Distance to Orion KL Measured with VERA

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Abstract

We present the initial results of multi-epoch VLBI observations of the 22 GHz H2O masers in the Orion KL region with VERA (VLBI Exploration of Radio Astrometry). With the VERA dual-beam receiving system, we have carried out phase-referencing VLBI astrometry and successfully detected an annual parallax of Orion KL to be 2.29±0.10 mas, corresponding to the distance of 437±19 pc from the Sun. The distance to Orion KL is determined for the first time with the annual parallax method in these observations. Although this value is consistent with that of the previously reported, 480±80 pc, which is estimated from the statistical parallax method using proper motions and radial velocities of the H2O maser features, our new results provide the much more accurate value with an uncertainty of only 4%. In addition to the annual parallax, we have detected an absolute proper motion of the maser feature, suggesting an outflow motion powered by the radio source I along with the systematic motion of source I itself.

Key words: Astrometry: — ISM: individual (Orion KL) — masers (H2O) — radio lines: ISM — ISM: jets and outflows

1. Introduction

Distance is one of the most fundamental parameters in astronomy. However, it has been difficult to measure accurate distances to stars, galaxies, and other astronomical objects without assumptions. The most reliable way to determine the distance is an annual trigonometric parallax method, based on precise measurements of position and motion of the object. In 1990’s, the Hipparcos satellite extensively measured annual parallaxes for more than 100 000 stars with a typical precision of 1 mas level (Perryman et al. 1995, 1997), which allowed us...
to refine various fields of astronomy and astrophysics. Nevertheless, the distances measured with Hipparcos were limited only within a few hundred pc from the Sun, which was far smaller than the size of the Galaxy, 15 kpc in radius.

In the last decade, phase-referencing VLBI astrometry has been developed, with which the position of a target source is measured with respect to a reference source (Beasley & Conway 1995). Using extragalactic radio sources as the position references (e.g. sources listed in the ICRF catalog; Ma et al. 1998), we can measure the absolute position of the target source, which lead us to derive its annual parallax. With recent highly precise VLBI astrometry, annual parallaxes have been successfully measured for the Galactic CH$_3$OH maser sources at the 12 GHz band (Xu et al. 2006) and H$_2$O maser sources at the 22 GHz band (Kurayama et al. 2005; Hachisuka et al. 2006) with the NRAO Very Long Baseline Array (VLBA). The annual parallax measurements with VLBI have also been carried out for non-thermal radio continuum emission from young stellar objects (e.g. Lestrade et al. 1999; Loinard et al. 2005). The highest accuracy of these VLBI astrometry is reported to be 0.05 mas, which provides a powerful tool to measure annual parallaxes with the accuracy by two orders of magnitude higher than that of the Hipparcos satellite, allowing us to measure the distances of maser sources up to 2 kpc away from the Sun (Kurayama et al. 2005; Xu et al. 2006; Hachisuka et al. 2006).

In order to extend the VLBI astrometry of maser sources to the whole region of the Galaxy, we have constructed a new VLBI network in Japan called VERA, VLBI Exploration of Radio Astrometry (Kobayashi et al. 2003), which is the first VLBI array dedicated to phase-referencing observations. Each VERA antenna is equipped with a unique dual beam receiving system (Kawaguchi et al. 2000; Honma et al. 2003), which enables us to observe the target and reference sources within 2.2 degrees separation on the sky simultaneously, thus facilitating more efficient phase-referencing VLBI observations compared with the conventional fast-switching observations. Very recently, the first results of astrometry with VERA have been reported (e.g. Honma et al. 2007; Sato et al. 2007), demonstrating its high capability of annual parallax and absolute proper motion measurements. The main goal of the VERA project is to reveal 3-dimensional Galactic structure and kinematics based on the accurate astrometry of hundreds of H$_2$O (at the 22 GHz band) and SiO (at the 43 GHz band) maser sources in the Galactic star-forming regions and late-type stars with the highest accuracy of 10 $\mu$as level (Kobayashi et al. 2003; Honma et al. 2000).

