcseconds (mas), which corresponds to a distance of 232 ± 18 pc from the Sun. The present result is in good agreement with that of another H$_2$O maser source, NGC 1333 SVS 13, in the Perseus molecular cloud, 235 pc. It is also consistent with the photometric distance, 220 pc. Thus, the distance to the western part of the Perseus molecular cloud complex would be constrained to be about 235 pc, rather than a larger value, 300 pc, previously reported.

Key words: astrometry — ISM: individual (L 1448 C) — ISM: jets and outflows — masers (H$_2$O) — stars: individual (L 1448 C)

1. Introduction

In order to understand the formation processes of stars, it is necessary to obtain accurate physical and dynamical properties of newly born young stellar objects (YSOs), such as the size, mass, and luminosity. For this purpose, an accurate distance to a YSO in a star-forming region is the most fundamental parameter for quantitative discussion. During the last decade, great efforts were made to establish the highest accuracy astrometric observations with very long baseline interferometry (VLBI). This VLBI astrometry enables one to measure annual parallaxes for bright radio sources, i.e., maser sources and non-thermal radio sources, associated with YSOs at a typical accuracy of sub-milliarcseconds (mas). It can achieve much better accuracy by 2–3 orders of magnitude than that of the optical astrometry satellite Hipparcos (Perryman et al. 1997). As a result, the distances to several well-studied star-forming regions, such as the Taurus (Loinard et al. 2005, 2007; Torres et al. 2007, 2009), Ophiuchus (Imai et al. 2007; Loinard et al. 2008), Orion (Hirota et al. 2007; Sandstrom et al. 2007; Menten et al. 2007; Kim et al. 2008), Perseus (Hirota et al. 2008a), and Cepheus (Hirota et al. 2008b; Moscadelli et al. 2009) regions, were refined with better than a few percent uncertainties.

Among them, we have been carrying out a VLBI astrometry project, “Measurements of annual parallaxes of nearby molecular clouds”, with VERA (VLBI Exploration of Radio Astrometry). VERA is a Japanese VLBI network operated by National Astronomical Observatory of Japan (NAOJ) and Kagoshima University. VERA is designed to be dedicated for astrometric observations aimed at revealing the three-dimensional structure of the Galaxy (e.g., Honma et al. 2007). Our project mainly focuses on accurate distance measurements of star-forming regions within 1 kpc from the Sun (Dame et al. 1987; Evans et al. 2003). Part of the results have been reported in a series of papers (Hirota et al. 2007; Imai et al. 2007; Hirota et al. 2008a, 2008b; Kim et al. 2008).

Here, we present a new result of our VLBI astrometry of the H$_2$O masers associated with L 1448 C (or L 1448-mm) in an optical dark cloud, Lynds 1448 (Lynds 1962). L 1448 is located at 1° southwest of another star-forming region, NGC 1333 (Hirota et al. 2008a), in the Perseus molecular cloud. L 1448 C was first detected at millimeter (Bachiller et al. 1991) and centimeter (Curiel et al. 1990) wavelengths, and was later classified as a deeply embedded Class 0 protostar based on its spectral energy distribution (SED) from infrared to millimeter wavelengths (Barsony et al. 1998). Recent observations with the Spitzer Space Telescope revealed that L 1448 C consists of two infrared counterparts, named as L 1448 C(N) and L 1448 C(S) (Jørgensen et al. 2006), or L 1448-mm A and B (Tobin et al. 2007), which are separated by 8", as shown in figure 1. These infrared sources have been observed more recently with higher-resolution interferometers at centimeter to submillimeter wavelengths (Reipurth et al. 2002; Hirano et al. 2010). L 1448 C is known to drive large-scale extremely high-velocity molecular outflow traced by the millimeter rotational lines of the CO and SiO molecules (Bachiller et al. 1990, 1995;
Fig. 1. Spitzer IRAC channel 2 image (left) and MIPS channel 1 image (right) of L 1448 C taken from the Spitzer Legacy Program “From Molecular Cores to Planet Forming Disks” (Evans et al. 2003). A white cross represents the reference position adopted in the present study. A black solid line represents the average position angle of the H$_2$O maser features in L 1448 C.

