*RevMexAA (Serie de Conferencias)*, **46**, 56–60 (2015)

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# GALACTIC DYNAMICAL STRUCTURE REVEALED BY VLBI ASTROMETRY

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RESUMEN

Astrometría es el método mas directo y preciso para revelar la estructura 3D de la Vía Láctea. En este artículo revisaré la estructura Galáctica basada en resultados del VLBI. En primer lugar se introducen algunos conceptos básicos de astrometría con VLBI y areglos existentes de VLBI. Luego, se muestran algunos resultados científicos recientes usando astrometría VLBI, en particular (i) Parámetros fundamentales de la Vía Láctea, (ii) La curva de rotación de la Vía Láctea, y (iii) El brazo (principal) de Perseus. Finalmente describo brevemente algunas posibilidades interesantes para astrometría de gas y estrellas en la era de Gaia.

ABSTRACT

Astrometry is the most direct and accurate method to reveal the 3D structure of the Milky Way. I review the Galactic structure based on VLBI astrometry results. First, I introduce some basic concepts of VLBI astrometry and actual VLBI arrays. Then, I show some recent scientific results with VLBI astrometry, namely (i) Fundamental parameters of the Milky Way, (ii) The rotation curve of the Milky Way, and (iii) The Perseus (main) arm of the Milky Way. Finally, I briefly describe future prospects for gas and stellar astrometry in the Gaia era.

*Key Words:* astrometry — Galaxy: structure — techniques: interferometric

## 1. GENERAL

### 1.1. *Astrometry*

Astrometry aims to measure positions, distances, and motions of astronomical objects directly and accurately. Thanks to the motion of the earth around the sun, a target shows an apparent elliptical motion projected onto the celestial sphere. The semi-major axis of this ellipse is called the trigonometric parallax ($\pi$), which is defined by:

$$\pi = \frac{1\,\mathrm{AU}}{d}, \qquad (1)$$

where AU is the astronomical unit and $d$ is the distance to the target. Note that 1 parsec (pc) is defined as 1 AU divided by 1 arcsecond.

Trigonometric parallaxes are called the “gold standards”, since geometric distances can be measured using the parallax without any assumptions (see equation 1). Precise distance measurements are important in astronomy, since they are related to size, luminosity, mass, and ages of most objects. Also, the parallactic distance is a standard of the cosmic ladder, and therefore astrometry contributes to many astronomical fields (e.g., de Grijs 2013).

Proper motion ($\mu$), the apparent tangential motion of a target projected onto the celestial sphere, is another observable quantity in astrometry, which originates in the target motion (e.g., due to Galactic rotation). The units of proper motion are often given in arcsecond yr$^{-1}$ or milliarcsecond yr $^{-1}$. The tangential velocity, $v_t$ (in km s$^{-1}$), can be obtained from the proper motion and the distance through:

$$v_t = \kappa \cdot \mu \cdot d, \qquad (2)$$

where $\kappa \sim 4.74$. Note that $\mu$ and $d$ are expressed in arcsecond yr$^{-1}$ and pc, or milliarcsecond yr$^{-1}$ and kpc, respectively. A combination of the tangential velocity and the line-of-sight velocity (measured through the Doppler effect) tells us 3D motion of a target.

In terms of history of astrometry, the Hipparcos satellite, the first space experiment devoted to precision astrometry, was launched in 1989 (Perryman 1989). It brought us stellar parallaxes with accuracies ($\Delta\pi$) of $\sim 1$ milliarcsecond (mas). The information was available for a volume of $\sim 100$ pc around the Sun, since $\frac{\Delta\pi}{\pi} < 0.1$ is required to avoid the Lutz-Kelker bias[2] (Lutz & Kelker 1973).

Nowadays, Very Long Baseline Interferometry (VLBI) arrays at radio wavelengths are used to carry

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[2]$< \frac{1}{\pi} > \neq \frac{1}{<\pi>}$

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out Galactic scale astrometry, and to understand the 3D structure and dynamics of the Milky Way. We introduce VLBI in the following section.

