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RADIO ASTROMETRIC OBSERVATIONS AND THE GALACTIC CONSTANT AS THE BASIS OF A GALACTIC KINEMATICS STUDY

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ABSTRACT

We made phase-referencing Very Long Baseline Interferometry (VLBI) observations of Galactic 22 GHz H_2O maser sources with VLBI Exploration of Radio Astrometry (VERA). We measured the parallax distances of G48.61+0.02, G48.99−0.30, G49.19−0.34, ON1, IRAS 20056+3350, IRAS 20143+3634, ON2N, and IRAS 20126+4104, which are located near the tangent point and the Solar circle. The angular velocity of the Galactic rotation at the LSR (i.e. the ratio of the Galactic constants) is derived using the measured parallax distances and proper motions of these sources. The derived value of $\Omega_0 = 28.8 \pm 1.7$ km s^{-1} kpc^{-1} is consistent with recent values obtained using VLBI astrometry but 10% larger than the International Astronomical Union (IAU) recommended value of 25.9 km s^{-1} kpc^{-1} = (220 km s^{-1}) / (8.5 kpc).

Key words: astrometry, parallaxes, techniques: interferometric

1. INTRODUCTION

Very Long Baseline Interferometry (VLBI) astrometry is an important method for measuring the the Galactic constants, the distance from the LSR to the Galactic center (R_0) and the Galactic rotation velocity at the LSR (Θ_0). Although the International Astronomical Union (IAU) has recommended the values of $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1} since 1985, recent VLBI astrometric studies report different values (Honma et al., 2012; Reid et al., 2014).

However, observational estimation of the Galactic constants is affected by the peculiar motion of the source, systemic non-circular motions of both the source and the LSR and the non-axisymmetric potential of the MWG, and the motion of Sun relative to the LSR. To minimize these effects, we should observe many sources located at various positions in the MWG.

The tangential point and the solar circle are kinematically unique position in the Milky Way Galaxy (MWG) (Nagayama et al., 2011a; Ando et al., 2011). In the case where a source is located at one of these point and has pure circular rotation, the proper motion of the source depends only on the angular rotation velocity of the Galactic rotation at the LSR, Ω_0. Therefore, we can estimate Ω_0 from the measured proper motion. We selected 8 H_2O maser sources, whose LSR velocities are close to the terminal velocity or zero, which are expected to be located near the tangent point or the solar circle. In the present study, we report on our successful determination of the parallaxes and proper motions of 8 H_2O maser sources located at the tangent point or the solar circle with VERA.

The observed proper motion is the sum of the Galactic rotation motions of both the LSR and source, the solar motion, the source peculiar motion, and the maser internal motion. The source systemic motion, which is the sum of the the Galactic rotation motions of both the LSR and source, the solar motion, and the source peculiar motion are common for all maser spots. Therefore, the source systemic motion can be obtained from the mean of the observed proper motions of all maser spots. The residuals from the mean should give the maser internal motions. Figure 2 shows the residual proper motion vectors of G48.99−0.30 and G49.19−0.34, which are the differences between the proper motions of individual spots and the mean, and represent the internal motions. The proper motion shown in Table 1 is the source systemic motion with respect to LSR. We convert the proper motion to one with respect to LSR using the Solar motion using the traditional definition of $(U_\odot, V_\odot, W_\odot) = (10.3, 15.3, 7.7)$ km s^{-1}.

Figure 3 shows the position of the 8 H_2O maser sources in the MWG. We found that these sources appear to be located near the tangent point or the solar circle.

2. OBSERVATIONS

We observed 8 H_2O masers sources, G48.61+0.02, G48.99−0.30, G49.19−0.34, ON1, IRAS 20056+3350,

Table 1
MEASURED PARALLAX AND PROPER MOTIONS OF 8 H_2O MASER SOURCES.

