MEASURING TRANSVERSE MOTIONS FOR NEARBY GALAXY CLUSTERS

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ABSTRACT
Measuring the full three-dimensional motions of extragalactic objects in the universe presents a seemingly insurmountable challenge. In this Letter, we investigate the application of a technique to measure tangential motion that has previously only been applied nearby within the Local Group of galaxies, to clusters of galaxies far beyond its borders. We show that mapping the mean line-of-sight motion throughout a galaxy cluster could in principle be used to detect the perspective rotation induced by the projection of the cluster’s tangential motion into the line of sight. The signal will be most prominent for clusters of the largest angular extent, most symmetric intrinsic velocity distribution and surveyed with the largest number of pointings possible. We investigate the feasibility of detecting this signal using three different approaches: measuring line-of-sight motions of individual cluster members, taking spectra of intracluster gas, and mapping distortions of the cosmic microwave background radiation. We conclude that future spectroscopic surveys of thousands of members of nearby galaxy clusters hold the most promise of measuring cluster tangential motions using this technique.

Key words: galaxies: clusters: general

1. INTRODUCTION

It is unfortunate that even though we live in three dimensions, we are forced to view most of the universe as a two-dimensional projection with only one dimension of velocity information. As such, we know very little about the motions of the things around us in any direction other than radially outward. A more comprehensive view of motions in the universe would provide a unique probe into the history and future of the things around us. Indeed, within the Milky Way, the HIPPARCOS (Perryman & ESA 1997) and near-future GAIA (Perryman 2002) missions have brought about a rebirth in the ancient field of astrometry, pushing accuracies for direct proper motion measurements down first to mas/year precision and then onto tens of μas/year. The prospect of billions of stars with full six-dimensional phase-space motion known for an appreciable fraction of the Galaxy has allowed astronomers to propose measuring Galactic structure (e.g., Johnston et al. 1999) and recovering Galactic history (e.g., Helmi & de Zeeuw 2000) in unprecedented detail.

Similar measurements of the full phase-space positions of objects throughout and beyond the Local Group would allow an analogous reconstruction of the masses and past interaction of these objects and test the existence of large-scale flows in the universe (see Shaya et al. 2003, for an investigation on Local Group scales). Cosmological simulations of structure formation suggest that the peculiar velocity distribution of galaxy clusters has an rms spread of σ_{pec} ~ 500 km s^{-1} (Sheth & Diaferio 2001), corresponding to proper motion scales for galaxy clusters at distance d from us of

\[ \mu \sim \left( \frac{v_{lim}}{500 \text{ km s}^{-1}} \right) \left( \frac{10 \text{ Mpc}}{d} \right) 10 \text{ μas year}^{-1}. \]  

At first sight, this suggests that the next generation of astrometric missions would have sufficient precision to detect these transverse motions. However, prospects for direct measurements remain dim both because individual galaxies are extended and because galaxy clusters have large internal velocity dispersions.

As an alternative to direct measurements of proper motions of nearby stellar clusters, Galactic astronomers have traditionally employed a neat geometrical trick that allows them to infer the motion of an object in three dimensions from line-of-sight velocities alone. The method relies on the fact that the projection of the transverse motion into the line of sight will induce a gradient in the average line-of-sight velocities measured across any extended object—an effect known as “perspective rotation” (hereafter PR; Feast et al. 1961). PR has been used to verify measurements of the proper motion of the globular cluster Omega Centauri (Merritt et al. 1997), as well as the distance to the Large Magellanic Cloud (LMC; Gould 2000). Most recently, Kaplinghat & Strigari (2008) pointed out that there are now sufficient spectra taken for stars in nearby dwarf spheroidal galaxies for a precision of ~100 km s^{-1} in tangential velocity estimates to be possible. Walker et al. (2008) subsequently verified this assertion with estimates for the motion of Fornax and Carina that agreed with prior astrometric measurements and the first three-dimensional measurement of the motion of Sextans. They also made estimates for Sculptor’s proper motion that disagreed with prior work—this disagreement could be explained as contamination by Sculptor’s intrinsic rotation.

To date, M31 is the most distant object that PR has been measured for (using the line-of-sight velocities of 17 of its satellite galaxies; see van der Marel & Guhathakurta 2008)—and this study represents over an order-of-magnitude leap in the distance to which this technique has been applied (though Brunthaler et al. 2005 have directly measured the proper motion of M33 at even greater distance using H$_2$O masers). However, there is no limit in principle to the distance of objects for which this technique could prove useful. Indeed, many nearby clusters of galaxies have angular sizes of the same order of magnitude as M31’s satellite system, with measurements of line-of-sight velocities of hundreds of members already taken and of ever increasing numbers of objects feasible in the near future.

