Galaxy Orientation and Alignment Effects in the SDSS DR6

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ABSTRACT

We identify, categorize, and quantify alignment effects among host and satellite galaxies using a low-redshift ($z < 0.23$) sample of spectroscopically-confirmed galaxies from the Sloan Digital Sky Survey Data Release 6. Consistent with other recent findings, we find that satellite galaxies of red, centrally-concentrated (elliptical) host galaxies with radial velocity separation $|\Delta V| < 600\text{ km/s}$ preferentially reside near the projected major axes of their host galaxies. This preference is stronger among red, centrally-concentrated satellite galaxies. We explore the dependence of this satellite-host alignment on $\Delta V$ and the projected radial separation $\Delta R$, finding that fractional anisotropy increases with decreasing $\Delta V$ and $\Delta R$. Fractional anisotropy among the closest satellites ($\Delta R < 250 h^{-1}\text{ kpc}$) is nearly 40% greater than that seen among most distant ($500 h^{-1}\text{ kpc} < \Delta R < 1000 h^{-1}\text{ kpc}$) companions. We also investigate the effects of sample selection and measurement errors on the measured alignment signals. Among highly concentrated satellite galaxies at small projected separation ($\Delta R < 300 h^{-1}\text{ kpc}$), we observe a strong radial (hostward) alignment signal in isophotal position angles due to isophotal twisting and contamination that is not present when using galaxy model position angles. Among objects for which both isophotal and galaxy model position angles agree to within $15^\circ$, this elongation signal is significantly weaker. We also investigate the “Holmberg Effect,” a well-known result wherein nearby ($< 40 h^{-1}\text{ kpc}$) satellites of large, inclined spiral hosts were seen to preferentially reside near the minor axes of their hosts.
in projection. Due to the flux limit and spatial sampling limitations, a strict test of the “Holmberg Effect” is not possible using only SDSS spectroscopic galaxies. By adopting a looser set of cuts than those of Holmberg’s original study, we recover a comparable preference of faint blue satellites for the host minor axis at marginal (\(\sim 3\sigma\)) significance. After carefully inspecting the methods used by various studies, we suggest that sample selection is largely to blame for discrepant and contradictory results on galaxy alignment effects in the literature. We conclude that several types of alignment likely exist among different galaxy populations, but that the observed nature and strength of those alignment trends depend sensitively not just on selection criteria but also on the method used to determine galaxy orientation.

1. Introduction

The study of galaxy alignments is an old and contentious topic. The importance of understanding galaxy alignment properties has grown over the past several decades, as ever-increasing precision in numerical simulations has revealed more about the galaxy formation process. The emergence of weak lensing as a precision cosmology tool has further increased the demands on our understanding of the intrinsic alignments of physically-related galaxies. An increase in the number of conflicting results merits thorough re-examination of not only the existing body of observational results, but also the methodologies used to acquire those results, which may be responsible for these apparent contradictions.

The angular distribution and alignment of satellite galaxies with respect to their hosts carries information about the dynamical mechanisms involved in the accretion and subsequent evolution of satellite galaxy halos. For example, it is known from observational and theoretical studies that the distribution of galaxies and their host halos is filamentary in nature. It has been suggested that larger galaxies accrete satellites along these filaments (Knebe et al. 2004; Libeskind et al. 2005; Zentner et al. 2005; Bailin et al. 2008). Subsequent evolution involves complex dynamical interactions between these satellites and the host gravitational potential, including dynamical friction and tidal stripping. Luminous galaxies within subhalos of larger cluster-size halos allow us to trace the large-scale dark matter-dominated cluster potential. The signatures of these dynamical processes may be imprinted on the alignments between the central and satellite galaxies.

While a primary motivation for studying the intrinsic alignment of physically-associated galaxies is to provide constraints for galaxy formation models, understanding the magnitude of these alignments is important for assessing possible contamination of weak lensing stud-
ies (Croft & Metzler 2000; Lee & Pen 2001). Since weak lensing of background galaxies by foreground substructures induces apparent alignments between these lensed galaxies, intrinsic alignment of galaxies can provide a contaminating signal to weak lensing studies. Calibrating the degree of this contamination and its impact on precision cosmology with any given dataset requires an accurate assessment of the magnitude and scale of intrinsic galaxy alignment (e.g., Croft & Metzler 2000; Lee & Pen 2001; Bernstein & Norberg 2002; Mandelbaum et al. 2005).

Numerous alignment effects have been observed, many of which are only observed in specific galaxy populations. One of the best known alignment effects, the “Holmberg Effect” (Holmberg 1969), is also currently one of the most contentious. Holmberg (1969) noted that satellite galaxies (SGs) preferentially occupy the space near the projected minor axis of very isolated, large, and inclined spiral galaxies. After statistically correcting for interloping field objects, there was a significant absence of satellites near the host galaxy (HG) projected major axes. This would seem to indicate that satellites preferentially travel or survive along polar orbits. This result has been both rediscovered at marginal significance (e.g. Zaritsky et al. 1997b) and strongly refuted (e.g. Brainerd 2005; Yang et al. 2006; Azzaro et al. 2007) in recent years.

In the cases of refutation, the inverse effect has been observed. Specifically, these studies found that satellites have a strong measured preference for the major axis of their host galaxy as seen in projection. In both Yang et al. (2006) and Azzaro et al. (2007), this alignment exhibits a color dependence, appearing strongest for satellites of red host galaxies. These red galaxy populations are obviously dissimilar from those targeted by Holmberg (1969).

