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THREE DIFFERENT TYPES OF GALAXY ALIGNMENT WITHIN DARK MATTER HALOS

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ABSTRACT

Using a large galaxy group catalog based on the Sloan Digital Sky Survey Data Release 4, we measure three different types of intrinsic galaxy alignment within groups: halo alignment between the orientation of the brightest group galaxies (BGG) and the distribution of its satellite galaxies, radial alignment between the orientation of a satellite galaxy and the direction toward its BGG, and direct alignment between the orientation of the BGG and that of its satellites. In agreement with previous studies, we find that satellite galaxies are preferentially located along the major axis. In addition, on scales $r < 0.7R_{\rm vir}$ we find that red satellites are preferentially aligned radially with the direction to the BGG. The orientations of blue satellites, however, are perfectly consistent with being isotropic. Finally, on scales $r < 0.1R_{\rm vir}$, we find a weak but significant indication for direct alignment between satellites and BGGs. We briefly discuss the implications for weak-lensing measurements.

Subject headings: galaxies: clusters: general — galaxies: kinematics and dynamics — surveys

1. INTRODUCTION

A precise assessment of galaxy alignments is important for two main reasons: it contains information regarding the impact of environment on the formation and evolution of galaxies, and it can be an important source of contamination for weak-lensing measurements. In theory, the large-scale tidal field is expected to induce large-scale correlations between galaxy spins and galaxy shapes (e.g., Pen et al. 2000; Croft & Metzler 2000; Heavens et al. 2000; Catelan et al. 2001; Crittenden et al. 2001; Porciani et al. 2002b; Jing 2002). In addition, the preferred accretion of new material along filaments tends to cause alignment with the large-scale filamentary structure in which dark matter halos and galaxies are embedded (e.g., Jing 2002; Faltenbacher et al. 2005; Bailin & Steinmetz 2005). On small scales, however, inside virialized dark matter halos, any primordial alignment is likely to have been significantly weakened due to nonlinear effects such as violent relaxation and (impulsive) encounters (e.g., Porciani et al. 2002a). On the other hand, tidal forces from the host halo may also induce new alignments, similar to the tidal locking mechanism that affects the Earth-Moon system (e.g., Ciotti & Dutta 1994; Usami & Fujimoto 1997; Fleck & Kuhn 2003).

Observationally, the search for galaxy alignments has a rich and often confusing history. To some extent this is owing to the fact that numerous different forms of alignment have been discussed in the literature: the alignment between neighboring clusters (Binggeli 1982; West 1989; Plionis 1994), between brightest cluster galaxies (BCGs) and their parent clusters (Carter & Metcalfe 1980; Binggeli 1982; Struble 1990), between the orientation of satellite galaxies and the orientation of the cluster (Dekel 1985; Plionis et al. 2003), and between the orientation of satellite galaxies and the orientation of the BCG (Struble 1990). Obviously, several of these alignments are correlated with each other, but independent measurements are difficult to compare, since they are often based on very different data sets.

With large galaxy redshift surveys, such as the Two Degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) and the Sloan Digital Sky Survey (SDSS; York et al. 2000), it has become possible to investigate alignments using large and homogeneous samples. This has resulted in robust detections of various alignments: Brainerd (2005), Yang et al. (2006), and Azzaro et al. (2007) all found that satellite galaxies are preferentially distributed along the major axes of their host galaxies, Trujillo et al. (2006) found that spiral galaxies located on the shells of large voids have rotation axes that lie preferentially on the void surface, and Pereira & Kuhn (2005) and Agustsson & Brainerd (2006a) noticed that satellite galaxies tend to be preferentially oriented toward the galaxy at the center of the halo.

In this Letter we use a large galaxy group catalog constructed from the SDSS to study galaxy alignments on small scales within dark matter halos that span a wide range of masses. The unique aspect of this study is that we investigate three different types of alignment using exactly the same data set consisting of over 60,000 galaxies. In addition, by using a carefully selected galaxy group catalog, we can discriminate between central galaxies and satellites, and study their mutual alignment. The latter is particularly important for galaxy-galaxy lensing, where it can be a significant source of contamination. Finally, exploiting the large number of galaxies in our sample, we also investigate how the alignment signal depends on the colors of the galaxies. Throughout we adopt $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ and a Hubble parameter $h = H_0/100$ km s^{-1} Mpc^{-1}.

