Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Galactic Maser Astrometry with VERA

Mareki Honma[1,2,3], Tomoya Hirota[1,3], Kazuya Hachisuka[1], Hiroshi Imai[4], Hideyuki Kobayashi[1,3], Takaaki Jike[1], Akiharu Nakagawa[4], Tomoaki Oyama[1], Kazuyshi Sunada[1], Daisuke Sakai[1], Nobuyuki Sakai[5] and Aya Yamauchi[1]

[1]National Astronomical Observatory of Japan, Oshu, Iwate 023-0861, Japan.
email: mareki.honma@nao.ac.jp

[2]University of Tokyo, Bunkyo, Tokyo 113-0033, Japan

[3]SOKENDA, Mitaka, Tokyo 181-8588, Japan

[4]Kagoshima University, Kagoshima, Kagoshima 890-0065, Japan

[5]National Astronomical Research Institute of Thailand, Chiangmai 50180, Thailand

Abstract. VERA has been regularly conducting astrometry of Galactic maser sources for ∼ 20 years, producing more than 100 measurements of parallaxes and proper motions of star-forming regions as well as AGB stars. By combining the observational results obtained by VLBA BeSSeL, EVN, and LBA, maser astrometry provides a unique opportunity to explore the fundamental structure of the Galaxy. Here we present the view of the Galaxy revealed by the maser astrometry, and also discuss the importance of maser astrometry in the era of GAIA by comparing the results obtained by VLBI and GAIA. We also present our view of "proper motions toward the future" of the relevant field, expected in the next decade based on global collaborations.

Keywords. VLBI, maser, Milky Way Galaxy

1. Introduction

Maser emissions are one of most powerful tools for astrometric measurements, as their compactness and high intensities allow us to conduct VLBI observations with high-angular resolution. In fact, all the major VLBI arrays in the world, including VERA (VLBI Exploration of Radio Astrometry), VLBA (Very Long Baseline Array), EVN (European VLBI Network) in the northern hemisphere and LBA (Long Baseline Array) in the southern hemisphere, are actively conducting astrometric observations of maser sources (for reviews, see e.g., Reid & Honma 2014, Immer & Rygl 2022). Among them, VERA is a dedicated array for maser astrometry, and has its unique feature of dual-beam observing system to effectively compensate for tropospheric fluctuations, the main source of astrometric errors above 10 GHz.

The construction of the VERA array was completed in 2002. One of the four stations is located in the Kagoshima prefecture, where this maser symposium is held. Since its start of science operations, NAOJ and the radio astronomy group in Kagoshima University have been working closely in observations and producing science results from VERA. For these reasons, we are very happy to host one of the series of "Cosmic Maser" symposiums in Kagoshima, with the Local Organizing Committee mainly organized by Kagoshima University. We would like to express our deepest gratitude to those who contributed to the success of the symposium, including the LOC, SOC as well as in-person and on-line participants.

The power of VLBI in astrometry has been demonstrated well during the last 15 years, since the initial astrometric results for kpc-scale distances were reported around 2006–2007 (Xu *et al.* 2006, Hachisuka *et al.* 2006, Hirota *et al.* 2007, Honma *et al.* 2007). These studies have proved that phase-referencing VLBI can achieve an astrometric accuracy of 10 μas, which is high enough to measure a distance of 10 kpc. To date, VLBI maser astrometry has already provided parallaxes and proper motions for more than 200 sources (Reid et al. 2019, Hirota *et al.* 2020).

In the meantime, at optical bands, the astrometric satellite GAIA has been producing an enormous number of astrometric results for the stars in the Milky Way Galaxy. Although the target astrometric accuracy is similar for GAIA and maser astrometry with VLBI, there is an essential difference between the two approaches: while GAIA observes stars in the optical bands, VLBI astrometry traces radio emissions from maser sources, which are mainly associated with star-forming regions or sometimes other populations like Mira variables and super-giant stars.

Thus, the two approaches, GAIA and VLBI, trace the two different aspects of the Galactic sources, and the measurements are technically independent as well. Also notably different is the location of the sources in the Galaxy: while radio observations can penetrate through the middle of the Galaxy's disk, GAIA observations suffer from large extinction toward the Galactic plane. The two are thus supplementary and complementary, and their comparison is more important than ever before for understanding the detailed structure of the Milky Way Galaxy. In this proceeding paper, we would like to summarize what we have obtained so far using VERA and other VLBI observations, and in particular to compare to the astrometric results from GAIA.

