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 the nature of 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 because 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). Possibly, the Milky Way looks like a cross between the two galaxies shown in Fig. 1.

Fig. 1.— Images of two spiral galaxies, NGC 1300 (*left panel*) and NGC 3370 (*right panel*), that might share some of the characteristics of the Milky Way, but we really don't know. The primary goal of this project, and a future southern extension, is to provide a "plan view" map of the Milky Way, revealing its true spiral structure.

The discovery of the 21-cm (HI) transition of atomic hydrogen 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. 2). Their approach involved combining optical observations of young stars and radio observations 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.

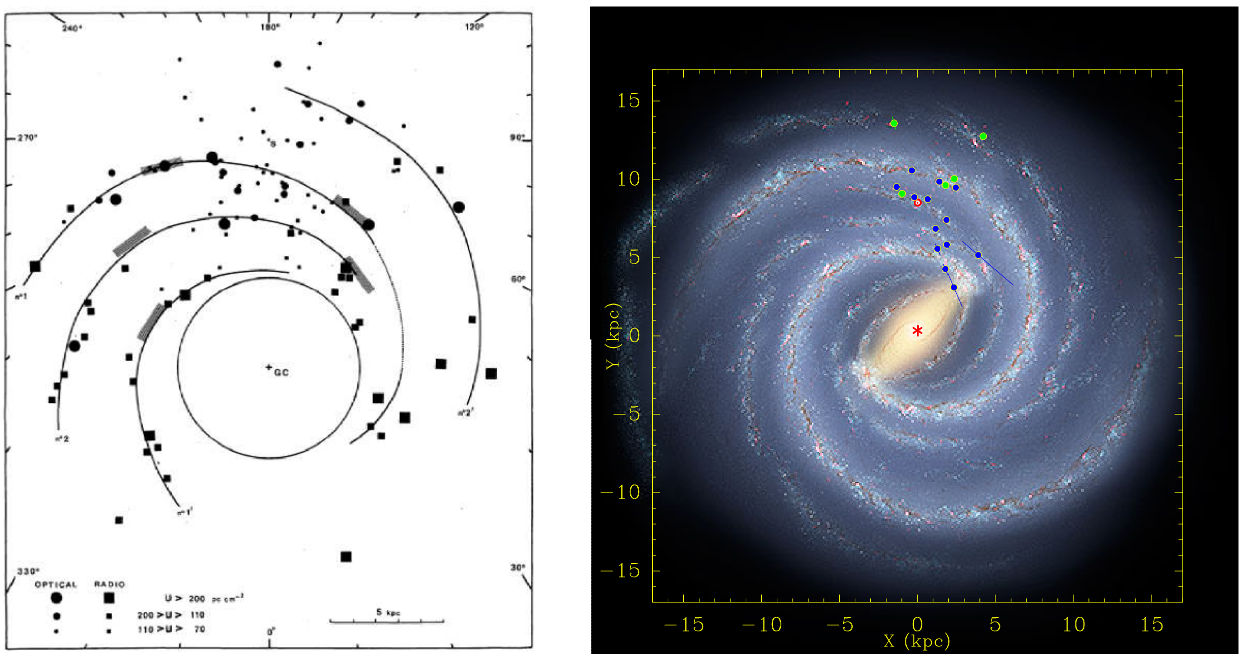

Fig. 2.— *Left Panel:* Georgelin & Georgelin (1976) spiral model of HII regions in the Milky Way. Considerable controversy exists as to the accuracy of this model, yet, over 30 years since publication, it remains the "standard" model. *Right Panel:* Locations of high-mass star forming regions for which 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. Mapping the Milky Way

Recent improvements in radio astrometry with VLBI techniques using the VLBA and the Japanese VERA project 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 (Xu et al. 2006; Hachisuka et al. 2006; Menten et al. 2007; Honma et al. 2007; Hirota et al. 2007;

Choi et al. 2008; Sato et al. 2008; Bartkiewicz et al. 2008; 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. 3 shows an example of 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 (≈ 15 kpc) with 10% accuracy!