In this paper, we present the initial results of the annual parallax measurements of Orion KL. Because Orion KL is the nearest high-mass star-forming region located at an estimated distance of only 480 pc from the Sun (Genzel et al. 1981), it has been recognized as one of the most important objects to study high-mass star-formation processes (e.g. Genzel & Stutzki 1989). Along with its proximity to the Sun, Orion KL is known to be one of the brightest H$_2$O maser sources in the Galaxy, and hence, it is the best test bench for the first stage of the annual parallax measurements with VERA.

2. Observations and Data Analyses

Observations of H$_2$O masers (6$_{15}$-$5_{23}$, 22235.080 MHz) in Orion KL were carried out in 19 observing sessions from Jan. 2004 to Jul. 2006 with VERA. In this paper, we employed the results of total 16 observing sessions which were carried out under relatively good weather conditions. A typical interval of observations was 1 month, while some of them, especially in the summer season, were a few months. All the 4 stations of VERA were used in most of the observing sessions, while only 3 stations were used in part of the sessions (2004/027, 2004/272, and 2004/333; hereafter an observing session is denoted by year/day of the year). The maximum baseline length was 2270 km (see Fig.1 of Petrov et al. 2007) and the typical synthesized beam size (FWHM) was 1.5 mas $\times$ 0.8 mas with a position angle of $-30$ degrees.

All the observations were made in the dual beam mode; Orion KL and an ICRF source J0541$-$0541 ($\alpha$(J2000) =05h41m38.08385s, $\delta$(J2000) = $-05d41.49.42839^\circ$; Ma et al. 1998; Petrov et al. 2007) were observed simultaneously. The separation angle between them was 1.62 degrees. J0541$-$0541 was detected fringes with a flux density of about 500 mJy in all the observations, which was suitable as a phase reference source. The instrumental phase difference between the two beams was measured in real time during the observations, using the correlated data of the random signal from artificial noise sources injected into two beams at each station (Kawaguchi et al. 2000). The typical value of the phase drift between the two beams was 3 degrees per hour. These results were used for calibrating instrumental effects in the observed phase difference between the two sources.

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 16 MHz bandwidth each were assigned to Orion KL and J0541$-$0541, respectively. In the earlier eight observing sessions from 2004/203 to 2005/144, we used the recording system at a rate of 128 Mbps, with two IF channels of 16 MHz bandwidth each for both Orion KL and J0541$-$0541. A bright continuum source, J0530+1331, was observed every 1-2 hours for bandpass and delay calibration. System temperatures including atmospheric attenuation were measured with the chopper-wheel method (Ulich & Haas 1976) to be 100-600 K, depending on weather conditions and elevation angle of the observed sources. The aperture efficiencies of the antennas ranged from 45 to 52% depending on the stations. A variation of the aperture efficiency of each antenna as a function of elevation angle was confirmed.
to be less than 10% even at the lowest elevation in the observations (\(\sim 20\) degrees).

Correlation processing was carried out on the Mitaka FX correlator (Chikada et al. 1991) located at the NAOJ Mitaka campus. For H$_2$O maser lines, a spectral resolution was set to be 15.625 kHz, corresponding to the velocity resolution of 0.21 km s$^{-1}$. The effective velocity coverage for the H$_2$O maser lines, which was common for all the observing sessions, was \(\pm 40\) km s$^{-1}$ relative to the systemic velocity of Orion KL, an LSR velocity of 8 km s$^{-1}$.

Calibration and imaging were performed using the NRAO Astronomical Image Processing System (AIPS). At first, amplitude and bandpass calibration were done for each target (Orion KL) and reference source (J0541–0541) independently. Then fringe fitting was made with the AIPS task FRING on the phase reference source (J0541–0541), and the phase solutions were applied to the target source (Orion KL). In addition, we adopted the results of dual-beam phase calibration measurements as described above (Kawaguchi et al. 2000).

