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Parallax measurement of H_2O maser sources beyond 5 kpc with VERA

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We report on the parallax measurement of S269 H_2O maser with VERA (VLBI Exploration of Radio Astrometry). We have monitored the positions of S269 H_2O masers for 1 year with VERA, and successfully measured its parallax to be 189 ± 8 micro-arcsec. This corresponds to the source distance of $5.28^{+0.24}_{-0.22}$ kpc, and is the smallest parallax (and thus the largest distance) ever measured by means of trigonometric parallax. We also discuss the constraints on the Galactic rotation speed obtained from the proper motion of S269.

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1. Introduction

Galaxy-scale astrometry still remains unexplored and is regarded as an issue to be tackled in next decades. In fact, there will be new satellite projects for Galaxy-scale astrometry such as SIM, GAIA and JASMINE aiming at 10 μarcsec accuracy. These are satellite-type missions with optical telescopes orbiting the Earth, where observations are free of a disturbance caused by the atmosphere. High-precision astrometry is also a challenge for ground-based radio observations using VLBI, which provide the highest angular resolution among the existing telescopes at any wavelength. However, normal VLBI observations directly suffer from the fluctuations of the atmosphere, mainly due to the water vapour content of the troposphere. In order to overcome this problem, namely to cancel out the tropospheric fluctuation, phase-referencing has been developed. In phase-referencing observations, a few sources (one target and one or more reference sources) are observed quasi simultaneously by means of fast switching between them, and then relative positions of the target with respect to the reference can be measured without the influence of the troposphere. Indeed, recently, Xu et al.(2006) and Hachisuka et al.(2006) presented the distance measurements of Galactic star-forming region W3 made with the VLBA, and solved the long-standing distance ambiguity of Perseus arm by measuring the source distance of 2 kpc with a few percent accuracy. These results demonstrate the promising future of ground-based VLBI as a tool of Galaxy-scale astrometry.

VERA (VLBI Exploration of Radio Astrometry) is a new Japanese VLBI array dedicated to VLBI astrometry (Honma et al. 2000; Kobayashi et al. 2003). Very uniquely, VERA telescopes are equipped with dual-beam systems allowing us to simultaneously observe a target and a reference within 2.2 degree. Such dual-beam systems enable to cancel out tropospheric fluctuations much more effectively than switching observations with standard single-beam telescopes. Thus, VERA can be regarded as an ultimate array for phase-referencing VLBI astrometry. With target accuracy of 10 μarcsec, VERA will be able to locate precisely $\sim$1000 maser sources in the Galaxy, revealing 3D structure and dynamics of the Galaxy, including an accurate determination of Galactic rotation curve, the key to understanding the dark matter distribution in the Galaxy. The VERA array was constructed by 2002, and regular observations have been conducted since autumn of 2003. Here, we present one of the initial results of high-precision astrometry with VERA, reporting on the parallax detection of Galactic star-forming region S269. It is the smallest parallax ever measured.

2. Observations and data reductions

S269 is a Galactic star-forming region towards the anticentre region located at (l, b)=(196.45°, $-$1.67°). VERA observations of S269 H_2O maser have been carried out on a regular basis since November 2004 with typical intervals of 1 to 2 months. In the present paper, we deal with the data of 6 epochs obtained with the full 4-station array (Mizusawa, Iriki, Ogasawara, and Ishigaki-jima) under relatively good conditions. The epochs are day of year (DOY) 323 in 2004, DOY 026, 073, 134, 266 and 326 in 2005 (18 Nov 2004, 26 Jan, 14 Mar, 14 May, 23 Sep and 21 Nov. 21 2005), spanning 1 year. At each epoch, S269 H_2O maser at 22 GHz [1] and a position reference source J0613+1306 were simultaneously observed in dual-beam mode for 9 hours. J0613+1306

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[1] The precise rest frequency of H_2O $6_{16} - 5_{23}$ transition is 22.235080 GHz.