No	Name	l (°)	b (°)	π (mas)	$\mu_l \cos b$ (mas/yr)	μ_b (mas/yr)	$v_{\rm LSR}$ (km/s)	Ω_0 (km/s/kpc)	Reference
1	G48.61+0.02	48.61	+0.02	0.199 ± 0.007	-5.87 ± 0.14	0.28 ± 0.09	19 ± 1	28.0 ± 0.7	(1)
2	G48.99−0.30	48.99	−0.30	0.178 ± 0.017	-6.11 ± 0.15	-0.57 ± 0.12	67 ± 1	28.2 ± 0.7	(2)
3	G49.19−0.34	49.19	−0.34	0.211 ± 0.016	-5.90 ± 0.22	0.78 ± 0.14	70 ± 1	29.2 ± 1.0	(2)
4	ON1	69.54	−0.98	0.404 ± 0.012	-6.00 ± 0.22	0.69 ± 0.20	12 ± 1	28.7 ± 1.0	(3)
5	20056+3350	71.31	+0.83	0.213 ± 0.026	-6.39 ± 0.48	-0.51 ± 0.39	9 ± 1	29.7 ± 2.3	(4)
6	20143+3634	74.56	+0.85	0.367 ± 0.037	-5.75 ± 0.33	0.62 ± 0.32	-1 ± 1	27.3 ± 1.6	(5)
7	ON2N	75.78	+0.34	0.261 ± 0.009	-5.76 ± 0.16	0.02 ± 0.14	0 ± 1	27.3 ± 0.8	(6)
8	20126+4104	78.12	+3.64	0.750 ± 0.092	-6.78 ± 0.51	2.26 ± 0.51	-4 ± 4	32.3 ± 2.4	(7)
	Mean							28.8 ± 1.1	

(1): Nagayama et al. (2011b); (2): Nagayama et al. (2015a); (3): Nagayama et al. (2011a); (4): Burns et al. (2014b); (5): Burns et al. (2014a); (6): Ando et al. (2011); (7): Nagayama et al. (2015b)

IRAS 20143+3634, ON2N, and IRAS 20126+4104, with VERA from 2006 to 2014. The target H_2O maser source and the position reference source were simultaneously observed in dual-beam mode. The data were recorded onto magnetic tapes at a rate of 1024 Mbps, providing a total bandwidth of 256 MHz, which consists of 16×16 MHz IF channels. One IF channel was assigned to the target H_2O maser source, and the other 15 IF channels were assigned to the position reference source. Correlation processing was carried out on the Mitaka FX correlator.

Data reduction was conducted using the NRAO Astronomical Image Processing System (AIPS). Amplitude calibration was performed using the system noise temperatures during the observations. For phase-referencing, fringe fitting was made using the AIPS task FRING on the position reference source with a typical integration time of 1–2 min. The solutions for the fringe phases, group delays, and delay rates were obtained every 30 sec. These solutions were applied to the data of the target H_2O maser source in order to calibrate the visibility data. 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. After the calibration, we made spectral-line image cubes using the AIPS task IMAGR around masers with 1024×1024 pixels of size 0.05 milliarcsecond (mas). The typical size of the synthesized beam was 1 mas with a position angle of −40D. A signal-to-noise ratio of 7 was adopted as the detection criterion.

3. RESULTS

Figure 1 shows examples of the parallax measurements of G48.99−0.30 and G49.19−0.34. In both sources, we can find a systematic sinusoidal motion with an amplitude of approximately 0.2 mas and a period of 1 year caused by the parallax. We could measure the parallaxes and the proper motions of 8 H_2O maser sources; G48.61+0.02, G48.99−0.30, G49.19−0.34, ON1, IRAS 20056+3350, IRAS 20143+3634, ON2N, and IRAS 20126+4104. The measured parallaxes and the proper motions are summarized in Table 1.

4. DISCUSSION

The ratio of Galactic constants, Θ_0/R_0, and the angular velocity of the Galactic rotation at the Sun, Ω_0, can be estimated from the observed proper motion in the case where the source is located near the tangent point or the solar circle. The estimation method is shown in Nagayama et al. (2011a) and Ando et al. (2011). In the case where the source has pure circular rotation at any position in the Galactic disk, the radial and tangential velocities of the source can be written as

$$v_r = \left(\frac{\Theta}{R} - \frac{\Theta_0}{R_0}\right) R_0 \sin l, \quad (1)$$

$$v_l = \left(\frac{\Theta}{R} - \frac{\Theta_0}{R_0}\right) R_0 \cos l - \frac{\Theta}{R} D. \quad (2)$$

From these equations, $\Omega_0 = \Theta_0/R_0$ is shown to be

$$\begin{aligned} \Omega_0 &= -\frac{v_l}{D} + v_r \left(\frac{1}{D \tan l} - \frac{1}{R_0 \sin l}\right) \\ &= -a_0 \mu_l + v_r \left(\frac{1}{D \tan l} - \frac{1}{R_0 \sin l}\right), \quad (3) \end{aligned}$$

where a_0 is the conversion constant from a proper motion to a linear velocity (4.74 km s^{-1} mas^{-1} yr kpc^{-1}). Equation (3) includes R_0, however, its dependence is small if the source is located near the tangent point or the solar circle. This is because $D \tan l \simeq R_0 \sin l$ in the case where the source is located near the tangent point. v_r is close to zero in the case where the source is located near the solar circle.

