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Towards Proper Motions in the Local Group

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Abstract. Key and still largely missing parameters for measuring the mass content and distribution of the Local Group are the proper motion vectors of its member galaxies. The problem when trying to derive the gravitational potential of the Local Group is that usually only radial velocities are known, and hence statistical approaches have to be used. The expected proper motions for galaxies within the Local Group, ranging from 20 to 100 μas/yr, are detectable with VLBI using the phase-referencing technique. We present phase-referencing observations of bright masers in IC 10 and M33 with respect to background quasars. We observed the H_2O masers in IC10 three times over a period of two months to check the accuracy of the relative positions. The relative positions were obtained by modeling the interferometer phase data for the maser sources referenced to the background quasars. The model allowed for a relative position shift for the source and a single vertical atmospheric delay error in the correlator model for each antenna. The rms of the relative positions for the three observations is only 0.01 mas, which is approximately the expected position error due to thermal noise. Also, we present a method to measure the geometric distance to M33. This will allow re-calibration of the extragalactic distance scale based on Cepheids. The method is to measure the relative proper motions of two H_2O maser sources on opposite sides of M33. The measured angular rotation rate, coupled with other measurements of the inclination and rotation speed of the galaxy, yields a direct distance measurement.

1. Introduction

An important astrophysical question is the nature and existence of dark matter in the Universe, which had been inferred originally from the flat rotation curves of galaxies (e.g. Fich & Tremaine 1991). The closest places to look for dark matter halos are the Milky Way and Andromeda galaxies in the Local Group. Various attempts have been made to weigh the galaxies in the Local Group and determine size and mass of the Milky Way and its not very prominent dark matter halo (Kulessa & Lynden-Bell 1992; Kochanek 1996). Other attempts use Local Group dynamics in combination with MACHO data to constrain the universal baryonic fraction (Steigman & Tkachev 1999).

The problem when tyring to derive the gravitational potential of the Local Group is that usually only radial velocities are known and hence statistical approaches have to be used. Kulessa & Lynden-Bell (1992) introduced a maximum likelihood method which requires only the line-of-sight velocities (Hartwick & Sargent 1978), but it is also based on some assumptions (eccentricities, equipartition).

Clearly, the most reliable way of deriving masses is using orbits, which require the knowledge of three-dimensional velocity vectors obtained from measurements of proper motions. The usefulness of proper motions was impressively demonstrated for the Galactic Center where the presence of a dark mass concentration (presumably a black hole, see Melia & Falcke 2001) has been umambiguously demonstrated by stellar proper motion measurements (Eckart & Genzel 1996; Ghez et al. 1998).

However, measuring proper motions of members of the Local Group to determine its mass is difficult. For the LMC Jones, Klemola, & Lin (1994) claim a proper motion of 1.2 ± 0.28 mas/yr obtained from comparing photographic plates over a timespan of 14 years. Schweitzer et al. (1995) claim 0.56 ± 0.25 mas/yr for the Sculptor dwarf spheroidal galaxy from plates spanning 50 years in time. Kochanek (1996) shows that inclusion of these marginal proper motions can already significantly improve the estimate for the mass of the Milky Way, since it reduces the ambiguity caused by Leo I, which can be treated as either bound or unbound to the Milky Way. The same work also concludes that if the claimed optical proper motions are true, the models also predict a relatively large tangential velocity of the other statellites of the Galaxy. The dynamics of nearby galaxies are also important to determine the solar motion with respect to the Local Group to help define a standard inertial reference frame.

Despite the promising start, the disadvantage of the available optical work is obvious: a further improvement and confirmation of these measurements requires an additional large time span of many decades and will still be limited to only the closest companions of the Milky Way.

1.1. Proper Motions with the VLBA

On the other hand, the expected proper motions for galaxies within the Local Group, ranging from 1 mas/yr to 20 μas/yr, are relatively easy to see with VLBI using the phase-referencing technique. A good reference point is the motion of Sgr A* across the sky at a speed of 6 mas/yr reflecting the Sun's rotation around the Galactic Center at a speed of about 220 km/s. This motion is well detected between epochs separated by only one month with the VLBA (Reid et al. 1999).

