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Maser Astrometry and Galactic Structure Study with VLBI

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Abstract. In this proceeding paper, we introduce the recent results of Galactic maser astrometry by mainly focusing on those obtained with Japanese VLBI array VERA. So far we have obtained parallaxes for 86 sources including preliminary results, and combination with the data obtained with VLBA/BeSSeL provides astrometric results for 159 sources. With these most updated results we conduct preliminary determinations of Galactic fundamental parameters, obtaining $R_0 = 8.16 \pm 0.26$ kpc and $\Theta_0 = 237 \pm 8$ km/s. We also derive the rotation curve of the Milky Way Galaxy and confirm the previous results that the rotation curve is fairly flat between 5 kpc and 16 kpc, while a remarkable deviation is seen toward the Galactic center region. In addition to the results on the Galactic structure, we also present brief overviews on other science topics related to masers conducted with VERA, and also discuss the future prospect of the project.

Keywords. maser, VLBI astrometry, VERA, the Milky Way Galaxy

1. Introduction

Phase-referencing VLBI observations of maser sources have been regularly producing accurate astrometric measurements relative to background QSOs at 10 micro-arcsecond level (e.g., see Reid & Honma 2014 and references therein). Currently two major groups have been conducting massive survey of maser parallaxes in the northern hemisphere, namely VLBA/BeSSeL (Reid *et al.* 2014 and references therein), and VERA (VLBI Exploration of Radio Astrometry, Kobayashi *et al.* 2003). The main targets for such astrometric observations are H_2O and CH_3OH masers in star-forming regions, with some cases H_2O and SiO masers in late-type stars. So far accurate parallaxes and proper motions have been measured for more than 100 maser sources, which provide critical information for determinations of the Galaxy's fundamental parameters, the rotation curve, structure of spiral arms, and so on.

Maser astrometry is unique and powerful for tracing the structure of the Milky Way Galaxy even in the GAIA era. Studies done so far already showed that maser astrometry with VLBI can achieve a parallax accuracy at 10 μas level or even better (e.g., see Reid & Honma 2014), which will be the only match-up of GAIA's target accuracy. Radio mission

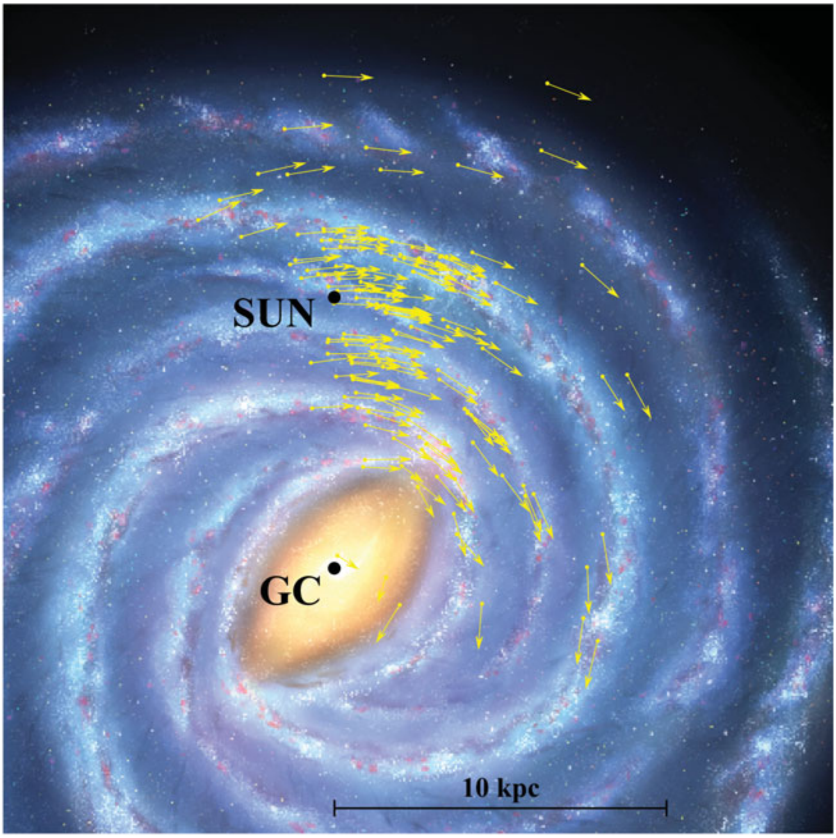

Figure 1. Maser source distribution overlaid on the face-on artistic view of the Milky Way. Points with an arrow show the sources for which accurate parallax and motion were measured with VLBI.