Girart & Acord 2001; Hirano et al. 2010) and the vibrationally excited H$_2$ line in near-infrared wavelengths (Bally et al. 1993). Thus, L 1448 C is one of the ideal laboratories to study in detail about the mass-loss processes through collimated jet and molecular outflow, as well as the nature of the protostar in a very young evolutionary phase. H$_2$O masers were detected with single-dish telescopes (Claussen et al. 1996) and the Very Large Array (VLA) (Chernin 1995). However, this is the first time to observe H$_2$O masers associated with L 1448 C with VLBI. The highest resolution observations with VERA yield the proper motions of the masers along with the annual parallax of L 1448 C.

2. Observations and Data Analyses

Observations of the H$_2$O maser line ($6_{16}-5_{23}$, 22235.080 MHz) associated with L 1448 C were conducted with VERA from 2007 November to 2008 February. All 4 stations of VERA (see figure 1 of Petrov et al. 2007) took part in all observing sessions, providing a maximum baseline length of 2270 km.

Observations were made in the dual-beam mode; the H$_2$O masers associated with L 1448 C and an extragalactic radio source J0319$^0$+3101 (Petrov et al. 2006), with a separation angle of 1$^\circ$37, were observed simultaneously. The instrumental phase difference between the two beams was measured continuously during the observations by injecting artificial noise sources into both beams at each station (Honma et al. 2003, 2008a).

Left-handed circular polarization was received and sampled with 2-bit quantization and filtered using the VERA digital filter unit (Iguchi et al. 2005). The data were recorded onto magnetic tapes at a rate of 1024 Mbps, providing a total bandwidth of 256 MHz in which one IF channel and the rest of 15 IF channels with a 16 MHz bandwidth each were assigned to L 1448 C and J0319$^0$+3101, respectively. A bright extragalactic radio source, 3C 84, was observed every 80 min as a delay and bandpass calibrator. Amplitude calibrations were made using the chopper-wheel method (Ulich & Haas 1976). A correlation processing was carried out on the Mitaka FX correlator (Chikada et al. 1991) located at the NAOJ Mitaka campus. For the H$_2$O maser line, the spectral resolution was set to be 15.625 kHz, corresponding to a velocity resolution of 0.21 km s$^{-1}$.

Data reduction was performed using the National Radio Astronomy Observatory (NRAO) Astronomical Image Processing System (AIPS). We first applied the results of the dual-beam phase calibration, as mentioned above, and the correction for the approximate delay model adopted in the correlation processing. Details in this procedure are described in previous papers (Honma et al. 2003, 2007, 2008a, 2008b). The reference position of L 1448 C was set to be the geometric center of two maser features, as discussed later, RA (J2000) = 03$^h$25$^m$38$^s$.87840 and Dec (J2000) = +30$^\circ$44$'$05$''$.002516, in a recalculation of the delay tracking model. Next, we calibrated the instrumental delays and phase offsets among all of the IF channels by the AIPS task FRING on 3C 84. Finally, we calibrated residual phases by the AIPS task FRING on J0319$^0$+3101. The solutions were applied to the target source L 1448 C. The reference source J0319$^0$+3101 has a flux density of only 30 mJy beam$^{-1}$ at 22 GHz, and hence it was only marginally detected with a signal-to-noise ratio of about 5 during most of the observing sessions. Therefore, we also calibrated the residual phases by the AIPS task FRING on the intense spectral feature of the H$_2$O maser in L 1448 C instead of J0319$^0$+3101. In this case, the solutions were also applied to J0319$^0$+3101. These two results will be compared in a later section.

Synthesis imaging and deconvolution (CLEAN) were
performed using the AIPS task IMAGR. The uniform weighted synthesized beam size (FWHM) was typically $1.2\,\text{mas} \times 0.8\,\text{mas}$ with a position angle of $-50^\circ$. The peak positions and flux densities of masers were derived by fitting elliptical Gaussian brightness distributions to each spectral channel map using the AIPS task SAD. The formal uncertainties in the maser positions given by SAD were better than 0.1 mas. The rms noise levels in the self-calibrated images are $1–2\,\text{mJy beam}^{-1}$ for J0319+3101 and $50–150\,\text{mJy beam}^{-1}$ for the channel maps of the L 1448 C masers with a net integration time of about 3 hr.