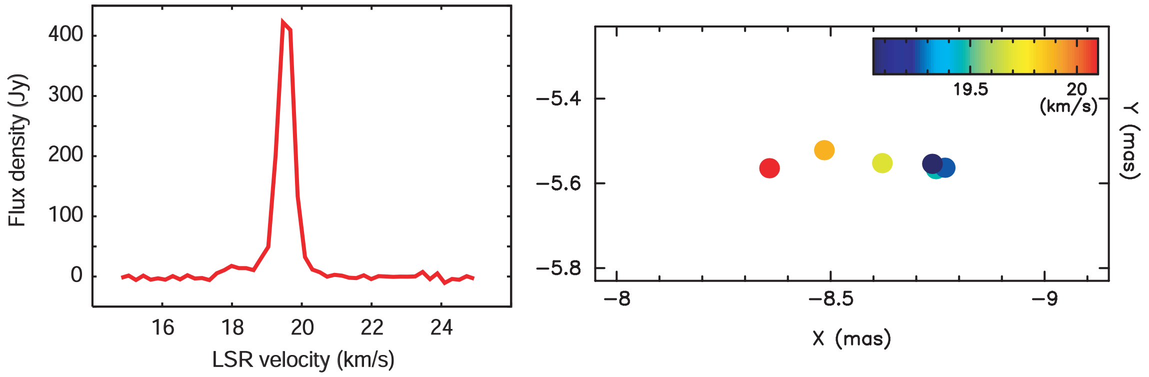

Figure 1: (a, left): the total power spectrum of S269 H_2O maser on DOY 073 in 2005. (b, right): VLBI map of H_2O maser spot distributions (also on DOY 073 in 2005).

is one of ICRF sources and has a flux density of about 300 mJy at 22 GHz, being bright enough to be detected within a typical coherence time at 22 GHz (2 – 3 minutes). The angular separation between the maser and the reference source is 0.73 degree. Left-hand circular polarization signals were received and digitally recorded on magnetic tapes with the VERA terminal. With a data rate of 1024 Mbps, the VERA terminal recorder (SONY DIR2000) provides a total bandwidth of 256 MHz (2-bit quantization). The signals from the two sources are digitally filtered to obtain one 16-MHz channel for S269 maser and fifteen 16-MHz channels for J0613+1306. Correlation processing was done with the Mitaka FX correlator, providing frequency and velocity resolutions for H_2O masers of 15.625 kHz and 0.21 km s^{-1}, respectively.

Since the correlator *a priori* delay model is not accurate enough for high precision astrometry, recalculations of precise delay were made after the correlation, and correlated visibilities were corrected for the difference between the first (rather crude) *a priori* model and the second (more accurate) delay model. The recalculation code is based on the geodynamics models described in IERS conventions 1996, and earth orientation parameters (EOP) were taken from IERS bulletin B final values, which currently provides the best estimates of EOP. Tropospheric zenith delays were estimated by GPS data recorded at each station. Also, ionospheric delays were corrected for, based on the global ionosphere map (GIM) provided by University of Bern on a daily basis.

As a first step of the data analysis for each epoch, fringes were searched for the reference continuum source J0613+1306. Since its position is known accurately, the fringe parameters of J0613+1306 were also used to calibrate clock offset parameters (such as delay and delay-rate offset). The phase solutions for J0613+1306 were converted into phases at observed maser frequency, and applied to visibilities of S269 together with dual-beam phase calibration data. Those dual-beam phase calibration data were taken in real-time during the observations, based on the correlation of artificial noise sources injected into both beams at each station. After those calibrations had been made, visibilities of S269 masers were Fourier transformed to synthesize images, and the positions of the brightness peaks were determined. In some seasons (especially in summer), the quality of phase-referenced map was not high, possibly because of residuals in tropospheric delay that still remains even after calibrations based on the GPS data had been made. To calibrate them, residual zenith delay at each station was re-estimated as a constant offset that maximizes the coherence of