Because the a priori delay model applied in the correlation processing was not accurate enough for precise astrometry, we calibrated the visibility phase using the more accurate delay model, based on the recent achievements of geodynamics (Honma et al. 2007) in the analyses. In this model, we calibrated the fluctuation of the visibility phase caused by the Earth’s atmosphere based on the GPS measurements of the atmospheric zenith delay due to the tropospheric water vapor.

The synthesized images were made using the AIPS task IMAGR with natural weighting. Even after the phase calibrations described above, we found that the dynamic range of the phase-referenced images was not high enough, possibly due to a residual in the atmospheric zenith delay, as pointed out by Honma et al. (2007). To improve the quality of these images, we estimated the atmospheric zenith delay residual as a constant offset for each station, which maximized the coherence of the resultant phase-referenced image. The atmospheric zenith delay residual was derived to be 0–10 cm on average, depending on the weather conditions, while it exceeded 20 cm in the worst case. As a result of this calibration, the dynamic range of each phase-referenced image was increased by a factor of up to 1.5.

3. Results

Figure 1 shows the cross power spectra of the H$_2$O masers toward Orion KL. The H$_2$O maser lines were detected within the LSR velocity range from \(-10\) km s$^{-1}$ to 40 km s$^{-1}$. We could not find high-velocity components in the LSR velocity of \(>40\) km s$^{-1}$ and \(<-10\) km s$^{-1}$ (Genzel et al. 1981) possibly due to our narrower effective velocity coverage (from \(-32\) to 48 km s$^{-1}$) and lower sensitivity.

In order to reveal the overall distribution of the H$_2$O masers, we first mapped the H$_2$O maser features in the Orion KL region at one of the observed sessions, 2005/081, by the method adopted in usual single-beam VLBI observations. The H$_2$O maser features are found to be extended over the 20” \(\times\) 30” region as shown in Figure 2. The distribution of H$_2$O maser features is in good agreement with those in Genzel et al. (1981) and Gaume et al. (1998). The number of H$_2$O maser features near source I, which is proposed to be a powering source of the outflow and the H$_2$O masers (Menten & Reid 1995; Greenhill et al. 1998), is smaller than that of the results of the NRAO Very Large Array (VLA) observations reported by Gaume et al. (1998). This is because most of the maser features near source I are resolved out with the synthesized beam of VERA, implying that their sizes are larger than a few mas (Genzel et al. 1981; Gaume et al. 1998).

Based on the H$_2$O maser map at the epoch of 2005/081, we searched for intense H$_2$O maser features whose cross power spectra observed with the Mizusawa-Iriki baseline (1267 km; see Fig.1 of Petrov et al. 2007) were detected with a signal to noise ratio larger than 10 at all the 16 observing epochs. We found that 10 maser features satisfied this criterion. Among them, we analyzed the data for one of the maser features at the LSR velocity of about 25 km s$^{-1}$, which was redshifted relative to that of the systemic velocity of Orion KL, an LSR velocity of 8 km s$^{-1}$, showing relatively less significant spatial structure in the synthesized images and the closure phases during all the observing sessions. Since the peak velocity of the maser feature was shifted systematically from 25.7 km s$^{-1}$ to 24.5 km s$^{-1}$ during the observing period of 2 years, we made images of maser spots for all the spectral channels within the velocity range of 24.5–25.7 km s$^{-1}$, and determined the position of the maser feature taking that of the
In this paper, we successfully measured the annual parallax of Orion KL. Assuming that the movement of the maser feature is the sum of linear motion and the annual parallax, we can obtain the proper motion in right ascension \( \mu_\alpha \) and declination \( \mu_\delta \), the initial position in right ascension \( \alpha_0 \) and declination \( \delta_0 \), and the annual parallax \( \pi \) for the maser feature by a least-squares analysis.