3. Results

3.1. Structure of the H$_2$O Maser Features

Figure 2 shows the spectra of the H$_2$O masers associated with L 1448 C. We detected the masers at five observing sessions (2007/324, 2007/361, 2008/035, 2008/063, and 2008/106, denoted by year/day of the year). For later sessions (2008/141, 2008/178, and 2009/047) we could not detect the masers due to the time variation, which is characteristic for H$_2$O masers associated with low-mass protostars (Claussen et al. 1996). The most intense feature was always at the local standard of rest (LSR) velocity of about $20\,\text{km s}^{-1}$. The second weak feature was detected at the LSR velocity of $7\,\text{km s}^{-1}$ from 2007/324 to 2008/106, although they are marginally seen in figure 2. Both features are red-shifted with respect to the systemic velocity of the molecular cloud L 1448, $4.5\,\text{km s}^{-1}$ (Bachiller et al. 1990). The velocities of the masers are within that of the molecular outflow ranging up to $\pm 70\,\text{km s}^{-1}$ with respect to the systemic velocity (Bachiller et al. 1990, 1995). These two features had been identified by Chernin (1995), whereas we could not detect other velocity components detected by Chernin (1995) and Claussen et al. (1996). We also detected another faint maser feature in 2009/047 at the LSR velocity of $-24\,\text{km s}^{-1}$. Because this feature could not be detected in the VLBI imaging, we exclude this feature in the following discussion.

The distribution of the maser spots is shown in figure 3. Hereafter, we define a “spot” as emission occurring in a single velocity channel and a “feature” as a group of spots. We define two features. One is located northwest of the reference position, while the other at southeast.

In order to obtain absolute positions of the maser spots, we first made synthesis imaging for each epoch by employing the result of the phase-calibration on the reference maser spot at the LSR velocity of $20.6\,\text{km s}^{-1}$. This is because we could obtain higher sensitivity images compared with those obtained by phase-referencing to J0319+3101 or other maser spots at different velocities. In this case, the positions of the maser spots were measured with respect to the reference spot. Next, we transferred the phase-calibration results to the J0319+3101 data. The absolute position of J0319+3101 was determined with an uncertainty of 1.63 and 1.68 mas in right ascension and declination, respectively (Petrov et al. 2006), so that we could convert the position offsets of the maser spots with respect to J0319+3101 into absolute positions.

As a result, we can easily locate the absolute position of the maser source to be one of the Spitzer sources, L 1448 C(N)/L 1448-mm A (Jørgensen et al. 2006; Tobin et al. 2007), as shown in figure 1. The position also agrees well with that of the radio continuum source (Reipurth et al. 2002) and the submillimeter continuum source (Hirano et al. 2010). Note that the positions of the continuum source obtained by the interferometer observations (Reipurth et al. 2002; Hirano et al. 2010) tend to be shifted toward $0.12–0.17$ northwest of our reference position. Although the astrometric accuracies seem to be insufficient with the beam sizes of $0.3–0.7$ achieved by these observations, the powering source of the masers could be located northwest of the maser images shown in figure 3.

The spatial distribution of the H$_2$O masers linearly aligned with a collimated jet-like structure seems to be analogous to the large-scale molecular outflow, although the size of the maser structure is much smaller by 3–4 orders of magnitude. The width of the H$_2$O maser jet is less than 5 mas, while its length is 60 mas, as can be seen in figure 3. This scale is significantly smaller than that found by Chernin (1995), 280 mas. The estimated size gives the lower limit for only part of the (red-shifted) jet because we could not detect the blue-shifted
H$_2$O maser jet in the present study. Details of the spatial and velocity structure of the maser features will be discussed in a later section.