Galaxy clusters afford another opportunity for alignment analyses. For several decades, focused observing campaigns and large-area surveys alike have furnished evidence for anisotropy in the spatial distribution of cluster members. Sastry (1968), using a sample of 9 Abell clusters, provided the first evidence that cluster anisotropy might be common. Over the following years, many more clusters were found to exhibit similar properties (e.g. Austin & Peach 1974; Dressler 1978; Carter & Metcalfe 1980; Binggeli 1982, and many others). Although conflicting results have sporadically emerged (Tucker & Peterson 1988; Ulmer et al. 1989), it is generally agreed that there exists a spatial anisotropy in favor of the projected major axis of the brightest cluster galaxy (BCG). This effect is so strong that the BCG major axis is a reliable indicator of the distribution of cluster satellites (Binggeli 1982). This is particularly useful when sample flux limits may prevent detection of many cluster members.

In addition to the alignment signal present within individual clusters, alignment has been observed between neighboring clusters (Binggeli 1982; Argyres et al. 1986; Rhee & Katgert 1987; West 1989a,b, among others). Although lower in amplitude, this effect is observed
to 10 Mpc scales and beyond. Certain recent results have linked this alignment to the local orientation of filamentary large-scale structures (Bailin et al. 2008; Faltenbacher et al. 2009).

Several studies have also investigated the elongation of satellite galaxies towards their hosts. Numerous studies (e.g., Croft & Metzler 2000) have suggested that an intrinsic alignment of this nature would mimic a weak lensing signal and would require careful calibration. Other recent studies (Pereira & Kuhn 2005; Agustsson & Brainerd 2006; Faltenbacher et al. 2007) find significant evidence of hostward elongation in an examination of galaxies from the Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2006; Abazajian et al. 2005; Stoughton et al. 2002; York et al. 2000) spectroscopic survey. Faltenbacher et al. (2008) find a similar effect between dark matter halos in N-body simulations. By contrast, Bernstein & Norberg (2002) observed no such elongation in a study based on the 2 Degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001).

The size and nature of one’s data set plays an important role in the detection and study of galaxy alignment effects. Recent large-area surveys (e.g., 2dFGRS & SDSS) contain large numbers of galaxies, each with a uniform set of data products. These greater numbers allow more stringent selection criteria while still maintaining large statistical samples. The uniformity afforded by a fixed reduction pipeline sidesteps most systematic problems with intercalibration of different data sets. When available, spectroscopic redshifts can be used to eliminate interlopers and greatly simplify selection of physically-related galaxies.

On the other hand, smaller data sets often benefit from by-eye quality control and selection which is impractical for very large surveys. Spurious results that might go undetected in an automated pipeline can be found and removed. Some smaller data campaigns also benefit from fainter limiting magnitudes, which has proven important in studies of individual clusters.

The purpose of the present study is to independently investigate the alignment effects mentioned above using the spectroscopic galaxy catalog of the Sloan Digital Sky Survey Data Release 6 (Adelman-McCarthy et al. 2008, hereafter SDSS DR6). We also seek to resolve any discrepancies between our results and those that have been presented to date.

Using a subsample of low-redshift \((z < 0.23)\) galaxies from the SDSS DR6 spectroscopic catalog, we explore the distribution and alignment properties of satellite galaxies in projection. Groups are determined by centering a cylinder of fixed physical size (2400 km/s in “height,” \(1 h^{-1}\) Mpc in radius; Fig. 3a) on the brightest local galaxy and counting objects that fall within the cylinder volume. We impose a variety of different cuts in observed galaxy properties and observe the resultant changes in satellite galaxy distribution and alignment.

The main focus of this study is quality control in both selection criteria and measure-
ments of galaxy properties. To do this we simultaneously use multiple independent measures of galaxy position angle and shape from SDSS. To determine reliable relative luminosities, we incorporate all 5 photometric bands through spectral templates, improving host determination among different galaxy types. Lastly, we examine distribution and alignment properties separately as functions of host and satellite color and concentration, host-satellite velocity separation, and projected radial separation, combining and improving upon results found in the literature.

The content of the present work is organized as follows. In §2 we describe the data products used in the study. In §3 we describe the selection criteria used to pare the initial data set and detect groups within it. In §4 we present the properties of our data sample and discuss our methods of quality control. We present our findings in §5. Numerous caveats and complications follow in §6. How these results compare to previous findings follows in §7. We present our investigation of the Holmberg Effect in §8. Lastly, a brief summary and discussion of our findings and their implications can be found in §9.

In what follows we adopt the following cosmological parameters: \( \Omega_\Lambda = 0.7, \Omega_M = 0.3, \) and \( h \equiv H_0/(100 \, \text{km/s/Mpc}) = 0.7. \)

## 2. Data Set

The galaxies we use are a subset of the SDSS DR6 ([Adelman-McCarthy et al. 2008](https://www.sdss.org)) spectroscopic galaxy sample. In its entirety, the main spectroscopic catalog contains 790,220 galaxies to limiting Petrosian magnitude \( m_r < 17.77. \) We include all spectroscopically-confirmed galaxies with well-established \( (z_{\text{Conf}} > 0.35) \) redshifts of \( 0.004 < z < 0.23. \) This lower bound safely excludes possible neighbors of our own galaxy while the upper bound minimizes the impact of fiber collisions. We further select galaxies with \( g > 0 \) and \( r > 0 \) \( (\text{modelMag}, \) see below). Lastly we require successful (not placeholder) measurements of isophotal axes \( (\text{iso}_A \ & \text{iso}_B) \). The resultant sample contains 572,495 galaxies which meet these criteria.