2. DATA AND METHODOLOGY

We apply our analysis to the SDSS galaxy group catalog of X. Yang et al. (2007, in preparation). This catalog is constructed using the halo-based group finder of Yang et al. (2005) and applied to the New York University Value Added Galaxy Catalog (NYU-VAGC)[5] that is based on the SDSS Data Release Four (DR4; Adelman-McCarthy et al. 2006). This group finder uses the general properties of CDM halos (i.e., virial radius, velocity dispersion, etc.) to determine the memberships of

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[5] See http://wassup.physics.nyu.edu/vagc/.

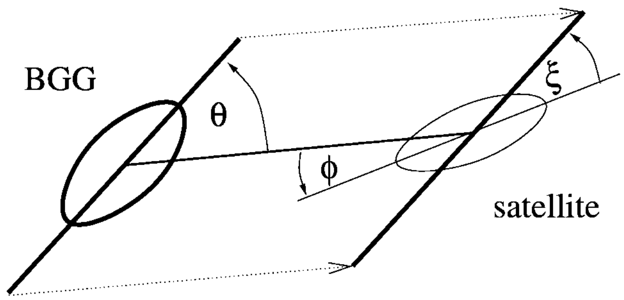

FIG. 1.—Illustration of the three angles θ, ϕ, and ξ, which are used to test for halo alignment, radial alignment, and direct alignment, respectively. The three angles are not independent: if ordered by size $\alpha \geq \beta \geq \gamma$, then $\alpha = \min\,[\beta + \gamma, 180° - \beta - \gamma]$.

groups (cf. Weinmann et al. 2006). In this study we only use those groups with redshifts in the range $0.01 \leq z \leq 0.2$ and with halo masses between 5×10^{12} and $5 \times 10^{14}\ h^{-1}\ M_{\odot}$. In addition, we only focus on group members with ${}^{0.1}M_r - 5\log h \leq -19$. Throughout this Letter all magnitudes are $k + e$ corrected to $z = 0.1$, following Blanton et al. (2003). Using the method of Li et al. (2006), we split our galaxies in three color bins. In short, we divide the full NYU-VAGC sample in 282 subsamples according to the r-band luminosity, and fit the ${}^{0.1}(g - r)$ color distribution for each subsample with a double-Gaussian. Galaxies in between the centers of the two Gaussians are classified as "green," while those with higher and lower values for the ${}^{0.1}(g - r)$ color are classified as "red" and "blue," respectively. The final sample, on which our analysis is based, consists of 18,576 groups with a total of 60,724 galaxies, of which 29,780 are red, 20,604 are green, and 10,340 are blue.

In what follows, we use these groups to examine (1) *halo alignment* between the orientation of the brightest group galaxies (BGG) and the distribution of its satellite galaxies, (2) *radial alignment* between the orientation of a satellite galaxy and the direction toward its BGG, and (3) *direct alignment* between the orientation of the BGG and that of its satellites. In particular, we define the angles θ, ϕ, and ξ as illustrated in Figure 1, and investigate whether their distributions are consistent with isotropy, or whether they indicate a preferred alignment. Following Brainerd (2005) and Yang et al. (2006), the orientation of each galaxy is defined by the major axis position angle (PA) of its 25 mag arcsec^{-2} isophote in the r band.

For each satellite galaxy we compute its projected distance, r, to the BGG, normalized by the virial radius, $R_{\rm vir}$, of its group (as derived from the group mass). For each of 5 radial bins, equally spaced in $r/R_{\rm vir}$, we then compute $\langle\theta\rangle$, $\langle\phi\rangle$, and $\langle\xi\rangle$, where $\langle.\rangle$ indicates the average over all BGG-satellite pairs in a given radial bin. Next we construct 100 random samples in which the positions of the galaxies are kept fixed, but their PAs are randomized. For each of these random samples we compute $\langle\theta\rangle$, $\langle\phi\rangle$, and $\langle\xi\rangle$ as function of $r/R_{\rm vir}$, which we use to compute the significance of any detected alignment signal.