3.2. Astrometry of the H$_2$O Masers in L 1448 C

We have successfully determined the absolute positions of the maser spots by referring to the position reference source J0319+3101. In the data analysis, we performed phase-calibration on either the intense maser spot in L 1448 C or continuum source J0319+3101, as mentioned above. Table 1 compares the results of both methods. Except for the epochs 2007/324 and 2008/106, where L 1448 C could not be detected by phase-referencing to the J0319+3101, the derived position offsets are consistent with each other. The uncertainties of about 0.3 mas (as summarized in the fourth column in table 1) would be the result of a low signal-to-noise ratio of J0319+3101, or structure in the maser spots. The peak fluxes of J0319+3101 obtained by phase-referencing to the maser spots of L 1448 C recover 29% and 52%–55% of those of self-calibrated images for 2007/324 and remainder of 4 epochs, respectively. On the other hand, phase-referenced images of the maser spots only recover 23%–44% of those of self-calibrated images for the epochs 2007/361, 2008/035, and 2008/063. This is due to a larger coherence loss in the phase calibration on J0319+3101 with a lower signal-to-noise ratio. Thus, we hereafter employ the astrometric results obtained by phase-referencing to the reference maser spot in L 1448 C.

Figure 4 shows the position offsets of the masers as a function of the observing epoch. The movement of the masers significantly deviates from a simple linear motion, and it can be fitted as a combination of the linear proper motion and the annual parallax by least-squares analysis. The results of the fitting are summarized in table 2. Using both the right ascension and declination data, the annual parallax of L 1448 C is derived to be 4.31 ± 0.33 mas, corresponding to a distance of 232 ± 18 pc from the Sun. The standard deviations of the post-fit residuals are $\sigma_{\alpha} = 0.19$ mas and $\sigma_{\delta} = 0.93$ mas in right ascension and declination, respectively.

The larger residual in declination is due to position errors in the observations at 2007/361 and possibly 2007/324, as can be seen in figures 4b and 4c. These errors are significantly larger than the formal errors in the Gaussian fitting of the maser
Table 1. Position offsets of the reference maser spots \((v_{\text{lsr}} = 20.6 \text{ km s}^{-1})\) derived from the phase-referencing methods.*

| Epoch     | Reference: L 1448 C \((\alpha, \delta)\) | Reference: J0319 \((\alpha, \delta)\) | Difference \((\Delta \alpha, \Delta \delta)\) |
|-----------|------------------------------------------|------------------------------------------|------------------------------------------|
| 2007/324  | (2.77, −10.80)                          | —                                        | (0.28, −0.05)                            |
| 2007/361  | (2.35, −16.20)                          | (2.07, −16.15)                          | (0.28, 0.14)                            |
| 2008/035  | (3.85, −18.28)                          | (3.57, −18.42)                          | (0.14, 0.15)                            |
| 2008/063  | (5.40, −20.35)                          | (5.26, −20.50)                          | —                                        |
| 2008/106  | (10.07, −22.86)                         | —                                        | —                                        |

* The position offsets are measured with respect to the reference position of the masers in units of milliarcseconds (mas).

Phase calibrations were done for L 1448 C and the results were transferred to J0319+3101.

Phase calibrations were done for J0319+3101 and the results were transferred to L 1448 C.

Table 2. Results of a least-squares analysis for the annual parallax and proper motion measurements.

| Parameter                                      | Best fit value* |
|------------------------------------------------|-----------------|
| Annual parallax \(\pi\) (mas)                 | 4.31 (33)       |
| Distance \(D\) (pc)                           | 232 (18)        |
| Proper motion (RA) \(\mu_{\alpha} \cos \delta\) (mas yr\(^{-1}\)) | 21.9 (7)       |
| Proper motion (Dec) \(\mu_{\delta}\) (mas yr\(^{-1}\)) | −23.1 (33)     |
| Proper motion (total) \(\mu\) (mas yr\(^{-1}\)) | 31.8 (33)       |
| Transverse velocity \(v_t\) (km s\(^{-1}\))   | 35.3 (37)       |
| Position angle of proper motion vector \(PA\) (°) | 137             |
| Post fit residual (RA) \(\sigma_{\alpha}\) (mas) | 0.19            |
| Post fit residual (Dec) \(\sigma_{\delta}\) (mas) | 0.93            |

* Numbers in parenthesis represent the errors in units of the last significant digits.