of maser sources is suitable for observing through the Galactic plane, where optical and near-infrared emissions suffer from severe dust obscuration. Furthermore, most common targets for maser astrometry are those associated with star-forming regions in the Milky Way, while the optical astrometry such as GAIA mainly observes normal stars. This makes the maser astrometry most suitable for tracing the structure and kinematics of the Galaxy's spiral arms, which can be best traced with the youngest populations. Also, in terms of galactic dynamics, these two populations (gases and stars) respond differently to the Galactic potential, as the stars are collisionless while star-forming regions are gaseous components and thus collisional. Therefore, in the GAIA era, it is essential to combine the optical astrometry and maser astrometry to obtain a comprehensive picture of the Milky Way Galaxy, and hence maser astrometry will be more important than ever.

For these reasons, we have been conducting maser astrometry with VERA, which is an array dedicated to maser astrometry, and in this presentation we introduce its most updated results.

2. Galaxy structure

We obtained the first parallax results with VERA in 2007 (Honma *et al.* 2007; Hirota *et al.* 2007), and since then we have been conducting maser astrometry program on regular basis with an average machine time of ~2000 hr per year. So far we have completed

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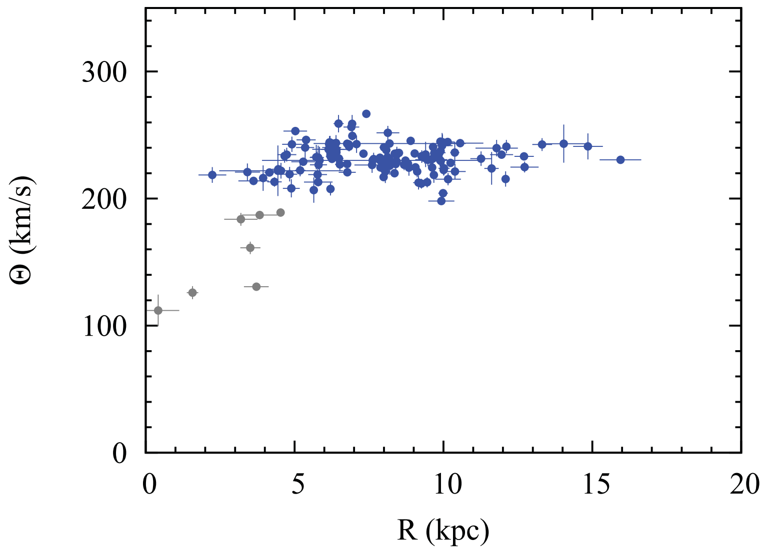

Figure 2. Rotation curve of the Milky Way determined from the maser sources with accurate parallaxes and proper motions. While the sources within 4 kpc show relatively large deviation (most probably due to the Galactic bar), the rotation curve is fairly flat between 5 kpc and 16 kpc.

observations of about180 sources, and now have been conducting the data analyses of them. As of October 2017, we have obtained parallaxes for 86 sources (of which roughly half of the results are already published and the rest to come quite soon). By combining the BeSSeL results (e.g., Reid *et al.* 2014), we compiled a list of 159 maser sources with accurate parallaxes and proper motions. Among them 144 sources are associated with star-forming regions, which we use for preliminary analysis of the Galactic structure in the present paper. For comparisons, in the previous studies, Honma *et al.*(2012) had 52 sources, and Reid *et al.*(2014) had 103 sources available at the time of their publications.

