Cosmic Masers - from OH to H_0
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Maser astrometry with VERA and Galactic structure

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Abstract. Since 2007 VERA (VLBI Exploration of Radio Astrometry) has been producing astrometric results (distances and/or proper motions) for Galactic maser sources. Nearly 30 parallaxes have been obtained for star-forming regions and late-type stars. By using VERA's astrometric results for star-forming regions, combined with those obtained with VLBA and EVN, fundamental Galactic parameters and Galactic structure may be derived. Our results show that $R_0 = 8.4 \pm 0.4$ kpc and $\Omega_\odot \equiv \Omega_0 + V_\odot/R_0 = 30.7 \pm 0.8$ km s^{-1} kpc^{-1}, and also show that the rotation curve of the Galaxy is nearly flat. The determinations of Galactic parameters and structures demonstrate that the maser astrometry can not only contribute significantly to research of individual maser sources, but also to studies of the structure of the Galaxy.

Keywords. maser, astrometry, VERA, the Galaxy

1. Introduction

Maser astrometry with phase-referencing VLBI is a powerful tool to measure parallaxes and proper motions of sources at kpc-scale distances. VERA (VLBI Exploration of Radio Astrometry) is a VLBI array dedicated to phase-referencing maser astrometry (Honma *et al.* 2000). With its unique dual-beam system with which one can effectively compensate tropospheric fluctuations, we have achieved accurate parallax and proper motion measurements of Galactic maser sources with distances up to ~ 5 kpc (e.g., Honma *et al.* 2007, Nagayama *et al.* 2011a). Since 2007, VERA has been regularly producing astrometric results of Galactic masers, and so far close to 30 parallax measurements have been obtained (e.g, see two VERA special issues in PASJ in 2008 and 2011). Here we summarize the recent output of VERA, focusing on astrometric results for individual sources as well as Galactic parameter determinations.

2. Summary of recent results for individual sources

Since the first measurements of parallaxes (Honma *et al.* 2007; Hirota et al. 2007), we have contiued to conduct astrometrc measurements of Galactic maser sources. In fact, 28 parallax measurements have already been published, and there are several more sources for which preliminary parallax data is avalable.

Figure 1 summarizes the current status of VERA's results: it shows distributions of the maser sources for which astrometric measurements are obtained. As seen figure 1, reliable parallaxes are available for sources within 5 kpc, while beyond 5 kpc it is still challenging