### 1.2. *Very Long Baseline Interferometry (VLBI)*

**Advantage: The highest angular resolution** Until now VLBI at radio wavelengths has achieved the highest angular resolution of any wavelength. The angular resolution can be estimated as $\sim \frac{\lambda}{D}$ where $\lambda$ is the observing wavelength and $D$ is the length of the baseline. If we set $D = 8{,}600$ km and $\lambda = 1.3$ cm based on Very Long Baseline Array (VLBA in the USA), then an angular resolution of $\sim 0.3$ mas can be achieved. If thermal (random) error is dominant in VLBI observations, the centroid accuracy with VLBI for a compact source can be roughly estimated as $\frac{\lambda}{D} \cdot 1/2 \cdot \frac{1}{\mathrm{SNR}}$, where SNR is the signal-to-noise ratio. Again, if we set $D = 8{,}600$ km and $\lambda = 1.3$ cm with a typical SNR for VLBA observations, then a centroid accuracy of $\sim 10$ microarcsecond ($\mu$as) is obtained.

However, systematic errors are dominant in VLBI observation (e.g., due to tropospheric zenith delay residuals). To reduce the systematic errors, relative VLBI observations are performed, in which the target and an adjacent reference (e.g., a distant QSO) source are observed alternately with an appropriate switching cycle depending on the observing wavelength. The centroid (position) accuracy ($\Delta$s) with relative VLBI observations can be roughly estimated as:

$$\Delta s = \frac{c\Delta\tau}{|D|} \cdot \theta_{\mathrm{sep}}, \tag{3}$$

where $c$ is the speed of light, $\Delta\tau$ is the delay, an observable quantity in VLBI observations, and $\theta_{\mathrm{sep}}$ is the separation angle between the target and the reference source. If we set $D = 8{,}600$ km, $\mathrm{c}\Delta\tau = 2$ cm, and $\theta_{\mathrm{sep}} = 1.0$ deg in equation 3, then $\Delta s \sim 10\ \mu$as is obtained.

As we can see, using relative VLBI astrometry we can carry out Galactic scale astrometry, measuring 3D positions and motions of Galactic objects.

**Disadvantage: Low sensitivity** Relative VLBI astrometry allows us to conduct Galactic scale astrometry with a positional accuracy of $\sim$10 $\mu$as, as summarized in Reid & Honma (2014). However, in VLBI, the size of the observed source ($\theta_0$) should be comparable to, or smaller than, the angular resolution of VLBI, $\frac{\lambda}{D}$, otherwise the source flux is reduced significantly (for more details see Sasao & Fletcher 2005). This condition for VLBI is described as:

$$\theta_0 \le \frac{\lambda}{D}. \tag{4}$$

Using equation (4), we can write the intensity $I_\nu$ and flux density $F_\nu$ of the source as follows:

$$I_\nu = \frac{2kT_{\mathrm{B}}}{\lambda^2} \le \frac{2kT_{\mathrm{B}}}{\theta_0^2 D^2}, \text{ and } F_\nu = \frac{2kT_{\mathrm{B}}}{\lambda^2}\frac{\pi\theta_0^2}{4} \le \frac{\pi k T_{\mathrm{B}}}{2D^2}, \tag{5}$$

where $k = 1.381 \times 10^{-23}$ J K$^{-1}$ is the Boltzmann constant and $T_{\mathrm{B}}$ is the brightness temperature of the source. If we set the minimum detectable flux density ($F_{\nu\mathrm{min}}$) by VLBI, we can write the lower limit ($T_{\mathrm{Bmin}}$) to the brightness temperature for the detectable source using equation (5) as follows:

$$T_{\mathrm{Bmin}} \simeq \frac{2D^2}{\pi k} F_{\nu min}. \tag{6}$$

If we set $D = 2{,}300$ km and $F_{\nu min} = 0.16$ Jy from the VERA Status Report[3] in equation (6), then $T_{\mathrm{Bmin}} \simeq 4{\times}10^8$ K. This means that VLBI astrometry can observe only compact and non-thermal sources such as; AGNs, masers and pulsars. However, we are unable to observe thermal sources such as; stars or molecular clouds.

In this paper, we especially focus on maser astrometry to discuss Galactic structure, because a large number of masers ($\sim$ 1,000) are distributed in Galactic star-forming regions and around late-type stars (e.g., Valdettaro et al. 2001), and also because they are bright and compact enough for VLBI astrometry.

### 1.3. *VLBI arrays in the world*

We briefly introduce VLBI arrays in the world as shown in Table 1. Galactic scale astrometry has been led by VLBA, VERA, and partly EVN in the Northern hemisphere. In fact, VLBA and VERA have succeeded to measure a parallactic distance larger than 10 kpc and 5 kpc with 10% error, respectively. The measurements are comparable to the size of the Galactic disk of $\sim$ 20 kpc, and therefore we can study the 3D structure and dynamics of the Milky Way using these results.

The Long Baseline Array (LBA) is the only array in the Southern hemisphere. This array is crucial to study the Milky Way as a whole.