SDSS employs matched de Vaucouleurs and exponential galaxy models to optimally extract many photometric properties, including some that we use in this study. A de Vaucouleurs \( R^{1/4} \) profile accurately describes the light profiles of many elliptical galaxies and spiral bulges. SDSS employs the following form ([Stoughton et al. 2002](https://www.sdss.org)):

\[
I(R) = I_0 \exp \left[ -7.67 \left( \frac{R}{R_{\text{eff}}} \right)^{1/4} \right].
\]  

(1)

This profile is truncated beyond \( 7R_{\text{eff}} \), decreasing smoothly to zero at \( 8R_{\text{eff}} \). The profile is softened slightly within \( R < R_{\text{eff}}/50. \)
Exponential light profiles are frequently used to describe dwarf ellipticals and the disks of spiral galaxies. The SDSS exponential model,

\[ I(R) = I_0 \exp \left[ -1.68 \left( \frac{R}{R_{\text{eff}}} \right) \right], \]

is truncated beyond \(3R_{\text{eff}}\), smoothly decreasing to zero at \(4R_{\text{eff}}\) (Stoughton et al. 2002).

The SDSS pipeline convolves two-dimensional variants of the above profiles with a double-Gaussian approximation of the locally-determined PSF in order to account for the effects of seeing. The best fit of the exponential and deVaucouleurs models to each galaxy simultaneously determine the axis ratio, position angle (PA, in degrees East from North), and effective scale radius \(R_{\text{eff}}\), in arcseconds) in each case. The axis ratio and position angle are taken to be constant throughout the model galaxy. Although fitted across a range of radius, these models tend to best trace the bright, inner regions of galaxies (Strateva et al. 2001; Stoughton et al. 2002).

SDSS provides several different galaxy flux measurements. Unbiased colors, which are necessary to determine K-corrections to the highest possible accuracy, must be obtained using the same aperture in each wavelength bands. To accomplish this we employ \textit{modelMag} (model magnitude, hereafter simply magnitude) fluxes in the present study. Both matched galaxy models (see above) are fitted to each object. The fit of higher likelihood in \textit{r}-band is re-applied to \textit{u, g, r, i,} and \textit{z}, allowing only the amplitude to vary (Lupton et al. 2001; Stoughton et al. 2002). The resultant measurement, termed \textit{modelMag}, thus uses the same effective aperture in all bands.

SDSS additionally computes a best-fit composite model flux in each band. This \textit{cmodel} magnitude very accurately captures the total flux of each galaxy by calculating the best-fit non-negative linear combination of exponential and de Vaucouleurs profiles separately for each of the five photometric bands. The fractional flux contribution of the de Vaucouleurs profile, \textit{fracDeV}, is a useful (seeing-corrected) measure of light profile concentration.

The Petrosian flux, also computed for each galaxy, measures the light within a circular aperture the radius of which is determined by the slope of the azimuthally-averaged galaxy brightness profile. In the SDSS, this Petrosian radius \(r_p\) is chosen such that \(\mathcal{R}_p(r_p) = 0.2\) (Stoughton et al. 2002), where \(\mathcal{R}_p(r)\), the Petrosian ratio, is the ratio of surface brightness in an annulus at radial position \(r\) to the mean surface brightness interior to \(r\) (Blanton et al. 2001; Yasuda et al. 2001; Stoughton et al. 2002):

\[ \mathcal{R}_p(r) = \frac{\int_{0.8r}^{1.25r} 2\pi r' I(r')/(\pi (1.25^2 - 0.8^2)r^2)}{\int_0^{r} 2\pi r' I(r')/(\pi r^2)}. \]  

The Petrosian flux is then computed by summing the flux within \(2r_p\). As implemented by SDSS, \(r_p\) measures the size of the bright inner regions of galaxies. Its distribution closely
matches (without artifacts) those of the exponential and de Vaucouleurs model radii. Using \( r_p \) we reject extremely close neighbors that are likely heavily blended or misidentified bright knots within a larger galaxy. In our study we exclusively use the \( r \)-band measurement.

Galaxy light profile concentration is frequently measured using the inverse concentration ratio (\( C \)), defined as the quotient of Petrosian 50\% and 90\% radii \( C \equiv R_{50}/R_{90} \), where \( R_{50} \) and \( R_{90} \) are the radii that contain 50\% and 90\% of Petrosian flux \cite{Stoughton2002, Blanton2001, Yasuda2001}. \( C \) is highly correlated with morphological type \cite{Shimasaku2001, Strateva2001} and provides a convenient and effective way to statistically separate large galaxies into different morphological classes. The Petrosian radii are not, however, corrected for the effects of seeing, reducing the accuracy of concentration ratio for smaller objects of sizes nearing that of the PSF. Furthermore, as seeing is depending on the time of observation, relying on \( C \) alone may introduce time-dependent systematic effects.

In the present work, we measure light profile concentration with SDSS galaxy parameter \( \text{fracDeV} \). Unlike Petrosian radii \( R_{50} \) and \( R_{90} \), the galaxy models are corrected for seeing conditions (see above) and should thus provide a straightforward and reliable measure of concentration which will depend less on the angular scale of the individual galaxy relative to that of the PSF. We illustrate the distributions of color and inverse concentration and how they relate to \( \text{fracDeV} \) in Figure 1.