2. Current view of the Milky Way Galaxy seen with Maser Astrometry

Astrometric observations have been regularly conducted with VERA, VLBA, EVN, LBA and other arrays for the last 15 years. During this period, the Galactic structure, including fundamental parameters, the shape of spiral arms and rotation curve, have been refined with the increase of available data of maser astrometry. The pioneering work was conducted with 18 sources by Reid *et al.* (2009), and then later studies evolved with ∼50 sources in Honma *et al.* (2012), and ∼100 sources in Reid *et al.* (2014). To date, astrometric measurements of maser sources have been obtained for more than 200 objects (Reid et al. 2019, Hirota *et al.* 2020). Figure 1 shows a plan view of the Milky Way Galaxy traced by the maser astrometry compiled in Hirota *et al.* (2020), super-imposed on an artistic-view of the spiral structures of the Milky Way Galaxy.

Figure 1 clearly demonstrates that the Galactic spiral arms are traced well up-to 10 kpc scale, particularly in the first $(0 < l < 90$ deg) and the second $(90 < l < 180$ deg) Galactic quadrant. One can trace the local arm as well as the major spiral arms of the Milky Way Galaxy including Scutum, Sagittarius, Perseus, and Outer arms. Remarkably contrasting is the lack of star-forming regions along the Galactic bar. Note that this is a real feature as long as the first quadrant is concerned, where there is little observational bias (though it exists for the fourth quadrant). This tendency is probably related with the star formation deficiency in the bar region, as is expected from simulation works of the Milky Way Galaxy.

The other remarkable feature in Figure 1 is the lack of maser sources in the third and fourth quadrant, which is a fully observational effect due to the geographic locations of VLBI arrays biased toward the northern hemisphere. Further exploration of the southern sky is essential to obtain the global view of the Milky Way Galaxy, and hopefully forthcoming observations with LBA, AuScope and SKA in future will be able to fill the gap in the southern sky. We would like to emphasize that there are only few sources in

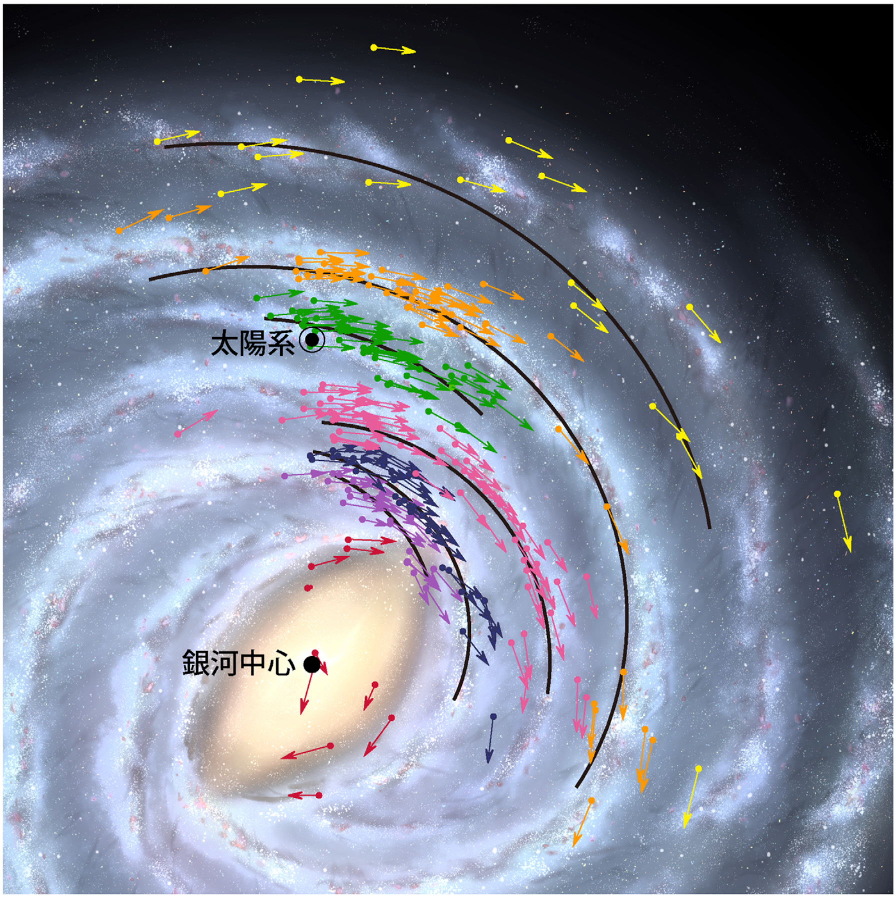

Figure 1. Plan view of the Milky Way Galaxy traced with maser astrometry, superposed on an artistic view of the Milky Way. Individual points show the location of star-forming regions with masers, and arrows show the proper motions of the maser source.