With the accuracy obtainable with VLBI one could in principle measure very accurate proper motions for most Local Group members within less than a decade. The main problem so far is finding appropriate radio sources. Useful sources would be either compact radio cores or strong maser lines associated with star forming regions. Fortunately, in a few galaxies bright masers are already known. Hence the task that lies ahead of us, if we want to significantly improve the Local Group proper motion data and mass estimate, is to make phase-referencing observations with respect to background quasars of known Local Group galaxies with strong H_2O masers.

1.2. Useful Local Group galaxies

The most suitable candidates for such a VLBI phase-referencing experiment are the strong H_2O masers in IC 10 ($\sim$ 10 Jy peak flux density in 0.5 km/s line, the brightest known extragalactic maser; Becker et al. 1993) and IC 133 in M33 ($\sim$ 2 Jy, the first extragalactic maser discovered). Both masers have been observed successfully with VLBI (e.g. Argon et al. 1994, Greenhill et al. 1993). Additional fainter masers also exist in M33 that could be used to extend and improve the studies (e.g. for constraining galactic rotation; see section 5).

The two galaxies belong to the brightest members of the Local Group and are thought to be associated with M31. Their line-of-sight velocities are -344 km/s and -180 km/s respectively and are located at a distance of about 800 kpc. In both cases a relatively bright phase-referencing source is known to exist within a degree. In addition their galactic rotation is well known from HI observations. Consequently, M33 and IC 10 seem to be the best known targets for attempting to measure Local Group proper motions with the VLBA.

2. Observations

We observed the H_2O masers in IC 10 three times with the VLBA on 2001 February 09, 2001 March 28 and 2001 April 12 under good weather conditions. We observed four 8 MHz bands, each at right and left circular polarization. The 128 spectral channels in each band yield a spectral resolution of 62.5 kHz, equivalent to 0.84 km/s.

The observations involved rapid switching between two compact extragalactic background sources and the H_2O masers in IC 10. The source J0027+5958 was taken from the VLBA calibrator survey and was used as the phase-reference source. Its flux density at 22 GHz was $\approx$ 200 mJy and the angular separation on the sky between IC 10 and J0027+5958 is 1°. The second source, J0021+5911, had a flux density of $\approx$ 10 mJy at 22 GHz and is separated by only 8' from IC 10. We went through the cycle J0027+5958 – IC10 – J0027+5958 – J0021+5911 – J0027+5958 and the sources were changed every 30 seconds. The total observation time was 10 hours each.

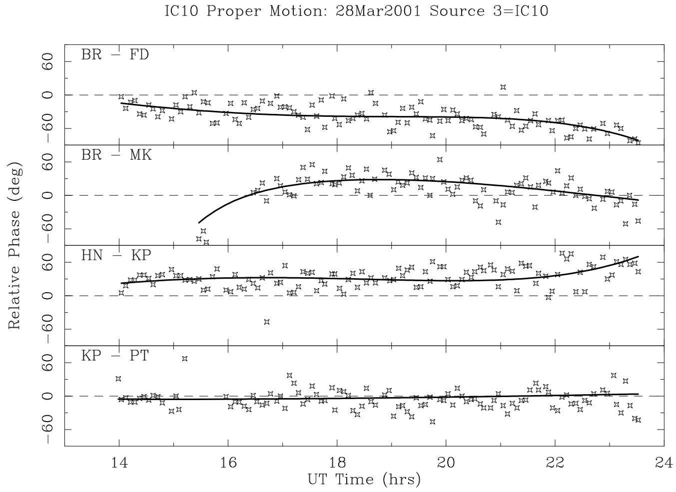

Fig. 1. Observed residual phases (stars) and model phase (line) for the baselines Brewster – Fort Davis, Brewster – Mauna Kea, Hancock – Kitt Peak and Kitt Peak – Pie Town. The model allows for a relative position offset and a single vertical atmospheric delay.

