Structure and Dynamics of the Milky Way: an Astro2010 Science White Paper

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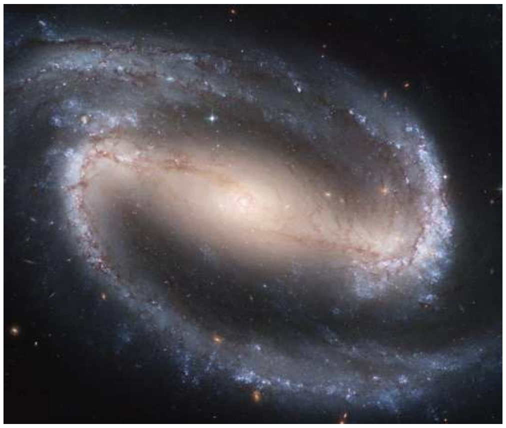

NGC 1300

NGC 3370

The Milky Way ???

ABSTRACT

Recent advances in radio astrometry with the VLBA have resulted in near micro-arcsecond accurate trigonometric parallax and proper motion measurements for masers in star forming regions. We are now poised to directly measure the full 3-dimensional locations and motions of *every* massive star forming region in the Milky Way and for the first time to map its spiral structure. Such measurements would also yield the full kinematics of the Milky Way and determine its fundamental parameters (R_0 and Θ_0) with 1% accuracy. Coupled with other observations this would yield the distribution of mass among the various components (including dark matter) of the Milky Way.

1. Background

Less than a century ago the very nature of "spiral nebulae" (galactic vs. extragalactic) was actively debated, whereas today we observe galaxies forming and interacting throughout the Universe. Surprisingly, we know other galaxies far better than we know the Milky Way. Since we are inside the Milky Way, it has proven very difficult to properly characterize its structure, because dust obscures most of the Galaxy at optical, and to some extent at IR, wavelengths and distances beyond the extended Solar Neighborhood are often quite uncertain. Thus, we only have an "educated guess" that the Milky Way is a barred Sb or Sc galaxy, and even the number of spiral arms (2 or 4) is actively debated (Benjamin 2008).

The discovery of a radio frequency transition of atomic hydrogen (HI at 21 cm wavelength) in the 1950s offered the hope that, freed from extinction problems, one could map the structure of the Milky Way. HI emission on Galactic longitude versus velocity plots clearly demonstrated that there are coherent, large-scale structures, which probably are spiral arms. However, determining accurate distances to HI clouds proved problematic, and this made the task of turning longitude-velocity data into a true "plan-view" of the Milky Way very uncertain (Burton 1988). Later, millimeter-wave observations of CO molecules also revealed coherent, large-scale structures with higher contrast than seen in HI (Dame, Hartmann & Thaddeus 2001). But, again, uncertain distances to molecular clouds precluded making a true map of the Milky Way with sufficient accuracy to trace its spiral structure.

Georgelin & Georgelin (1976) constructed a plan-view model of the spiral structure of the Milky Way (see Fig. 1). Their approach involved combining optical observations of young stars and radio data of HI clouds and HII regions. Luminosity distances to nearby stars were used where available and kinematic distances elsewhere, mostly for distant HII regions. While subject to very significant uncertainties from kinematic distances, the Georgelin model has remained the "standard" model of the spiral structure of the Milky Way for over 30 years. However, debate continues over such basic facts as the existence of some spiral arms, the number of arms, and the size, rotation speed and mass of the Milky Way.

