# Mapping the Milky Way and the Local Group

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**Summary.** Over the past decade, the astrometric accuracy of Very Long Baseline Inteferometry has improved dramatically. Currently relative positions between sources separated by about 1° are being measured with accuracies of $\sim 10$ $\mu$as. With this accuracy, trigonometric parallaxes throughout the Milky Way and proper motions of Local Group galaxies are now being measured. These observations will lead to direct mapping of the structure of the Milky Way, testing of the spiral density wave paradigm, measuring the dark matter halos of Local Group galaxies, and better understanding of the past history and future fate of these galaxies.

## 1 Advances in VLBI Astrometric Accuracy

Very Long Baseline Interferometry has always held the promise for near microarcsecond ($\mu$as) astrometry. In some cases such accuracy has been achieved, for example, for relative positions of maser spots within a source [1, 2]. Also, there are some pairs of continuum sources (eg, QSOs) very close together on the sky for which $\mu$as relative positions have been determined [3]. However, such accuracies have not been routine until recently.

Routine astrometric accuracy for VLBI observations of pairs of sources separated by about 1° has advanced from about 1 mas in 1995 to about 20–50 $\mu$as in 2005. One example of high astrometric accuracy is the measurement of the proper motion of Sgr A*. Observations originally started in the late 1970s, but not successful until the VLBA came on-line in the 1990s, have been used to track the apparent position of Sgr A*. Fig. 1 displays the position of Sgr A*, relative to a distant "QSO" J1745-283, from 1995 currently through 2003 [4].

The apparent motion of Sgr A* is dominated by the orbit of the Sun about the center of the Milky Way. The Sun travels in a nearly circular ($e < 0.1$) orbit at a speed of about 220 km s$^{-1}$ at a radius of 8 kpc [5]. The small

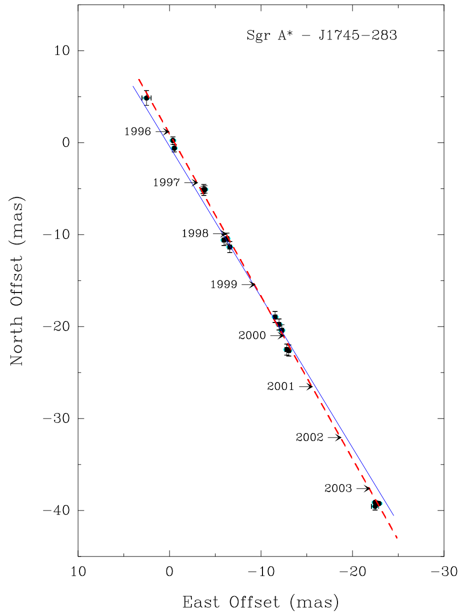


**Fig. 1.** Apparent proper motion of Sgr A* on plane of the sky. Position residuals of Sgr A* relative to J1745–283 on the plane of the sky are plotted. Each measurement is indicated with an ellipse, approximating the scatter-broadened size of Sgr A* at 43 GHz, and $1\sigma$ error bars. The dashed line is the variance-weighted best-fit proper motion, and the solid line gives the orientation of the IAU Galactic plane. The different slopes of the two lines corresponds to the motion of the Sun perpendicular to the Galactic Plane.

component of motion out of the Plane is caused by the 7.2 km $s^{-1}$ component of the peculiar motion of the Sun. After accounting for the motion of the Sun, the residual motion of Sgr A* out of the Plane is less than about 1 km $s^{-1}$ [4]. Were Sgr A* a stellar object and not a super-massive black hole, it would be moving at speeds of $\sim 10^{3-4}$ km $s^{-1}$, as observed for stars near its position.

## 2 Trigonometric Parallax Measurements

With relative positional accuracy of $\sim 10$ $\mu$as, one can obtain trigonometric parallaxes to sources as far away as the Galactic Center with accuracies of better than 10%. By comparison, the very successful astrometric satellite *Hipparcos* [6], which determined $\sim 10^5$ parallaxes, only achieved an accuracy of $\sim 1$ mas – a factor of nearly 100 poorer than from VLBI techniques.

A trigonometric parallax is the "gold standard" for astronomical distance measurements, involving simple triangulation with the Earth's orbit about the Sun as one leg of a triangle. The parallax signatures for three representative

Galactic sources are shown in Fig. 2. From the vantage point of a source at Galactic longitude 134° (eg, W3OH), the Earth's orbit appears nearly face-on and the sinusoidal excursions observed in the R.A. and Dec. directions are nearly the same magnitude. For sources closer to the Galactic Center, the orbital plane of the Earth tilts and the Declination parallax amplitude decreases. At the Galactic Center, the Earth's orbit appears nearly edge-on and the R.A. parallax sinusoid completely dominates.