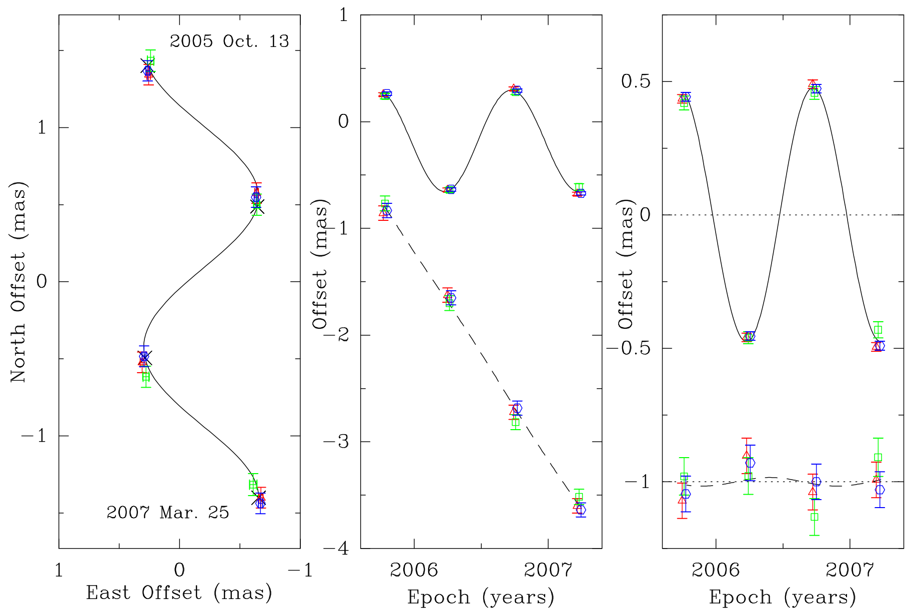

Fig. 3.— Astrometric data for S 252 showing the parallax fit of 476 ± 6 μas after Reid et al. (2009a). Plotted are position measurements of one maser spot relative to the three background quasars: J0603+2159 *(red triangles)*, J0607+2218 *(green squares)* and J0608+2229 *(blue hexagons)*. A second maser spot gave nearly identical results. The three panels display the data in different ways: *Left Panel:* Positions on the sky with first and last epochs labeled. 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; 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 of 18 parallax measurements from the VLBA and VERA shows the potential for mapping the Milky Way (Reid et al. 2009b). The results begin to locate spiral arms (see Fig. 2) and yield the first direct measurement of arm pitch angles. For example, we have directly measured the pitch angle of a portion of the Perseus spiral arm to be $16^\circ \pm 3^\circ$, which favors 4 rather than 2 spiral arms for the Milky Way. However, more such measurements are necessary before one can make firm conclusions.

In addition, by modeling the full 3-dimensional locations and velocity vectors of star forming regions, fundamental parameters of the Milky Way can be determined: we have found that the distance to the Galactic center (R_0) is 8.4 ± 0.6 and the Galactic rotation speed at the Sun (Θ_0) is 254 ± 16 km s^{-1}. These values of R_0 and Θ_0 are *independently* confirmed by a combination of 1) measurement of the proper motion of the Galactic center black hole (Sgr A*), which gives $\Theta_0/R_0 = 29.45 \pm 0.15$ km s^{-1} kpc^{-1} (Reid & Brunthaler 2004), and 2) stars orbiting the black hole which yields $R_0 = 8.4 \pm 0.4$ kpc (Ghez et al. 2008; Gillessen et al. 2009). Improving the value of R_0 has widespread importance as it affects distances, masses and luminosities for almost all objects in the Galaxy. For example, the mass of the supermassive black hole (Sgr A*) at the center of the Galaxy, as determined from stellar orbits, sensitively depends on R_0 (approximately as R_0^3).

It now appears that the rotation speed of the Milky Way is 15% faster than the IAU value of $\Theta_0 = 220$ km s^{-1}. A rotation speed, determined from the parallaxes and proper motions of star forming regions (Reid et al. 2009b) can be compared to that of the Andromeda galaxy (Carignan et al. 2006). Our first astrometric results indicate that the Milky Way and the Andromeda galaxy have nearly identical rotational properties. The simplest interpretation is that the dark matter halo sizes and masses of these two dominant Local Group galaxies are comparable, 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 ≈ 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 the HST proper motion of the LMC, that it 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 5 years, we could measure the distance to most high-mass star forming regions in the Milky Way ($0^\circ < \ell < 240^\circ$) with parallax accuracies of ~ 10 μas. Even at distances of ~ 10 kpc, which takes one inward beyond the Galactic center or outward to the end of the range where major star formation occurs, this would correspond to $\sim 10\%$ distance accuracy. *Thus, for the first time we could map in detail the spiral structure of the (northern) Milky Way and learn what it really looks like.* A similar campaign in the southern hemisphere, perhaps using a modest expansion of Australian VLBI capabilities or prototype SKA-mid facilities, could complete the job.

