Advancing the Physics of Cosmic Distances
Proceedings IAU Symposium No. 289, 2012
Richard de Grijs, ed.

doi:10.1017/S1743921312021850

VERA observations of the Galactic star-forming regions ON1 and ON2N

Takumi Nagayama[1] **and** ***VERA*** **project members**

[1]Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, 2-21-1 Osawa,
Mitaka, Tokyo, 181-8588, Japan
email: `takumi.nagayama@nao.ac.jp`

Abstract. We carried out astrometric observations with *VERA* of H_2O masers in ON1 and ON2N. The measured distances to ON1 and ON2N are 2.47 ± 0.11 and 3.83 ± 0.13 kpc, respectively. We found that ON1 and ON2N are located near the tangent point and the Solar circle, respectively. We derive an angular velocity of the Galactic rotation at the Sun's position (i.e. the ratio of the Galactic constants) of 28 ± 2 km s^{-1} kpc^{-1} using the measured distances and three-dimensional velocity components of the two sources. This value is consistent with recent estimates obtained using Very Long Baseline Interferometry but different from the IAU-recommended value of 25.9 km s^{-1} kpc^{-1}.

Keywords. astrometry, Galaxy: fundamental parameters, Galaxy: kinematics and dynamics

1. Introduction

The Galactic constants—the Galactocentric distance of the Sun (R_0) and the Galactic rotation velocity at the Sun's position (Θ_0)—are basic parameters that are needed to study the structure of the Milky Way (MW). Since 1985, the IAU has recommended the values of $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1}. However, different values are persistently reported in recent studies (e.g., Reid *et al.* 2009).

The Solar circle and the tangent point are kinematically unique positions in the MW. We can estimate the ratio of the Galactic constants, $\Omega_0 = \Theta_0/R_0$ (see Sect. 3), if a source is located in the vicinity of these positions. ON1 appears to be located near the tangent point, because its radial velocity of 12 ± 1 km s^{-1} is similar to the terminal velocity at $l = 69.54°$, i.e. 15 ± 5 km s^{-1}. The radial velocity of ON2N is 0 ± 1 km s^{-1}. This suggests that ON2N is located near the Solar circle. In the present study, we report on parallax measurements of ON1 and ON2N with *VERA*. These results have been published in Nagayama *et al.* (2011) and Ando *et al.* (2011).

2. Observations

We performed astrometirc observations of H_2O masers in the star-forming regions ON1 and ON2N with *VERA* during 11 epochs over the period 2006–2008. The position reference sources for ON1 and ON2N were J2010+3322 and J2015+3710, respectively, which are separated by 1.85 and 1.27°, respectively, from the objects of interest. The masers and the position reference sources were observed simultaneously for approximately 10 hoursusing the *VERA* dual-beam mode. The data were recorded onto magnetic tapes at a rate of 1024 Mb s^{-1}, providing a total bandwidth of 256 MHz, consisting of 16×16 MHz intermediate-frequency (IF) channels. One IF channel was assigned to the maser source, and the other 15 IF channels were assigned to the position reference source. Correlation processing was carried out with the Mitaka FX correlator. Data reduction was conducted using the National Radio Astronomy Observatory's Astronomical Image Processing System (AIPS).

3. Results and Discussion

Figs 1 and 2 show the parallaxes and proper motions of the H_2O masers in ON1 and ON2N, respectively. We obtained parallaxes of ON1 and ON2N of 0.404 ± 0.019 mas (2.47 ± 0.11 kpc) and 0.261 ± 0.009 mas (3.83 ± 0.13 kpc), respectively. Fig. 3 shows the positions of ON1 and ON2N in the MW. ON1 and ON2N appear to be located near the tangent point at $l = 69.54°$ and the Solar circle, respectively.

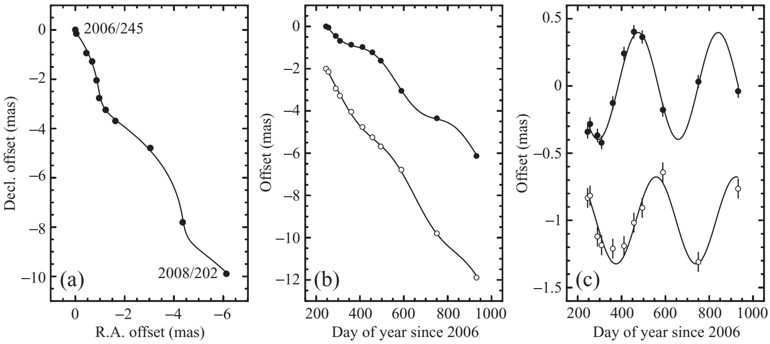

Figure 1. Parallax and proper motion of ON1. (a) Positions on the sky, with first and last epochs labeled. (b) x (filled circles) and y (open circles) position offsets as a function of time. (c) Same as (b), expect that the proper motion fit has been removed.