Fig. 4. Position measurements of the maser spots at \(v_{\text{lsr}} = 20.6 \text{ km s}^{-1}\). (a) Movement in right ascension as a function of time. (b) Same as (a), but in declination. (c) Same as (a) and (b), but the best-fit proper motions are removed. (d) Movement of the maser spots on the sky plane. The solid line represents the best-fit model of the annual parallax. The associated error bars, 0.21 mas and 1.02 mas, in right ascension and declination, respectively, are also plotted. Small crosses in panel (d) indicate the expected position for each epoch, as labeled in the figure.

spots, 0.03–0.1 mas. Therefore, we introduced an error floor of 0.21 mas and 1.02 mas in right ascension and declination, respectively, for all of the results of the position measurements to make the reduced \(\chi^2\) to be unity in the least-squares analysis. These error floors represent the positional uncertainties in the present astrometric observations. The possible origin of these uncertainties is most likely due to the difference in the optical path lengths between the target and reference sources caused by the atmospheric zenith delay residual and/or a variability of the structure of the maser feature (see detailed discussions in Honma et al. 2007; Hirota et al. 2007, 2008a, 2008b).

Based on a simulation by Honma, Tamura, and Reid (2008b), positional errors due to the typical zenith delay residual in the VERA observations, 2 cm, can be estimated to be 0.03 mas and 0.01 mas in right ascension and declination, respectively, under the condition close to the present observations (i.e., the separation angle of 1°37, position angle on the sky from the target sources to the reference sources of 90°, and the source declination of 15° were employed). Although the assumed value of declination is different from that of L 1448 C, the estimated position offsets are much smaller than the observed results. Therefore, only the zenith delay residual would not be the cause of the large positional uncertainties, unless unexpectedly large zenith delay residuals remain in the data.

The larger positional uncertainties found in the H\(_2\)O masers...
associated with nearby low-mass YSOs (Hirotta et al. 2007; Imai et al. 2007; Hirotta et al. 2008a, 2008b) than in the distant massive YSOs (e.g., Honma et al. 2007) are possibly attributed to the source structure. In fact, such a variation of the internal maser structures has been observed directly by recent VLBI observations of the H\textsubscript{2}O masers in a nearby low-mass YSO, NGC 1333 IRAS 4 (Marvel et al. 2008; Desmurs et al. 2009), with a typical timescale of as short as 2–4 weeks. This may strongly affect the results of identifications for H\textsubscript{2}O maser spots between two consecutive epochs separated by only 1 month.

Nevertheless, we can obtain a consistent result, $\pi = 4.30 \pm 0.37$ mas and $\sigma_\pi = 0.23$ mas, even if only the right ascension data are used in the least-squares analysis. When we fit the data excluding those of the second epoch 2007/361, the resultant parallax value is consistent within the mutual error ($4.23 \pm 0.29$ mas). In this case, the post-fit residuals, $\sigma_\pi = 0.15$ mas and $\sigma_\delta = 0.39$ mas in right ascension and declination, respectively, are reduced. Unfortunately, the masers associated with L 1448 C disappeared after the 6-month monitoring observations with VERA, which is also similar to the case for NGC 1333 SVS 13 (Hirotta et al. 2008a). If the above error sources affect the position measurements as random noise, the accuracy of the parallax measurement could be improved by increasing the number of observed epochs as well as the detected maser spots. Thus, we need to continue longer monitoring observations of the H\textsubscript{2}O maser sources to improve the accuracy of the annual parallax measurements with VERA.

4. Discussions

4.1. Collimated H\textsubscript{2}O Maser Jet from L 1448 C

Both the spectra and distribution of the maser spots, as shown in figures 2 and 3, imply that the masers trace the base of the protostellar jet driven by the Class 0 source L 1448 C. In this section, we discuss the velocity structure of the H\textsubscript{2}O masers.

