Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
Proceedings IAU Symposium No. 380, 2024
T. Hirota, H. Imai, K. Menten, & Y. Pihlström, eds.
doi:10.1017/S1743921323003010

Astrometry of Water Maser sources in the Outer Galaxy with VERA

Hiroyuki Nakanishi[1], Nobuyuki Sakai[2], Kohei Kurahara[3] and VERA Outer Rotation Curve project members

[1]Graduate School of Science and Engineering, Kagoshima University.
email: hnakanis@sci.kagoshima-u.ac.jp

[2]National Astronomical Research Institute of Thailand

[3]National Astronomical Observatory of Japan

Abstract. While the rotation curve of the inner Galactic disk is well determined, study of the outer rotation curve requires observational measurements of distances and proper motions of individual sources in the Outer Galaxy. We report astrometric observation for water maser sources in the Outer Galactic disk conducted with VERA, aiming to measure the Outer Rotation Curve. We have measured annual parallaxes and proper motions for these objects. Our result was consistent with recent other works based on astrometry and classical Cepheid observations. Epicyclic frequency seems to suggest that 2 and 4 spiral mode are dominant in the inner and outer Galaxy, respectively.

Keywords. VERA, Water Maser, Milky Way Galaxy, Rotation Curve

1. Introduction

Rotation curve is one of the essential parameters of the Galaxy. Inner rotation curve can be well determined by measuring the terminal velocities of the HI and CO data. However, outer rotation curve needs to be derived by measuring both distance and velocity of each object in the outer Galaxy. Period-Luminosity relation of Cepheids is one of the tools to measure the outer rotation curve (e.g., Mróz *et al.* 2019). While recently Gaia Collaboration *et al.* (2018) provided a velocity field of the Milky Way Galaxy using 3.2 million stars, there are some reports that Gaia results are sometimes contradictory to VLBI results (e.g., Matsuno *et al.* 2020). Hence, it is necessary to check the result independently with VLBI observational work.

2. VERA ORC Project

We aim to measure annual parallaxes and proper motions for H_2O maser (22 GHz) sources in the Outer Galaxy with VERA in order to study Outer Rotation Curve (ORC).

We selected 76 objects in the Galactic longitude and latitude ranges of $90° < l < 240°$, $-10° < b < 10°$, respectively. Through monitoring observations, we had carried out VLBI astrometric observations for 35 bright maser sources because a maser's flux generally varies.

Data reductions were conducted by applying phase-referencing technique to increase Signal-to-Noise ratio and to improve positional accuracy with a software AIPS.

Parallaxes and proper motions for 24 objects have been measured and a part of them have been published (Sakai *et al.* 2012; Nakanishi *et al.* 2015; Sakai *et al.* 2015; Koide *et al.*

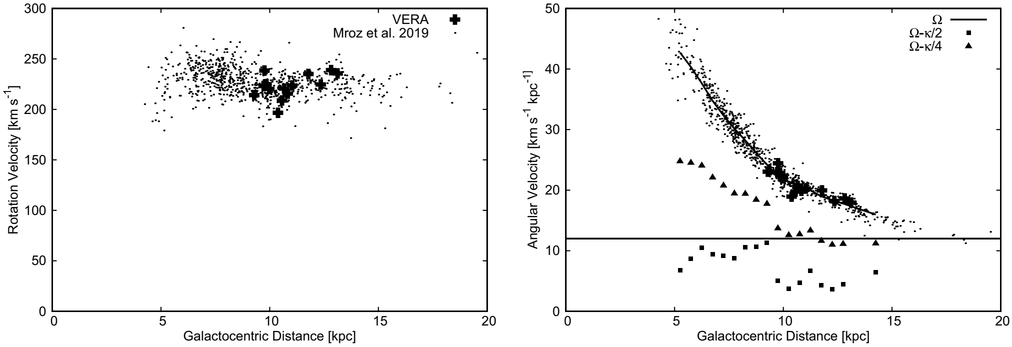

Figure 1. Rotation curve (left) and angular velocity (right) as functions of the Galactocentric distance.

2019; VERA Collaboration *et al.* 2020) so far. Details of data reductions are described in these references.

3. Result and Discussion

We have obtained parallaxes and proper motions and calculated three-dimensional position (R, θ, z) and velocity $(V_{\rm R}, V_\theta, V_z)$ for 24 objects. As shown in Figure 1, almost flat outer rotation curve was obtained and consistent with recent works such as Reid *et al.* (2019) and Mróz *et al.* (2019).

Angular velocity (Ω) and epicyclic frequency (κ) were calculated. Plotting $\Omega - \kappa/2$ and $\Omega - \kappa/4$ as shown in the right panel of Figure 1, we found that the former and latter are almost constant at about 10 km/s/kpc in the inner and outer Galaxy, respectively. These values of the former and latter are pattern speed of 2- and 4-arm spiral. If pattern speed of 12 km/s/kpc (Eilers *et al.* 2020), 2- and 4-arm spirals seem to stably exist in the inner and outer Galaxy, respectively. According to some former works on spiral mode such as Fuchs & Möllenhoff (1999) and Bottema (2003), it is suggested that number of mode increases with the Galactocentric distance. Our result is consistent with these former works.

The swing amplification theory (e.g., Fujii *et al.* 2011; Baba, *et al.* 2013) suggests that the dominating number of spiral arms, m, is estimated as $m \sim \kappa^2 R/(4\pi G\Sigma)$ using epicyclic frequency (κ), Galactocentrid distance (R), Gravitational constant (G), and surface mass density (Σ). If the disk is an exponential $(\Sigma \propto e^{-R/h})$, where h is scale length, the number of spiral number (m) tends to increase with the Galactocentric distance. This is also consistent with plots of $\Omega - \kappa/2$ and $\Omega - \kappa/4$.

Furthermore, recent study on the Galactic structure by Xu *et al.* (2023) suggests that the Milky Way Galaxy has 2-arm spiral in the inner region and 4-arm spiral in the outer region and seems to support our results.

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https://doi.org/10.1017/S1743921323003010 Published online by Cambridge University Press

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