By modeling the Milky Way, these data would yield extraordinarily accurate measurements of R_0 and Θ_0 (projected to be near $\pm 1\%$) and should give us unprecedented detail for the rotation curve. Note that future billion-dollar astrometric space missions like GAIA or SIM, which ultimately 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 best way to map this structure is through radio astrometry.

Indeed, with our demonstrated accuracy one could resolve structure, not only across nearby spiral arms, but also along the bar in the Galactic center region. Thus, for example, we can study in detail the kinematic effects of the Galactic center bar, spiral density waves and shocks, and the effects of superbubbles (Sato et al. 2008) caused by supernova explosions in spiral arms.

A reasonably dense sampling of sources in spiral arms is necessary to fully trace spiral structure and not simply obtain their general locations. Most galaxies exhibit complex structure that is not well described by simple log-periodic formulae. Instead, spiral arms often have pitch angles that vary along the arms, have discontinuous arm segments or spurs, and have astrophysically interesting internal arm structures. Assuming that the Milky Way can be characterized by four major arms, some spurs, and a complex inner region near the bar, the observations proposed in §3 would yield ≈ 80 parallaxes per arm, corresponding to an average density of a few sources per kpc along each arm. Of course the density will vary considerably with Galactocentric radius.

Additionally, large numbers of sources are needed to study Galactic kinematics in detail. For example, there has been considerable debate over the decades regarding the validity of an azimuthally averaged rotation curve and possible differences in rotation in the first and second quadrants compared to the third and fourth quadrants. Our large data-base will allow detailed kinematic study on scales of tenths to tens of kpc. Also, in conjunction with other observations of HI, halo stars (Xue et al. 2008), globular clusters and satellite galaxies (Sakamoto, Chiba & Beers 2003), we hope to be able to tightly constrain models of the distribution of mass in the various components of the Galaxy, including the disk, bulge, and dark-matter halo.

3. Proposed Observations

The observations needed to map the (northern) Milky Way outlined above can be accomplished over a period of 5 years with the VLBA. We would observe methanol and H_2O masers that are associated with newly formed (or forming) massive stars, using techniques that have been well demonstrated in previous VLBA programs (e.g. see Papers I – V in References). We propose to measure ≈ 400 sources in 5 years, requiring about ≈ 1000 hours of VLBA time per year. The combined results of our proposed measurements and those being done by VERA (≈ 30 per year) would locate a significant fraction of high-mass star forming regions in the Milky Way. We would coordinate with the VERA project to assure minimal overlap of sources.

In Figure 4, we show the approximate locations of ≈ 400 6.7-GHz methanol masers stronger than 5 Jy, of which 220 are above $\delta = -30^\circ$ (Pestalozzi, Minier & Booth 2005), and ≈ 200 northern 22 GHz water masers stronger than 10 Jy (Palagi et al. 1993). These and other surveys would form the basis for our sample of sources. Note that for this figure we have used kinematic distances, which are highly inaccurate, and thus spiral structure is nearly completely washed out. The choice of which types of maser to use as astrometric targets requires some discussion. Currently most parallax measurements for high-mass star forming regions with the VLBA have employed 12 GHz methanol masers or 22 GHz H_2O masers. Methanol masers associated with high-mass star forming