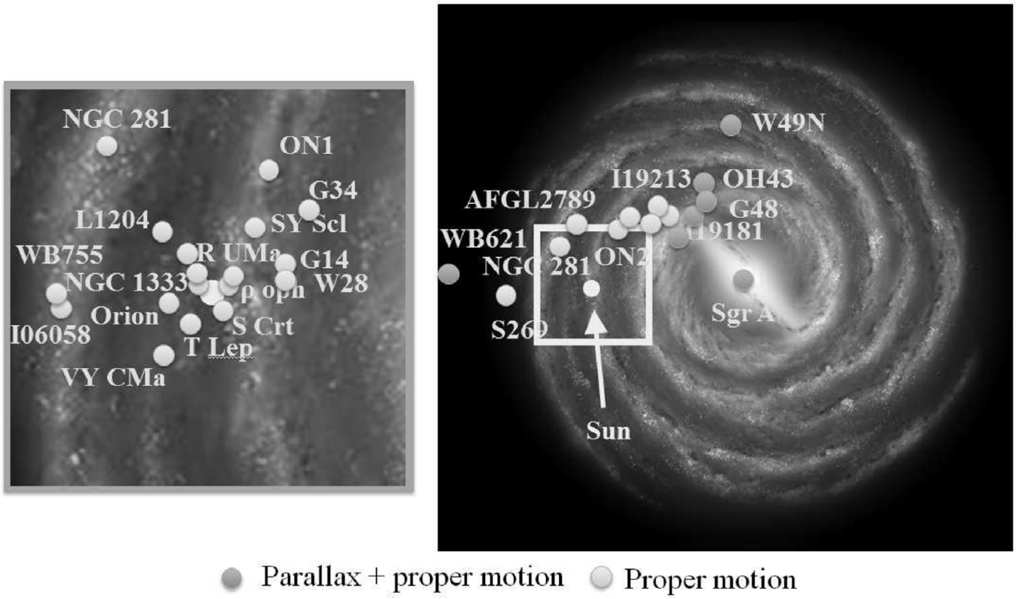

Figure 1. Galactic distributions of maser sources with VERA's astrometric results. Right panel shows a face-on view of the whole Galaxy, and left panel shows a zoom-up of the area around the Sun, which is indicated by a square in the right panel (Background image: NASA/JPL-Caltech/R. Hurt)

to obtain accurate distances. However, for these distant sources accurate proper motions can readily be measured.

Before discussing Galactic structures revealed by such kpc-scale astrometry, we would like to present a brief summary of the highlights of our observational results for individual maser sources. Most-recent parallax measurements are summarized in the PASJ special VERA issue (PASJ, 2011, Vol. 63, no. 2), where new parallaxes for 9 sources are presented. These include L1448 (Hirota *et al.* 2011a), IRAS 06061+2151 (Niinuma *et al.* 2011), ON1 (Nagayama *et al.* 2011b), ON2 (Ando *et al.* 2011) etc. These results are of great importance in the derivation of accurate physical properties of these star-forming regions e.g. physical size, mass, luminosity and etc.

Since VERA regularly monitors maser sources, our data is also useful for studies of the maser sources themselves, through measurements of flux variations and internal maser proper motions. One of such example is the study of the maser burst in Orion KL (Hirota *et al.* 2011b; Hirota *et al.* 2012), in which the location and motion of the bursting maser component has been identified with mas-precision for the first time. Based on its location and motion, Hirota *et al.*(2011b) suggested that the burst was probably caused by the interaction of an outflow and the molecular gas in the Orion Compact Ridge. Another example is H_2O maser monitoring of G353.273+0.641 conducted by Motogi *et al.*(2011), which revealed a possible acceleration in the maser motions associated with high velocity outflow.

Installation of new C-band receivers to VERA added another window for maser research through observations of 6.7 GHz methanol masers. In collaborations with other radio telescopes in Japan and China, we have been conducting a massive imaging survey for methanol maser sources (Fujisawa *et al.* 2011). This methanol maser data will be useful not only for VLBI astrometry, but also for understanding the massive star formation process. In fact, sources with mas-scale maser distributions will be potential targets for

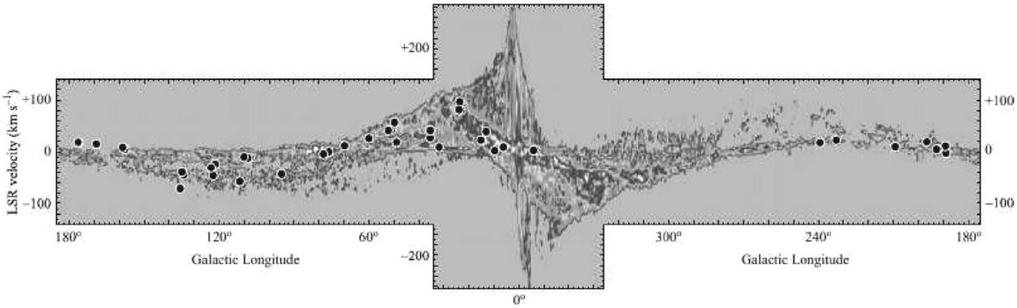

Figure 2. Distributions in l-v diagram of 44 maser sources used for the analyses of Galactic structures. The sources include those observed with VERA, VLBA and EVN.

future observations with ALMA. Measurements of thermal emissions from dust combined with molecular data on gas with maser emission will provide for a deeper understanding of star-formation processes.

