Motions of Galaxies in the Local Group and Beyond: An Astro2010 Science White Paper

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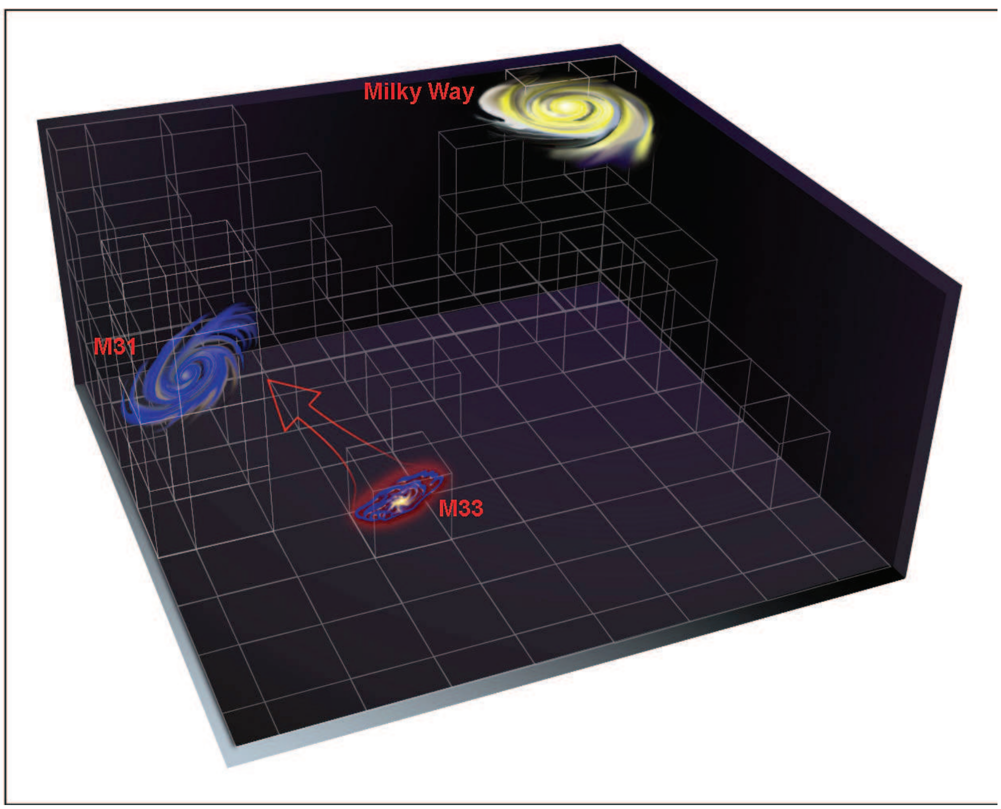

ABSTRACT

Recent advances with the VLBA have resulted in $\sim 10\ \mu$as astrometry for compact sources in external galaxies, and measurement of the proper motion of Local Group galaxies has been demonstrated. With improved telescopes and equipment, we could greatly improve upon and expand these measurements, including a measurement of the proper motion of the Andromeda galaxy, which is key to understanding the history and fate of the Local Group. The combination of optical velocities and radio astrometric data would allow detailed modeling of the mass distributions of the disks, bulges, and dark matter halos of galaxies in clusters.

1. Background

The nature of spiral nebulae was actively debated in the 1920's. While some astronomers favored a short distance and a Galactic origin, others argued for their extragalactic nature. In 1923, van Maanen measured photographic plates of M 33 separated by about 12 years and claimed to have detected the galaxy rotating at ~ 20 mas y^{-1}, clearly requiring a near distance (van Maanen 1923). However, a few years later, Hubble discovered Cepheids in M 33, providing evidence for a very large distance and requiring it to be extragalactic (Hubble 1926). At Hubble's distance, the expected proper motions from the rotation of M 33 are only $\approx 30\ \mu$as y^{-1}, nearly three orders of magnitude smaller than the motions claimed by van Maanen. (The source of error in van Maanen's measurements was never clearly identified.) After more than 80 years, the goal of measuring the rotation and absolute proper motions of galaxies remains interesting for our understanding of the dynamics and geometry of the Local Group and beyond.

2. Scientific Context: Extragalactic Proper Motions

We are currently poised to make truly dramatic progress in understanding the dynamics, and hence dark matter mass distribution, of the Local Group. Over the next 10 to 20 years, we could make measurements with accuracies of $\sim 0.1\ \mu$as y^{-1} and thus measure the 3-dimensional velocities of galaxies in the Local Group and in nearby groups out to the Virgo Cluster.