3. RESULTS

3.1. *Halo Alignment*

Figure 2 shows the results thus obtained for the angle θ between the orientation of the BGG and the line connecting the BGG with the satellite galaxy. Clearly, for all four samples shown (all, red, green, and blue, where the color refers to that of the satellite galaxy, not that of the BGG) we obtain $\langle\theta\rangle <$ 45° at all 5 radial bins and at high significance.[6] This indicates that satellite galaxies are preferentially distributed along the major axis of the BGG, in good agreement with the findings of Brainerd (2005), Yang et al. (2006), and Azzaro et al. (2007), but opposite to the old Holmberg (1969) effect. Note that there is a clear indication that the distribution of red satellites is more strongly aligned with the orientation of the BGG than that of blue satellites, again in good agreement with previous studies (e.g. Yang et al. 2006; Azzaro et al. 2007).

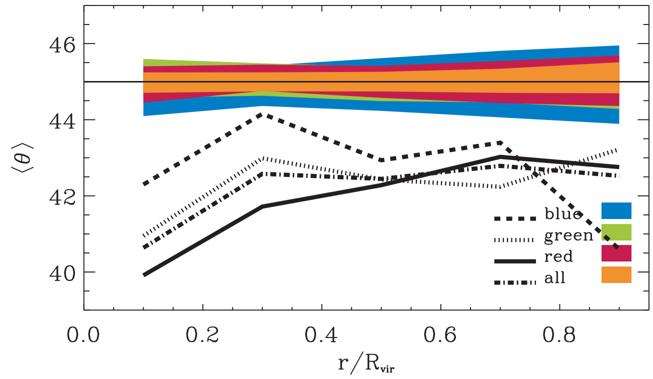

FIG. 2.—Mean angle, θ, between the PA of the BGG and the line connecting the BGG with a satellite galaxy, as function of $r/R_{\rm vir}$. Different line styles indicate (sub)samples determined according to the satellites' color. The shaded areas mark the parameter space between the 16th and 84th percentiles of the distributions obtained from the 100 random samples. A signal outside this shaded region means that it is inconsistent with no alignment (i.e., with isotropy) at more than 68% confidence.

3.2. *Radial Alignment*

Hawley & Peebles (1975) were the first to report a possible detection of radial alignment in the Coma cluster, which has subsequently been confirmed by Thompson (1976) and Djorgovski (1983). However, in a more systematic study based on the 2dFGRS, Bernstein & Norberg (2002) were unable to detect any significant radial alignment of satellite galaxies around isolated host galaxies. On the other hand, using a very similar selection of hosts and satellites, but applied to the SDSS, Agustsson & Brainerd (2006a) found significant evidence for radial alignment on scales $\lesssim 70\ h^{-1}$ kpc. In addition, Pereira & Kuhn (2005) found a statistically robust tendency toward radial alignment in a large sample of 85 X-ray-selected clusters.

Figure 3 shows the results obtained from our group catalog. It shows, as function of $r/R_{\rm vir}$, the mean angle ϕ between the PA of the satellite and the line connecting the satellite with its BGG. As in Figure 2, results are shown for all four different samples, together with the 16th and 84th percentiles obtained from the random samples. There is a clear and very significant indication that the major axes of red satellites point toward the BGG (i.e., $\langle\phi\rangle < 45°$), at least for projected radii $r \lesssim 0.7R_{\rm vir}$. The signal for the green satellites is significantly weaker, but still reveals a preference for radial alignment on small scales: in fact, for the 3 radial bins with $r \leq 0.5R_{\rm vir}$, the null hypothesis of no radial alignment can be rejected at more than 95% confidence level. In contrast, for the blue galaxies the data are perfectly consistent with no radial alignment. Since the 2dFGRS is more biased toward blue galaxies than the SDSS, this

[6] More than 99%, except for the $0.3R_{\rm vir}$ bin for the blue and the $0.9R_{\rm vir}$ bin for the green satellites.