Although the galaxy fluxes are very well characterized, systematic effects in the model-fitting procedure lead to some discretization in the determined model scale radii and consequently into the model axis ratio \cite{Adelman-McCarthy2008, Bernstein2002, Hirata2003}. Therefore, to quantify the galaxy shape, we instead calculate second-order adaptive moments \cite{Bernstein2002, Hirata2003}. The distribution of galaxy shapes determined in this way closely matches the distribution determined by fitting the deVaucouleurs and exponential models, but the adaptive moment method is free of the model-fitting artifacts.

Adaptive moments shape measures are easily calculated using data provided by SDSS. SDSS DR6 uses a Gaussian weight function \( w(x, y) \) matched to the shape and size of the galaxy image \( I(x, y) \). The first-order moments

\[
\mathbf{x}_0 = \frac{\int x w(x, y) I(x, y) \, dx \, dy}{\int w(x, y) I(x, y) \, dx \, dy}
\]  

yield the galaxy positions. Using this value, the second-order adaptive moments can be computed as in

\[
M_{xx} = \frac{\int (x - x_0)^2 w(x, y) I(x, y) \, dx \, dy}{\int w(x, y) I(x, y) \, dx \, dy}.
\]
The SDSS DR6 provides the second-order parameters $\tau$, $e_+$ and $e_\times$ for all galaxies, where $\tau = M_{xx} + M_{yy}$, $e_+ = (M_{xx} - M_{yy})/\tau$, and $e_\times = 2M_{xy}/\tau$. Using these values, we define the adaptive moments axis ratio

$$q_{mom} = \left(\frac{1 - e}{1 + e}\right)^{1/2},$$

(6)

where $e = (e_+^2 + e_\times^2)^{1/2}$ (Ryden 2004). This shape is not corrected for effects of seeing. For objects larger than the PSF (true of the objects in our sample), however, any such correction will be negligible. In our analysis we exclusively adopt the value of $q_{mom}$ determined from the $r$-band measurements.

SDSS provides model-independent measurements of PA and ellipticity by fitting to the 25 magnitudes / arcsec$^2$ isophote. After first determining the object centroid, the reduction pipeline determines the radius of this isophote as a function of angle on the sky. This angular profile is then expanded in a Fourier series, the coefficients of which determine the isophotal major ($iso_A$) and minor ($iso_B$) axes, plus position angle. Although this procedure is performed separately in all 5 photometric bands, we use the $r$-band PA exclusively for both isophotal and galaxy model PA.

Although anticipated in a future Data Release, SDSS does not presently provide error estimates for its position angle (PA) measurements. We note, however, that the galaxies in the spectroscopic sample are considerably brighter than the SDSS photometric limit. As a result, for those objects that meet our shape criteria (see §3.1), PA measurement errors should be negligible. We do, however, observe significant systematic errors in the PA measurements. These must therefore be treated with care (see §6.1).

From $iso_A$ and $iso_B$, we compute both the axis ratio and an isophotal “radius.” We define isophotal axis ratio $q_{iso} \equiv iso_A/iso_B$ ($0 < q_{iso} \leq 1$) and isophotal radius $iso_R \equiv \sqrt{iso_A iso_B}$. We use the latter to exclude spurious satellite galaxies (e.g., blended objects or bright substructure) and to eliminate possible cases of isophotal contamination (see §6.1).

In practice, the 25 mag arcsec$^{-2}$ isophote tends to trace the outermost observable regions of galaxies. The measured isophotal PA may, in fact, be very different from the PA determined from fitting models to the galaxy light distribution. In our analysis, we compute the position angle difference ($\Delta$PA) between isophotal and model PAs which we then use to identify cases where one (or both) PA measurements are unreliable or where the two PA measurements are genuinely discrepant. Several recent studies (Brainerd 2005; Yang et al. 2006; Faltenbacher et al. 2007) have reported alignment findings based on isophotal PA alone. We believe that these two different PA measurements can have different physical meaning with respect to galaxy structure. As a result, both should be considered. We explore the effects of using one or the other PA determination in §6.1.
Following Bailin et al. (2008), we K-correct our galaxy colors to \( z = 0.1 \). Selection of this “neutral” redshift (\( z = 0.1 \) is both the mean and median of redshift our sample) minimizes K-correction error for the bulk of our galaxies. We denote K-corrected magnitudes in the usual way with the redshift in superscript (e.g., \( \text{1r} \)). To perform the corrections, we employ the Low-Resolution Template (LRT) software package of Assef et al. (2008). This package also uses these templates to calculate the bolometric luminosity (where \( L_{\text{bol}} \) spans 0.2 to 10 \( \mu \text{m} \)), which we use to robustly separate host and satellite galaxies.

Finally, we use this K-corrected photometry to assign each galaxy one of two color types (red or blue) using the following criteria (Bailin et al. 2008):

\[
\text{red galaxies: } 0.1(g - r) > 0.78 - 0.0325(M_r - 5 \log h + 19) \tag{7}
\]
\[
\text{blue galaxies: } 0.1(g - r) < 0.78 - 0.0325(M_r - 5 \log h + 19) \tag{8}
\]

This effectively separates the so-called red sequence and blue cloud (Fig. 2). These data products allow us to isolate and characterize the populations which give rise to the alignment trends we observe.

3. Group Selection and Alignment Geometry

Before analyzing alignment effects, we must first identify physically-related galaxies. To do so we separate galaxies into groups. We define a fixed-size cylindrical “neighbor volume” of 2400 km/s in height and \( 1 \, h^{-1} \text{Mpc} \) in radius (Fig. 3a) centered on each galaxy, within which we search for companions. Each group consists of one host galaxy (HG) and at least one satellite galaxy (SG).