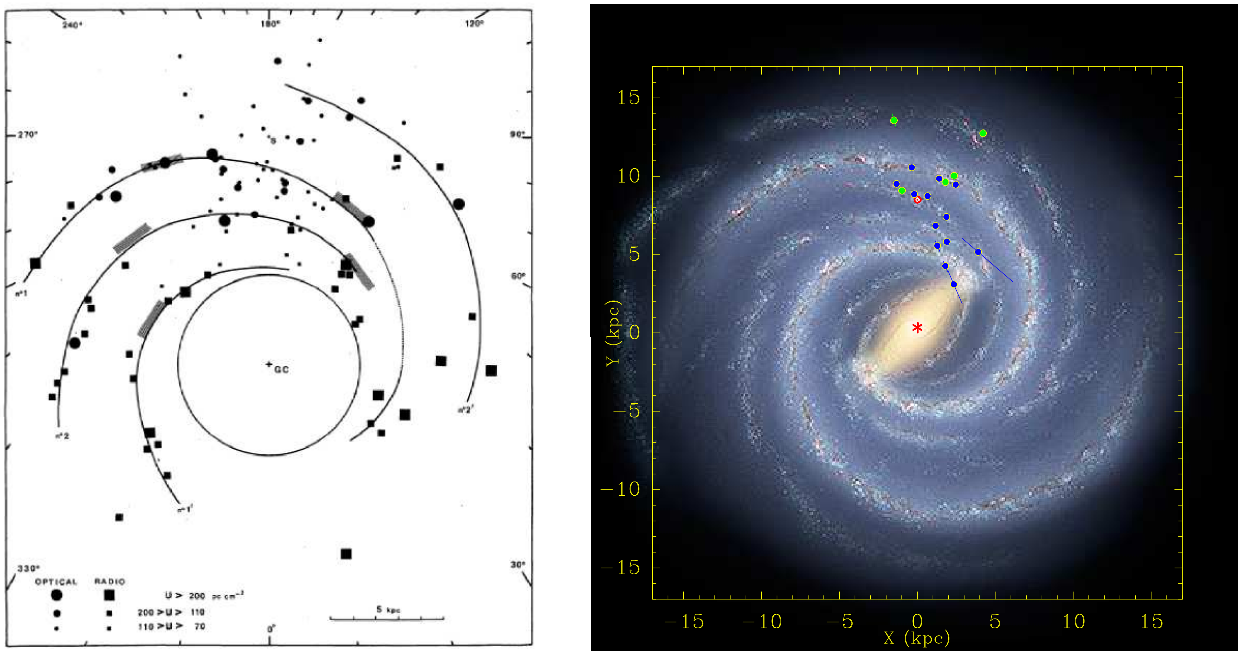

Fig. 1.— *Left Panel:* Georgelin & Georgelin (1976) spiral model of HII regions in the Milky Way. Considerable controversy exists as to the accuracy of this model, largely because many of the distances used are very uncertain. Researchers in the field even disagree on the number of spiral arms. Yet, over 30 years since publication, it remains the "standard" model. *Right Panel:* Locations of high-mass star forming regions for which trigonometric parallaxes have been measured with VLBI. Parallaxes of 12 GHz methanol masers are indicated with *dark blue dots* and those from water masers are indicated with *light green dots.* Distance error bars are indicated, but most are smaller than the dots. The Galactic center (*red asterisk*) is at (0,0) and the Sun (*red Sun symbol*) at (0,8.5). The background is an artist's conception of Milky Way (R. Hurt: NASA/JPL-Caltech/SSC) viewed from the NGP. The artist's image has been scaled to place the star forming regions in the spiral arms.

2. Scientific Context: Mapping the Milky Way

Recent improvements in radio astrometry with the VLBA have yielded parallaxes and proper motions to star forming regions across a significant portion of the Milky Way with accuracies of ∼ 10 μas and ∼ 1 km s^{-1}, respectively (Reid et al. 2009a; Moscadelli et al. 2009; Xu et al. 2009; Zhang et al. 2009; Brunthaler et al. 2009; Moellenbrock, Claussen & Goss 2009). Fig. 2 shows the results of VLBA observations of 12 GHz methanol masers associated with a massive young stellar object in the star forming region S 252. The data yield a parallax of 476 ± 6 μas. With such data one can measure distances to sources on the far side of the Milky Way with 10% accuracy!