In table 2, we derived the absolute proper motion of the reference maser spot at the LSR velocity of 20.6 km\,s\textsuperscript{-1}. In addition, we also derived the relative proper motions for other maser spots with respect to this reference spot. As a result, the northern spots at the LSR velocity of 7.1–7.7 km\,s\textsuperscript{-1} are found to be moving away from the reference spot. The average of the proper motions is $10.7 \pm 11.9$ km\,s\textsuperscript{-1} with a position angle of $-34^\circ$ ($\mu_\alpha \cos \delta = -5.9$ mas\,yr\textsuperscript{-1}, $\mu_\delta = 8.9$ mas\,yr\textsuperscript{-1}) with respect to the reference spot. Based on the fact that the observed red-shifted jet lobe should be expanding toward the southeast direction (Girart & Acord 2001), the above motion could be naturally interpreted as meaning that the southern components are systematically moving toward the southeast direction with respect to the northern one. This is consistent with the expected position of the protostar located northwest of the masers, as mentioned in the previous section. If this is the case, the maser spots with larger proper motion tend to be distributed away from the driving source.

The radial velocity distribution of the H\textsubscript{2}O masers shown in figure 3 also suggests that the higher velocity components (20 km\,s\textsuperscript{-1}) are distributed at the more distant positions from the powering source, which is possibly northwest of the masers, than the lower velocity components (7 km\,s\textsuperscript{-1}). In addition, the LSR velocities within the southern maser feature gradually increase from 19 km\,s\textsuperscript{-1} at the northern end to 21 km\,s\textsuperscript{-1} at the southern end (figure 3c). Therefore, both the proper motion and radial velocity structure might exhibit an apparent acceleration of the jet driven by the protostar L 1448 C.

Based on the velocity shift in both the proper motion and the radial velocity between the northern and southern features, we roughly estimate the inclination angle of the maser jet to the line of sight to be 43\textdegree. This is smaller than that of the kinematic model proposed for large-scale bipolar outflow, 70\textdegree, even if the opening angle of the red-shifted jet lobe, 30\textdegree, is taken into account (Bachiller et al. 1995; Girart & Acord 2001). Although our estimation of the inclination angle would contain a large uncertainty, this result suggests evidence for precession of the jet axis.

As shown in figure 3, the maser spots are aligned along the northwest–southeast direction. We obtained the position angle of the alignment of the H\textsubscript{2}O maser features to be $-15^\circ$ on average. This is in good agreement with that of the large-scale collimated molecular outflow from L 1448 C, $-21^\circ$ (e.g., Bachiller et al. 1995), while slightly different from the direction of the proper motion, as mentioned above, $-34^\circ$. According to the Spitzer IRAC2 image in figure 1, the infrared jet is almost parallel to the H\textsubscript{2}O masers, while it shows a slightly curved structure at the northern part of the jet. This is thought to be evidence for interactions with the jet and ambient gas around another protostar, L 1448 N (Bachiller et al. 1995). In addition, Hirano et al. (2010) found deflection of both the blue-shifted and red-shifted SiO jet with almost point-symmetry with respect to its driving source, which is possibly caused by the orbital motion of the binary system.

Thus, it is likely that the variation in the position angles of the jets derived from the different tracers would be due to precession of the jet axis. It should be noted that possible evidence for the precession is also reported for the H\textsubscript{2}O maser jet in NGC 1333 IRAS 4 (Marvel et al. 2008; Desmurs et al. 2009).

We could evaluate the timescale of the maser jet to be at least 9 yr based on the velocity difference in the proper motion between the northern and southern maser features. If the maser spots are accelerated at a constant rate ($10.7 \pm 11.9$ km\,s\textsuperscript{-1}/9 yr = 1.2 mas\,yr\textsuperscript{-1}), the proper motion would increase by 0.6 mas\,yr\textsuperscript{-1} within the monitoring period of 0.5 yr. Although such acceleration might affect the accuracy of the annual parallax and proper motion measurements, we could not see any significant deviation from the linear proper motion with respect to the reference spot within the fitting errors. This would mean that the physical gas clumps appeared as the H\textsubscript{2}O maser features are not really accelerated for 9 yr, but they just represent the velocity structure of the jet showing apparent acceleration.