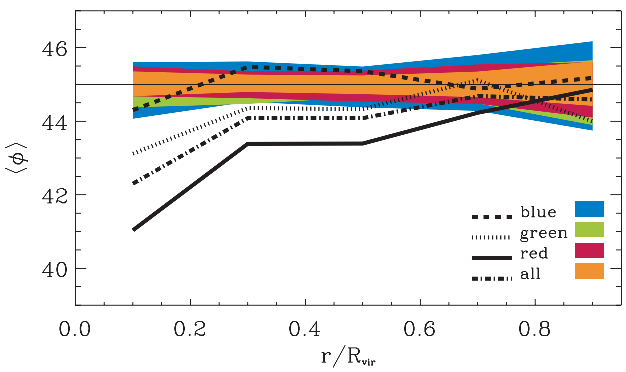

FIG. 3.—Same as Fig. 2, but for the angle ϕ (see Fig. 1).

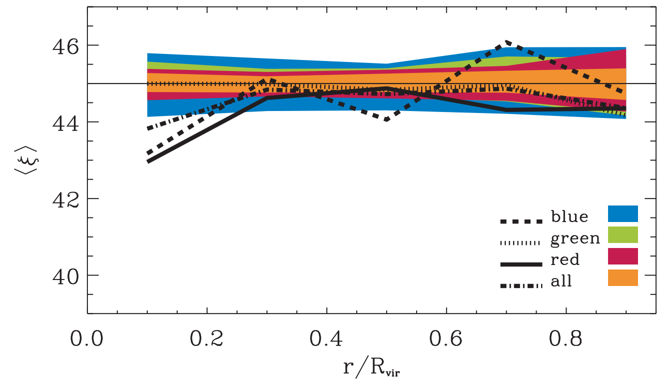

FIG. 4.—Same as Fig. 2, but for the angle ξ (see Fig. 1).

may at least partially explain why Bernstein & Norberg (2002) were unable to detect significant radial alignment.

3.3. *Direct Alignment*

The search for direct alignment has mainly been restricted to galaxy clusters (e.g., Plionis et al. 2003; Strazzullo et al. 2005; Torlina et al. 2007), mostly resulting in no or very weak indications for alignment between the orientations of BCG and satellite galaxies. Agustsson & Brainerd (2006a) extended the search for direct alignment to a samples of 4289 host-satellites pairs selected from the SDSS DR4, finding a weak but significant signal on scales $\lesssim 35\ h^{-1}$ kpc. On larger scales, however, no significant alignment was found, in agreement with Mandelbaum et al. (2006).

Figure 4 displays our results for the direct alignment, based on the angle ξ between the orientations of a satellite galaxy and that of its BGG. With the exception of the central bin ($r/R_{\rm vir} = 0.1$), the null hypothesis of a random distribution cannot be rejected at more than 1 σ confidence level. Our study, based on over 40,000 BGG-satellite pairs, therefore agrees with Agustsson & Brainerd (2006a) that there is a weak indication for direct alignment, but only on relatively small scales: for the average group mass in our sample, $M = 3.6 \times 10^{13}\ h^{-1}\ M_{\odot}$, a radius of $r = 0.1R_{\rm vir}$ corresponds to 70 h^{-1} kpc. However, at least for the red satellites there is a systematic trend toward angles <45°, which may be caused by the group tidal field (cf. Lee et al. 2005).

3.4. *Dependence on Selection Criteria*

The sample used above is based on galaxies with ${}^{0.1}M_r - 5\log h \leq -19$. Typically, including fainter galaxies improves the number statistics but not necessarily the signal-to-noise ratio, since the PAs of fainter galaxies carry larger errors. To test the sensitivity of our results, we repeated the above analysis using magnitude limits of −17, −18, and −20. This resulted in alignment signals that were only marginally different. We have also tested the sensitivity of our results to the range of group masses considered. Changing the lower limit to $10^{12}\ h^{-1}\ M_{\odot}$ or $10^{13}\ h^{-1}\ M_{\odot}$, or imposing no upper mass limit, all yields very similar alignment signals. These tests ensure that our selection criteria lead to representative results.