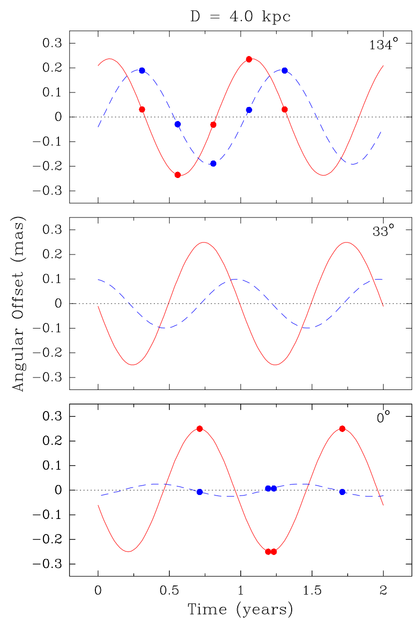


**Fig. 2.** Example trigonometric parallax signatures for sources in the Galactic Plane at three Galactic longitudes (indicated in each panel). The effect of the Earth's orbit around the Sun in the East-West (*solid lines*) and North-South (*dashed lines*) directions are shown. Sample data, which are nearly optimum for parallax measurement, are shown on the top and bottom panels. A distance of 4 kpc is assumed.

When determining a trigonometric parallax, one must also solve for a proper motion. Parallax accuracy is improved by minimizing correlations between the parallax and proper motion parameters. Symmetric sampling of the parallax signature near the maximum position excursions is optimal. The top panel of Fig. 2 shows a case where the R.A. and Dec. parallax excursions are comparable and a near optimum time sampling every 3 months is indicated. However, in the bottom panel, when the R.A. parallax excursion is significantly greater than the Dec. excursion, the time sampling shown every 6 months is a better strategy.

## 3 Trigonometric Parallax for W3OH

Recently the parallax of W3OH, a massive newly-formed star in the Perseus spiral arm of the Milky Way, has been measured by two groups, using $CH_3OH$ [7] and $H_2O$ [8] masers as astrometric targets. In general, $CH_3OH$ masers, whose lifetimes are $\gg 1$ year, are better suited for parallax measurements than $H_2O$ masers, whose typical lifetimes are $< 1$ year. (However, $H_2O$ masers are generally stronger and more numerous in the Milky Way.) Fig. 4 demonstrates the stability of $CH_3OH$ masers by showing a portion of the W3OH source at two epochs spaced by one year.

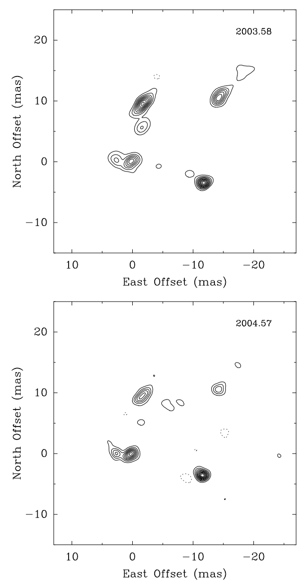


**Fig. 3.** A cluster of 12 GHz methanol maser spots in W3OH. These masers change only slightly over the 1 year between observations, making them excellent astrometric targets.

Positions of a single $CH_3OH$ maser spot in W3OH, relative to three QSOs, are shown in Fig. 4. The parallax signature plus the source proper motion results in the "tilted" sinusoids. Combining parallax data from 9 maser spots and 3 background QSOs yields a parallax of $0.512 \pm 0.010$ mas ($1.95 \pm 0.04$ kpc) [7]. This parallax resolves a long-standing problem of a discrepancy of a factor of 2 between kinematic (4.3 kpc) and luminosity (2.2 kpc) distances to star forming regions in this portion of the Perseus spiral arm. The kinematic distances are a factor of 2 too large, while the luminosity distances are correct to within 15%.

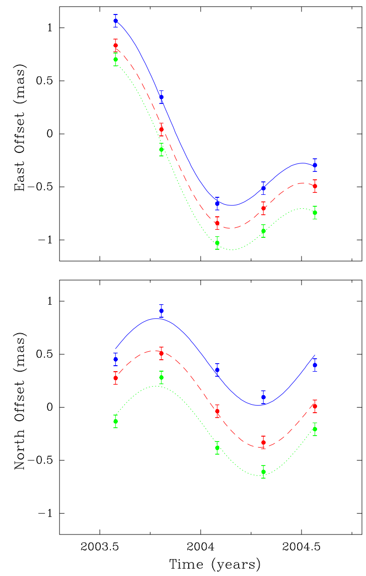


**Fig. 4.** Positions for one 12 GHz maser spot in W3OH relative to 3 background sources (offset from each other for clarity). The data show the sinusoidal parallax signature superposed on the proper motions.