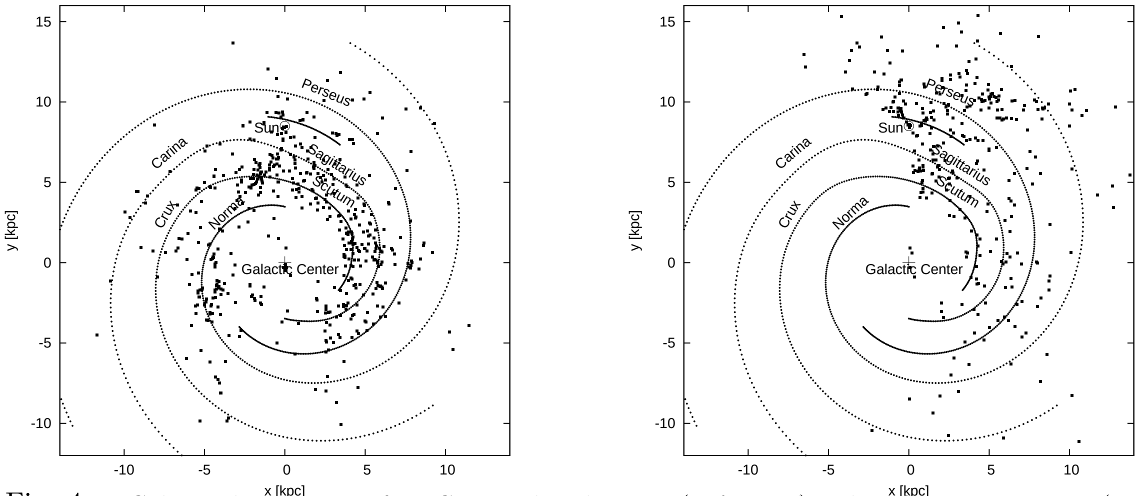

Fig. 4.— Galactic distributions of 6.7 GHz methanol masers (*Left Panel*) and 22 GHz water masers (*Right Panel*). Kinematic distances have been used to generate these plots and distance ambiguities have been resolved using the prescription of Fish et al. (2003), based simply on Galactic latitude. Note that these distances are highly uncertain and are essentially useless to determine spiral structure. The Georgelin & Georgelin model of the Milky Way spiral arms has been superposed only to provide scale information.

regions are nearly ideal astrometric targets; they are compact, long-lived, and their slow internal motions (few km s^{-1}) are closely tied to the massive star that excites them. H_2O maser parallaxes have also been measured with accuracies comparable to those of methanol masers. However, H_2O masers are more difficult astrometric targets, as individual maser spots often have lifetimes less than the 1 year which is optimal for parallax measurements. (Also, H_2O masers participate in fast outflows and have large ($\sim$ 30 km s^{-1}) internal motions. While this does not affect parallax measurements, it does complicate estimation of the motion of the underlying massive star, which is important for the interpretation of the proper motions for Galactic dynamics.) Unfortunately, there are only about 30 12-GHz methanol masers whose parallaxes have yet to be measured and are strong enough to serve as a phase-reference for the measurements. Adding a new VLBA receiver, capable of observing the much stronger and vastly more numerous 6.7 GHz methanol masers, has been proposed to the NSF MRI program and, hopefully, will be funded shortly. If so, we could begin measurements of 6.7 GHz methanol masers in about 2 years.

Interstellar scattering is a potential limitation for (lower frequency) 6.7 GHz maser parallaxes. In the Galactic plane, our lines of sight to distant sources are likely to pass through some regions of enhanced electron density. Scattering broadens the images of maser spots (and the broadening scales as wavelength squared). At 6.7 GHz, we expect many masers to be scatter broadened to a few milli-arcseconds and fully resolved on the longest VLBA baselines. This reduces positional accuracy, which degrades linearly as baselines shorten, and may limit some 6.7 GHz parallaxes to ≈ 20 μas accuracy with 1 year's data. This is adequate for mapping sources out to ≈ 5 kpc distances with 10% accuracy. However, for inner Galaxy sources at distances > 5 kpc, we plan to shift to 22 GHz H_2O masers, in order to obtain the highest accuracy parallaxes at the greatest distances.

We propose the following program of VLBA observations that will allow us to measure parallaxes and proper motions of ≈ 400 sources:

- Year 1: 30 12-GHz methanol and 50 22-GHz H_2O masers
- Year 2: 70 22-GHz H_2O masers
- Year 3: 60 6.7-GHz methanol and 20 22-GHz H_2O masers
- Year 4: 60 6.7-GHz methanol and 20 22-GHz H_2O masers
- Year 5: 60 6.7-GHz methanol and 20 22-GHz H_2O masers

Since H_2O masers require 6 instead of 4 epochs spaced more closely in time, in order to mitigate maser spot variability (see on-line material for details: **www.cfa.harvard.edu/~reid/moreinfo.pdf**), we can only observe about two-thirds as many H_2O as opposed to methanol masers with the same number of VLBA observing tracks. Should the new VLBA receiver designed to cover the 6.7 GHz methanol transition not be funded, we would measure 70 H_2O masers per year starting in Year 3 and possibly continue for one extra year (Year 6).