4. DISCUSSION

The origin of the halo alignment described in § 3.1 has been studied by Agustsson & Brainerd (2006b) and Kang et al. (2007) using semianalytical models of galaxy formation combined with large N-body simulations. Since dark matter halos are in general flattened, and satellite galaxies are a reasonably fair tracer of the dark matter mass distribution, $\langle\theta\rangle$ will be smaller than 45° as long as the BGG is aligned with its dark matter halo. In particular, Kang et al. (2007) were able to accurately reproduce the data of Yang et al. (2006) under the assumption that the minor axis of the BGG is perfectly aligned with the spin axis of its dark matter halo.

Kang et al. (2007) also showed that the color dependence of the halo alignment has a natural explanation in the framework of hierarchical structure formation: red satellites are typically associated with subhalos that were more massive at their time of accretion. Since the orientation of a halo is correlated with the direction along which it accreted most of its matter (e.g., Wang et al. 2005; Libeskind et al. 2005), red satellites are a more accurate tracer of the halo orientation than blue satellites.

The origin of the radial alignment is less clear. One possibility is that it reflects a leftover from large-scale alignments introduced by the large-scale tidal field and the preferred accretion of matter along filaments. Such alignment, however, is unlikely to survive for more than a few orbits within the halo of the BGG, so that the observed alignment must be mainly due to the satellite galaxies that were accreted most recently. Since these satellites typically reside at relatively large halo-centric radii, this picture predicts a stronger radial alignment at larger radii, clearly opposite to what we find.

A more likely explanation, therefore, is that radial alignment has been created locally by the group tidal field. As shown by Ciotti & Dutta (1994), the timescale on which a prolate galaxy can adjust its orientation to the tidal field of a cluster is much shorter than the Hubble time, but longer than its intrinsic dynamical time. Consequently, prolate galaxies have a tendency to orient themselves toward the cluster center. The fact that the observed signal increases toward the group center supports this interpretation. In particular, satellites that were accreted early not only are more likely to be red, but also are more likely to reside at small group-centric radii and to have relatively low group-centric velocities (e.g., Mathews et al. 2004). This will enhance their tendency to align themselves along the gradient in the cluster's gravitational potential, and they may well be the major contributors to the pronounced signal on small scales. In the case of disk galaxies, the conservation of intrinsic angular momentum prevents the disk from readjusting to the tidal field, which may explain why blue satellites show no sign of radial alignment. Finally, the tidal field of the parent halo also results in tidal stripping, and the tidal debris may influence the inferred orientation of the satellite galaxy (e.g. Johnston et al. 2001; Fardal et al. 2006). Detailed studies are required to investigate the interplay between intrinsic satellite orientations and the groups' tidal field.

In order to understand the direct alignment results, first realize that the angles θ, ϕ, and ξ are not independent (see Fig. 1). However, the equation given in the caption is only applicable for single cases, not for the mean angles. Our results indicate that satellite galaxies are more likely to be aligned "radially" with the direction toward the BGG, than "directly" with the orientation of the BGG. Since there is no clear theoretical prediction for direct alignment, at least not one that can survive for several orbital periods in a dark matter halo, while radial alignment can be understood as originating from the halo's tidal field, we consider the relative weakness of direct alignment to be consistent with expectations.

In recent years, galaxy-galaxy lensing has emerged as a primary tool for constraining the masses of dark matter halos around galaxies (e.g., Brainerd 2004). If satellite galaxies are falsely identified as sources lensed by the BGG, which is likely to happen in the absence of redshift information, the radial alignment detected here will dilute the tangential galaxy-galaxy lensing signal induced by the dark matter halo associated with the BGG, thus resulting in an underestimate of the halo mass. In agreement with Agustsson & Brainerd (2006a) our findings therefore emphasize the importance of an accurate rejection of satellite galaxies to achieve precision constraints on dark matter halo masses from galaxy-galaxy lensing measurements. Similarly, the weak but significant detection of direct alignment may contaminate the cosmic shear measurements. Since we only detected a weak signal on small scales, one can easily avoid this contamination by simply removing or down-weighting close pairs of galaxies in projection (King & Schneider 2002; Heymans & Heavens 2003).

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