Initially, we determined these 5 parameters simultaneously, using both right ascension and declination data. In this case, the derived annual parallax was \( 2.29 \pm 0.21 \) mas, corresponding to the distance of \( 445 \pm 42 \) pc, and the standard deviations of the least-squares analysis in right ascension \( \sigma_\alpha \) and in declination \( \sigma_\delta \) were \( 0.36 \) mas and \( 0.74 \) mas, respectively. The larger standard deviation in declination suggests that the astrometric accuracy in the declination is significantly worse than that in the right ascension. This trend can be seen in other observations with VERA (Honma et al. 2007; Sato et al. 2007). One of the possible reasons for this is that the residual of the atmospheric zenith delay would affect the astrometric accuracy, as discussed later. Therefore, we at first determined the absolute proper motion and initial position in right ascension together with the annual parallax using the data for right ascension only. As a result, we obtained the annual parallax with higher precision to be \( 2.29 \pm 0.10 \) mas, corresponding to the distance of \( 437 \pm 21 \) pc. After the annual parallax was derived from the right ascension data, we estimated the absolute proper motion and initial position in declination using the data for declination. The results are summarized in Table 1.

### Table 1. Results of the least-squares analysis for the annual parallax and proper motion measurements

| Parameter | Best fit value |
|-----------|----------------|
| \( \pi \) | 2.29(0.10) mas |
| \( \mu_\alpha \) | 2.77(0.09) mas yr\(^{-1} \) |
| \( \mu_\delta \) | -8.97(0.21) mas yr\(^{-1} \) |
| \( \sigma_\alpha \) | 0.36 mas |
| \( \sigma_\delta \) | 0.74 mas |

Note — Numbers in parenthesis represent the estimated uncertainties. Annual parallax \( \pi \) is derived from the right ascension data only.

4. **Discussions**

#### 4.1. Astrometric error sources

In this paper, we successfully measured the annual parallax of Orion KL to be \( 2.29 \pm 0.10 \) mas through the 2-year monitoring observations of the \( \text{H}_2\text{O} \) maser feature with VERA. The sinusoidal curve of the movement of the maser feature as shown in Figure 3 is almost coincident with the predicted annual parallax of Orion KL both in period (1 year) and phase (date of the peaks in the sinusoidal curve). Therefore, the deviation from the best fit model, which is the combination of annual parallax and linear proper motion of the maser feature, should be regarded as astrometric errors in our observations, rather than observational errors. These errors are summarized in Table 1.
than due to an inappropriate model in the least-squares analysis. In this section, we will consider possible sources of these astrometric errors.

As reported previously in the literature (Kurayama et al. 2005; Hachisuka et al. 2006; Honma et al. 2007; Sato et al. 2007), it is difficult to estimate the individual error sources in the VLBI astrometry quantitatively. We therefore estimate the uncertainties in the measured position of the maser feature to be 0.36 mas and 0.74 mas in right ascension and declination, respectively, based on the standard deviations of the least-squares analysis as listed in Table 1. The standard deviations obtained in this paper are larger than those of previous observations with VERA (Honma et al. 2007; Sato et al. 2007), especially in declination.

The most serious error source in the VLBI astrometry in the 22 GHz band is likely to be the atmospheric zenith delay residual due to the tropospheric water vapor. This is caused by the difference in the optical path lengths through the atmosphere between the target and reference sources because the elevation angle of the target source is usually different from that of the reference source. According to the discussions in Honma et al. (2007), a path length error due to the atmospheric zenith delay residual of 3 cm would cause a position error of 0.04-0.12 mas in the case of a separation angle between the target and reference sources of 0.7 degrees at the elevation angle of 20-90 degrees. If we consider an extreme example, with the observed elevation angle of 20 degrees and the atmospheric zenith delay residual of 10 cm, the position error in the observations of Orion KL and J0541−0541, with a separation angle of 1.62 degrees, is estimated to be 0.75 mas. This value is clearly overestimated because the path length errors should be suppressed at the higher elevation angle. Furthermore, the atmospheric zenith delay residual of 10 cm is unrealistic because we have corrected such a large residual before phase-referencing imaging. Therefore, the atmospheric zenith delay residual alone
cannot fully explain our position errors, although it would contribute to the large part of the error source in our astrometry, especially in declination.