The kinematics of the H\textsubscript{2}O maser jet and its time scale are still uncertain, mainly because we could not detect the blue-shifted H\textsubscript{2}O maser features. In order to reveal the launching mechanism of the protostellar jet associated with L 1448 C, which might be the binary system (Hirano et al. 2010), proper motion measurements of both red- and blue-shifted masers would be a key issue.
4.2. Overall Structure of the Perseus Molecular Cloud Complex

The present astrometric observations with VERA imply that the distance to L 1448 C is most likely 232 pc, which is in excellent agreement with that of our previous results for NGC 1333 SVS 13, 235 ± 18 pc (Hirota et al. 2008a). Because the angular separation between these two sources, 1°, corresponds to a linear size of 5 pc, a similar extent along the line of sight is also plausible. Although we could not distinguish the difference in their distances, more precise parallax measurements will allow us to reveal the depth of the molecular cloud.

Our distance measurements are consistent with the photometric distance to NGC 1333 reported by Černis (1990) of 220 pc with an uncertainty of 25%, rather than the larger value of about 300 pc (e.g., Herbig & Jones 1983; de Zeeuw et al. 1999). Therefore, the present result provides a constraint on the distance to the western part of the Perseus molecular cloud complex to be closer value.

Enoch et al. (2006) suggested that a single distance for the whole of the Perseus molecular cloud complex might not be appropriate, although they adopted a distance of 250 pc for the entire area of the Perseus region. According to the photometric observations by Černis (1990, 1993), there exists a gradient in the distances across the Perseus molecular-cloud complex. NGC 1333 is proposed to be the nearest cloud at a distance of 220 pc (Černis 1990), while IC 348 is more distant, 300 pc (Černis 1993). The latter value is consistent with that of the Hipparcos result (318 ± 27 pc: de Zeeuw et al. 1999). Thus, it would be interesting to carry out VLBI astrometry of the H$_2$O maser sources and radio-emitting T-Tauri stars (e.g., Loinard et al. 2005) in other Perseus clouds, particularly for the eastern part of the complex, such as B1, IC 348, and B5 (see figure 5).

As listed in table 2, the absolute proper motion of the reference maser spot is 31.8 mas yr$^{-1}$ or 35.3 km s$^{-1}$ toward the southeast with a position angle of 137°. The direction of the proper motion seems to be consistent with those of NGC 1333 SVS 13 (Hirota et al. 2008a), as plotted in figure 5.

It is also reported that the average proper motion for the radio continuum sources in NGC 1333 agrees well with those of the H$_2$O masers (Carrasco-González et al. 2008). These systematic motions could be indicative of the proper motion of the Perseus molecular cloud, itself. The larger proper motions for L 1448 C than NGC 1333 SVS 13 might be caused by contamination of the jet motion. High-resolution interferometric observations of continuum emission from YSOs at the centimeter, millimeter, and submillimeter wavelengths with EVLA and ALMA will be crucial to distinguish the contribution from the proper motions of outflows, stars, and host clouds.

We are grateful to the staff of all the VERA stations for their assistance in observations. TH is financially supported by Grant-in-Aids from the Ministry of Education, Culture, Sports, Science and Technology (13640242, 16540224, and 20740112).