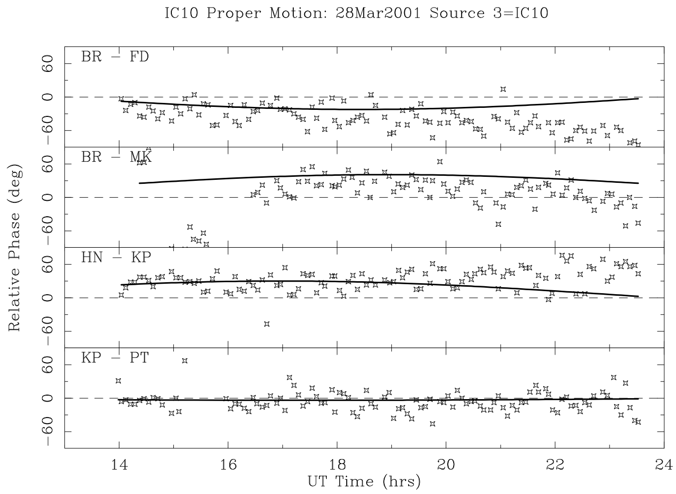

Fig. 2. Same as Fig. 1 but the model allows for a relative position offset only.

The data were calibrated and imaged with standard techniques using the AIPS software package. A priori amplitude calibration was applied using system temperature measurements and standard gain curves. A fringe fit was performed on J0027+5958 and the solutions were applied to IC 10 and J0021+5911. The phase corrections for all stations except St. Croix showed only slow variations with time and it was easy to connect the phases. The data from the antenna on St. Croix were flagged in all observations due to the bad quality of the data.

3. Results

The three observations within two months were made to check the accuracy and the repeatability of our results.

Table 1. Residual positions of IC 10 relative to J0027+5958.

Date	East Offset [mas]	North Offset [mas]
2001/02/09	0.034	0.103
2001/03/28	0.039	0.120
2001/04/12	0.041	0.106
Mean	0.038 ± 0.003	0.110 ± 0.007

The second background source was included to verify the results and to reduce systematic errors. The positions of the masers in IC 10 relative to the phase-reference source J0027+5958 were first obtained from a model fit to the map for all epochs. The differences in the positions between the observations were ≈ 0.1 mas.

The most likely source of relative position error is a small error in the atmospheric model used by the VLBA correlator (see discussion in Reid et al. 1999). To improve our relative position measurements, we modeled our differenced-phase data for the J0027+5958 minus IC 10 pair. The model allowed for a relative position offset for IC 10 and a single vertical atmospheric delay error in the correlator model for each antenna. Fig. 1 shows the residual phase of IC 10 and our best model fit for four typical baselines. One can see that the data and the model are in good agreement. Fig. 2 shows the same plot with a model that allows for a relative position shift only. Here the agreement between data and model is much worse.

The results of the position offsets from the model which includes the atmospheric corrections are presented in Table 1. The deviations of the relative position for the three observations decreased significantly and the rms is now ≈ 10 μas. The values of the vertical atmospheric delay error were typically of the order of a few cm. These are similar to the values in Reid et al. (1999).

4. Local Group Proper Motions

The proper motion vectors of the observed masers will consist of various contributions, which we list in the following (with numbers for M33 roughly valid also for IC 10):

a) solar motion around the Galactic Center: 220 km/s ($\sim$ 60 μas/yr at a distance of 800 kpc times the sine of the angle between the solar motion vector and the line-of-sight to the galaxy);
b) motion of M31 with respect to the Milky Way: predicted to be $\sim$ 60 km/s (16 μas/yr);
c) orbital motion of M33 (or IC 10) around M31: 100-200 km/s (25-50 μas/yr);
d) internal galactic rotation: 110 km/s (30 μas/yr);
e) velocity of individual maser components: $\sim$ 20-50 km/s ($\sim$5-13 μas/yr).