Our experience indicates that we can achieve parallax uncertainties of ± 6 μas for sources at high Declination (e.g. S 252), whereas for sources near the Galactic center we currently have uncertainties of ± 20 μas (e.g. G23.0-0.4). Since low Declination source parallaxes are limited more by systematic error than thermal noise, we plan to add an extra geodetic-block to the observing tracks in order to more carefully track and remove zenith path-delay errors. Even better would be to finish the deployment of GPS receivers at the remaining 4 VLBA antennas that do not have them, as this would allow *continuous* monitoring of zenith path delays. Either or both of these enhanced calibrations should improve the parallax accuracy compared to our previous results. However, for the most distant (low Declination) sources in the first Galactic quadrant, we could, if necessary, re-observe for another parallax cycle and obtain a $\sqrt{2}$ improvement.

In preparation for the VLBA parallax observations, we need 1) to find compact background sources near in angle to our target masers and 2) to measure positions of the maser targets to $\sim 0.5''$ accuracy. The background source survey could be done in yearly blocks of about 50 hours with the GBT (as a VLBI antenna) and the VLBA. However, this calibrator survey would be extremely valuable, not only for our parallax project, but also for many EVLA, VLBA, and even ALMA projects, since the density of known calibrators in the Galactic plane is low. Therefore, instead of conducting the search toward individual maser targets in yearly blocks, we could do a single complete Galactic plane survey at the start of our program. It would take approximately 160 hours of GBT–VLBA time to survey all compact sources stronger than ~ 10 mJy in the range $0^\circ < \ell < 240^\circ$ and $|b| < 1.0^\circ$ based on the CORNISH and NVSS "point" sources. From our experience this would produce about 1 calibrator per square degree, or about 500 calibrators total. These observations will be done at X-band (to maximize sensitivity and minimize the need for good weather) and can be dynamically scheduled when the GBT does *not* have good high-frequency weather.

Finally, in order to obtain sub-arcec accurate positions for all $\approx$ 400 masers, we will need about 16 hours of VLA time in any configuration. Detailed justifications for the time requests for the GBT–VLBA calibrator survey and the VLA maser position measurement observations can be found in supporting on-line material (see **www.cfa.harvard.edu/~reid/moreinfo.pdf**).

Ultimately, in order to complete the map of the entire Milky Way, we will later need a VLBA- or VERA-like capability in the southern hemisphere. This could be well met by (even a prototype of) 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.

4. Project Management, Data Products and Manpower Requirements

For our previous parallax projects, we have analyzed the data rapidly and submitted papers on the results, usually within 1 year of the end of observing. This includes our first project on W3OH (BX005; observations 2003/2004; Xu et al. (2006)), our Orion nebula parallax (BM234; observations 2005/2007, Menten et al. (2007), and our large 300-hr program that resulted in parallaxes for 11 sources (BR100; observations 2006/2007; published 6 papers in the Ap. J. in 2009, Papers I – VI). We currently have three on-going projects, BR129, BR134 and BM272, that are just completing the observing phases as this proposal is being drafted. We always analyze the first epoch data before the second epoch observations are conducted, in order to catch potential problems, and for all active projects the data look fine.

We now have extensive experience in planning for parallax measurements (including finding nearby background quasars), making observing scripts (including software for optimum scheduling of calibration blocks), and analyzing the data (via special programs and standard AIPS runfiles). For a parallax project involving 4 epochs and two maser targets (and their background quasars), we have found that one person can analyze the data completely within two weeks. Adding a third target to each track would take less than 1 additional week (as they share common calibration steps). Thus, each target source will require a total of less than 1 person-week to arrive at a parallax measurement. Since we are proposing to do upwards of 100 target sources per year, we need up to 100 person-weeks or 2 person-years per year for data analysis. (The calibrator surveys and maser position measurements take comparatively little analysis time and do not add significantly to these estimates.) So, realistically, we need roughly 8 people, each spending 25% of their time on data analysis, to keep up with the data. We have more this much manpower in the assembled team.

We plan to keep up with the data analysis and submit parallax and proper motion results for publication within 1 year of completion of each yearly parallax observing cycle, as we have done in the past. More detailed data products, including the positions of all maser spots and background quasars, would be placed on-line on the project web site within 1 year of completion of each parallax observing cycle. The results of the calibrator survey and the VLA maser flux/position measurements will be made available as soon as they are analyzed (within $\approx$ 1 month of correlation).