2.1. Motions in the Local Group

The distribution of dark matter in galaxies and groups of galaxies is one of the major problems in observational cosmology. The Local Group provides the nearest and best system for detailed study. Various attempts to "weigh" the Milky Way and the Andromeda galaxy have resulted in a large range of values. The major problem is that most studies work with only one-dimensional (radial) velocity components, introducing significant ambiguities and requiring statistical mass estimators, which suffer from small sample sizes and/or unknown biases from non-isotropic distributions. Clearly the most reliable way to derive mass distributions is from 3-dimensional velocity measurements through proper motions.

Currently, proper motion measurements, done optically, are only possible for close satellites of the Milky Way (eg, for the LMC see Kallivayalil et al. (2006)). The satellites of Andromeda are an oder of magnitude more distant and current optical telescopes are inadequate. Only VLBI has yielded proper motions for the Andromeda satellites M 33 and IC10 (Brunthaler et al. 2005, 2007). Fig. 1 shows recent astrometric data for two sites of H_2O masers in M 33 relative to a background quasar. The relative motion of the two masers on opposite sides of the galaxy directly yields the angular rotation of the galaxy ("solving" the van Maanen/Hubble debate); when combined with the rotation curve from HI mapping, this yields a direct estimate of the galaxy's distance. Removing the effects of the galaxy's rotation, the absolute proper motion of M 33 is obtained, leading to strong constraints on the dark matter halo and motion of Andromeda (Loeb et al. 2005).

The full 3-dimensional motion vectors for two Andromeda satellites, plus the 1-dimensional motion (radial) of the Andromeda galaxy, are shown in Fig. 2. The proper motion of the Andromeda galaxy (yet to be directly measured) is key to understanding the history and fate of the Local Group, since a potential collision of the Andromeda galaxy and the Milky Way would "reconfigure" the entire Local Group. Depending on the proper motion of Andromeda, the two dominant galaxies could have a "head on" collision, a grazing collision, or no collision at all. With a sizeable proper motion of ~ 100 km s^{-1}, depending on the total dark matter mass in the Local Group, they could orbit each other or even be unbound. A high accuracy measurement of the proper motion of Andromeda is possible in the coming decade with modest upgrades to the VLBA.

Measurements of the proper motions of more Milky Way and Andromeda satellite galaxies (some of which will come from radio interferometry), and improved numerical simulations, will be critical to understanding the size and mass of the disk, bulge, and dark matter halos of these two dominant galaxies in the Local Group. Measuring the proper motions of several maser sources within one galaxy can also give a direct measurement of the galaxy's distance (rotational parallax). This method, applied to M 31, M 33, and the LMC, could yield distances with accuracies of a few percent. These *direct* geometric distance estimates to galaxies, which are inherently free of systematic effects, such as metalicity differences, are of great importance for an independent re-calibration of extragalactic distance indicators.

2.2. Motions outside the Local Group

With astrometry at the μas level one can extend extragalactic proper motion studies to galaxies outside the Local Group and address important questions related to galaxy evolution and flows. The M81 group, the nearest group with interacting galaxies, is an excellent system to study the evolution of galaxies through interactions. In physical contrast, the galaxy flow in the nearby Canes Venatici I cloud appears to be driven by free Hubble expansion, and that flow can be traced via the proper motions of the low-luminosity active galactic nuclei hosted by galaxies in the cloud.

Another important target for proper motion studies is the Virgo Cluster, the nearest and best studied galaxy cluster. While it is much further away than galaxies in the Local Group, the relative velocities of the galaxies in the deep gravitational potential in the center of the Virgo Cluster can be several thousand km s^{-1}, an order of magnitude larger than in the Local Group. Knowledge of the 3-dimensional motions of the galaxies can help one to address the mechanisms by which the cluster environment affects galaxy properties. For example, it has been well established that cluster spirals are quite gas poor compared to spirals in the field. This is generally thought to be due to ram-pressure stripping of the galaxy's interstellar medium as the galaxy moves through the intracluster medium and is observed to occur in several Virgo spirals, where large tails of gas are being torn from the galaxy by interaction with the intracluster medium.