In this Letter, we examine to what extent we can expect to map bulk motions in the nearby universe using current or near-future capabilities. We review the technique of PR in more detail in Section 2, discuss three different types of data that should contain PR signatures in Section 3, and summarize our conclusions in Section 4.
2. APPROACH: PERSPECTIVE ROTATION AND GALAXY CLUSTERS

Consider an object, moving with radial and tangential velocities \(v_{\text{sys,rad}}, v_{\text{sys,tan}}\) relative to an observer. The method of PR relies on the fact that the line-of-sight velocity \(v_{\text{los}}\) measured at any position in this object will contain some contribution from the projection of both these systematic motions. Looking directly at the center of an object, the line of sight is perpendicular to \(v_{\text{sys,rad}}\), so \(v_{\text{los}} = v_{\text{sys,rad}}\). However, at any other position the line of sight makes with the transverse motion is no longer 90°, and some portion of \(v_{\text{sys,tan}}\) will be projected onto the line of sight. As the angular separation \(\theta\) of the line of sight from the center increases, this effect becomes more pronounced—the total line-of-sight velocity at angular separation \(\theta\) and azimuthal angle \((\phi - \phi_{\text{tan}})\) to the direction of tangential motion can be expressed as

\[
v_{\text{los}}(\theta, \phi) = v_{\text{sys,los}} \cos \theta + v_{\text{sys,tan}} \sin \theta \cos(\phi - \phi_{\text{tan}}) + v_{\text{local}}(\theta, \phi),
\]

(2)

where \(v_{\text{local}}\) represents the local mean motion within the object.

In the case of a solid, non-rotating object (i.e., where \(v_{\text{local}}(\theta, \phi) \equiv 0\)), the three unknowns \((v_{\text{sys,rad}}, v_{\text{sys,tan}}, \text{and } \phi_{\text{tan}})\) in Equation (2) can be solved for any given three measurements of \(v_{\text{los}}\). More realistically, we expect \(v_{\text{local}}\) to be non-zero due to a combination of random motions and rotation internal to the system, both of which could in principle be solved for in addition given an object of sufficient angular size measured at many positions (i.e., to maximize the signal, as done by van der Marel et al. 2002, for the LMC). Note, in particular, that a system does not need to be relaxed and in equilibrium with a Maxwellian velocity distribution for PR to be apparent, though ideally it would have a fairly symmetric intrinsic velocity distribution and contain only limited substructures.

As noted in the introduction, PR has typically been used in the past to find transverse motions of Local Group objects that are degrees across and might be expected to have relative motions of 100–300 km s\(^{-1}\). In contrast, clusters of galaxies should have transverse velocities of order the expected rms peculiar velocity or \(v_{\text{sys,tan}} \sim \sigma_{\text{pec}}\) (where \(\sigma_{\text{pec}} \sim 500 \text{ km s}^{-1}\) according to linear theory; see Sheth & Diaferio 2001). The nearest galaxy clusters have angular radii of up to \(\theta_{\text{max}} = 5°\) (for the Virgo Cluster). Hence, from the second term in Equation (2) we can expect to be looking for a signal of a velocity difference across the galaxy cluster of order

\[
\Delta v \sim \frac{v_{\text{pec}}}{500 \text{ km s}^{-1}} \times \frac{\theta_{\text{max}}}{5°} \sim 180 \text{ km s}^{-1}.
\]

This “signal” can be compared to the expected sources of confusion. First, galaxies in galaxy clusters have a range in orbital velocities of order \(\sigma \sim 500–1000 \text{ km s}^{-1}\) (depending on the galaxy cluster’s mass). They could also be rotating as a system due to tidal torques on the galaxy cluster as a whole—Cooray & Chen (2002) estimate rotation amplitudes of order 36–180 km s\(^{-1}\) at the galaxy cluster virial radius using linear theory (Peebles 1969). Lastly, they could have much larger apparent rotation due to substructure induced from recent off-axis mergers, or accretions of smaller groups (Ricker & Sarazin 2001).

These considerations suggest that the most interesting galaxy clusters in which to look for PR would be those: (1) for which large numbers of velocity measurements could be made to beat down the uncertainty due to \(\sigma\); (2) that are nearby enough for their virial radii to subtend a large angle (of order a degree or more) so that the PR signal is not much smaller than that due to intrinsic rotation; and (3) that are not clearly substructured.