Initially, any galaxy in our data set is a potential HG. We begin the selection process by eliminating all galaxies whose neighbor volume intersects either an SDSS spectroscopic survey border or the limiting redshift of our sample. For each remaining object, we produce a list of companions (all galaxies within the neighbor volume), eliminating any solitary hosts. Next, using the bolometric luminosity calculated with the LRT code (§2), we eliminate all galaxies which have a more luminous companion within the neighbor volume. The remaining objects comprise our final HG list.

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1 The Low-Resolution Templates of Assef et al. (2008) are a collection of publicly available Fortran routines. See http://www.astronomy.ohio-state.edu/~rjassef/lrt for more information.

2 This division deviates slightly from that presented in Bailin et al. (2008). We use the values from version 1 of their arXiv preprint (Bailin et al. 2007). The differences between the two divisions are minor and do not affect our results.
Our group sample consists of all companions (SGs) within the neighbor volume of all HG list members. In total, we find 291,435 SGs in the vicinity of 101,850 unique HGs. In our implementation, SGs can belong to multiple groups while the HGs cannot.

### 3.1. Alignment Angles

Several distinct alignment trends have been observed to date (see §1). Identifying and quantifying these effects requires more than one angular separation measurement. For each HG-SG pair, we compute a location angle ($\theta$) and radial alignment angle ($\phi$). These quantities characterize the geometries we investigate (see Fig. 3). For simplicity we have adopted the symbols of Faltenbacher et al. (2007). We separately calculate each using isophotal, exponential, and de Vaucouleurs PA values. To exploit inherent symmetries, we reduce all angles to values between $0^\circ$ and $90^\circ$.

We define $\theta$ to be the angle between the HG major axis and the line connecting the centers of host and satellite (i.e., the host-satellite separation vector). This quantity describes the location of a companion galaxy with respect to the major ($\theta = 0^\circ$) or minor ($\theta = 90^\circ$) axis of its host (see Fig. 3). We use this to characterize anisotropy in the satellite galaxy distribution (i.e., the Holmberg Effect).

Calculating $\theta$ accurately requires a robust measurement of the HG PA. To this end, we include only those HGs with $q_{iso} \leq 0.9$ and $q_{mom} \leq 0.9$. This shape requirement eliminates 78,070 galaxy pairs (27%). We also exclude all objects with $\Delta PA > 15^\circ$. By itself, this cut eliminates 90,341 pairs (31%). In combination, the shape and $\Delta PA$ cuts eliminate 43% of our group sample but ensure that the remaining galaxy pairs (166654 SGs around 58259 unique HGs) have usefully high HG PA accuracy and thus reliable $\theta$ measurements. This procedure maximizes the sample size without risking inclusion of spurious PA measurements.

Our second angular separation, $\phi$, is the projected angle between satellite galaxy position angle and the projected host-satellite separation vector (Fig. 3). We use $\phi$ to expose any preferred direction in SG elongation. The orientation extrema are radial ($\phi = 0^\circ$, directly toward the host) and tangential ($\phi = 90^\circ$).

To properly measure $\phi$, we require a robust measurement of SG PA. We thus include only those SGs with $q_{iso} \leq 0.9$ and $q_{mom} \leq 0.9$. Applied to SGs, this shape cut eliminates 66,159 pairs (23%). We also eliminate SGs that lack good agreement between model and isophotal PA (i.e. SG $\Delta PA > 15^\circ$). On its own, this $\Delta PA$ requirement eliminates 85,105 galaxy pairs (29%). Together, these criteria reduce our sample size by 38% (to 180,777 SGs around 77,213 unique HGs) but minimize the inclusion of spurious PA measurements. We
do not apply any shape cuts to HGs in measuring $\phi$.

For each object, we calculate angular separations using spherical trigonometry, adopting the galaxy centers indicated by the SDSS J2000 coordinates. Position uncertainty is negligible for our purposes. SDSS determines centroids (the first moment of light distribution) using an adaptively-smoothed, PSF-length-scaled quartic interpolation algorithm (Pier et al. 2003) which is accurate to within a few tens of milliarcseconds. The greatest sources of uncertainty in calculating $\theta$ and $\phi$ are due to the PA measurements. We follow the shape and $\Delta$PA prescriptions outlined above to minimize the potential impact of ambiguous, uncertain, or contaminated PA determinations on our results.

4. Statistical Sample Properties

Before the cuts on HG ellipticity and position angles, the group sample consists of 291,435 satellite galaxies (SGs) within the cylindrical neighbor volume of 101,850 unique host galaxies (HGs), indicating a mean SG count of 2.86 per system. Nearly half of systems (48,018) are galaxy pairs and 99% of systems contain 20 or fewer SGs. The largest observed group contains 169 satellites (Abell 2197).

In Figure 4 we present spatial, velocity, concentration, and shape distributions of objects in our sample of grouped galaxies. Figure 4a shows the number of SGs within annular bins of projected radial separation ($r^2dN/dr$, where $r$ is the HG-SG projected radial separation and $N$ is the number of SGs per bin). Although this metric does not properly portray the SG spatial density, it serves to illustrate the rapid fall in galaxy counts at small projected separations ($\Delta R \lesssim 150 h^{-1}$ kpc) due to the fiber collision effect. In reality, of course, galaxy density ($dN/dr$) is a steeply dropping function of separation. Satellite density also falls off steeply with increasing velocity separation ($\Delta V$, Fig. 4b).