3. Telescope Needs

The observations needed to measure proper motions of Local Group galaxies outlined above can be accomplished with the advances outlined in Table 1. Some of the goals can be achieved with modest upgrades in data recording equipment at the VLBA. Increasing the VLBA data recording rate by more than two orders of magnitude, from 256 Mbps to 32 Gbps (which requires no new technology), would have two dramatic advantages: 1) increase the signal-to-noise ratio for continuum sources (both AGN in target galaxies and in background reference quasars) and 2) improve astrometric accuracy by making far more background quasars available as position references. Regarding advantage 2), VLBI astrometric observations are often limited by systematics that cancel proportionally to the separation of the maser target and background quasar. The factor of 11 (i.e. $\sqrt{32\text{Gbps}/256\text{Mbps}}$) improvement in continuum sensitivity from the increased recording capability would lead to an average decrease in target-quasar separation by a factor of 20 (for standard $\log N/\log S$ statistics). This should allow single epoch astrometric accuracy of better than ± 1 μas.

Combining the above mentioned advances in recording capabilities with increased collecting area would allow measurement of the proper motions of weak radio sources in other galaxies. AGN in many galaxies outside the Local Group have been detected, typically below 100 μJy. Noise levels approaching ~ 1 μJy could be achieved by combining 32 Gbps recordings and modest increases in collecting area from a "pathfinder" project that would prototype and test antenna "patches" (with 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, not only for continuum but also for spectral-line sources. The critical goal of measuring the proper motion of the Andromeda galaxy (M 31), which has a compact, but faint nuclear source of about 30 μJy, could be attempted with the recording rate upgrade (with about 30 tracks per epoch) and easily accomplished (with a few tracks per epoch) with both the recording rate and collecting area upgrades.

Some of these telescope advances discussed above could come from the phased implementation of the plans outlined in the "North American Array" initiative (J. Ulvestad, coordinator) submitted to the Decadal Survey. In addition, in order to map southern sources, we will need a high-sensitivity VLBA-like capability in the southern hemisphere. This could be well met by a prototype (e.g. 5%) SKA, which is planned for the southern hemisphere. Finally, we note that the construction of the full SKA would revolutionize all of these activities and lead to truly dramatic astrometric results well beyond the Virgo Cluster.

4. Summary

Over the next decades, a program of observational advances could enable radio astrometry to address the following key questions:

- What is the distribution of dark matter in the Local Group?
- What is the history and fate of Local Group galaxies?
- What is the distribution of dark matter in nearby clusters of galaxies?

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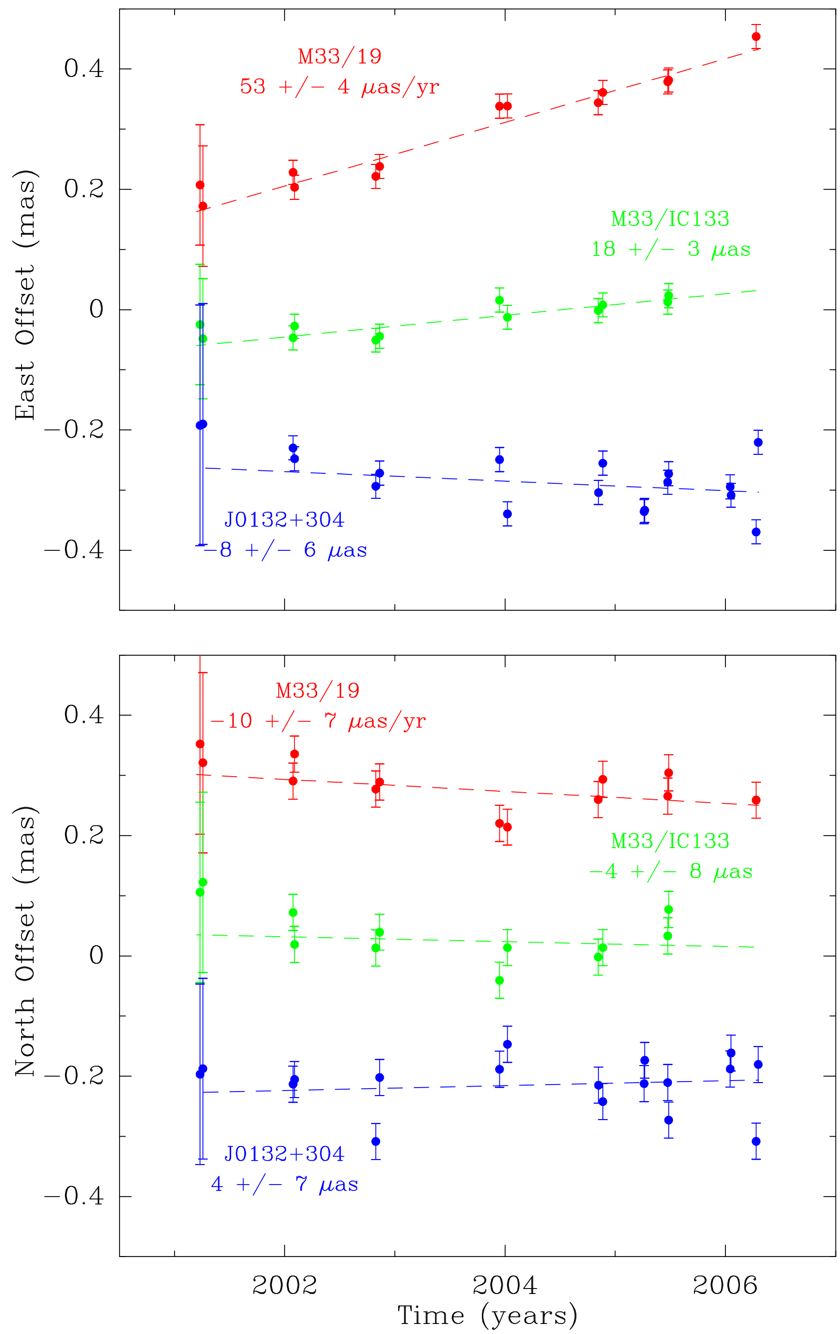