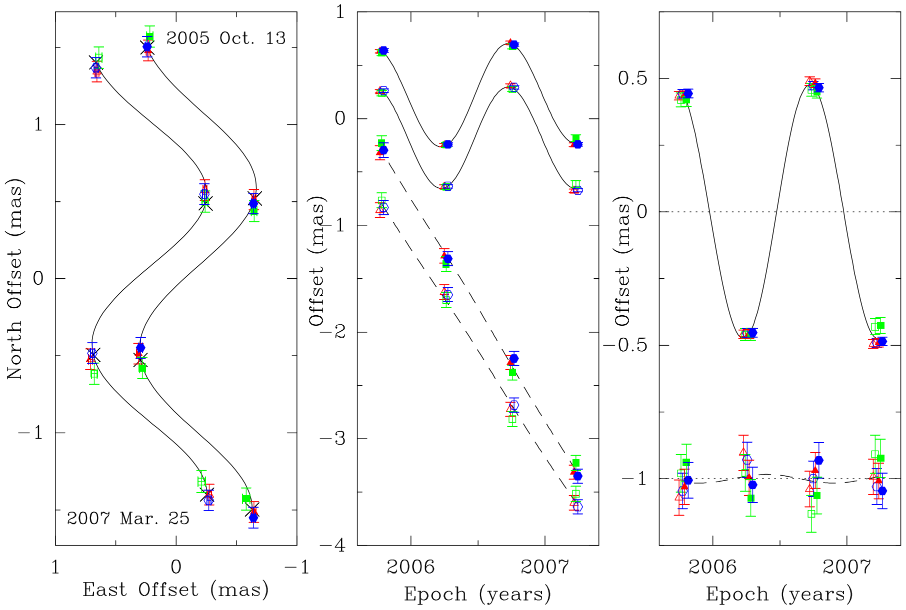

Fig. 2.— Astrometric data for S 252 showing the parallax fit of 476 ± 6 μas from Reid et al. (2009a). Plotted are position measurements of two maser spots *(open and solid symbols)* relative to the three background quasars: J0603+2159 *(red triangles)*, J0607+2218 *(green squares)* and J0608+2229 *(blue hexagons)*. *Left Panel:* Positions on the sky with first and last epochs labeled. Data for the two maser spots are offset horizontally for clarity. The expected positions from the parallax and proper motion fit are indicated *(crosses)*. *Middle Panel:* East *(solid lines)* and North *(dashed lines)* position offsets and parallax and proper motions fits versus time. Data for the two maser spots are offset vertically, the northward data have been offset from the eastward data, and small time shifts have been added to the data for clarity. *Right Panel:* Same as the *middle panel*, except the best-fit proper motions have been removed, allowing all data to be overlaid and the effects of only the parallax seen.

Combining the results from 16 similar measurements shows the potential of VLBA parallaxes for mapping the Milky Way (Reid et al. 2009b). The results begin to locate spiral arms (see Fig. 1) and yield the first direct measurement of arm pitch angles. In addition, estimates of the fundamental parameters of the Milky Way, R_0 and Θ_0, indicate a rotation speed of $\Theta_0 = 254$ km s^{-1}, some 15% faster than usually assumed. Interestingly, these first astrometric results indicate that the Milky Way and the Andromeda galaxy (Carignan et al. 2006) have nearly identical rotational properties, suggesting similar dark matter sizes and masses and contrary to the general assertion that Andromeda is significantly more massive than the Milky Way.

Changing the value of Θ_0 from the IAU standard 220 km s^{-1} to $\approx$ 250 km s^{-1} significantly affects models of the Local Group of galaxies. It results in a decrease of about 20 km s^{-1} in the space velocity of the LMC *relative to the center of the Milky Way* and an increase of about 50% in the estimated (dark matter) mass of the Milky Way. Both help to bind the LMC to the Milky Way (Shattow & Loeb 2008) and reverse the conclusion, based on HST measurements of the proper motion of the LMC, that the LMC was unbound and making its first pass near the Milky Way (Kallivayalil et al. 2006).