the Galactic disk beyond the Galactic Center (e.g., distance from the Sun larger than 10 kpc). This is mainly due to the observational limit in both sensitivity and astrometric accuracy, since the sources there have smaller maser fluxes as well as parallaxes. How to overcome this issue will be certainly one of the fundamental steps toward the next decades, and the use of 3-d kinematic distance (the combination of proper motions and $V_{\rm LSR}$) seems a promising tool for solving the problem (Yamauchi *et al.* 2016, Reid 2022, Sakai *et al.* 2023), in addition to improvement of astrometric accuracy.

Figure 1 also shows the proper motions of maser sources, which basically follow the Galactic rotation (clock-wise rotation in the figure). Galaxy-scale directional changes of the proper motions is evident, and based on the statistics of these proper motions, one can determine the location of the dynamical center of the Galaxy as well as the mean circular velocity. Hence one can accurately measure the fundamental parameters of the Milky Way Galaxy, namely the distance from the Sun to the Galaxy center, R_0, and the rotation velocity of the Local Standard of Rest, Θ_0. Table 1 summarizes the history of fundamental parameter determinations with maser astrometry, from Reid *et al.* (2009) to more recent one by Hirota *et al.* (2020). As one can see from the table, both R_0 and Θ_0 are converging to certain values with decreasing error bars. According to the most recent results (Reid et al. 2019, Hirota *et al.* 2020), R_0 is around 8.0 kpc with an error bar of

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Table 1. Comparison of Galactic fundamental constant determinations with maser astrometry.

Reference	N_{src}	R_0 (kpc)	Θ_0 (km s^{-1})
Reid *et al.* 2009	18	8.4 ± 0.6	254 ± 16
Honma *et al.* 2012	52	8.05 ± 0.45	238 ± 14
Reid & Honma 2014	103	8.34 ± 0.16	240 ± 8
Reid et al. 2019	∼200	8.15 ± 0.15	236 ± 7
Hirota *et al.* 2020	224	7.92 ± 0.16	227 ± 7

±2%, and Θ_0 230 km/s with an error of ±3%. R_0 is in good agreement with independent measurements based on the stellar motions around Sgr A*, the supermassive black hole at the center of the Galaxy. Do *et al.* (2019) provided R_0 of $7.946 \pm 0.050(\text{stat.}) \pm 0.032(\text{sys.})$ kpc, and Gravity Collaboration (2019) obtained R_0 of $8.178 \pm 0.013(\text{stat.}) \pm 0.022(\text{sys.})$ kpc. The consistency between the maser astrometry and the stellar motions around Sgr A* ensures that the Sgr A* is indeed located at the dynamical center of the Galaxy.

The rotation curve of the Milky Way Galaxy is accurately determined with maser astrometry of ∼200 sources (Reid et al. 2019, Hirota *et al.* 2020). Basically, the rotation curve shows a flat feature between 5 kpc and 15 kpc, being similar to the rotation curves of other spiral galaxies in a similar size. The flatness of the rotation curve confirms that the Galaxy contains plenty of dark matter particularly in the outer regions, as is expected to be in the form of a dark halo surrounding the Galactic disk. On the other hand, the rotation curve toward the inner region shows a clear deviation from the flat rotation: the overall shape shows a positive gradient of the rotation velocity (i.e., the rotation velocity increases with the Galacto-centric radius), with larger scatter of individual maser sources compared to that of the outer regions. This feature of the rotation curve is consistent with the existence of the Galactic bar, which causes asymmetric and rather complex orbits of the gas around the bar.

Another interesting feature that is currently being partially traced is the warp of the Galactic disk. Studies such as Sakai *et al.* (2020) and Immer & Rygl (2022) demonstrated that the disk warp toward the north is seen in the first Galactic quadrant, being consistent with the HI and stellar disk. However, to obtain the complete view of the disk warp, it is certainly necessary to extend the disk region covered by the maser observations, both in the southern hemisphere and in the region behind the Galactic center.

3. Comparison of GAIA and maser astrometry

The GAIA satellite, launched by ESA, has been producing huge amount of astrometric data of stars in the Galaxy seen at optical bands, and it is worth conducting direct comparison of the Galaxy's views obtained by GAIA and maser astrometry as well as individual sources observable by both GAIA and VLBI. The first step is to compare the common populations that can be observed with both optical and radio, namely, young stars (note that OB stars at optical bands and star-forming regions seen at radio are close in ages, with age difference of an order of 10^{5-6} years, that is much shorter than the time scale of Galaxy rotation, being 10^9 yr).