The proper motion of W3OH, measured with an accuracy of better than 1 km $s^{-1}$, indicates the reason for the kinematic distance anomaly. W3OH has a very large peculiar motion of 22 km $s^{-1}$, with respect to circular motion in the Milky Way. Essentially all of this peculiar motion is toward the Sun, resulting in a very large kinematic distance error. While spiral density wave theories allow for such a peculiar motion [9], the magnitude of the motion is larger than most models predict. Parallax and proper motion measurements with the VLBA and VERA for large numbers of massive star forming regions can be used to determine the spiral structure of the Milky Way and to test critically the spiral density wave paradigm.

## 4 Proper Motions in the Local Group

With near $\mu$as relative position accuracy, there are many interesting applications of VLBI astrometry to extragalactic astronomy. In the 1920s, van Maanen claimed to have measured the angular rotation of nearby spiral galaxies. Fig. 5 reproduces a plate from his 1923 paper [10], purporting to show large rotation, which was offered as evidence against the extragalactic nature of "spiral nebulae."

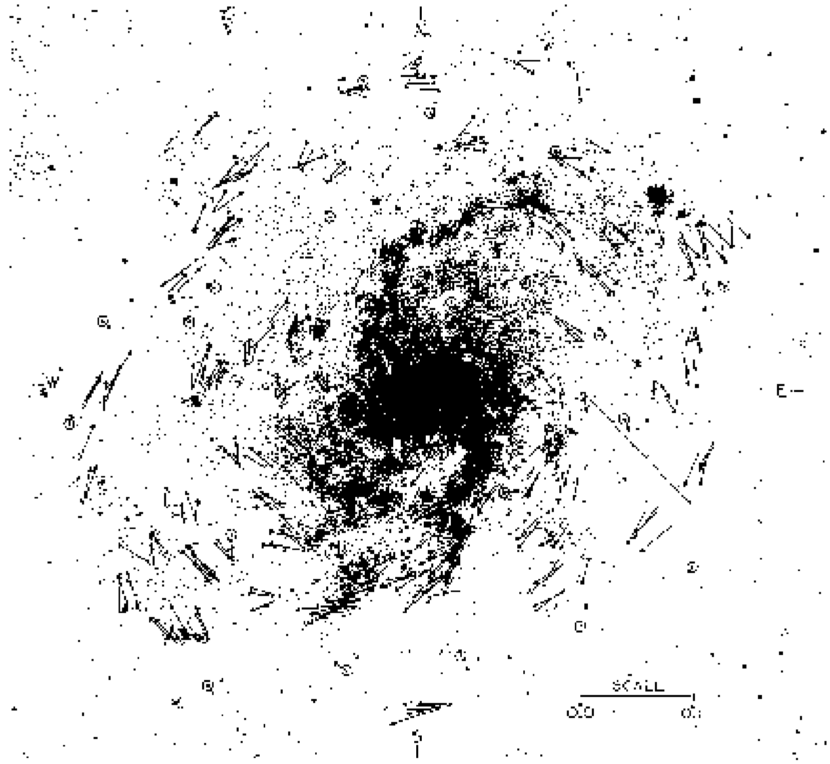


**Fig. 5.** The van Maanen Experiment [10]: relative proper motions in M33 obtained from optical plates in the 1920s. The proper motions are far larger than possible for an external galaxy; the reason for the exaggerated motions have never been determined.

Andreas Brunthaler, as part of he PhD thesis work, was able to accomplish the "van Maanen experiment" and measure the angular rotation of M33 [11]. Fig. 6 shows schematically the location and expected motion of two $H_2O$ maser sources relative to the center of M33. The measured motions are close to the expected motions. Combining the measured angular rotation with a model of the rotation speed and inclination of M33 (from HI observations) gives a distance of $730 \pm 168$ kpc. Since proper motion accuracies improve rapidly with increased observing time span (as $t^{3/2}$), continued VLBA observations will soon yield a very accurate distance to M33.

Brunthaler's observations were phase-referenced to distant QSOs. This allows the proper motion of the entire galaxy to be estimated. Galaxy proper motions are key to understanding the past history and future fate of galaxies in groups. Fig. 7 shows the measured motions of M31 (radial velocity only) and M33 (3-D velocity), relative to the Milky Way. Were M31 to have a near zero proper motion, as might be expected since M31 and the Milky Way are