We are currently poised to make truly dramatic progress in understanding the Milky Way. Over the next 10 to 20 years, we could measure the distance to *every* high mass star forming region in the Galaxy with parallax accuracies of ~ 1 μas. At the far side of the Galaxy (16 kpc) this would correspond to better than $\sim 2\%$ distance accuracy. *Thus, for the first time we could map in detail the spiral structure of the Milky Way and learn what it really looks like.*

Indeed, with this accuracy one could easily resolve structure, not only across spiral arms, but also across the bar in the Galactic center region, provided the density of target sources is adequate to reveal structure. Finally, we would have not only the 3-dimensional locations of all major star forming regions, but also their 3-dimensional velocity vectors. This would yield extraordinarily accurate measurements (projected to be better than $\pm 1\%$) of such fundamental parameters as the distance to the Galactic center (R_0), the rotation speed of the LSR (Θ_0), the form of the rotation curve, and the kinematic effects of spiral structure. Note that GAIA or SIM, which may have comparable astrometric accuracy, will operate at optical wavelengths and cannot see through the dust in the plane of the Milky Way, nor to deeply embedded regions of star formation. Since the ionizing radiation from OB-type stars in high mass star forming regions in the Galactic plane best defines spiral structure, the most straightforward way to map this structure is through radio astrometry.

3. Telescope Needs

The observations needed to map the Milky Way outlined above can be accomplished with the advances outlined in Table 1. Some of the goals can be achieved with modest upgrades in receiver and data recording equipment at the VLBA. Currently most of the parallax measurements with the VLBA have employed 12 GHz methanol masers. Methanol masers associated with high mass star forming regions are nearly ideal astrometric targets; they are compact, long-lived, and their motions are closely tied to the massive star that excites them. (H_2O masers are not a good substitute. They participate in fast outflows and have lifetimes less than the 1 year necessary for good parallax measurements. Also, their large internal motions make it difficult to associate a maser motion with that of its central massive star. This latter problem does not affect parallax measurement, but it does limit the interpretation of the proper motions for Galactic dynamics.) Unfortunately, there are only several tens of 12 GHz methanol masers that are strong enough for VLBA parallax measurement. Adding a new VLBA receiver, capable of observing the much stronger 6.7 GHz methanol masers, is needed to map the locations and motions of hundreds of star forming regions across major portions of the Milky Way.

Upgrading the VLBA data recording rate by more than two orders of magnitude from 256 Mbps to 32 Gbps (which requires no new technology) would dramatically improve astrometric accuracy by making far more background quasars available as position references. VLBA astrometric observations are usually limited by systematics that cancel proportionally to the separation of the maser target and background quasar. The factor of 11 (i.e. $\sqrt{32\mathrm{Gbps}/256\mathrm{Mbps}}$) improvement in continuum sensitivity from the increased recording capability would lead to an average decrease in target-quasar separation by a factor of 20 (assuming standard $\log N/\log S$ statistics). This should allow parallaxes accurate to better than ± 1 μas!

In order to map the entire Milky Way, we will need a VLBA-like capability in the southern hemisphere. This could be well met by the "SKA-mid" project, which will be placed in the southern hemisphere, provided the antennas can reach the 6.7 GHz transition of methanol masers. Alternatively a relatively modest upgrade to the Australian VLBI capabilities could also provide the required capabilities.

Combining the above mentioned advances in receiver and recording capabilities with increased collecting area would allow measurement of weaker target sources. This could be achieved in conjunction with a "path-finder" project that would prototype and test antenna "patches" with $\sim 5\%$ of an SKA collecting area. Placing some of these antenna patches at VLBA sites and at some new sites between the EVLA and the VLBA would greatly increase the sensitivity of the array. Some of these telescope advances could come from the phased implementation of the plans outlined in the "North American Array" initiative (J. Ulvestad, coordinator) submitted to the Decadal Survey. The construction of even a 5% SKA in the Southern Hemisphere would allow exquisite mapping of the entire Milky Way. Finally, we note that the construction of the entire SKA concept would revolutionize all of these activities and lead to truly dramatic astrometric results.

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Table 1. Telescopes Advances and their Scientific Impact

Telescope Advance	Scientific Impact
6.7 GHz receivers for VLBA	Expand number of parallax targets by ×10 to map spiral structure and dynamics of the (northern) Milky Way
High (32 Gbps) data recording rate and/or additional telescopes/collecting area	Parallax calibrators a factor of > 20 nearer to targets, enabling sub-μas astrometry
Improved southern hemisphere VLBI capability (e.g. partial SKA)	Map southern portion of Milky Way