Figure 1 shows the distribution of the maser sources in the plan view of the Milky Way. The sources are mostly located at galactic latitudes between $l = 0°$ and 240°, which is caused by the geographic locations of the arrays, i.e., both VLBA and VERA are located in the northern hemisphere. The source distances from the Sun reach well beyond 10 kpc, and hence VLBI astrometry is readily tracing the Galaxy-scale structure at a 10-kpc scale. One can see association of the maser sources with spiral arms such as the local arm and Perseus Arm, showing that the maser sources are a good tracer of spiral arms. In figure 1, the proper motions are also shown with an arrow attached to each source. Overall distribution of the motion vectors clearly demonstrates that the Milky Way Galaxy is in a circular rotation as a first-order representation. Masers associated with spiral arms provide a unique opportunity to investigate the kinematics/dynamics of the spiral arms of the Galaxy. In fact, recently Sakai *et al.*(2015) argued that the non-circular motion associated with the Perseus arm can be modeled with a density-wave-type dynamical model for a spiral arm. Since the number of the spiral-arm masers with accurate distances is still limited, this should be investigated further by increasing the number of maser sources.

From the proper motion distribution, one can determine the dynamical center of the Milky Way, which provides an accurate dynamical measurement of the Galactic center distance R_0 as well as the mean angular velocity at the Sun $\Omega_\odot$. The latter is linked to the fundamental constant Θ_0 as $\Theta_0 = R_0\Omega_\odot - V_\odot$, where $V_\odot$ is the peculiar motion of the Sun in the direction of the Galactic rotation. Based on an MCMC analysis, we obtained preliminary results for these parameters as summarized in table 1. We obtained $R_0 = 8.16 \pm 0.26$ kpc, reaching at an accuracy of 3%. The value is slightly smaller than the 1985 IAU standard of 8.5 kpc, but being consistent with recent studies, such as Reid *et al.*(2014) from maser astrometry, and Boehle *et al.*(2016) from stellar motions around Sgr A*.

The Galactic rotation velocity of $\Theta_0 = 237 \pm 8$ km $^{-1}$ is larger than the IAU value of 220 km s^{-1} by 10%. The significance is still at 2-σ level, but the uncertainty mainly comes from the error in R_0 rather than $\Omega_\odot$. As seen in table 1, the angular velocity $\Omega_\odot$ itself is determined at a 1%-level. As far as the angular velocity of the LSR (Ω_0) is concerned, the IAU standards give $\Omega_0 = 220/8.5 = 25.9$ km s^{-1} kpc^{-1} while our results provide $\Omega_0 = \Omega_\odot - V_\odot/R_0 = 29.02 \pm 0.39$ km s^{-1} kpc^{-1}. Therefore, in terms of the angular velocity Ω_0, the difference is significant at 8-σ, suggesting that the Galactic rotation speed should be revised in near future.

The rotation curve determined from maser astrometry is also shown in figure 2. The figure shows that the rotation curve of the Milky Way is fairly flat in a galacto-centric distance between 5 and 16 kpc. Also notable is that the in the central part within 5 kpc from the Galaxy's center shows a large deviation from a flat rotation curve. Several sources with R <5 kpc lie below the flat rotation curve, which is presumably due to the effect of the bar. Therefore, measuring more sources in this region will potentially trace the gas dynamics associated with the bar.

Astrometry beyond 10 kpc is an remaining future issue, which requires improvement of astrometric accuracy by array expansion and/or better calibration. Meanwhile we developed a new method to use 3-D motion measured with VLBI astrometry to determine a kinematic-based distance. Yamauchi *et al.*(2016) applied this technique to G7.47+0.06, an SFR located at a 20 kpc distance, and measured its distance at an accuracy of ~10%. Very recently Sanna *et al.*(2017) successfully measured the parallax for G7.47+0.06 with VLBA and confirmed its location at a distance of 20 kpc, showing the reliability of our 3-D kinematic approach.

3. Results beyond the Galaxy structure

Maser astrometry also provides useful information to investigate individual sources such as AGB stars and star-forming regions. Recently new parallax determinations have been done with VERA for some nearby AGB stars (e.g., Nakagawa *et al.* 2016 and the references therein), which are used to accurately calibrate the period-luminosity (PL) relation of Mira variables. VERA has been conducting survey of tens of AGB parallaxes, and when completed, it is expected to provide an accurate calibration of the absolute magnitude of the Mira's PL relation. Other late-type stars such as OH/IR stars, water-fountain sources and red-super-giant stars are also good targets for maser astrometry to trace mass-loss process in their circumstellar regions through observations of maser spot motions.