Figure 4c compares the $fracDeV$ distribution of HGs and SGs in our group sample to that of our entire data set which also includes ungrouped galaxies, i.e. isolated galaxies or galaxies near the survey boundary. Relative to the ungrouped objects, HGs are more likely to have high $fracDeV (> 0.9)$ and slightly less likely to have very low $fracDeV (< 0.1)$. SGs in groups show the opposite trend: there are fewer high $fracDeV (> 0.9)$ galaxies and more low $fracDeV (< 0.1)$ galaxies relative to the ungrouped sample. Neither HGs nor SGs deviate noticeably from the parent population for $0.1 < fracDeV < 0.9$. Lastly, Fig. 4d compares isophotal and moments-based axis ratios of HGs and SGs. We find (in order of increasing ellipticity) that HG $q_{mom} >$ SG $q_{mom} >$ HG $q_{iso} >$ SG $q_{iso}$. We obtain this same order using both mean and median $q_{iso}$ and $q_{mom}$. Using $q_{mom}$ we also find, however, that a larger
fraction of SGs exhibit extreme elongation ($q < 0.2$) than HGs.

5. Results

5.1. Analysis Methods and Significance

To date, most galaxy alignment studies have focused on trend detection rather than characterization. We wish to verify and extend these previous analyses by quantifying the strength of all alignment signals we find. To that end, we employ the following procedure. Within our grouped galaxy catalog, we apply various cuts in different observables (e.g. color, $\Delta V$, $\Delta R$ and $\text{fracDeV}$). The resulting subsamples are binned into histograms to which we apply weighted linear least-squares fits. Fit parameters provide measures of both trend strength (line slope) and significance (slope uncertainty). We then verify our estimates of the significance of the trends we find by comparing to simple analytic estimates. In quantifying the magnitude of alignment effects, we are better equipped to isolate the galaxy populations responsible for these alignments.

Our histogram-based analysis affords several advantages. Firstly, linear fits to binned data are simple to perform and provide very reliable results with our typical subsample sizes. Because of this simple approach, an analytic estimate of the statistical significance of any alignment trend is straightforward to calculate. More importantly, by capturing the shape of the histogram in a single value (the fractional slope), we are able to concisely investigate alignment signal strength in the multidimensional parameter space of galaxy attributes. Fortunately, all of the alignment trends we observe are very well described by a linear trend. Lastly, the histograms we produce are visually similar to, and thus directly comparable to, the results of many previous studies.

For this analysis, we define a galaxy alignment trend as a systematic variation in the linear density of galaxies (the histogram) as a function of either $\theta$, the angular position of SGs relative to the HG major axis, or $\phi$, the orientation of the SG relative to the HG-SG separation vector (§3.1). A flat (zero slope) histogram implies no alignment signal (isotropy) whereas a very steep slope constitutes a strong alignment effect. We use fractional measurements to better compare alignment trends in galaxy subsamples of different sizes.

Our trend-fitting procedure operates as follows. First, we define a subsample of grouped objects with the desired criteria. We then produce a histogram by binning these objects in separation angle. Assuming Poisson errors, each bin $i$, which contains $N_i$ galaxies, has an uncertainty $\sigma_i = \sqrt{N_i}$. Dividing each bin and uncertainty by the bin width yields galaxy line density ($\rho_i$) in each bin. We obtain the best-fit slope ($A$), its uncertainty ($\sigma_A$), and
intercept \((B)\) with a weighted least-squares \((\chi^2\) minimization) fit to these density values. From these values we compute the fractional slope \((A/B)\) and alignment significance \((A/\sigma_A)\). For convenience, we convert these to percent galaxy density change across the angular interval \([0, 90^\circ]\),

\[
\Delta N(\%) = 100\% \cdot (90^\circ A/B) \tag{9}
\]

and its uncertainty,

\[
\sigma_{\Delta N}(\%) = 100\% \cdot (90^\circ \sigma_A/B) \tag{10}
\]

By computing the above values in different galaxy subsets, we can quickly identify where in parameter space a given effect originates and whether or not variations between subsamples are statistically significant.

To find the source of an alignment effect, we observe how alignment strength and significance vary when the parent population is split into subsamples. For each galaxy attribute we investigate (e.g., \(\text{fracDeV}\), color), we divide the group sample into different bins according to that attribute. If a particular subpopulation is responsible for the observed alignment trend, its alignment strength will be diluted by the inclusion of galaxies from other populations. If, in dividing the group sample, we improve our selection accuracy (i.e., we create a subsample wherein a larger fraction of galaxies produce the alignment trend), we observe an increase in alignment strength (steepening of histogram slope). If, however, the resulting subsamples all have similar strength to each other or to the parent population, then the alignment effect does not depend on that particular attribute used to subdivide them. By repeating this procedure we can identify what galaxy subpopulations do and do not exhibit different types of alignment.

In representing individual histograms by a single number (the fractional galaxy density change), we are able to expand our histogram-based analysis to multiple parameters simultaneously. We illustrate this technique in Figure 5. The final result (Fig. 5a) divides the subsample of highly concentrated host and satellite galaxies \((\text{fracDeV} > 0.9)\) into 10 bins of radial separation \((100\ h^{-1}\ kpc\ per\ bin)\). We separately fit the galaxy density histogram and compute the fractional change within each subdivision (Figures 5b1 - 5b10) and plot these findings as a function of radial separation (Fig. 5a). The error bars are in the condensed result panel are the slope uncertainties from the individual histogram fits. Applying this technique for many different subsamples of observable host and satellite galaxy properties (e.g., concentration or color) allows us to identify the more complex parameter dependence of certain alignment trends.