Drimmel *et al.* (2023) created a spiral arm map within 5 kpc from the Solar system using OB stars traced by GAIA. The population of the young stars successfully traces the Sagittarius Arm, Local Arm and Perseus Arm, being consistent with the arms located by maser astrometry. To trace more distant regions, Drimmel *et al.* (2023) used AGB stars (brighter but older populations) as well to map the region within 10 kpc, but the spiral structures are less prominent with such an old population, being in contrast to the map traced by masers showing spiral structures even at a distance of 10 kpc or more. This comparison clearly demonstrates the importance of observing multiple tracers (both young and old populations, with optical and radio observations) to understand the Galaxy structure, since these different populations are complementary to each other in terms of population ages as well as observing technique. The latter is particularly important for exploring the distant regions along the Galactic plane, since the optical observations are severely hampered by the dust obscuration.

GAIA and maser astrometry provide good opportunities of direct comparison of astrometric results for some types of stars that are observable at both optical and radio. Among such populations are AGB stars with strong maser emissions in H_2O and/or SiO, and young low-mass stars emitting continuum emissions are another type of targets, although they are not maser sources. Xu et al. (2019) conducted a direct comparison of parallaxes for these stars, showing that optical and radio astrometry are broadly consistent with each other. Nakagawa *et al.* (2019) conducted a similar study for AGB stars, confirming the two methods generally provide consistent results. However, these studies also revealed that there are some cases of discrepancy in parallax. Most notable examples were SV Peg (Sudoh *et al.* 2019) and BX Cam (Matsuno *et al.* 2020), for which GAIA DR2 and maser astrometry showed parallax discrepancy at more than 5-σ level. However, according to most updated results (GAIA DR3, Vallenari *et al.* 2023), the parallaxes are more consistent, with difference less than 2-σ level. Such a comparison demonstrates that confirmation and cross-check of parallaxes between optical and radio astrometry are essential for providing a firm basis for future astrometry.

4. Proper motion toward futures

As seen in figure 1, maser astrometry successfully traces the Galaxy scale structure, particularly well in the second Galactic quadrant. In the meantime, there is a lack of sources in the distant region (i.e., 10 kpc or more from the Sun) and in the southern hemisphere. The “proper motion toward the future” in the field of Galaxy-scale astrometry is to cover the regions currently unexplored. Since the parallax becomes small there (i.e., less than 100 μas), it is necessary to improve the accuracy of VLBI astrometry. In Asia, we have been developing East Asian VLBI Network (EAVN, Tao *et al.* 2018, Akiyama et al. 2022), which is a combined array in the collaboration with China, Japan and Korea. EAVN will by far improve the array sensitivity and the parallax accuracy compared to VERA, with the maximum baseline doubled and the total aperture area increased by an order of magnitude.

Also interesting for future astrometry is the use of proper motion and radial velocity to determine the 3-d kinematic distance. A good demonstration of such a method was done by Yamauchi *et al.* (2016), which located a maser source at 19 kpc based only on kinematics without parallax, and later confirmed by parallax measurement by VLBA (Sanna *et al.* 2017). Recently Reid (2022) also extensively discussed the power of 3-d kinematic distance, concluding that the methods provide fairly accurate distances except Galactic bar regions, as long as non-circular motion is substantially small. Sakai *et al.* (2023) recently reported another case of distance measurements with 3-d kinematics, locating a star forming region G034.84-00.95 at a distance of 19$\pm$1 kpc. Note that this technique is potentially applicable to non-VLBI observations, for instance, such as high-resolution ALMA observations that are able to measure proper motions of cores in star-forming regions.

Finally, in order to explore the southern part of the Galaxy, we definitely need the VLBI arrays in the southern hemisphere. Currently LBA is operational in VLBI astrometry (e.g., Krisnan *et al.* 2015, Krisnan *et al.* 2017), and more recently, AuScope started producing astrometric results by utilizing a sophisticated phase-referencing technique called Multi-View (Rioja & Dodson 2020, Hyland *et al.* 2022). In the next years, hopefully these existing arrays will produce more results on astrometry in the southern maser parallaxes, and then in the next decade, the advent of SKA will lead to a major breakthrough in the exploration of the southern sky, when it is combined with existing radio telescopes to build up the most powerful VLBI array in the southern hemisphere based on global collaborations.

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