The values of Ω_0 which are obtained using the astrometric results of each source are summarized in Table 1. From the mean, we obtained $\Omega_0 = 28.8$ km s^{-1} kpc^{-1}. The random error is estimated to be $\sigma_{\rm ran} = 1.1$ km s^{-1} kpc^{-1} from the standard deviation of the 8 values. Our estimation method includes the systemic errors which depend on the error of the solar motion. The $V_\odot$ of the solar motion has an error of approximately 10 km s^{-1}. The systemic error depending on the error of $V_\odot$ is estimated to be $\sigma_{\rm sys}$ = (10 km s^{-1})/(8 kpc) = 1.3 km s^{-1} kpc^{-1}. The total error is estimated to be $\sigma_{\rm tot} = (\sigma_{\rm ran}^2 + \sigma_{\rm sys}^2)^{1/2} = 1.7$ km s^{-1} kpc^{-1}. We

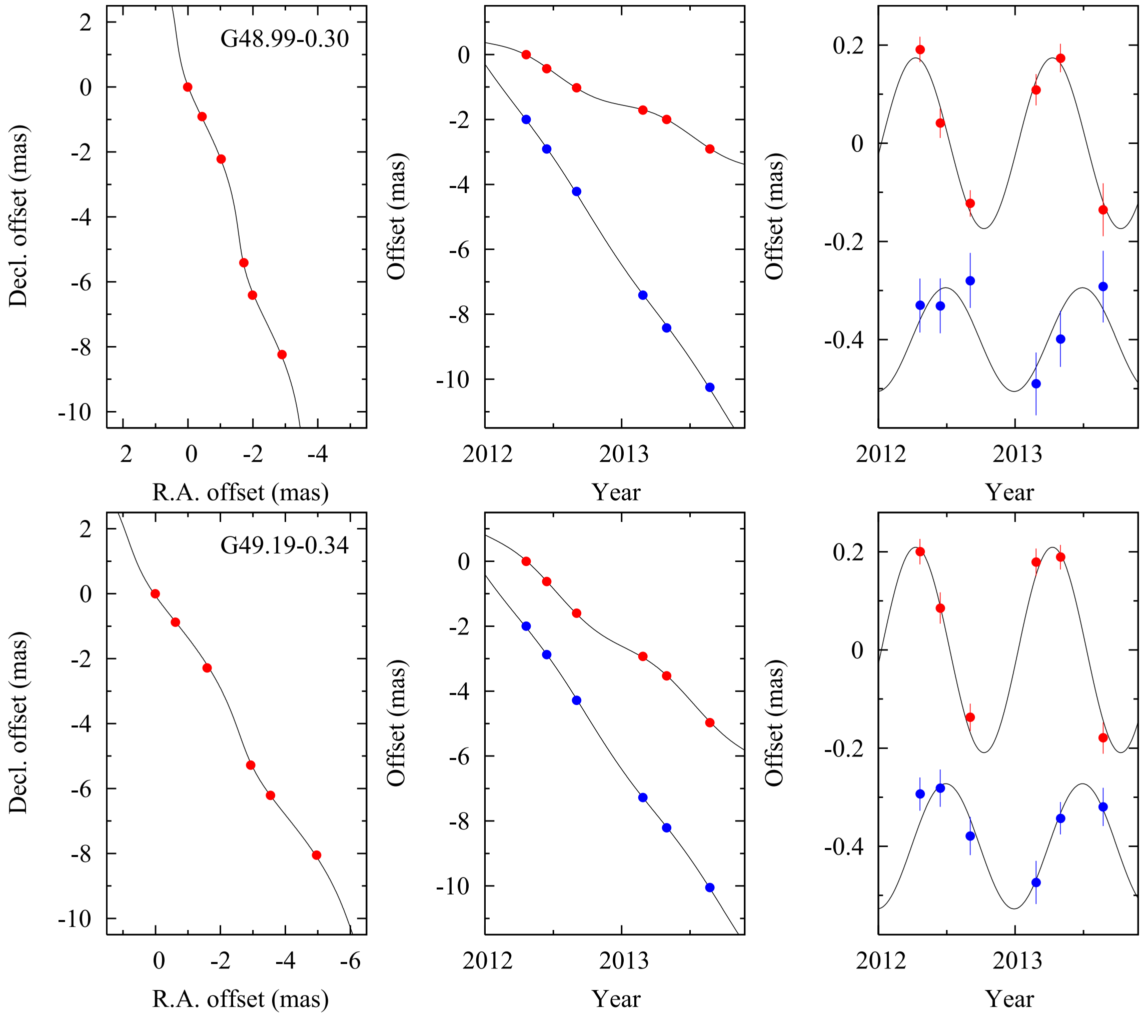

Figure 1. Parallax and proper motion data and fits of G48.99−0.30 (top) and G49.19−0.34 (bottom). The solid line shows the best-fit results of parallax and proper motion. Left: Positions on the sky. Middle: R.A. (red circle) and Decl. (blue circle) offset versus time. Right: same as the middle panel, except the proper motion has been removed, allowing the effect of only the parallax to be seen.