[3] `http://veraserver.mtk.nao.ac.jp/restricted/CFP2012/status12.pdf`

TABLE 1

VLBI ARRAYS IN THE WORLD

| Array | Antenna diameter and number in array | Beam size at 22 GHz | Maximum baseline (km) | Baseline sensitivity* (mJy) | Image sensitivity† (μJy) | Memo |
|---|---|---|---|---|---|---|
| VLBA | 25 m × 10 | 0.3 mas | 8,600 | 5‡ | 44‡ | |
| VERA | 20 m × 4 | 1.2 mas | 2,300 | 14§ | 356§ | Dedicated to astrometry |
| EVN | 14 m − 100 m, × ∼ 10 | 0.2 mas | 2,900 − 12,000 | 1 − 10** | 43** | Astrometry has been conducted at a frequency ≤ 6.7 GHz |
| LBA | 22 m − 70 m, × ∼ 7 | 0.3 mas | 1,700 − 9,800 | 1 − 24†† | 50†† | The only VLBI array in the Southern hemisphere |

* An integration time of 120 seconds and an observing frequency of 22 GHz were assumed for the continuum source.
† An integration time of 8 hours and an observing frequency of 22 GHz were assumed for the continuum source.
‡ The values were estimated based on Choi et al. (2014) and
https://science.nrao.edu/facilities/vlba/docs/manuals/oss2013b/referencemanual-all-pages
§ The values were estimated based on http://veraserver.mtk.nao.ac.jp/restricted/CFP2015A/status15A.pdf
** The values were estimated based on Rygl et al. (2012), http://www.evlbi.org/user_guide/EVNstatus.txt
and http://www.atnf.csiro.au/vlbi/calculator_2009/
†† The values were estimated based on http://www.atnf.csiro.au/vlbi/calculator_2009/

TABLE 2

A HISTORY OF DETERMINATIONS OF THE GALACTIC CONSTANTS

| Paper | # of sources | $R_0$ (kpc) | $\Theta_0$ (km s$^{-1}$) | Method |
|---|---|---|---|---|
| Reid et al. 2009 | 18 | $8.40 \pm 0.60$ | $254 \pm 16$ | Least squares fit |
| Honma et al. 2012 | 52 | $8.05 \pm 0.45$ | $238 \pm 14$ | MCMC |
| Reid et al. 2014 | 103 | $8.34 \pm 0.16$ | $240 \pm 8$ | MCMC |

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## 2. RESULTS & DISCUSSIONS

### 2.1. *Fundamental parameters of the Milky Way*

Astrometry can be used to determine fundamental parameters of the Milky Way such as the Galactic constants ($R_0$, $\Theta_0$). The accuracy of the Galactic constants have increased with the increasing number of astrometric results, as shown in Table 2. Reid et al. (2009) determined Galactic constants of ($R_0$, $\Theta_0$) = (8.4 ± 0.6 kpc, 254 ± 16 km s$^{-1}$) with 18 astrometry results, which are different from the IAU recommended values of ($R_0$, $\Theta_0$) = (8.5 kpc, 220 km s$^{-1}$) especially for $\Theta_0$. Note that the sum of $\Theta_0$ and $V_\odot$ (peculiar solar motion in the direction of Galactic rotation) was well constrained in Reid et al. (2014), while $\Theta_0$ and $V_\odot$ showed a negative correlation.

The difference between $\Theta_0 = 254$ and 220 km s$^{-1}$ brings a big impact on Milky Way structure, since the mass of the dark matter halo scales as $(\Theta_0)^{\sim 3}$ (e.g., Navarro, Frenk & White 1997). It means that the mass of the Milky Way is increased by ∼ 50 % compared to the previous result. This big impact was explained in the NRAO press release [4]. The implied greater mass of the Milky Way means that it has a mass equal to that of the Andromeda galaxy. The Milky Way is not the little sister of the Andromeda galaxy anymore, they look like twins.

### 2.2. *The Rotation Curve of the Milky Way*

Reid et al. (2014) compiled 103 VLBI astrometry results, as shown in Figure 1. Using these results, Figure 2 shows a rotation curve of the Milky Way. The important point in Figure 2 is that the rotation curve is flat between ∼ 5 and 15 kpc of Galactocentric radii ($R$). This is indicative of large amounts of dark matter.