References

Bachiller, R., André, P., & Cabrit, S. 1991, A&A, 241, L43
Bachiller, R., Cernicharo, J., Martín-Pintado, J., Tafalla, M., & Lazareff, B. 1990, A&A, 231, 174
Bachiller, R., Guilloteau, S., Dutrey, A., Planesas, P., & Martin-Pintado, J. 1995, A&A, 299, 857
Bally, J., Lada, E. A., & Lane, A. P. 1993, ApJ, 418, 322
Barsony, M., Ward-Thompson, D., André, P., & O’Linger, J. 1998, ApJ, 509, 733
Carrasco-González, C., Anglada, G., Rodríguez, L. F., Torrelles, J. M., & Osorio, M. 2008, AJ, 136, 2238
Černis, K. 1990, Ap&SS, 166, 315
Černis, K. 1993, Baltic Astron., 2, 214
Chemin, L. M. 1995, ApJ, 440, L97
Chikada, Y., et al. 1991, in Frontiers of VLBI, ed. H. Hirabayashi et al. (Tokyo: Universal Academy Press), 79
Claussen, M. J., Wilking, B. A., Benson, P. J., Wootten, A., Myers, P. C., & Terebey, S. 1996, ApJS, 106, 111
Curiel, S., Raymond, J. C., Rodríguez, L. F., Cantó, J., & Moran, J. M. 1990, ApJ, 365, L85
Dame, T. M., et al. 1987, ApJ, 322, 706
de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354
Desmurs, J.-F., Codella, C., Santiago-García, J., Tafalla, M., & Bachiller, R. 2009, A&A, 498, 753
Enoch, M. L., et al. 2006, ApJ, 638, 293
Evans, N. J., II, et al. 2003, PASP, 115, 965
Girart, J. M., & Acord, J. M. P. 2001, ApJ, 552, L63
Herbig, G. H., & Jones, B. F. 1983, AJ, 88, 1040
Hirano, N., Ho, P. T. P., Liu, S.-Y., Shang, H., Lee, C.-F., & Bourke, T. L. 2010, ApJ, 717, 58
Hirota, T., et al. 2007, PASJ, 59, 897
Hirota, T., et al. 2008a, PASJ, 60, 37
Hirota, T., et al. 2008b, PASJ, 60, 961
Honma, M., et al. 2003, PASJ, 55, L57
Honma, M., et al. 2007, PASJ, 59, 889
Honma, M., et al. 2008a, PASJ, 60, 935
Honma, M., Tamura, Y., & Reid, M. J. 2008b, PASJ, 60, 951
Iguchi, S., Kurayama, T., Kawaguchi, N., & Kawakami, K. 2005, PASJ, 57, 259
Imai, H., et al. 2007, PASJ, 59, 1107
Jørgensen, J. K., et al. 2006, ApJ, 645, 1246
Kim, M. K., et al. 2008, PASJ, 60, 991
Loinard, L., Mioduszewski, A. J., Rodríguez, L. F., González, R. A., Rodríguez, M. I., & Torres, R. M. 2005, ApJ, 619, L179
Loinard, L., Torres, R. M., Mioduszewski, A. J., & Rodríguez, L. F. 2008, ApJ, 675, L29
Loinard, L., Torres, R. M., Mioduszewski, A. J., Rodríguez, L. F., González-Lópezlira, R. A., Lachaume, R., Vázquez, V., & González, E. 2007, ApJ, 671, 546
Lynds, B. T. 1962, ApJS, 7, 1
Marvel, K. B., Wilking, B. A., Claussen, M. J., & Wootten, A. 2008, ApJ, 685, 285
Menten, K. M., Reid, M. J., Forbrich, J., & Brunthaler, A. 2007, A&A, 474, 515
Moscadelli, L., Reid, M. J., Menten, K. M., Brunthaler, A., Zheng, X. W., & Xu, Y. 2009, ApJ, 693, 406
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Petrov, L., Hirota, T., Honma, M., Shibata, K. M., Jike, T., & Kobayashi, H. 2007, AJ, 133, 2487
Petrov, L., Kovalev, Y. Y., Fomalont, E. B., & Gordon, D. 2006, AJ, 131, 1872
Reipurth, B., Rodríguez, L. F., Anglada, G., & Bally, J. 2002, AJ, 124, 1045
Ridge, N. A., et al. 2006, AJ, 131, 2921
Sandstrom, K. M., Peek, J. E. G., Bower, G. C., Bolatto, A. D., & Plambeck, R. L. 2007, ApJ, 667, 1161
Tobin, J. J., Looney, L. W., Mundy, L. G., Kwon, W., & Hamidouche, M. 2007, ApJ, 659, 1404
Torres, R. M., Loinard, L., Mioduszewski, A. J., & Rodríguez, L. F. 2007, ApJ, 671, 1813
Torres, R. M., Loinard, L., Mioduszewski, A. J., & Rodríguez, L. F. 2009, ApJ, 698, 242
Ulich, B. L., & Haas, R. W. 1976, ApJS, 30, 247