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Galactic rotation measurements based on H_2O maser astrometry with VERA

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Abstract. We present results of astrometric observations of S269 H_2O maser performed with VERA (VLBI Exploration of Radio Astrometry). We have monitored the positions of S269 H_2O masers for 1 year and successfully detected its parallax to be 189 ± 8 micro-arcsecond. This corresponds to a source distance of $5.28^{+0.24}_{-0.22}$ kpc, and is the smallest parallax (and thus the largest distance) that has ever been measured by means of annual parallax. Proper motions of S269 H_2O maser were also measured and used to determine the Galactic rotation velocity at the position of S269. Our measurements show that the Galactic rotation velocity at S269 is the same to that at the Sun within 3%, indicating that the Galactic rotation curve is flat out to R$\sim$13 kpc.

Keywords. ISM:star forming regions — ISM:individual(Sharpless 269) — masers (H_2O) — VERA

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1. Introduction

VLBI astrometry of maser sources provide unique tools to explore the 3-D structure of the Galaxy. For instance, recent maser observations with VLBA proved that kpc-scale astrometry is possible with phase-referencing technic (Kurayama *et al.* 2005; Xu *et al.* 2006, Hachisuka *et al.* 2006). VERA (VLBI Exploration of Radio Astrometry) is a new Japanese VLBI array dedicated to VLBI astrometry (Honma *et al.* 2000, Kobayashi *et al.* 2003). With its dual-beam system, the VERA telescope has a capability to observe simultaneously a target and a reference source within 2.2 degrees. This dual-beam system allows us to cancel out tropospheric fluctuations effectively and to achieve an astrometry accuracy of 10 μas-level (Honma *et al.* 2003). With the accuracy at the 10 μas, VERA aims to precisely locate hundreds of maser sources and to explore the 3-D structure and dynamics of the Galaxy. The VERA projected was funded in 1999, and the construction of the array was started in 2000. At the time of the last maser meeting in Brazil in 2001, the array was under construction, and the construction status was reported at the meeting (Honma 2002). The VERA array was completed in 2002, and regular observations have been started since the fall of 2003. Here we present initial results of high precision astrometry with VERA toward the Galactic star forming region S269, in particular to do the parallax measurements and to constrain the Galactic rotation velocity in the outer Galaxy.

2. Astrometry of S269 H_2O maser

H_2O masers in the Galactic star forming region Sharpless 269 (S269) were regularly monitored with VERA since November of 2004. In this paper, we present the data of 6 epochs spanning nearly one year. At each epoch, the S269 H_2O maser at 22 GHz (rest frequency of 22.235080 GHz, H_2O 6_{16}-5_{23} transition) and an ICRF calibrator source J0613+1306 were simultaneously observed in dual-beam mode for nearly 9 hours. The separation angle between the maser and the reference source is 0.73 degree. Details of observations and data reductions are presented in Honma *et al.* (2007).

Figure 1(a) and 1(b) show the total-power spectrum of the S269 H_2O maser and the maser spot distribution on DOY (day-of-year) 073 in 2005. Six maser spots were detected in the velocity range from 19.0 to 20.1 km s^{-1}, and these maser spots are aligned in the east-west direction with a scale of 0.4 mas. Positions in Figure 1(b) are the residuals to the tracking center positions of the maser and the reference sources, which are taken to be (α, δ)=(06h14m37.08s, +13d49′36.7″) for S269, and (06h13m57.692764s, +13d06′45.40116″) for J0613+1306, both in J2000 coordinates. The absolute position of the S269 H_2O maser is consistent with the position of S269 IRS2w, which is the most luminous infrared star in the S269 YSO cluster (Jiang *et al.* 2003).

The positional variations of the brightest maser spot are shown in Figure 1(c) (for east-west offset, X) and figure 1(d) (for north-south offset, Y). The east-west position offsets clearly show a systematic sinusoidal modulation with a period of 1 yr, that is the parallax of S269. In this paper we use only the east-west component to determine the parallax of S269, partly because the Y-direction error is large and also because S269 is near the ecliptic and the parallax ellipse is highly elongated in the $X-$direction, making the contribution of Y to the parallax determination small. Based on least-squares fit to positions of the three brightest maser spots, the best estimate of the parallax π is obtained to be 189 ± 8 μas. This corresponds to a source distance of $5.28^{+0.24}_{-0.22}$ kpc, being the largest distance ever measured by means of trigonometric parallax. The distance to S269 is found to be slightly larger than previous estimates, which claimed a distance of $\sim$4 kpc (Moffat *et al.* 1979).