3. Galactic Structure

Astrometric measurements can also be used to explore fundamental details of Galactic structure such as Galactic constants and the shape of Galactic rotation curve. To obtain the best estimates of such parameters, we compiled a list of astrometric results obtained with VERA, VLBA and EVN. The list consists of 44 star-forming regions with precise astrometry, from which we determine the basic structure of the Galaxy (Honma *et al.* 2012). In figure 2, we show distributions of 44 star-forming regions in the l-v diagram of the Galaxy, overlaid on the CO l-v diagram (Dame et al. 2001). As seen in figure 2, the sources are basically distributed in the northern part of the Galaxy, with a hole around the region between $l = 240°$ to $350°$ due to the bias in array location. However, except for the hole in the southern hemisphere, the sources are well scattered over a wide range of Galactic longitude l (2/3 of the whole Galaxy), and are thus useful for tracing Galactic structure.

In order to explore the basic structure of the Galaxy, we introduce thos parameters to be determined from the data of maser astrometry: the Galactic constants R_0 and Ω_0, which are the distance from the Sun to the Galactic center, and the angular Galactic rotation velocity at Local Standard of Rest (note that $\Omega_0 \equiv \Theta_0/R_0$, where Θ_0 is the Galactic rotation velocity at the LSR), the power-law index of the rotation curve α (which describes the shape of rotation curve as $\Theta = \Theta_0(R/R_0)^\alpha$), and the mean peculiar motion of the star-forming regions ($U_{\rm SFR}$, $V_{\rm SFR}$, $W_{\rm SFR}$). With these sample sources and parameters, we have run MCMC (Markov-Chain Monte Carlo) simulations to evaluate the best estimate of the Galactic parameters. The 44 sources in our sample could include some outliers which have significant deviation from circular Galactic rotation, and could affect the parameter determinations. To handle the effect of outliers with care, we have conducted MCMC simulations with different samples by removing possible outliers that have large deviations. By doing such a careful analysis for 36 of the 44 sources (eliminating up to 8 outliers), we determined the best values of the parameters with estimates of the systematic errors caused by possible outliers (Honme et al. 2012).

The determined parameters are summarized in table 1. Here we adopted a solar motion of $V_\odot = 5.25\,\mathrm{km\ s^{-1}}$ by Dehnen & Binney (1998), but note that recently there are claims of upward modifications up to ~ 12 km s^{-1} (Schönrich *et al.* 2010). We adopted $V_\odot = 5.25\,\mathrm{km\ s^{-1}}$ just for simplicity in comparison with previous studies, which were mostly

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Table 1. Summary of Galactic parameter determinations based on 44 star-forming regions.

parameter	value	unit	note
R_0	8.4 ± 0.4	kpc	distance to Galactic center
Ω_0	30.1 ± 0.8	km s^{-1} kpc^{-1}	angular rotation velocity at LSR
α	0.01 ± 0.03		power-low index of rotation curve
$U_{\rm SFR}$	3.6 ± 1.2	km s^{-1}	mean peculiar motion of sources toward Galactic center
$V_{\rm SFR}$	-13.4 ± 1.5	km s^{-1}	mean peculiar motion of sources toward Galactic rotation
$W_{\rm SFR}$	-1.3 ± 1.3	km s^{-1}	mean peculiar motion of sources toward north Galactic pole

All the results shown here are based on the solar motion $V_\odot = 5.25\,\text{km s}^{-1}$ (Dehnen & Binney 1998). The results could be affected by adopting a different value of $V_\odot$, especially the parameters related to Galactic rotations such Ω_0 and $V_{\rm SFR}$.