obtained $\Omega_0 = 28.8 \pm 1.7$ km s^{-1} kpc^{-1} from our astrometric results for the tangent point and solar circle sources. Our estimated Ω_0 is consistent with that of the proper motion measurement of Sgr A* (Reid & Brunthaler, 2004) and recent VLBI astrometric results (Honma et al., 2012; Reid et al., 2014). However our estimated value is larger than the IAU recommended value of 220 km s^{-1}/8.5 kpc = 25.9 km s^{-1} kpc^{-1}.

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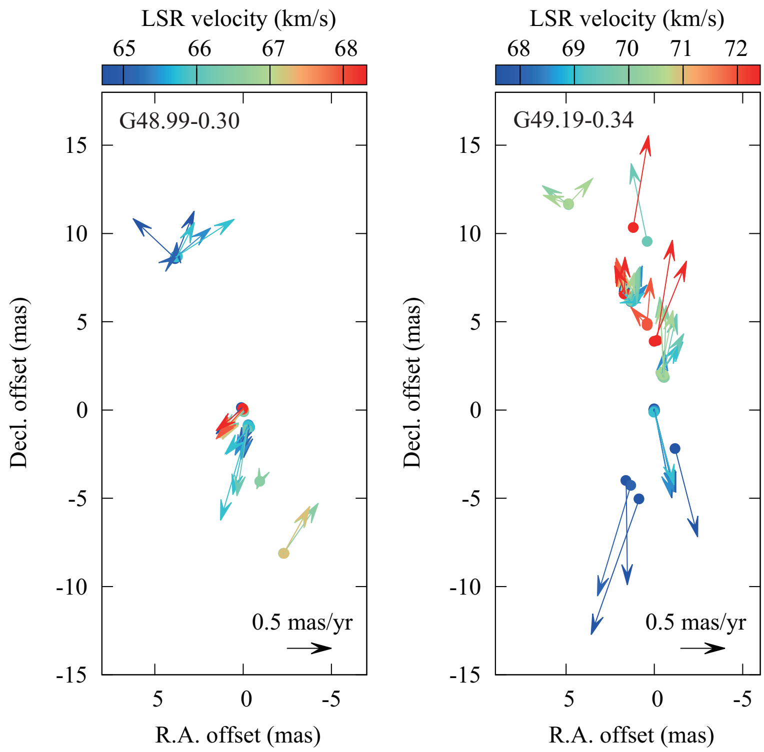

Figure 2. Distributions and internal motions of H_2O masers in G48.99−0.30 (left) and G49.19−0.34 (right). 0.5 mas yr^{-1} at the distances of G48.99−0.30 and G49.19−0.34 correspond to 13.3 km s^{-1} and 11.2 km s^{-1}, respectively.

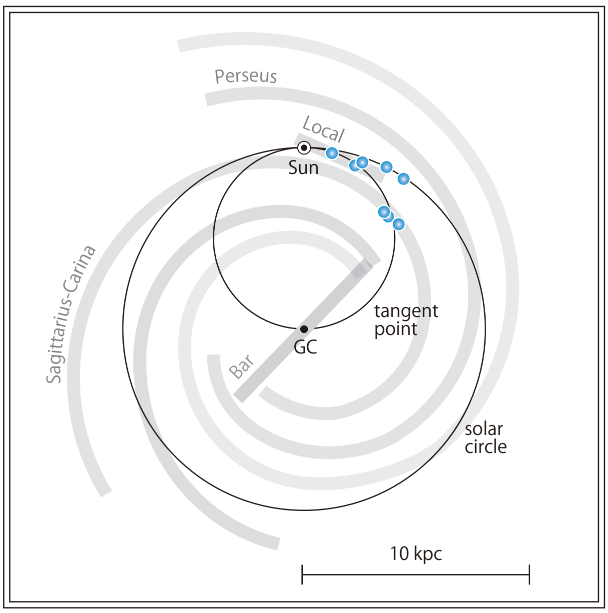

Figure 3. Positions of 8 H_2O maser sources in the MWG.

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