One of other possibilities for the error sources in the observed position is a variation of the structure in the maser feature. With regard to this, we confirmed that peak positions of the maser spots within the analyzed maser feature were sometimes shifted by about 0.2 mas from those of the adjacent channels. In addition, the systematic velocity shift from 25.7 km s\(^{-1}\) to 24.5 km s\(^{-1}\) was observed during the observing period of 2 years, indicating the variation of the maser feature. Although there is no reason that the structure in the maser feature affects the astrometric accuracy only in declination, it would be one of the major sources of errors in the astrometry with the H\(_2\)O maser lines as well as the atmospheric zenith delay residual. The effect of the spatial structure of the maser feature is more significant for Orion KL than the other sources (Kurayama et al. 2005; Hachisuka et al. 2006; Honma et al. 2007; Sato et al. 2007) because the distance to Orion KL (437 pc) is nearer than the others by a factor of 2-5 kpc. However, this effect is inversely proportional to the distance to the target source just the same as its annual parallax. This means that the annual parallaxes of the more distant sources can be measured with almost the same precision as in the case of Orion KL, if the dominant error source in astrometry is due to the structure effect rather than the atmospheric zenith delay residual. In fact, the relative uncertainty in the annual parallax of the further source, S269, is found to be comparable to that of Orion KL, about 4\%, in the case of using the data for right ascension only (Honma et al. 2007). Further VLBI observations of maser features with shorter baselines should be able to confirm this effect, with which more extended structures of maser features are imaged.

On the other hand, the variation of the structure of the reference source, J0541–0541, would be negligible for the measurements of the annual parallax and proper motion because we found no evidence for significant structure of J0541–0541 in our observations. The uncertainty in the absolute position of the reference source J0541–0541, 0.28 mas and 0.46 mas in right ascension and declination, respectively (Ma et al. 1998), also does not affect the derived annual parallax and proper motion because this uncertainty gives only a constant offset to the position of the maser feature. According to the discussions in Honma et al. (2007), astrometric errors in the VERA observations arising from uncertainties in the station position, delay model, and path length errors due to ionosphere are estimated to be smaller by an order of magnitude, and hence, they do not have significant effects on astrometric accuracy. Therefore, we conclude that the major sources of our astrometric errors are due to the atmospheric zenith delay residual and variability of the structure of the maser feature.

4.2. Annual Parallax and Distance to Orion KL

We successfully obtained the annual parallax of Orion KL to be 2.29±0.10 mas, corresponding to the distance of 437±19 pc. This is the first time that the distance to Orion KL is determined based on the annual parallax measurements. Genzel et al. (1981) derived the distance to Orion KL to be 480±80 pc from the statistical parallax method, using proper motions and radial velocities of the H\(_2\)O maser features. Our result is consistent with that of Genzel et al. (1981), although the accuracy of our measurements is significantly improved. The most important progress in our new results is due to the geometric nature of our measurements without any assumption unlike the statistical parallax method, in which appropriate kinematic modeling for Orion KL is required (Genzel et al. 1981). The accuracy of the annual parallax measurements in our study is limited mainly due to the atmospheric zenith delay residual and the structure of the maser feature, both of which are difficult to be predicted and measured completely in the current observational study. In principle, it will be possible to achieve much higher precision using the results of all the maser features in Orion KL, which will reduce the statistical error by a factor of \(N^{-0.5}\) where \(N\) represents the number of observed maser features. This expectation will be confirmed in the further analyses of the VERA observations.