The proper motion vectors (a-c) depend on the mass of M31 and the Milky Way and the distance to the galaxies. These are parameters we want to constrain with our observations. The galactic rotation (d) is very well determined from HI observations. For the intrinsic velocity of maser components relative to the Local Standard of Rest (e) we note that though individual maser components can have velocities of several tens of km/s, the average velocity (79 components in IC 133) is just a few km/s and hence negligible.

Depending on how the vectors add up, we can conservatively expect a measurable motion of 50-100 μas/yr. With an astrometric precision of 10-20 μas a 5σ proper motion result should be achieved within a year. Roughly half of this detectable motion is due to the astrophyscially interesting vectors (a-c). Vector (a), for example, simply contains a secular parallax which is, however, not independent of the mass of Andromeda and the Milky Way (vectors b & c). For a simple model of the Local Group with two dominant galaxies and a fixed mass ratio between Milky Way and Andromeda (usually assumed to be 1:1.5) our two proper motion measurements would already significantly constrain any mass model for the Local Group. In a more elaborate approach, which takes the full data set of radial and proper motions in the Local Group into account (see Kochanek 1996), the constraints would be even stronger leading to significantly improved mass estimates and distances.

5. A Direct Measurement of the Distance to M33

Currently, the calibration of most standard candles used for extragalactic distances, are tied in one way or another to the distance to the Large Magellanic Cloud (LMC) (e.g. Mould et al. 2000). However, two relatively new methods suggest a "short distance" to the LMC, about 10% to 20% smaller than from Cepheids. These methods involve the emission from "red clump" stars using Hipparcos distance calibrations (Stanek, Zaritsky, & Harris 1998), and analysis of light and radial velocity curves for the eclipsing binary HV 2274 (Guinan et al. 1998, Udalski et al. 1998). If the short distance is correct, then indirectly measured distances to other objects would shrink, increasing estimates of H_0 by 10 to 20%.

We want to obtain a *geometric* distance to the nearby galaxy M33 to permit an independent re-calibration of extragalactic distance indicators. This will lead not only to more accurate distances, and corresponding changes in many physical parameters, but it will lead to revised estimates of the expansion rate and age of the Universe. M33 is close enough that both primary and secondary distance indicators may be readily isolated in ground- and space-based observations with existing instrumentation.

We intend to measure the angular rotation rate of M 33 by measuring the relative position of two H_2O maser sources (associated with different regions of massive star formation), that lie on opposite sides of the galaxy. Owing to the rotation of the galaxy, the northern source moves roughly westward while the southern source moves roughly eastward at a *relative* speed of about 220 km/s (Corbelli &

Salucci 2000). By measuring the angular rotation rate, and comparing it to the known rotation speed and galaxy inclination, the distance can be obtained. Measurements over a 1 year period, each with an accuracy of $10-20$ μas, would yield an uncertainty in the proper motion, converted to a rotation speed, of $\approx 40-80$ km/s (for a distance of 800 kpc) or a $3-5$ σ detection. Further observations over a longer time range would improve the accuracy of the distance ultimately to better than 5 %. At this point, the distance accuracy would probably be limited by knowledge of the inclination of the galaxy.

6. Conclusion

The first results of our observations of H_2O masers in IC 10 and M33 have demonstrated the feasibility of high-precision astrometry at the 10 μas level. With this accuracy we expect a 5 σ detection of the proper motions of IC 10 and M33 within one year. The H_2O masers in M33 were also observed, but the data reduction has not been finished yet. The observational techniques are nearly the same for IC 10 and M33 and so we expect promising results also for M33.

A possible pitfall for such a project is that individual maser components could be short lived and lost with time. However, in M33 the stronger maser components are known to exist for now two decades. An additional problem could arise if the observed phase referencing sources show motion in a core-jet structure which is unresolved with the VLBA. This could lead to a small apparent shift in the position of the phase referencing source which would be misinterpreted as a motion of IC 10 or M33. Using two calibrator sources, we are however able to exclude such a bias.

With the second and third set of observations in January 2002 and presumably in October 2002 we therefore will be able for the first time to detect significant proper motions in the Local Group out to 800 kpc.

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