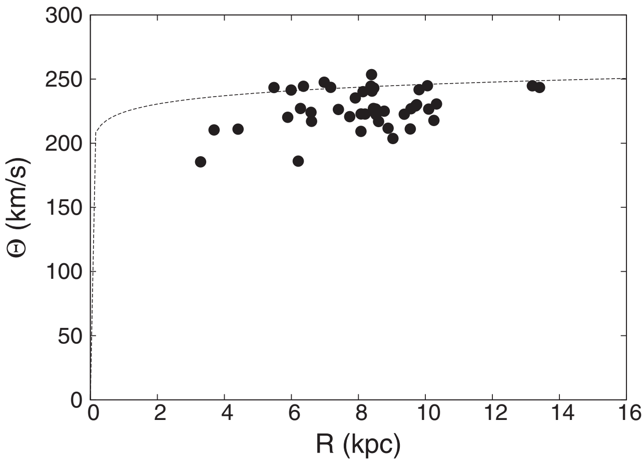

Figure 3. Galactic rotation curve determined in this study. The curve shows the power low fit, and filled circle are observational data. In addition to scatter which appears rather random, there is systematic offset between the curve and observed data, showing possible lag of star-forming regions. Note that this curve is for $V_\odot = 5.25\,\text{km s}^{-1}$, and the lag strongly depends on adopted value of $V_\odot$ as is described in text.

based on Dehnen & Binney (1998). Although the number of sources is still around $\sim$ 40, as seen in table 1, Galactic parameters are constrained reasonably well. For instance, R_0 is determined at 5% level, and is consistent with recent determinations of R_0 which are independent of our results (e.g., Ghez *et al.* 2008; Gillessen *et al.* 2009). Ω_0 is also determined at 3% level, which can be converted into $\Theta_0 = 254 \pm 14$ km s^{-1} by adopting $R_0 = 8.4 \pm 0.4$ kpc. However, we point out that Ω_0 and Θ_0 are dependent of the adopted value of $V_\odot$, and hence the values presented here are not decisive ones. Instead, we can define another parameter which is less dependent on $V_\odot$ as $\Omega_\odot \equiv \Omega_0 + V_\odot/R_0$. We obtained $\Omega_\odot = 30.7 \pm 0.8$ km s^{-1} kpc^{-1}, with little dependence of choice of $V_\odot$.

The rotation curve index is found to be $\alpha = 0.01 \pm 0.03$, indicating that the Galactic rotation curve is basically flat. This result is consistent with previous studies of rotation curves (e.g., Sofue & Rubin 2001). Regarding $U_{\rm SFR}$ and $W_{\rm SFR}$ components, mean peculiar motion of star-forming regions are not prominent. In contrast, in $V_{\rm SFR}$ component, there is a notable lag behind the Galactic rotation ($V_{\rm SFR} = -13.4 \pm 1.5$ km s^{-1}), which confirms the suggestion originally made by Reid *et al.* (2009). However, we also note that this lag is dependent of the adopted value of $V_\odot$, and we found a clear relation between $V_{\rm SFR}$ and $V_\odot$ as $V_{\rm SFR} = V_\odot - 19(\pm 2)$ km s^{-1}. Therefore, the lag of star-forming regions could be

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an artifact caused by an inappropriate value of $V_{\rm SFR}$, but we still have to wait for precise determination of $V_\odot$ to obtain final conclusion.

4. Future prospect

In the next decade, VERA will continue astrometric monitoring of maser sources, and hopefully obtain astrometric results for 300–400 sources by ∼2020. To accelerate the observations, we are in collaboration with KVN (Korean VLBI Network), which has three of 21-m telescopes in Korea, to combine KVN and VERA. The combined array of KVN and VERA will be powerful for Galactic maser astrometry in terms of better baseline coverage as well as better sensitivity. Targets are H_2O masers at 22 GHz and SiO masers at 43 GHz, with a possible extension to CH_3OH masers at 6.7 GHz (VERA already has receivers for this band, and there is a plan to install new receivers for this band on KVN). Another possibly-new target is CH_3OH maser at 44 GHz, originally discovered Morimoto *et al.*(1985). Recent test observations with KVN show that some sources are detectable with VLBI (with relatively short baselines), and so they may be new target sources for maser astrometry in near future.

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