

AGN astrometry: A powerful tool for galaxy kinematic studies

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Abstract. This article highlights the successes of the high resolution astrometric VLBI observations used for measuring proper motion of galaxies in the Local group. The required, high accuracies, often in the $\mu\text{as yr}^{-1}$ regime, are only attainable through the use of the phase-referencing technique. These require either a compact radio source (AGN) or strong maser emission in the target galaxy and, additionally, some compact extra-galactic radio sources (quasars) to serve as ideal background reference source. The derived proper motions can lead to lower limits on the orbital lower estimates to the mass of the host galaxy, promise a new handle on dynamical models of interacting galaxy systems and offer insights on the spatial distribution of dark matter in the near universe.

Keywords. AGN, VLBI, proper motion, Galaxy evolution

1. Introduction

Galaxies within a group or a cluster have their radial velocities and positions known to a high degree of accuracy. This information is sufficient to estimate the group mass from the observed deviations from the external Hubble field of velocities by making critical assumptions on eccentricities and equipartition (Kulesa & Lynden-Bell 1992; Karachentsev & Kashibadze 2006). For a full understanding of the evolution of a galaxy group, we require accurate knowledge of the distances and the three-dimensional velocity vectors. Knowing the 3-D velocity structure within a group requires knowledge of a combination of precise radial and proper motions. Even without accurate distances, proper motions should yield lower limits to the mass of the host galaxy, merger speed in merging clusters of galaxies, and/or provide information whether galaxies in clusters are on their first infalls (Maccarone & Gonzalez 2018). Observationally derived proper motions also provide important constraints on a dynamical model of an interacting galaxy system by establishing both the past history and the fate of such a system. Moreover, the 3-D velocity structure helps our understanding of the environment of galaxy groups and clusters, shedding light on the spatial distribution of the dark matter associated with them (Yepes *et al.* 2013).

In recent years, especially due to the high angular resolution and stability of the Hubble Space Telescope (HST) and other ground based optical telescopes (van der Marel *et al.* 2014), proper motions have now been reliably measured for a number of galaxies in the Local Group i.e. the LMC (Kallivayalil *et al.* 2006; Pedreros *et al.* 2006) the SMC (Kallivayalil *et al.* 2006) the Sculptor dwarf spheroidal galaxy (dShp) (Piatek *et al.* 2006) the Canis Major dwarf galaxy (Dinescu *et al.* 2005), the Ursa Minor dSph (Piatek *et al.* 2005), the Sagittarius dSph (Dinescu *et al.* 2005), the Fornax dSph (Piatek *et al.* 2002; Dinescu *et al.* 2004), and the Carina dSph (Piatek *et al.* 2005). On the other hand, the

expected proper motion for galaxies within the Local Group and neighboring groups, which are $\ll 1 \text{ mas yr}^{-1}$, are detectable with the Very Long Baseline Interferometry (VLBI) using the phase-referencing technique (Brunthaler *et al.* 2005a).

2. Overview

Astrometric VLBI phase-referencing observations require either a compact radio source or strong maser emission in the target source and, additionally, some compact extra-galactic radio sources such as quasars serving as background reference source. The technique is based on the assumption that the phase errors of two sources with a small angular separation are similar. Such an observation therefore, involves observing a target source and its adjacent calibrator ($\sim 1^\circ$) in a fast-switching mode (a \sim minute cycle). In the following we summarize successful astrometric VLBI observations done using the phase-referencing technique to detect $\mu\text{as yr}^{-1}$ extra-galactic proper motions as part of a campaign to measure the 3-D velocity structure of the Local Universe out to the Virgo Cluster.

Milky Way (Sgr A)*: Very Long Baseline Array (VLBA) observations were conducted for about 8 years, between 1995 and 2003, involving rapid switching between compact extra-galactic sources, J1745-283 and J1748-291, and Sgr A* as the phase-referencing source. The apparent proper motion of Sgr A* relative to J1745-283 was obtained as $6.379 \pm 0.024 \text{ mas yr}^{-1}$, almost entirely in the plane of the Galaxy. Assuming a distance to the Galactic center of $8.0 \pm 0.5 \text{ kpc}$, the apparent angular motion of Sgr A* in the plane of the Galaxy was obtained to be $-241 \pm 15 \text{ km s}^{-1}$ (Reid & Brunthaler 2004).