For a given subsample with \(N_{\text{tot}}\) galaxies, the following analytic estimate determines the
expected alignment significance:

\[
\frac{S}{N} \equiv \left( \frac{A}{\sigma_A} \right) = \sqrt{\frac{4}{3} \frac{A \langle \Delta \theta \rangle^2}{\sqrt{\text{N}_{\text{tot}}}}},
\]

where \( \Delta \theta = 45^\circ \) is the half width of the possible range of alignment angles (see Appendix A). We find excellent agreement between this estimate and the significance determined explicitly by our fitting procedure.

We now summarize our results for the major axis preference and hostward elongation. We compare our results with those from the literature in §7.

5.2. Major Axis Preference

The most noticeable anisotropy we find is a satellite galaxy (SG) distribution which favors the host galaxy (HG) projected major axes in projection. For the full group sample we observe a \(-12.4 \pm 0.8\%\) change in galaxy density between major and minor axis at 15\(\sigma\) significance (black line in Figures 6-11). As we will now show, this anisotropy is strongest for red, centrally-concentrated SGs of red, centrally-concentrated HGs. Further, the effect appears to increase in strength and significance with decreasing physical (3-D) separation.

Selecting host-satellite pairs by host fracDeV sheds more light on the origin of this effect (Fig. 6). While our catalog as a whole exhibits this anisotropy at the 15\(\sigma\) level, we find that it arises entirely from systems with HG fracDeV > 0.5. More specifically, the signal is strongest among systems with HG fracDeV > 0.9 which show a \(-23.9 \pm 1.1\%\) SG density change from major to minor axis at 21.2\(\sigma\). Galaxy groups with 0.5 < HG fracDeV < 0.9 show a weaker preference \((-6.8 \pm 1.6\%, \ 4.3\sigma)\). At the same time, our fit to this group shows a 3.6-fold decrease in significance relative to the total galaxy population. We see no significant trend for HG fracDeV < 0.5.

Splitting the group sample by SG fracDeV, we observe a decreased range of alignment strengths (Fig. 7). The two de Vaucouleurs profile-dominated SG subsamples (SG fracDeV > 0.9 and 0.9 > SG fracDeV > 0.5) show enhanced alignment strength \((-17.2 \pm 1.3\% \text{ and } -15.9 \pm 1.8\%\) relative to the total population and are consistent with each other. The two exponential profile-dominated SG subsamples (0.1 < SG fracDeV < 0.5 and SG fracDeV < 0.1) are also consistent with each other (changes of \(-7.1\pm1.8\% \text{ and } -6.2\pm1.7\%, \text{ respectively}) but shallower than the combined group sample.

Breaking the sample down by HG and SG color shows a similar picture. We observe a very strong effect between red HG - red SG pairs \((-26.2 \pm 1.3\%, 19.5\sigma, \text{ Fig. 8})\).
SGs around red HGs show a less significant alignment trend ($-14.3 \pm 1.5\%$, $9.6\sigma$). We find no evidence of anisotropy among either red or blue SGs of blue HGs. These latter two subsamples are consistent with each other ($-1.5 \pm 1.8\%$ and $-2.6 \pm 2.2\%$ decreases) and with isotropy. We deduce that red and centrally-concentrated (i.e. elliptical) HGs and SGs are almost exclusively responsible for the major axis alignment preference.

We observe this major axis preference across a wide range of HG-SG velocity separation (Fig. 9). Although it is most significant for $|\Delta V| < 300$ km/s ($-14.8 \pm 1.0\%$, $14.3\sigma$), we observe an equally strong ($14.8\%$ decrease) trend for $300$ km/s < $|\Delta V| < 600$ km/s albeit at somewhat reduced significance ($8.3\sigma$) due to the smaller subsample size. The subsamples at greater velocity separations ($\Delta V > 600$ km/s) are consistent with each other and with isotropy. We find a similar effect in projected radial separation (Fig. 10). Alignment is strongest ($-20.4 \pm 2.0\%$, $10\sigma$) for the closest SGs ($\Delta R < 250$ h$^{-1}$ kpc) but is still detected at nearly $6\sigma$ to the group size limit of $1$ h$^{-1}$ Mpc. Taken together, these velocity and radial separation trends indicate an increasing spatial anisotropy in favor of projected HG major axis with decreasing 3-D separation.

We also investigate anisotropy as a function of (spectroscopic) galaxy group size (Fig. 11). We find that alignment strength increases steadily with increasing group size. Among SGs from the smallest groups ($1 < N_{SG} < 5; 95186$ objects) we observe a $-9.6 \pm 1.1\%$ galaxy density change towards the minor axis at $9\sigma$ significance. In the largest groups ($N_{SG} > 20; 16122$ objects) we find a $-23.5 \pm 2.4\%$ change ($9.6\sigma$). Interestingly, the latter subsample exhibits the strongest alignment and highest significance despite having the fewest galaxies. From this we deduce that major axis preference exists for all group sizes but is strongest for the largest galaxy groups.