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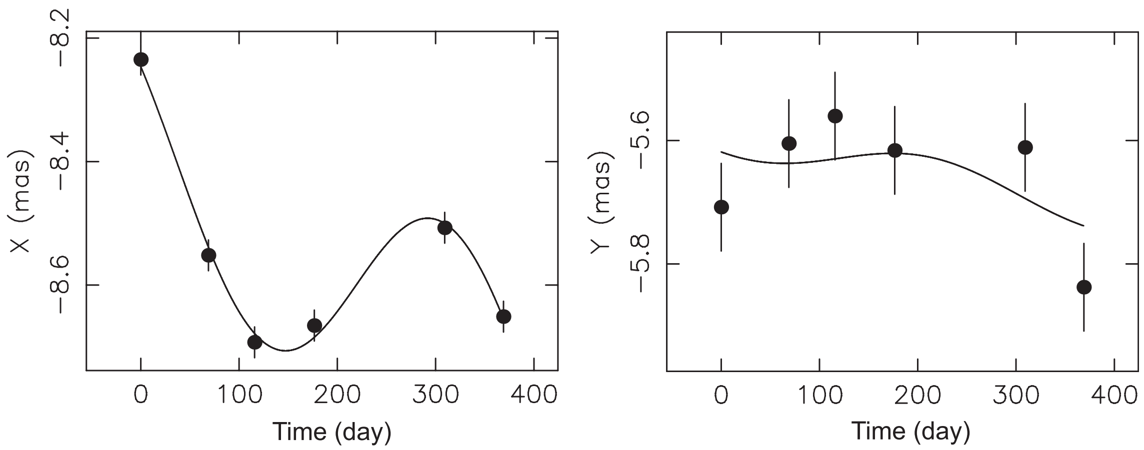

Figure 2: Motions of the brightest maser spot in S269. Left panel is for X component (the east-west direction), and right is for Y component (the north-south direction). X component clearly shows annual modulation, which is the parallax of S269. Note that positions are relative to the tracking centre position (RA=06h14m37.08s, Dec=+13°49′36.″7) in J2000 coordinates.

the phase-referenced map. Typical re-estimated values of zenith delay offsets range from 1 to 5 cm.

3. Parallax measurements

Figure 1(a) shows the total-power spectrum of S269 on DOY 073 in 2005. It consists of a single feature at $V_{\rm LSR}$ of 19.5 km s^{-1} with a velocity width of 1 km s^{-1}. This main feature was always bright and observable during all the epochs presented here. Figure 1(b) is the maser spot map of the main feature taken on DOY 073 in 2005. Six maser spots have been detected. They are aligned in the east-west direction with a scale of 0.4 mas making a pattern of a simple velocity gradient. It is remarkable that the thickness of the feature (spots distribution in the north-south direction) is only $\sim 50\ \mu$as, 10 times smaller than the width in the east-west direction. Note that positions in figure 1(b) are the residuals relative to the tracking centre positions of the maser source S269, which are assumed to be (RA=06h14m37.08s, Dec=+13°49′36.″7) in J2000 coordinates. Thus, the absolute position of the brightest spot at 19.5 km s^{-1} on DOY 073 of 2005 has been calculated to be (RA=06h14m37.0793s, Dec=+13°49′36.″694) with an uncertainty of 1 mas, which mainly comes from the uncertainty of absolute position of the calibrator J0613+1306. The absolute position of the maser feature shown in figure 1(b) agrees well with the position of IRS2w, which is the most luminous infrared source in the S269 region (Jiang et al. 2003).

Astrometric results for the main feature are presented in figure 2. The figures show variation of the position with time in both X and Y directions for monitoring campaign spanning over one year. As clearly seen in the X-component plot, the position shows systematic sinusoidal variation with a period of 1 yr, which is obviously the parallax of S269. Here, we use only X component to determine the parallax of S269, because: 1) the Y-direction error is large and 2) S269 is near the ecliptic and so the parallax ellipse is highly elongated in the X direction, making the Y-contribution to parallax smaller. Based on the best-fit to the brightest three spots (at the radial velocity from 19.4 to 19.8 km s^{-1}), the parallax of S 269 has been determined to be 189 ± 8 μas, which corresponds to the source distance of $5.28^{+0.24}_{-0.22}$ kpc. It is the smallest parallax measured to date, and this result demonstrates the high capability of VERA to perform the Galactic-scale astrometry. The distance to S269 has been found to be slightly larger than previous estimates of $\sim$4 kpc (e.g., Moffat et al. 1979).