IC 10: Using the VLBA, the proper motion of the Local Group galaxy IC10 was determined by measuring the position of a H_2O maser in IC10 relative to two background quasars (VCS1 J0027+5958 and NVSS J002108+591132) over a period of 4.3 years. The derived motion was $-39 \pm 9 \mu\text{as yr}^{-1}$ toward the East and $31 \pm 8 \mu\text{as yr}^{-1}$ toward the North. Assuming a distance to the IC10 of $660 \pm 66 \text{ kpc}$, its total space velocity of $215 \pm 43 \text{ km s}^{-1}$ relative to the Milky Way was obtained (Brunthaler *et al.* 2007).

Triangulum Galaxy (M33): The proper motions of the two H_2O maser regions relative to the quasar J0137+312 were determined. The masers are associated with star-forming regions located on opposite sides of the disk of M33. The measured angular motion of the two masers allowed for an independent geometric distance estimation to M33 of $730 \pm 168 \text{ kpc}$, consistent with standard candle estimates. The derived proper motion was $-29 \pm 7 \mu\text{as yr}^{-1}$ toward the East and $45 \pm 9 \mu\text{as yr}^{-1}$ toward the North. The derived total velocity of M33 relative to the Milky Way is $190 \pm 59 \text{ km s}^{-1}$ (Brunthaler *et al.* 2005b).

M81 group: The proper motion of M81's central compact radio source (M81*) relative to the background quasars (0945+6924, 1004+6936) over 11 years was determined. M81* was used as the phase-referencing source. A preliminary analysis indicates that M81 is moving with a total velocity of about 500 km s^{-1} relative to the Milky Way (Kimani 2016).

3. Implications

Lower limits to the galaxy mass. The most reliable way of deriving masses is by determining orbits, which requires the knowledge of three-dimensional velocity vectors. For instance, assuming the Andromeda (M31) satellite galaxies M33 and IC10 are gravitationally bound to it, their 3-D velocities yields a lower estimate to the mass of M31 of $7.5 \times 10^{11} \text{ M}_\odot$ (Brunthaler *et al.* 2007). Similarly, in the M81 group, the separation between the centers of M81 and M82 is 38 kpc, implying that M82 is deeply embedded in the dark matter halo of M81 which spreads out to 140 kpc. A measurement of the proper motion of M82 will allow an estimate of the lower limit on the mass of M81 in the near future (Oehm *et al.* 2017).

Evolution of interacting galaxy systems. Measuring proper motions of galaxies is of great value for understanding a variety of other issues related to galaxy and cluster evolution. For instance, due to its proximity, the M81 group features a fascinating interacting galaxy system comprising of M81, M82 and NGC3077. To understand the dynamics of this system, several numerical simulation studies have been performed (e.g. Sofue 1998; Yun 1999 and Gomez *et al.* 2004). The challenge that was encountered was getting the right initial conditions for the model and getting the right interaction time that results in the currently observed configuration. Key parameters for modeling of the history, evolution and fate of the group, are present spatial velocity vectors of its members which have otherwise been statistically estimated. With these velocities known, it is now possible to reconstruct and predict the past and future of the system, providing crucial information on the consequences of tidal interactions in a group environment. In the near future, with the current attempts to derive the proper motion of Andromeda (using M31*) relative to some background quasars, it will be possible to model the history and fate of the local group (Reid & Honma 2014).

Dark matter distribution. There is now an immense amount of observational evidence that firmly supports the idea that there exists much more matter in the Universe than just the luminous matter (Yepes *et al.* 2013). The non-visible mass is often referred to as Dark Matter. The Local Universe becomes the best place for the observational studies of dark matter distribution and for testing the predictions of the standard λ Cold Dark Matter (Λ CDM) model of cosmological structure formation, which describes very well the observations of the large scale structure (Yepes *et al.* 2013; Frenk & White 2012). Observational data for galaxies in the nearby universe such as proper motions, masses and distances are necessary for constraining initial conditions and placing constraints on simulations that reproduce the observed large scale structure and give insight on the future of the present structures.

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