Of course the primary product of our research project will be a better understanding of the nature of the Milky Way. We hope to use this to develop educational aids that are visually engaging and scientifically accurate. Once we have determined the locations and motions of the spiral arms of the Milky Way, we plan to generate a 3-dimensional model of the Milky Way. We plan to use this model as the basis for a computer generated "movie" that would allow one to tour the Milky Way from the vantage point of 1) an extragalactic space traveler who could navigate the Milky Way and 2) a time traveler who could stand back and watch the Milky Way rotate.

Observation of the Milky Way is one of most interesting and basic scientific activities available to children (and adults). We hope to foster this educational experience by making the "movie of the Milky Way" available on Internet, both for individual viewing and for teachers to incorporate into curricula. Toward the end of the project, we would seek funds from various sources (e.g. Smithsonian, NRAO, Nanjing University/Purple Mountain Observatory & MPIfR) to accomplish these goals.

REFERENCES

Bartkiewicz, A., Brunthaler, A., Szymczak, M. van Langevelde, H. J & Reid, M. J. 2008, A&A, 490, 787

Benjamin, R. A. 2008, in Massive Star Formation: Observations Confront Theory, eds. H. Beuther, H. Linz & Th. Henning, ASP Conference Series, Vol. 387, p. 375

Brunthaler, A., Reid, M. J., Menten, K. M., Zheng, X. W., Moscadelli, L. & Xu, Y. 2009, ApJ, 693, 424 (Paper V)

Burton, W. B. 1988, in Galactic and Extragalactic Radio Astronomy, 2nd ed., eds. G. L. Verschuur & K. I. Kellermann, (Springer-Verlag, New York), p. 295

Carignan, C., Chemin, L., Huchtmeier, W. K. & Lockman, F. J. 2006, ApJ, 641, L109

Choi, Y. K. et al. , 2008, PASJ, 60, 1007

Dame, T. M., Hartmann, D. & Thaddeus, P. 2001, ApJ, 547, 792

Fish, V. L., Reid, M. J., Wilner, D. J. & Churchwell, E. 2003, ApJ, 587, 701

Georgelin, Y. M. & Georgelin, Y. P., 1976, A&A, 49, 57

Ghez, A. M. et al. 2008, ApJ, 689, 1044

Gillessen, S., Eisenhauer, F., Trippe, S., Alexander, T., Genzel, R., Martins, F. & Ott, T. 2009, ApJ, 692, 1075

Hachisuka, K. et al. 2006, ApJ, 645, 337

Hirota, T et al. 2007, PASJ, 59, 897

Honma,M. et al. 2007, PASJ, 59, 889

Kallivayalil, N., van der Marel, R. P., Alcock, C., Axelrod, T., Cook, K. H., Drake, A. J. & Geha, M. 2006, ApJ, 638, 772

Menten, K. M., Reid, M. J., Forbrich, J. & Brunthaler, A. 2007, A&A, 474, 515

Moellenbrock, G. A., Claussen, M. J. & Goss, W. M. 2009, ApJ, 694, 192

Moscadelli, L, Reid, M. J., Menten, K. M., Brunthaler, A., Zheng, X. W. & Xu, Y. 2009, ApJ, 693, 406 (Paper II)

Palagi, F., Cesaroni, R., Comoretto, G., Felli, M. & Natale, V. 1993, A&ASupp., 101, 153

Pestalozzi, M. R., Minier, V. & Booth, R. S. 2005, A&A, 432, 737

Reid, M. J. & Brunthaler, A., 2004, ApJ, 616, 872

Reid, M. J., Menten, K. M., Brunthaler, A., Zheng, X. W., Moscadelli, L. & Xu, Y. 2009a, ApJ, 693, 397 (Paper I)

Reid, M. J. et al. 2009b, to appear in ApJ (arXiv:0902.3913)

Sakamoto, T, Chiba, M. & Beers, T. C. 2003, A&A, 397, 899

Sato, M. et al. 2008, PASJ, 60, 975

Shattow, G. & Loeb, A. 2008, MNRAS, 392, L21

Xu, Y., Reid, M. J., Zheng, X. W. & Menten, K. M. 2006, Science, 311, 54

Xu, Y, Reid, M. J., Menten, K. M., Brunthaler, A., Zheng, X. W. & Moscadelli, L. 2009, ApJ, 693, 413 (Paper III)

Xue, X. X. et al. 2008, ApJ, 684, 1143

Zhang, B., Zheng, X. W., Reid, M. J., Menten, K. M., Xu, Y., Moscadelli, L. & Brunthaler, A. 2009, ApJ, 693, 419 (Paper IV)