3. RESULTS: MEASURING PERSPECTIVE ROTATION USING...

3.1. Cluster Galaxies

The most obvious approach using PR to find the transverse motion of galaxy clusters is simply to acquire as many line-of-sight velocity measurements of galaxies as possible. We tested this idea by randomly generating the projected positions and line-of-sight velocities for sample of \(N = 500\) galaxies in an idealized, spherically symmetric galaxy cluster, moving with \(v_{\text{sys,los}} = 720 \text{ km s}^{-1}\) (consistent with the Hubble flow at the distance of the Virgo cluster) and the two components of \(v_{\text{sys,tan}}\) chosen at random from a Gaussian with \(\sigma_{\text{pec}} = 400 \text{ km s}^{-1}\). The galaxies were uniform in projected density out to radius \(\theta_{\text{max}} = 5°\) and had an isotropic Gaussian velocity distribution with dispersion \(\sigma = 400 \text{ km s}^{-1}\). The unknowns \((v_{\text{sys,rad}}, v_{\text{sys,tan}}, \text{and } \phi_{\text{tan}})\) in Equation (2) were solved for by finding the minimum of \(\Sigma(v_{\text{los}} - v_{\text{los}}(\theta, \phi))^2\) in a simple grid-based search of parameter space (where the subscript \(\text{pec}\) indicates the value “observed” for an individual galaxy). By repeating this experiment for many different sets, we found that our uncertainty in the tangential velocity was (as expected) of order

\[
\Delta v_{\text{tan}} \sim \frac{1}{\sin(\theta_{\text{max}})} \sqrt{N} \sim \frac{5°}{\theta_{\text{max}}} \sqrt{\frac{100}{N}} \sigma.
\]

(4)

The bold solid histogram in Figure 1 shows the distribution of difference between our recovered and input tangential velocities \(v_{\text{tan,rec}} - v_{\text{tan}}\) normalized by the expected error \(\Delta v_{\text{tan}}\) for a set of 60 experiments on our idealized data sets. Note that the method for bootstrapping estimates of errors from observed data sets adopted by van der Marel & Guhathakurta (2008) was found to agree well with this estimate.

Using our results so far, we can assess which real galaxy clusters may be interesting targets for a study of PR, i.e., those for which our estimated uncertainty \(\Delta v_{\text{tan}}\) is less than the expected signal \(\sim \sigma_{\text{pec}}\), which is comparable to \(\sigma\) for galaxy clusters. Figure 2 shows contours of \(f = \Delta v_{\text{tan}}/\sigma\) for objects of various \(\theta_{\text{max}}\), and \(N\), with current values for some nearby galaxy clusters overlaid. It is clear that the number of measurements for these objects is just becoming interesting for our purpose—those that have \(f \leq 1\) (i.e., within lightest-gray area of the plot) should have errors due to random motions of order \(\sigma\) which is similar in amplitude to what we are trying to measure.

Nevertheless, a straightforward application of our grid-based search to the \(N = 379, \theta_{\text{max}} = 3°4\) Virgo galaxies selected by Rines & Geller (2008) from the Sloan Digital Sky Survey spectroscopic database, and augmented to \(N = 520, \theta_{\text{max}} = 7°7\) with the Binggeli et al. (1987) sample, found a tangential velocity of several thousand km s\(^{-1}\) with even larger error bars. We interpret this as a null result, most likely due to systematic motions of groups of galaxies falling into Virgo. Indeed, Virgo is classified as an “irregular” galaxy cluster just for this reason (e.g., Böhringer et al. 1994).

When we applied the search to the Ursa Major Cluster using a sample with \(N = 90, \theta_{\text{max}} = 7°8\) galaxies culled from Tully et al. (1996) and Trentham et al. (2001), we found \(v_{\text{sys}} = 919 \pm 39 \text{ km s}^{-1}, v_{\text{North}} = 370 \pm 556 \text{ km s}^{-1}, v_{\text{West}} = 980 \pm 794 \text{ km s}^{-1},\) and \(\sigma = 378 \pm 30 \text{ km s}^{-1}\)
The collisional nature of gas suggests that the intracluster medium (ICM) could provide a cleaner probe of PR than cluster galaxies—naively, the ICM might be expected to follow a more symmetric distribution of velocities around the system mean and to have lower random local motions (i.e., smaller $v_{\text{local}}$) term in Equation (2)). The measurement of gas velocities from X-ray spectroscopy of the ICM is just becoming feasible, for example, Dupke & Bregman (2006) report direct detections of velocity differences from X-ray observations of the ICM across the Centaurus galaxy cluster of 2000 km s$^{-1}$. Indeed, the planned International X-ray Observatory (IXO) is aiming to have the capability of surveying galaxy cluster gas at high spectral resolution ($\Delta E \sim 2.5$ eV for $E \sim 0.3$–7 keV on few arcminute scales) in order to study turbulent motions of cluster gas with 100 km s$^{-1}$ resolution at $z \sim 2$ (Arnaud et al. 2009). While PR, with an expected signal of order $\sim 100$ km s$^{-1}$ (see Equation (3)), would be barely detectable in the largest nearby galaxy clusters with this resolution, the IXO design does at least demonstrate the technical feasibility of these measurements. Unfortunately, the interpretation of any such observations is likely to be difficult: numerical simulations do imply the existence of long-lived turbulent velocities and bulk flows of order $300$–$600$ km s$^{-1}$ on scales of 100–500 kpc in the typical ICM (Norman & Bryan 1999) and a comparable degree of rotational support throughout the inner parts of the cluster (as seen in Fang et al. 2009, although these results may in part be due to numerical effects such as over cooling). Indeed, numerical studies suggest that the rotation of gas following mergers of clusters may be longer lived than for galaxies (Roettiger & Flores 2000).