Also, Figure 2 gives us hints about the effects of asymmetric potentials (e.g., due to the bar and spiral

[4] http://www.nrao.edu/pr/2009/mwrotate/

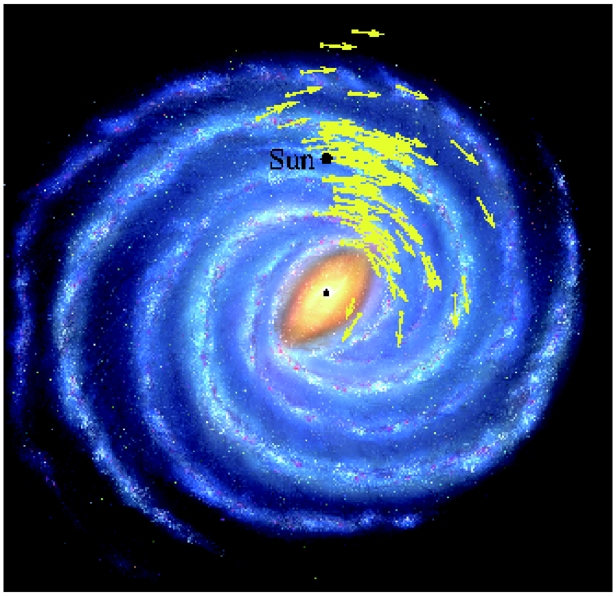


Fig. 1. Previous VLBI astrometry results mainly based on Reid et al. (2014), which are superimposed on a schematic view of the Milky Way. The results display clockwise galactic rotations. ⊙ denotes the solar position.

arms). The results with $R$ less than 5 kpc may be affected by the bar potential. Fluctuations are seen at $\sim 6 \le R \le \sim 10$ kpc, which indicates the effect of spiral arms. We will further discuss the effect of spiral arms in the next section.

### 2.3. *Systematic peculiar (non-circular) motions in the Perseus arm*

The Perseus arm traced by star and gas is one of the main arms in the Milky Way (e.g., Churchwell et al. 2009). The Perseus arm has been studied by many authors (e.g., Roberts 1972; Georgelin & Georgelin 1976; Drimmel & Spergel 2001; Russeil 2003).

Sakai et al. (2012) and (2013) studied the 3D structure and kinematics of the Perseus arm using VLBI astrometry (see Figures 3 and 4). Figure 3 shows the peculiar motions in the $U$-$V$ plane, on which several arms are superimposed. Note that $U$ and $V$ are directed to the Galactic center and Galactic rotation, respectively. The sources in the Perseus arm are located in the lower right of the figure, meaning that the sources are moving systematically toward the Galactic Center, and lag behind Galactic rotation.

Sakai et al. (2012) determined averaged peculiar motions of $(U_{\rm mean}, V_{\rm mean}) = (11 \pm 3, -17 \pm 3)$ km s$^{-1}$ with seven sources in the Perseus arm with $\sim$ 4-$\sigma$ significance. Figure 4 represents a schematic view of

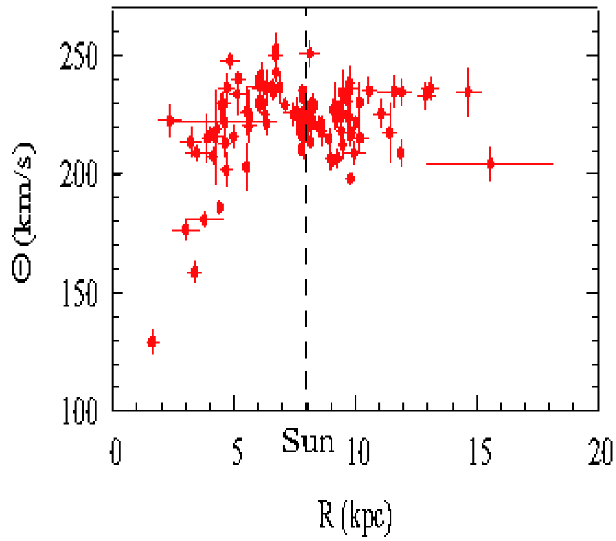


Fig. 2. Rotation curve of the Milky Way based on the astrometry results shown in Figure 1.

the systematic peculiar motions. These systematic peculiar motions were also confirmed by Choi et al. (2014), who determined averaged peculiar motions of $(U_{\rm mean}, V_{\rm mean}) = (9.2 \pm 1.2, -8.0 \pm 1.3)$ km s$^{-1}$ with 25 sources in the Perseus arm. The systematic peculiar motion is consistent with the Galactic shock model proposed by Fujimoto (1968) and Roberts (1969).