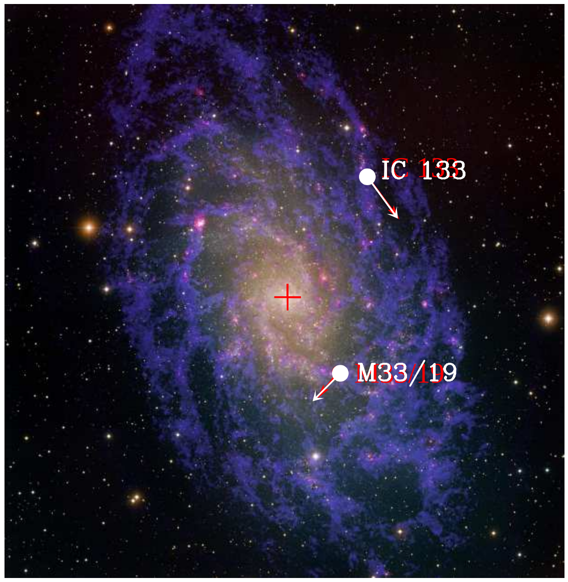


**Fig. 6.** The locations and expected proper motions of two sites of $H_2O$ masers in M33. These motions (the "van Maanen experiment") have been measured by VLBI observations [11].

the dominant galaxies in the Local Group, one could calculate the "orbits" of M33, M31, and the Milky Way.

Loeb et al [12] calculated Local Group orbits for different trial proper motions of M31. Over large ranges of trial proper motions, M33 was found to have interacted strongly with M31. Such interactions would have tidally heated and stripped stars in M33, which seems inconsistent with M33's undisturbed disk. In this manner, M31's proper motion is strongly constrained.

Calculations of "orbits" of Local Group galaxies are sensitive to the mass of dark matter halos. Reducing dark matter halos masses can avoid having strong tidal interactions between M33 and M31, as well as close encounters between M31 and the Milky Way in the past [12]. Clearly, proper motions of Local Group galaxies provide powerful information on dark matter.

## 5 The Future Today

Recently, Sofue & Rubin [13] reviewed progress on understanding rotation curves of spiral galaxies. They also made predictions of where significant advances could be expected. Three of these predictions are already close to fruition: 1) "Rotation of the Galaxy...will be directly measured from proper motions and parallaxes...using microarcsecond radio interferometry; 2) "Ra-

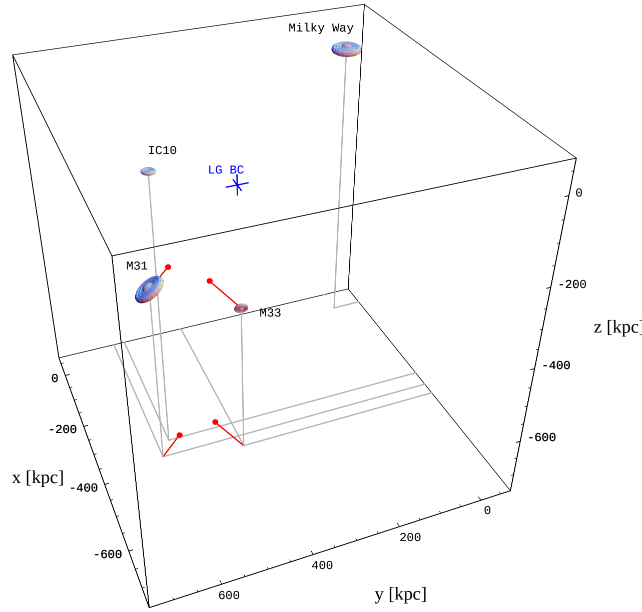


**Fig. 7.** Motions of M33 and M31 relative to the Milky Way [11]. M33's radial and proper motion has been measured, however, only the radial component if M31's motion has been measured.

dio interferometry of maser stars will be used to directly measure rotation on the sky of the nearest galaxies; and 3) "Dark halos...Will we learn if our halo brushes the halo of M31?"

We can certainly look forward to the fantastic results that the VLBA and VERA will provide.

## References


1. M. J. Reid et al: ApJ, **330**, 809 (1988)
2. C. Gwinn, J. M. Moran & M. J. Reid: ApJ, **393**, 149 (1992)
3. M. J. Rioja et al: A&A, **325**, 383 (1997)
4. M. J. Reid & A. Brunthaler: ApJ, **616**, 872 (2004)
5. M. J. Reid: ARA&A, **31**, 345 (1993)
6. M. A. C. Perryman et al: A&A, **323**, 49P (1997)
7. Y. Xu, M. J. Reid, X. W. Zheng & K. M. Menten: Science, **311**, 54 (2005)
8. K. Hachisuka et al: ApJ, **645**, 337 (2006)
9. W. W. Roberts: ApJ, **259**, 283 (1972)
10. A. van Maanen: ApJ, **57**, 264 (1923)
11. A. Brunthaler et al: Science, **307**, 1440 (2005)
12. A. Loeb, M. J. Reid, A. Brunthaler & H. Falcke: ApJ, **633**, 894 (2005)
13. Y. Sofue & V. Rubin: ARA&A, **39**, 137 (2001)