SiO masers are quite often observed toward the circumstellar regions of late-type stars, and its radiation mechanism is one of the long-standing question in maser physics. For addressing this issue, a key would be multi-transition observations covering SiO lines at v=1, 2 and 3 transitions. Recently we have developed a wide-band data-acquisition system which is capable of observing the three SiO lines at Q band at the same time, as demonstrated in Oyama *et al.*(2016).

Massive star-forming regions are well-known sites showing strong maser emissions such as those from H_2O and CH_3OH molecules. In addition to distance calibration of

Table 1. Galactic parameter determination

R_0	8.16 ± 0.26 kpc
$\Omega_\odot$	30.49 ± 0.39 km s^{-1} kpc^{-1}
Θ_0	237 ± 8 km s^{-1} (*)

(*) $V_\odot$ = 12 km^{-1} is adopted.

star-forming regions, maser astrometry observations provide information on internal motions of maser spots, which are mostly tracing the outflow/jet driven by the central forming star(s). Recently, KaVA (KVN and VERA Array), a joint Korea-Japan VLBI array, started its regular operation, and one of its Large Program is dedicated to survery and monitor of masers in star-forming regions. Kim *et al.*(2018) presented the initial results of KaVA mapping observations for 10 H_2O maser sources. Based on monitoring program starting from 2017 fall, it is anticipated that outflow/jet motions as well as locations of driving sources will be revealed with KaVA.

In the era of ALMA, combination of thermal emissions traced with ALMA and non-thermal maser emissions are essential for further understanding of physical properties of star-forming regions, and ALMA follow-up observations are on-going for the star-forming regions in the KaVA Large Program. In fact, recently Hirota *et al.*(2017) demonstrated the power of such a combined VLBI-ALMA study by successfully tracing the rotation of outflow emanating from the gas disk around Orion source-I.

Time domain astronomy is nowadays getting more and more popular, and the same applies to maser observations. Maser emissions are known to be time-variable, quite often showing a large flare in a specific velocity channel. Therefore, single-dish monitoring of maser sources are important to study such phenomena, and we have been conducting a maser monitoring program of hundreds of sources with VERA single-dish mode, as presented by Sunada *et al.*(2018). During this symposium, there was a discussion on possible global collaborations of maser monitoring, which initiated a coordinated maser monitoring as well as Target-of-Opportunity observations of flaring maser sources with VLBI.

4. Future prospect

In the GAIA era, VLBI astrometry of maser hopefully becomes more important, mainly for two reasons: firstly, comparison between optical and radio astrometry will be the only possibility for consistency check of astrometric results at high accuracy. This should provide firm bases in the future astrometry at 10-μas level. Secondly, the GAIA and maser astrometry traces different species (stars for GAIA and gases for VLBI astrometry). While stars are collisionless components in the Galaxy, the gases are collisional, and hence the motions of these two species are totally different even in the same Galactic potential. Therefore, it is fundamental to trace both collisional and collisionless components for comprehensive understandings of Galactic dynamics.

Future improvement of maser astrometry is two-fold: one way is to extend the distance reach by improving parallax accuracy, and the other is to extend the sky coverage toward the southern hemisphere. To obtain better accuracy, we have been currently extending our VERA array to combine with Korean and Chinese stations, which will be providing better sensitivity as well as better astrometric accuracy. KaVA, Korean-Japan joint array, is already in regular operation, and its astrometry performance is under evaluation. Also, we have initiated a series of test observations of EAVN (East Asian VLBI Network), which consists of VERA in Japan, KVN in Korea, and a few Chinese stations such as Tianma

65m in Shanghai and Nanshan 25m near Urumqi. The inclusion of these Chinese stations is critical for EAVN, because Tianma boosts the array sensitivity and Nanshan station doubles the maximum baseline of the array over $\sim$5000 km.

Also important is to extend the sky coverage to the souther hemisphere, where currently VERA or VLBA cannot observe. VLBI array in Australia such as LBA and AuScope should be useful for this, and for long-term future, SKA combined with global stations will be the ultimate array for maser astrometry.

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