In addition to the source parallax, mean proper motions of the brightest three spots are obtained as (μ_X, μ_Y)=(-0.422 ± 0.010, -0.121 ± 0.042) mas yr^{-1}, respectively. Using the solar motion based on the HIPPARCOS satellite data (Dehnen & Binney 1998), the proper motions in the Galactic coordinate are obtained as (μ_l, μ_b)=(-0.184 ± 0.032, -0.149 ± 0.029) mas yr^{-1}. With the source distance of 5.28 kpc, these proper motions correspond to the velocity vector of (v_l, v_b)=(-4.60 ± 0.81, -3.72 ± 0.72) km s^{-1}.

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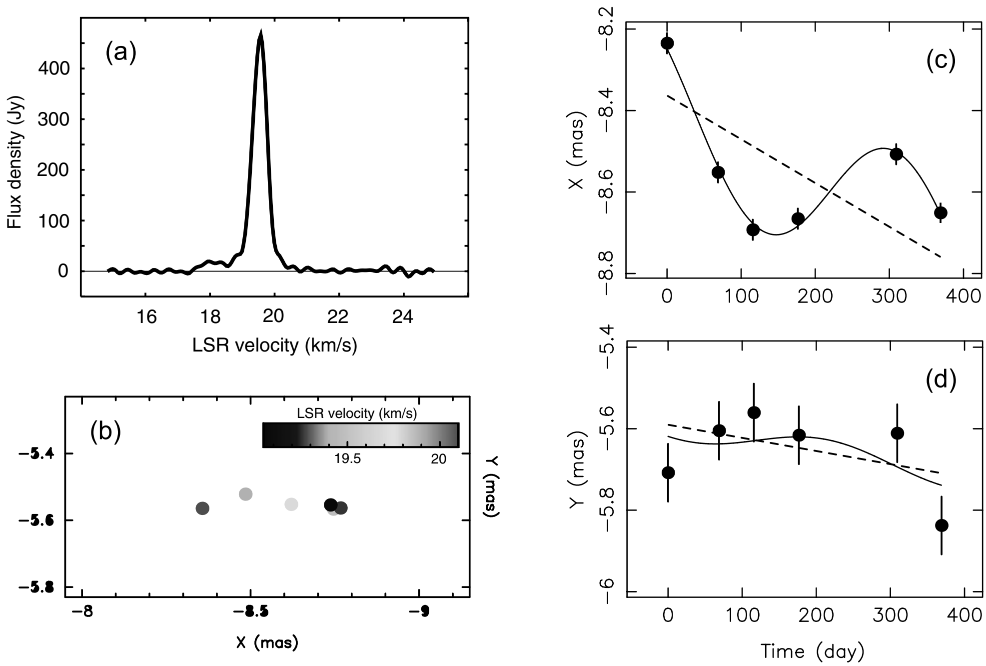

Figure 1. (a, top left) Auto-correlation spectrum of S 269 H_2O maser emissions taken on DOY 073 in 2005. (b, bottom left) maser spot distribution obtained with VERA on DOY 073 in 2005. The coordinates are with respect to the tracking center position, which is (06h14m37.08s, +13d49'36.7") in J2000. (c, top right) Positional variations of the brightest maser spot at $V_{\rm LSR}$=19.6 km $^{-1}$ for X (east-west) direction. (d, bottom right) the same plot for Y (north–south) direction. The time origin is the first epoch of our observations, which is DOY 323 in 2004. Solid curves are best-fit results with parallax and proper motions, and dashed lines show the best-fit proper motions.

3. Galactic rotation measurements

Here we use the proper motions and parallax obtained above to constrain the Galactic rotation velocity at the position of S269. The two velocity components (v_l, v_b)=$(-4.60 \pm 0.81, -3.72 \pm 0.72)$ km s^{-1}, are remarkably small compared to the rotation speed of the Galaxy, which is an order of ~ 200 km s^{-1}. The small proper motion perpendicular to the Galactic plane ($v_b = -3.72 \pm 0.72$ km s^{-1}) implies that S269 is basically on its galactic rotation and also that the H_2O maser proper motions truly reflect the systemic motion of S269. Then, given that S269 is located in the anti-center region ($l = 196°$), the small value of v_l indicates that the Galactic rotation velocity at the Sun and that at S269 are close to each other and proper motions were cancelled out in relative proper motion measurements. If a source is in perfect Galactic rotation, tangential velocity with respect to the LSR observer can be written as,

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

Using the above equation, the Galactic rotation velocity at the position of S269 is obtained as $\Theta = 1.00(\pm 0.03) \times \Theta_0$. Thus, the rotation velocity at the S269 (Θ) must be the same with Θ_0 within 3% level. This is the strongest constraint of the rotation velocity in the outer galaxy ever obtained.