4.3. Absolute Proper Motion of the Maser feature in Orion KL

Along with the annual parallax measurements, we successfully detected the absolute proper motion in

| Source Name | Absolute proper motion | Proper motion relative to source I |
|-------------|------------------------|----------------------------------|
|             | \(\mu_\alpha\) (mas yr\(^{-1}\)) | \(\mu_\delta\) (mas yr\(^{-1}\)) | \(\mu\) (mas yr\(^{-1}\)) | \(v_t\) (km s\(^{-1}\)) | \(\mu^I_\alpha\) (mas yr\(^{-1}\)) | \(\mu^I_\delta\) (mas yr\(^{-1}\)) | \(\mu^I\) (mas yr\(^{-1}\)) | \(v^I_t\) (km s\(^{-1}\)) |
| Maser       | 2.77(0.09)             | -8.97(0.21)                  | 9.39(0.20) | 19.7(0.4)\(^b\) | -0.7(0.7) | -4.6(0.7) | 4.6(0.7) | 9.7(1.5)\(^b\) |
| source I    | 3.5(0.7)               | -4.4(0.7)                   | 5.6(0.7)  | 12(2)\(^b\)    | 0.00      | 0.00      | 0.00      | 0.00        |

Note — Numbers in parenthesis represent the estimated uncertainties.

a: Absolute proper motion of source I is taken from Rodriguez et al. (2005).
b: Calculated assuming the distance of 437 pc.
our phase-referencing astrometry with VERA. Figure 2, Tables 1 and 2 show the absolute proper motion of the maser feature in Orion KL. At the distance of 437 pc, the proper motion of 1 mas yr$^{-1}$ corresponds to the transverse velocity of 2.1 km s$^{-1}$. The observed absolute proper motion of the H$_2$O maser feature (2.77±0.09 mas yr$^{-1}$ and −8.97±0.21 mas yr$^{-1}$ in right ascension and declination, respectively) corresponds to 9.39±0.20 mas yr$^{-1}$ or 19.7±0.4 km s$^{-1}$ toward south.

Recently, Rodríguez et al. (2005) and Gómez et al. (2005) measured the proper motion of radio continuum sources in the Orion KL region with the VLA, as shown in Figure 2 and Table 2. Subtracting the proper motion vector of source I from that of the observed maser feature, we can obtain the proper motion of the maser feature with respect to source I. As Gómez et al. (2005) have already mentioned, the precision of the absolute proper motion measurements by Rodríguez et al. (2005) is higher than that by Gómez et al. (2005). Therefore, we adopt the proper motion of source I inferred by Rodríguez et al. (2005), 3.5±0.7 mas yr$^{-1}$ and −4.4±0.7 mas yr$^{-1}$ in right ascension and declination, respectively. In the following discussions, the proper motion of the maser feature with respect to source I is inferred to be −0.7±0.7 mas yr$^{-1}$ and −4.6±0.7 mas yr$^{-1}$ in right ascension and declination, respectively, as listed in Table 2. The magnitude of the proper motion is 4.6±0.7 mas yr$^{-1}$ or 9.7±1.5 km s$^{-1}$ toward south with a position angle of −171 degrees, which agrees well with the direction of the outflow powered by source I. Therefore, we conclude that the absolute proper motion of the observed maser feature is the sum of outflow motion powered by source I and the systematic motion of source I itself.

However, a detailed model of the outflow powered by source I is still debatable. Greenhill et al. (1998) first proposed that the biconical high-velocity outflow traced by the SiO maser lines lies along the northwest-southeast direction, while the low-velocity equatorial outflow traced by the H$_2$O maser lines exists along the northeast-southwest direction. On the other hand, they changed the interpretation based on the recent results that the outflow is along the northeast-southwest direction, which is perpendicular to the first model, and that the SiO maser lines trace the edge-on disk perpendicular to the outflow (Greenhill et al. 2004). We cannot distinguish these two different models in this paper because the distribution of the H$_2$O masers, elongated along the northeast-southwest direction as shown in Figure 2, is consistent with both models and in addition, the proper motion of the observed H$_2$O maser feature is almost intermediate (toward south) between the proposed outflow axes (Greenhill et al. 1998, 2004). The velocity structure in the Orion KL region is quite complicated as Greenhill et al. (2004) suggested, and hence, further discussions about the proper motions of all the H$_2$O maser features are required to construct the detailed model of the outflow in the Orion KL region, which will be presented in a forthcoming paper.

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