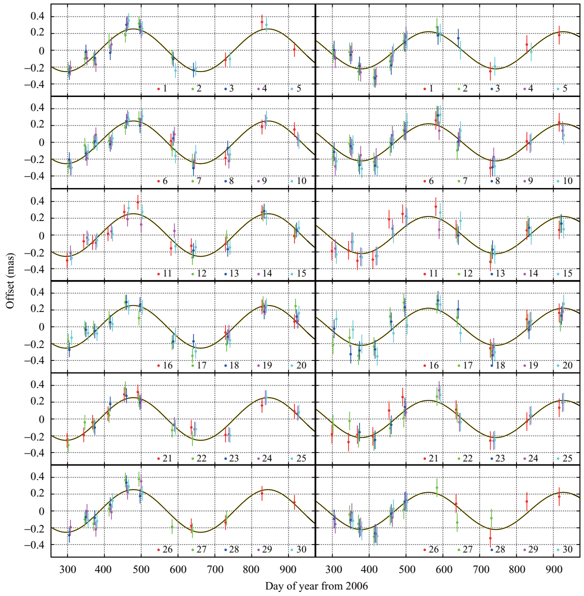

Figure 2. Parallax of ON2N. Individual proper motions and position offsets have been removed. The left (right) panel shows the parallax in right ascension (declination).

We obtained the systemic proper motions of ON1 and ON2N, $(\mu_\alpha \cos\delta, \mu_\delta) = (-3.10 \pm 0.18, -4.70 \pm 0.24)$ and $(-2.79 \pm 0.13, -4.66 \pm 0.17)$ mas yr^{-1}. Using the Solar motion

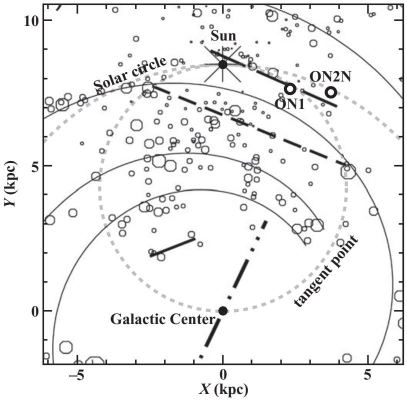

Figure 3. Locations of ON1 and ON2N in the MW. The background shows the four-spiral-arm structure of the MW (Russeil 2003).

according to the traditional definition of $(U_\odot, V_\odot, W_\odot) = (10.3, 15.3, 7.7)$ km s^{-1}, we converted these values to the relevant proper motions with respect to local standard of rest. The proper motions in the l and b directions were $(\mu_l, \mu_b) = (-6.00 \pm 0.22, 0.69 \pm 0.20)$ and $(-5.42 \pm 0.16, -0.36 \pm 0.14)$ mas yr^{-1}, respectively. These values correspond to velocities $(v_l, v_b) = (-70.2 \pm 2.6, 8.1 \pm 2.3)$ and $(-98.4 \pm 2.9, -6.6 \pm 2.6)$ km s^{-1}.

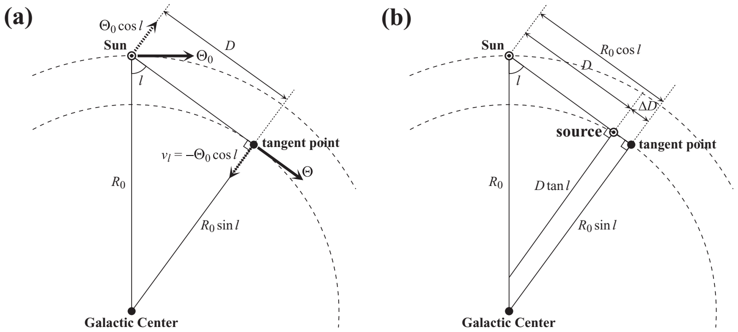

Figure 4. Geometry of the Galactic Center, the Sun, the tangent point, and the source. (a) Geometry if the source is located at the tangent point. (b) Geometry if there is a offset between the source and the tangent point.

If the source is located exactly at the tangent point, and if it is on an orbit following pure circular rotation, the source, the Sun, and the Galactic Center define a right triangle (see Fig. 4a), and the source's proper motion depends only on Θ_0. Therefore, we can calculate R_0 and Θ_0 from the observed distance, D, and the proper motion along the Galactic plane, v_l, as

$$\mathrm{R}_0 = D/\cos l, \quad \Theta_0 = -v_l/\cos l. \tag{3.1}$$

The Galactic constants are estimated at $\mathrm{R}_0 = 7.1 \pm 0.3$ kpc and $\Theta_0 = 201 \pm 7$ km s^{-1}, respectively, from $D = 2.47 \pm 0.11$ kpc and $v_l = -70.2 \pm 2.6$ km s^{-1}. However the estimated values of the Galactic constants are strongly affected by one's assumption of the source's location in the MW (Nagayama *et al.* 2011).

