Probing dark matter and galaxy evolution with proper motions of galaxies

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Abstract.

We discuss several problems that can be solved by measuring the proper motions of galaxies in clusters of galaxies, something that should be feasible in the Next Generation Very Large Array era. First, in the Virgo Cluster, the Laser Interferometric Space-based Antenna should provide standard siren distances for a substantial number of galaxies which contain black hole-black hole binaries. Measuring the proper motions of these galaxies will give 6-dimensional phase space information about the orbits of these galaxies, providing a unique set of tracers of cluster dynamics. Additionally, in other clusters proper motion measurements should allow the determination of whether spiral galaxies are on their first infall into the cluster, and measurements of the proper motions of galaxies in merging clusters will allow direct measures of the speed of the merger, which can then be compared with estimates from shocks.

1. Description of the problem

Understanding the nature of the dark matter and how it impacts structure formation is a key problem in astrophysics. On the scales of individual galaxies, rotation curves can provide good understandings of the relationship between distance from the center of mass of the galaxies, and the mass enclosed, albeit with some uncertainty about deviations from sphericity of the Galactic halo. Over the next ~ 15 years we can expect to see the launch of the LISA mission, which will have the sensitivity to detect stellar-mass double black holes in the Virgo Cluster of galaxies, and from which we expect to see a non-negligible number of sources (Kremer et al. 2018; Jin 2018). These sources should have positional accuracies on the order 1 square degree and, crucially, standard siren distances accurate to about 1%, allowing them to be associated uniquely with their host galaxies. In other contexts, the proper motions of galaxies alone, even without the precise distances expected from gravitational wave sources, should allow fundamental tests of the dark matter hypothesis in nearby groups. Even without standard siren distance measurements, proper motions should yield useful estimates of the merger speed in merging clusters of galaxies, and determination of whether galaxies in clusters are on their first infalls, and how this might correlate with galaxy morphology and gas content.
2. **Scientific importance and astronomical impact**

We are now at the start of an era in which Gaia is revolutionizing our understanding of the structure of the Milky Way galaxy by obtaining 6-D phase space measurements for a large number of objects. At the present time, no such information is available for any galaxies in clusters of galaxies, or even in nearby groups of galaxies. The Next Generation Very Large Array (ngVLA) has the potential to measure proper motions for large numbers of active galactic nuclei in nearby clusters and groups of galaxies. Given sufficient angular resolution, radio data can also provide precise, direct geometric distances to a small number of galaxies with either expanding supernova shells or with bright masers in disks. Excitingly, around the time we anticipate the ngVLA to be commissioned, we also anticipate that LISA will launch, opening up the era of standard siren distances to nearby galaxies which can be used to obtain precise distances to many galaxies, and also to provide precise calibration of the distances to the others.

Understanding the spatial distribution of dark matter in clusters of galaxies is one of the keys to understanding structure formation. Probes of dark matter halos typically rely on observables that are integrated along the line of sight (e.g. gravitational lensing shear, X-ray and Sunyaev-Zel’dovich surface brightness profiles), which must be transformed modulo physical assumptions to yield a mass distribution.

Collecting “test masses” within clusters of galaxies with well-specified positions and three-dimensional velocities can give precision information about the gravitational potential at specific locations within the potential. This information can then be combined with information collected through other techniques to eliminate degeneracies associated with line-of-sight projection and provide a far more precise determination of the mass distribution than is currently possible. The above technique is precisely the approach taken in measuring the mass distribution of the Milky Way. The observations described below would probe the mass distribution of Virgo at nearly the fidelity that has been possible for the Milky Way prior to Gaia, taking a first key step towards a detailed mass model for the Virgo cluster.

Moreover, measuring proper motions of galaxies is of great value for understanding a variety of other issues related to understanding galaxy evolution and cluster evolution. Precision proper motions of galaxies can be measured via masers in ordered disks, for the galaxies where they are found (Reid et al. in this volume; see also Reid et al. (2009)). Here we focus on alternative tracers of the galaxies’ positions that can be used at large distances, even for galaxies without masers.

3. **Anticipated results**

Galaxies within clusters already have their positions on the sky and their radial velocities well measured. This information is sufficient to obtain estimates of the mass enclosed within a given radius based on some assumptions about how the clusters de-project themselves. To improve upon these results, precise distances and proper motions are necessary. We can expect in the next 20 years to have a good set of standard siren distances for many galaxies in the Virgo Cluster, and perhaps a few galaxies in the Fornax Cluster. Obtaining the proper motions requires the combination of sensitivity and angular resolution of the ngVLA, and benefits strongly from having significant sensitivity on baselines well in excess of 300 km.
The Laser Interferometric Gravitational-wave Antenna will detect double black hole binaries within its period range as continuously emitting sources of gravitational waves. From the gravitational waves themselves, it should be possible to measure standard siren distances to a few percent, and to identify the host galaxy from within an error volume of about $1 \text{ Mpc}^3$ or less. Once the host galaxy has been correctly identified, its location can be used to refine the distance estimate, bringing the error in distance down to about 1%. This will rely on having small gravitational accelerations of the merging black holes; however, this is expected, because even in models where they form in globular clusters, they are expected to be ejected (Kremer et al. 2018). Furthermore, for the shortest period binaries in the LISA band, the cluster acceleration will affect the measurement of the period derivative by only a few percent.