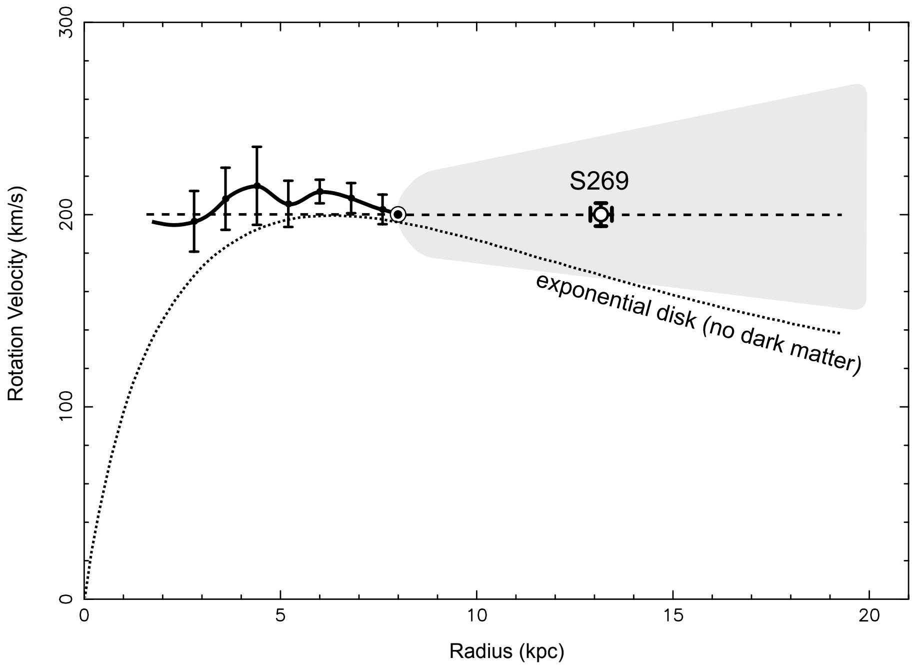

Figure 2. Rotation curve of the Galaxy obtained in the previous studies as well as the result from S269 using Galactic constants of R_0=8 kpc and Θ_0=200 km $^{-1}$. The dashed line is the flat rotation curve with Θ=200 km $^{-1}$, and the shadowed area shows the possible range of outer rotation curves in previous studies (Honma & Sofue 1997). Points at $R \leqslant 8$ kpc are inner rotation curves determined from the tangential velocities of Galactic HI gases (Honma & Sofue 1997), with a smoothed fit (thick curve). The dotted curve is the rotation curve for an exponential disk, corresponding to a constant mass-to-light ratio disk without dark matter. The discrepancy between the observed point for S269 and the exponential disk is evident, demonstrating the existence of large amount of dark matter in the outer region of the Galaxy.

In previous works, the Galactic rotation curve has an uncertainty up to 100 km s^{-1} in the outer region if one includes the strong dependence on the Galactic constant Θ_0 (Honma & Sofue 1997). This situation is summarized in Figure 2, showing the area of uncertainty in previous studies. The point for S269 determined in this study is also shown in figure 2. The coincidence of rotation velocities at the Sun and at S269 confirms the idea that the rotation curve of the outer Galaxy is basically flat, as widely known for other spiral galaxies (e.g., Rubin *et al.* 1980, Sofue & Rubin 2001). In disk galaxies like the Galaxy, optical surface brightness obeys an exponential law, i.e., $I(R) = I_0 \exp(-R/h)$, where R is the radius and h is the disk scale length. Assuming that the surface brightness traces the mass density (i.e., constant mass-to-light ratio), one can calculate the rotation curve of the optical disk without dark matter (Freeman 1970). In Figure 2, we also showed such a rotation curve for the Galaxy's disk, assuming the disk scale length of $h = 3$ kpc and the maximum rotation velocity of 200 km s^{-1}. Our measurements of S269 clearly rules out such a no-dark-matter case. At the position of S269, the rotation velocity of the exponential disk ($V_{\rm exp}$) is smaller than $V_{\rm obs}$ by 16%. The ratio of these two velocities gives $(V_{\rm exp}/V_{\rm obs})^2 = 0.70$, and hence, assuming a spherical mass distribution (where an enclosed mass can be estimated as $M \sim RV^2/G$), at least $\sim 30\%$ of the enclosed mass within 13 kpc must be composed of dark matter.

4. Future prospects

Although this is an astrometric measurements for only one source, the S269 case demonstrates the strong capability of VERA in studying the Galactic rotation based on Galaxy-scale astrometry. VERA has been conducting monitoring programs of tens of maser sources per year, and some interesting astrometric results are already obtained, as presented in other VERA-related papers in this proceeding volume. In the next decade, VERA will continue astrometry of nearly 1000 H_2O and SiO maser sources in the Galaxy. There is also a plan to install 6.7 GHz receivers so that $\sim$500 of 6.7 GHz methanol maser sources are also used to trace the structure of the Galaxy. Hopefully, in the near future, VERA will provide a dramatic revolution in our understanding the Galaxy's structure and dynamics.

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