We found that the ratio of the Galactic constants, Θ_0/R_0, can be estimated with only small uncertainties. If the source is on a purely circular orbit at any position in the

Galactic disk, the radial and tangential velocities of the source can be written as

$$v_r = \left(\frac{\Theta}{R} - \frac{\Theta_0}{\mathrm{R}_0}\right) \mathrm{R}_0 \sin l, \quad v_l = \left(\frac{\Theta}{R} - \frac{\Theta_0}{\mathrm{R}_0}\right) \mathrm{R}_0 \cos l - \frac{\Theta}{R} D. \tag{3.2}$$

From these equations, the relation between the Θ_0 and R_0 is obtained,

$$\Theta_0 = \left[-\frac{v_l}{D} + v_r \left(\frac{1}{D \tan l} - \frac{1}{\mathrm{R}_0 \sin l}\right)\right] \mathrm{R}_0 = \left[-a_0 \mu_l + v_r \left(\frac{1}{D \tan l} - \frac{1}{\mathrm{R}_0 \sin l}\right)\right] \mathrm{R}_0, \tag{3.3}$$

where a_0 is a conversion constant from a proper motion to a linear velocity ($a_0 = 4.74$ km s^{-1} mas^{-1} yr kpc^{-1}). Eq. (3.3) is visualized in Fig. 5a using the observed values $D = 2.47 \pm 0.11$ kpc, $\mu_l = -6.00 \pm 0.22$ mas yr^{-1}, and $v_r = 12 \pm 1$ km s^{-1}. We found that the slope in Fig. 5a is nearly constant at $7 \leqslant \mathrm{R}_0 \leqslant 9$ kpc. The slope yields

$$\frac{\Theta_0}{\mathrm{R}_0} = -\frac{v_l}{D} + v_r \left(\frac{1}{D \tan l} - \frac{1}{\mathrm{R}_0 \sin l}\right) = -a_0 \mu_l + v_r \left(\frac{1}{D \tan l} - \frac{1}{\mathrm{R}_0 \sin l}\right). \tag{3.4}$$

Eq. (3.4) is shown in Fig. 5b. The ratio is estimated at $\Theta_0/\mathrm{R}_0 = 28.7 \pm 1.3$ km s^{-1} kpc^{-1} using the observed values, and $7 \leqslant \mathrm{R}_0 \leqslant 9$ kpc. The error in Θ_0/R_0 mainly depends on that in μ_l; the associated errors due to those in v_r and D can be neglected, since their values are small (± 0.02 and ± 0.05 km s^{-1} kpc^{-1}, respectively). This is because $D \tan l \simeq \mathrm{R}_0 \sin l$ if the source is located near the tangent point (see Fig. 4b).

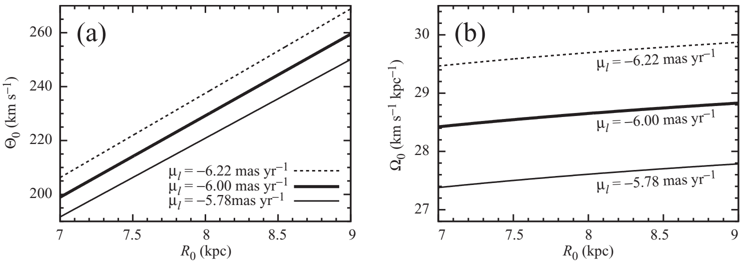

Figure 5. Relations between (a) R_0 and Θ_0, Eq. (3.3), and (b) R_0 and Θ_0/R_0, Eq. (3.4).

The ratio can also be estimated from the observed distance, proper motion, and radial velocity of the source near the Solar circle. The radial velocity of the source near the Solar circle is close to zero. Therefore, the ratio is also independent of R_0. The ratio is $\Theta_0/\mathrm{R}_0 = 27.3 \pm 0.8$ km s^{-1} kpc^{-1}, obtained using the observed ON2N parameters $D = 3.83 \pm 0.13$ kpc, $\mu_l = -5.76 \pm 0.16$ mas yr^{-1}, and $v_r = 0 \pm 1$ km s^{-1}.

We estimate $\Theta_0/\mathrm{R}_0 = 28 \pm 2$ km s^{-1} kpc^{-1} from the average of the values obtained for ON1 and ON2N. This value is consistent with $\Theta_0/\mathrm{R}_0 = 28.6 \pm 0.2$ km s^{-1} kpc^{-1} obtained from the proper-motion measurement of Sgr A* (Reid & Brunthaler 2004), which was revised using the traditional definition of the solar motion. However, this value is 10% larger than the IAU value 220 km s^{-1} / 8.5 kpc = 25.9 km s^{-1} kpc^{-1}.

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