### 3.3. The Kinetic Sunyaev–Zeldovich Effect

Another way to measure galaxy cluster motions is to look for distortions of the cosmic microwave background (CMB) due to the cluster’s intervening gas. Sunyaev & Zeldovich (1972) demonstrated that how inverse Compton scattering of CMB photons from energetic electrons in the ICM could be detectable as a (frequency-dependent) temperature change. This effect—commonly referred to as the thermal or static Sunyaev–Zeldovich effect—has since become a standard tool
for analyzing ICM properties (e.g., Muchovje et al. 2007, and references therein). Sunyaev & Zeldovich (1980) also noted that any motion of the ICM relative to the CMB rest frame would impart an additional (frequency-independent) Doppler distortion to the temperature of the CMB—dubbed the kinetic Sunyaev–Zeldovich effect (kSZ)—of order

\[
\frac{\Delta T}{T} = -\frac{v_{\text{los}}}{c} \tau,
\]

where \( \tau \) is the optical depth with respect to Thomson scattering. The current generation of CMB experiments should be able to use the kSZ effect to successfully measure the peculiar motions of galaxy clusters along the line of sight (see for e.g., Cunnama et al. 2009), which are expected in general to produce maximum distortions \( \Delta T \sim 20 \mu K \) (Molnar & Birkinshaw 2000). PR induced by the galaxy cluster’s transverse motion would be apparent as a dipole signature in the kSZ temperature distortion. The amplitude of this distortion would be smaller than the typical line-of-sight velocity signature by two factors: the first of order \( \sin \theta_{\text{max}} \) (or 5%–10% for nearby galaxy clusters) due to the projection effect and the second due to the falloff in gas density (and corresponding decrease in \( \tau \)) away from the center of the galaxy cluster. Hence, we might expect PR to induce a distortion of order 0.1–1 \( \mu K \) across nearby galaxy clusters—clearly a challenge for near-future experiments. As before, the signal of PR in the kSZ effect will also be competing with signatures of turbulent motions (expected to be of order 10 \( \mu K \); see Sunyaev et al. 2003) and intrinsic rotation (expected to be of order 2 \( \mu K \) due to tidally induced rotation alone; Cooray & Chen 2002).

4. SUMMARY, DISCUSSION, AND CONCLUSION

We have outlined three possible ways to measure the PR of galaxy clusters and estimate their transverse motions: from line-of-sight velocity measurements of galaxy cluster galaxies, the motion of cluster gas, and mapping the kSZ distortions in the CMB. All these measurements are unfeasible with the current data but could become feasible with near-future instruments or larger data sets. The amplitude of PR is most significant for galaxy clusters with larger angular extent. Hence, the most promising approach with current capabilities is to survey as large a sample as possible of spectra of galaxies in nearby galaxy clusters.

With all approaches, the signal of PR could be confused by random (or turbulent) motions and intrinsic rotation of their system of targets. We are optimistic that it will be possible to disentangle these effects with sufficiently large data sets since PR imposes a unique signature of solid-body rotation on top of these sources of confusion. Indeed, Kaplinghat & Strigari (2008) found that, when they included a small intrinsic rotation in their models of dwarf spheroidal galaxies, the error bars on the transverse velocity estimates derived by “observing” line-of-sight velocities of stars in their models increased by only a factor of 2. While galaxy clusters are unlike dwarfs spheroidal galaxies in that they are not expected to be as relaxed or spherically symmetric, the Kaplinghat & Strigari (2008) study provides a first step toward a comprehensive modeling effort.

Note that several other approaches to detecting transverse motions of galaxy clusters have also been proposed, for example, using polarization maps of the CMB (Sunyaev & Zeldovich 1980), gravitational lensing of the CMB (Birkinshaw & Gull 1983), and weak and strong lensing of background galaxies (Molnar & Birkinshaw 2003). The strength of the signatures in these methods are not dependent on the angular extent of the galaxy cluster and hence have the advantage over PR of being applicable to distant as well as nearby clusters.

With multiple possible directions for detection, we conclude that measurements of the full space motions of galaxy clusters are on the horizon.

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