Obtaining proper motions of the host galaxies of the gravitational wave sources then fills out the six-dimensional phase space measurements. The velocity dispersion of galaxies in the Virgo Cluster is about 700 km/sec, while the velocity dispersions within the more massive galaxies can be $\sim 300 – 400 \text{ km/sec}$. As a result, the use of optically bright tracers (e.g. red giants, planetary nebulae or globular clusters) to measure the proper motions of the massive galaxies that are most likely to contain the binary black holes providing standard siren distances is problematic – even with precise measurements of the velocities of individual objects, several thousand of them would be required to centroid the broad velocity dispersions to 10 km/sec precision. While some of the largest galaxies in the Virgo Cluster have thousands of globular clusters, some fraction of these (especially in M87) are likely to be intracluster, intergalactic globular clusters projected against the host galaxy, and many of the clusters, whether members or not, will be too faint for precise proper motion measurements, even with JWST. Furthermore, the uncertainties on these measurements will not improve substantially with a long time baseline, because the primary source of uncertainty will be how well the velocity distribution has been sampled, rather than the uncertainties on the individual measurements. Given that the standard siren distances will be accurate to a few percent, it is of great value to obtain similar precision in the proper motions in order not to have them dominate the total uncertainty budget for the phase space measurements. Making these measurements thus requires the use of the galaxies’ nuclei, rather than their stellar populations.

A few of the nearby groups of galaxies are also excellent candidates for studies of dark matter halos on different scales. (Oehm et al. 2017) have shown that proper motion dispersions of the centers of mass of the galaxies of tens of microarcseconds per year, corresponding to hundreds of km/sec are expected among the galaxies in the M81 group, and that the relative magnitudes of these space velocities can provide tests of whether dynamical friction is happening as predicted by dark matter theory (Kroupa 2015). Here, the smaller galaxies, M82 and NGC 3077 may not contain bright enough active galactic nuclei for estimating their proper motions, but as dwarf galaxies, with small internal velocity dispersions, other radio sources may be effective tracers of their motions. These tracers could include planetary nebulae and the brightest HII regions, and, in some cases, individual luminous blue variable stars, through their wind emission.

Finally, at a lower precision level, merging clusters and merging groups of galaxies can be studied to determine the relative merger speeds, and hence to determine the ratio between the masses of the two clusters. The Bullet Cluster (Clowe et al. 2006), for example, has easily detectable AGN in both subclusters (Malu et al. 2016), and with
a relative velocity of 4500 km/sec at $z = 0.296$, would be expected to show a space velocity of about 1 $\mu$arcsec/year, as would Abell 2034, which has a merger speed which is somewhat slower, but which is located more nearby. The Bullet Cluster itself is too far south for ngVLA. In the near future, with $e$ROSITA, WFIRST and Euclid, we can expect new merging clusters and merger compact groups of galaxies to be discovered, allowing for precise tests of the extremes of the dynamic intermediate redshift Universe.

4. Ancillary astrophysics: understanding the morphology-density correlation in clusters

In addition to enabling modelling of the dark matter distribution, proper motions for cluster galaxies provide an incredibly powerful tool for disentangling the physical factors impacting the evolution of these galaxies. In particular, it has long been known that spiral galaxies are quite rare in dense clusters of galaxies, especially in their cores (Oemler 1974). The subset of spirals that do exist in cluster cores therefore provide an important sample for understanding in detail the processes by which these galaxies are quenched. These galaxies are most likely on their first approach into the cluster, but full 6-D phase space information is necessary to determine their orbits, locations relative to the cluster center, and full orbital velocities. All of these quantities are critical for understanding the impact of cluster-specific quenching processes. For instance, quantifying the impact of present (future) ram pressure requires knowledge of the orbital velocity (and orbit). Such information currently does not exist – proper motions are required.

Even for galaxies that lack standard siren distance measurements, full 3-D velocities and angular positions combined with a model for the mass distribution are sufficient to identify substructures and constrain orbital motions at a fidelity that enables one to disentangle whether a galaxy is infalling for the first time, is associated with an accreted substructure, or had resided in the cluster core for Gyrs. Consequently, it becomes possible to infer the distribution of environments that galaxy has encountered within the cluster.