In figure 2, error bars represent the standard deviation from the best fit to the parallax plus linear proper motions. The estimated error bars are 25 μas for X and 75 μas for Y. It is remarkable that the error in Y is three times larger than that in X. The magnitude of both errors (as well as their ratio) can be explained assuming that the major share of the error budget belongs to the uncertainty of the tropospheric zenith delay. For instance, an uncertainty of 3 cm of the tropospheric zenith delay causes a path length difference of 0.4 mm (= 30 mm /0.7 deg, where 0.7 deg is the separation between S269 and the calibrator) between the two sources. This uncertainty of the path length difference roughly corresponds to 40 μas (=$0.4/2.3\times10^9$, where $2.3\ \times10^9$ mm is the maximum baseline length of VERA array). In practice, the effect of zenith delay error is multiplied by a factor of 1 to 3 depending on the source declinations and observing elevation angles. If this factor is taken into account, one can expect an astrometric error close to the value obtained above ($\sim$ 75 μas). Apart from that, astrometric error in the X direction can be suppressed thanks to two favourable circumstances: firstly, the source pair considered here has smaller separation in X direction compared to Y (i.e., north-south pair), and secondly, the observational *u*–*v*–*w* tracks are roughly symmetric with respect to the meridian transit, and this symmetry can help to reduce the astrometric error in the X direction caused by the tropospheric zenith delay offset.

The average proper motion components of the three brightest spots are as follows: $\dot{X} = -0.422 \pm 0.010$, $\dot{Y} = -0.121 \pm 0.042$ mas yr^{-1}. To convert these observed (heliocentric) proper motions to the ones with respect to LSR, we use the solar motion determined from the HIPPARCOS satellite data (Dehnen & Binney 1998), which is (u, v, w)=(10.0, 5.25, 7.17) km s^{-1}. Using the distance of 5.28 kpc obtained above, these proper motions correspond to velocities in the galactic coordinates (v_l, v_b)=(-4.60 ± 0.81, -3.72 ± 0.72) km s^{-1}, respectively. These velocity components are remarkably small compared to the rotation speed of the Galaxy, which is $\sim$ 200 km s^{-1}. The lack of large proper motion in b direction suggests that S269 basically follows the galactic rotation and its peculiar velocity is as small as 4 km s^{-1}. The small velocity in l direction indicates that the galactic rotation speed at S269 is similar to that at the Sun when one takes into account that S269 is located at the galactic anticentre.

If a source follows the Galactic rotation perfectly, the tangential velocity with respect to the LSR observer can be written as

$$v_l = \left(\frac{\Theta}{R} - \frac{\Theta_0}{R_0}\right) R_0 \cos l - \frac{\Theta}{R} D. \qquad (3.1)$$

This equation relates the observed tangential velocity to the rotation velocity at the source (Θ) through the Galactic constants R_0 and Θ_0. From the fact that the velocity component perpendicular to the Galactic plane is $\sim$4 km s^{-1}, we conservatively adopt here the possible range of the true tangential velocity as $v_l = -5 \pm 5$ km s^{-1}, and then, through equation (3.1), we find that the ratio of rotation velocity at S269 and that at the Sun ($\theta \equiv \Theta/\Theta_0$) is 1.00 ± 0.03. (Here the Galactic constant R_0 is assumed to be 8.0 ± 0.5 kpc (Reid 1993), and three values of Θ_0: 180, 200, and 220 km s^{-1} are considered but the results are almost independent of Θ_0.) Therefore, the rotation velocity at S269 must be the same as Θ_0 within 3% level, providing the strongest constraint on the rotation velocity in the outer Galaxy ever obtained. To date, the outer rotation curve has uncertainty up to 50 km s^{-1} in the outer area (e.g. Honma & Sofue 1997), whereas our constraint is as small as ~ 200 km s^{-1} $\times 3\% \approx 6$ km s^{-1} – an improvement by a factor of 5. The coincidence of rotation velocities at the Sun and S269 simply indicates that the rotation curve is flat, as is well known for rotation curves in other spiral galaxies.

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