## 3. FUTURE PROSPECTS IN THE GAIA ERA

Gaia, the next generation satellite devoted to astrometry, was lunched on December 19, 2013. Gaia will conduct astrometry for one billion stars with a target accuracy of 10 $\mu$as, which will enable us to measure distances out to 10 kpc with 10 % error. Gaia and VLBI have a mutually complementary relationship in terms of both quantity and quality of Galactic astrometry.

For instance, Gaia will bring us a large sample of stellar astrometry, while at optical wavelengths it will suffer from dust extinction in the Galactic disk. On the other hand, VLBI astrometry at radio wavelengths can observe the entire Galactic disk and, as such, it will provide us with astrometric results toward several hundreds star-forming regions (SFRs).

A combination of star and gas astrometry will be a powerful tool to discriminate among different Galactic dynamical models, such as the density-wave theory (Lin & Shu 1964) and the "recurrent and transient spiral" proposed by N-body simulations (e.g., Baba et al. 2013), since various models have predicted different results for the distribution and

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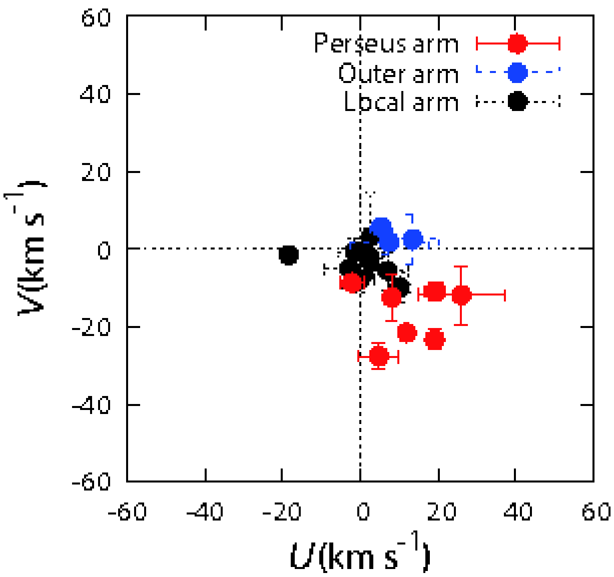


Fig. 3. $U$ *vs.* $V$ plane on which previous VLBI astrometry results are superimposed (from Sakai et al. 2012). $U$ and $V$ are peculiar (non-circular) motions, and are directed to the Galactic Center and Galactic rotation, respectively. For deriving the peculiar motions, we assumed Galactic constants of ($R_0$, $\Theta_0$) = (8.33 kpc, 240 km s$^{-1}$), peculiar solar motions of ($U_\odot$, $V_\odot$, $W_\odot$) = (11.1 ± 1, 12.24 ± 2, 7.25 ± 0.5) km s$^{-1}$, and a flat Galactic rotation (i.e., $\Theta(R)$ = $\Theta_0$). Different colored circles mean different arms (Red = Perseus arm; Blue = Outer arm; Black = Local arm).

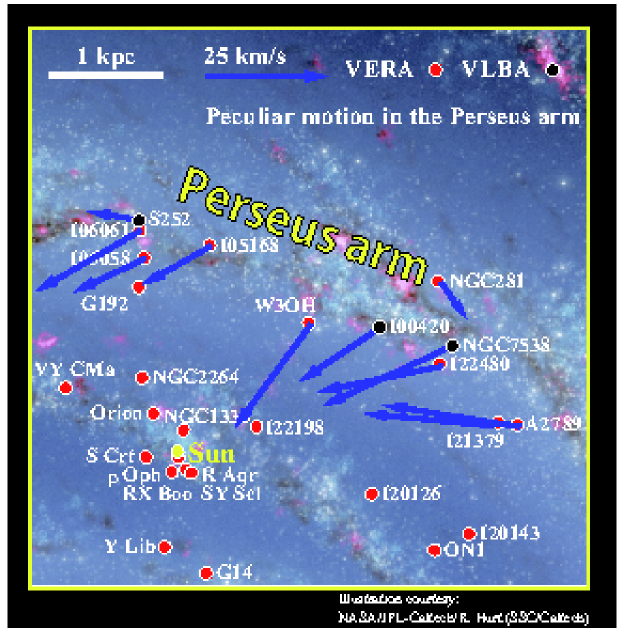


Fig. 4. Schematic view of the systematic peculiar motions seen in the Perseus arm (from Sakai et al. 2013).

motions of gas and stars. In the next decade, astrometry will allow us to understand the origin and evolution of the spiral arms as well as that of the Milky Way.

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