Fig. 1.— Absolute proper motion data for 2 sources of H_2O masers on opposite sides of M 33 relative to a background quasar. The two panels show motions in R.A. and in Dec. In each panel, data plotted in red (*top*) are for the maser M 33/19 and in green *(middle)* are for the maser M 33/IC133. Also shown in blue *(bottom)* is a "control" measurement of a weak quasar J0132+304 relative to the background quasar used for the masers. Note that even with current VLBI capabilities, proper motion uncertainties of a few μas y^{-1} are achieved in only 4 years of observation.

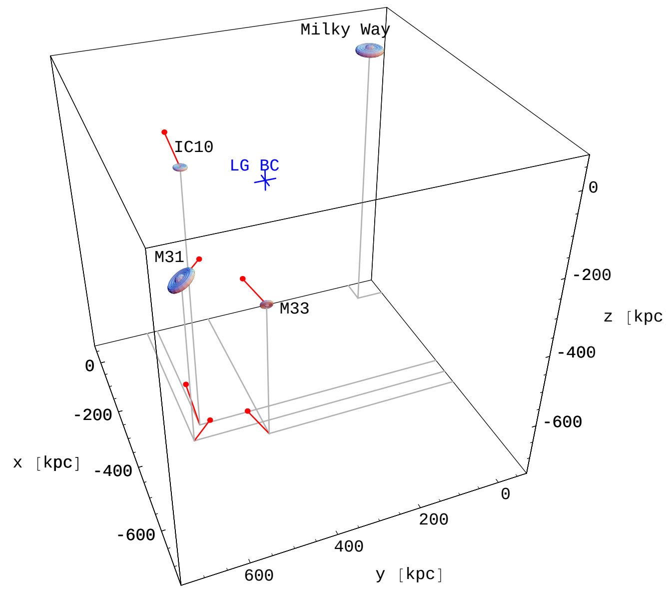

Fig. 2.— Local Group proper motions. Schematic view of the Local Group of Galaxies with the Milky Way in the upper right and the Andromeda galaxy (M 31) in the left. The measured 3-D motions of M 33 and IC 10 are indicated with red lines. Only the known radial component of the motion of Andromeda is indicated. Unless the Andromeda galaxy has a substantial proper motion (~ 100 km s^{-1}) or much less dark matter than previously estimated (Loeb et al. 2005), M 33 would have "hit" Andromeda in the past and would not appear as a thin disk today.

Table 1. Telescopes Advances and their Scientific Impact

Telescope Advance	Scientific Impact
High (32 Gbps) data recording rate and/or additional telescopes/collecting area	Background calibrators $\times 20$ nearer to targets, enabling sub-μas astrometry
	Proper motions of weak (~ 10 μJy) AGNs in Local Group and beyond (e.g. Andromeda, M81, Virgo Cluster)
Improved Southern Hemisphere VLBI capability (e.g. SKA)	Proper motions and geometric distances of southern galaxies (e.g. LMC, SMC)