5. Limitations of current astronomical instrumentation

The instrument best suited to address this problem at the current time would be the VLBA. It has 0.185 mJy noise in one hour at 40 GHz and 0.2 masec resolution. This leads to two key disadvantages relative to the ngVLA. First, the exposure times start to become prohibitive (although some long observations to provide a first epoch at the present time, so that the ngVLA has a long time baseline for proper motions would be valuable). Second, the systematics with the VLBA are likely to be significantly worse than with ngVLA if the Long Baseline Major Option is implemented; systematics increase with the separation between the source and the phase calibrator, and with approximately ten times better sensitivity the angular separation of the nearest good calibrator will typically be much smaller. Optical telescopes can obtain the combination of signal-to-noise and resolution nominally needed to address these questions, but then rely strongly on extremely precise flat-fielding and modelling of the point spread function that goes well beyond what has currently been established to be possible. With Continental baselines, relative astrometry of AGN to microarcsecond accuracy per
epoch in the radio should be straightforward to achieve, while optical astrometry appears to be limited by systematics at a level roughly 10-100 times worse.

6. Connection to unique ngVLA capabilities

As discussed above, this work can be done only with radio-based proper motion measurements of the active galactic nuclei of Virgo Cluster galaxies. The excellent sensitivity of the ngVLA is needed to make these measurements at high frequency where the systematics due to core shifts are least important, and with the ability to use moderately bright phase calibrators located very close to the source. Some aspects of this work can be done with the Southwest configuration for the ngVLA, but many of these projects would require, or at least strongly benefit from,

7. Experimental layout

7.1. Virgo Cluster

The radio flux densities of the large galaxies in the Virgo Cluster are mostly $\sim 1$ mJy or more (Merloni et al. 2003). We take this as a baseline value. For an AGN at this brightness, with the ngVLA we can expect a noise level of about $0.3 \mu$Jy in one hour with the ngVLA, working at 40 GHz with a beam size of 2 milliarcseconds. For a 1 mJy source, this then gives signal to noise of about 3000, meaning that the positional accuracy of the AGN will be good to about $0.7 \mu$arcsec, which is likely to be approximately the systematic limit. Obtaining a better handle on the systematics, so that the statistical limits can be reached, provides a strong motivation here for the Long Baseline Major Option; still, taking more observations and over a longer time baseline can also be done to help ensure that the results are robust. Positions measured to this accuracy will yield proper motions accurate at the level of $\approx 50$ km/s on a one-year time baseline, so that within 5 years, proper motions could be measured to an accuracy of 10 km/sec. Because the observations needed are quite short this also allows for extra checks to be done to ensure that systematics such as core shifts are not problematic, by allowing extra observations at different frequencies, and observations over a range of source fluxes. Additionally, use of longer baselines would improve both the systematics and the sensitivity.

While only the galaxies with LISA binaries are likely to be useful for the six-dimensional phase space measurements, even having good five-dimensional phase space measurements for all the large galaxies will provide very valuable information. We thus believe it would make most sense to observe the 50 or so most luminous galaxies. This also has the advantage of not requiring that the LISA detections have already been made at the time the ngVLA starts collecting data. For astrometric projects, given the importance of having a long time baseline, this is vital. We thus expect that conducting this project would require about 50 hours per epoch to observe the 50 radio-brightest galaxies. It may occur that LISA uncovers some stellar-mass binary black holes in fainter galaxies, which may lead to a bit of extra time being required, but as a first order estimate, we can expect this program to require about 250 hours of ngVLA time, spread over five years.
7.2. M81 group

For the M81 group, the test of whether dark matter is producing dynamical friction proposed by Oehm et al. (2017) relies on making precise proper motions of M81, M82 and NGC 3077, and precision of 2 µsec/year is needed. To obtain such precision over a 5 year baseline, one needs precision of 7 µsec per measurement (slightly worse precision can be tolerated using more than 2 measurements).

7.3. Merging clusters

As a template object, we consider Abell 2034. This is a merging cluster of galaxies with an estimated merger speed of about 2000 km/sec (Owers et al. 2014), mostly across the plane of the sky (Monteiro-Oliveira et al. 2018). The cluster is at a redshift of \( z = 0.115 \), or a distance of 433 Mpc. The proper motion should thus be 0.8µarcsecond per year. Thus, with systematics that should be achievable in a straightforward manner with the Long Baseline Major Option, it should be possible to measure the proper motion at 10σ in a little over a decade. In fact, it is not yet certain if this cluster is in the early or late phases of its merger at the present time (Monteiro-Oliveira et al. 2018). At the present time, only relatively low angular resolution radio images have been obtained for this galaxy. It is likely, though that there should be at least a few AGN with flux densities above 50 µJy in each sub-cluster, allowing for micro-arcsecond positional accuracy in reasonable exposure times. This system is clearly the best case right now for a merger cluster which is near enough, with fast enough tangential velocities, and far enough North for proper motions to be useful. It is likely, though, that in the near future, new surveys will uncover some additional candidates.

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