In Figure 12 we explore the interdependence of physical separation and light profile type on the observed alignment trend. We limit velocity separation to $|\Delta V| < 500$ km/s and explore the dependence of alignment strength on projected radial separation ($\Delta R$). We find that when both HG and SG have high fracDeV (especially $fracDeV > 0.9$, top-right panel), the anisotropy strength (fractional slope) increases with decreasing $\Delta R$. We conclude that the dependence of anisotropy on physical separation occurs largely among the same red, centrally-concentrated galaxy pairs described above. We further discuss the significance of these results in §7.1.
5.3. Hostward Elongation

We find that satellites tend to elongate towards their host galaxies. For the full group sample, we observe a $-5.7 \pm 0.8\%$ change (at $7\sigma$) between the frequency of satellites that exhibit perfect radial (hostward) alignment relative to those that exhibit tangential alignment (black histogram in Figures 13-18). Of the galaxy properties we examined, the degree of alignment is most strongly dependent on SG $\frac{DeV}{V}$ (concentration, Fig. 13). SGs with $\frac{DeV}{V} > 0.9$ (52,817 objects, 29% of sample) exhibit a $-13.9 \pm 1.4\%$ density change favoring direct hostward alignment at $9.9\sigma$. None of the other SG $\frac{DeV}{V}$ subsamples exhibit significant alignment.

We present hostward elongation ($\phi$) for different HG profile types in Figure 14. Satellites of high-$\frac{DeV}{V}$ HGs (HG $\frac{DeV}{V} > 0.9$, 94,716 objects, 52% of sample) show a $-5.8 \pm 1.1\%$ change in density at $5.3\sigma$. Satellites of HGs with $0.5 < \frac{DeV}{V} < 0.9$ show only a marginal ($3.9\sigma$) $-6.2 \pm 1.6\%$ change. The slopes of the trends seen in all four bins are statistically consistent with the total group sample, suggesting that hostward elongation is largely independent of HG $\frac{DeV}{V}$.

Galaxy colors (Fig. 15) have some effect on alignment strength. Red SGs around red HGs (56,421 objects, 31% of sample) show a $-9.8 \pm 1.4\%$ density change at $7\sigma$. Red SGs around blue HGs exhibit a slightly steeper trend of $-11.3 \pm 1.9\%$ at somewhat lower significance ($5.8\sigma$). These two subsamples are statistically consistent, providing further evidence that hostward elongation is principally dependent on SG properties. We do not observe a statistically significant alignment trend among blue SGs of either blue or red HGs.

There is no evidence that the degree of hostward elongation depends on velocity separation (see Fig. 16). All four subsamples are essentially statistically consistent with the full group sample. In projected radial separation (Fig. 17), we find marginal ($5\sigma$) evidence for hostward elongation in both the largest $\Delta R$ and smallest $\Delta R$ bins. At large separation ($750 \, h^{-1} \text{kpc} < \Delta R < 1 \, h^{-1} \text{Mpc}$) we find a $-7.2 \pm 1.4\%$ density change at $5.3\sigma$. In the innermost radius bin ($\Delta R < 250 \, h^{-1} \text{kpc}$), we find a $-9.7 \pm 1.9\%$ density change at $5.1\sigma$. These results suggest that 3-D physical separation plays a minimal role in the degree of hostward elongation.

Lastly, we examine the influence of group size on hostward elongation (Fig. 18). All four group size subsamples are consistent with the whole group sample, suggesting that hostward elongation is independent of group size.
6. Caveats and Complications

6.1. Discrepant Position Angles

Our greatest cause for concern is the accuracy of measured galaxy position angles (PAs). During our analysis, we identified systematic PA discrepancies between model- and isophote-based position angles (PA_{deV} and PA_{iso}) that critically affect our results. Some of these differences, primarily those due to isophotal twisting, are physically genuine. However, in many cases, isophotal contamination by artifacts and nearby objects appears to be the culprit. We suspect that these variations may be largely responsible for the general disagreement between many of the results on hostward elongation presented in the literature. We detail our findings in the remainder of this section.

To investigate this PA discrepancy, we compare alignment signals of identical galaxies using PA_{iso} and PA_{deV}. In order to illustrate the discrepancy, we do not enforce agreement between the two measured PA values. We do, however, continue to require that ∆R > 4r_p. We first examine location angle (θ) which requires accurate host galaxy (HG) PA. Comparing our PA_{iso}- and PA_{deV}-based results (Fig. 20), we observe few significant differences.

The situation changes dramatically for the hostward elongation case (Fig. 21). Isophotal and model PAs produce markedly different results in high fracDeV SGs (rightmost column), particularly those of high fracDeV HGs (fracDeV > 0.9, top-right panel). The strong (and high-significance) hostward alignment we see with PA_{iso} at small projected radii (∆R < 100 h^{-1} kpc) is absent from PA_{deV}-based measurements of the same satellite galaxies. Figure 22 compares side-by-side the individual histograms of this highly discrepant subsample before and after applying the ∆PA < 15° criterion. After rejecting SGs with ∆PA > 15° (30% of objects), both the alignment trend and discrepancy are significantly reduced. These results indicate that the apparent degree of hostward elongation is quite sensitive to PA selection. How best to deal with this depends on the cause of the discrepancy, which we now investigate.

Neither PA measure is perfect. The galaxy models (exponential and de Vaucouleurs) are fitted to each galaxy across a range of radius. These fits account for seeing effects (§2) and may interpolate across artifacts and substructures as necessary, which reduces the potential for errors due to contamination. There are, however, several known yet unsolved problems within the model-fitting routine. Most importantly, the galaxy model PA distribution is significantly enhanced between 60° and 145° (nearly East-West in orientation) rather than uniformly distributed in angle (Fig. 23). In addition, the derived galaxy scale radii (and thus the derived axis ratios) exhibit some discretization (Adelman-McCarthy et al. 2008). Isophotal PAs, by contrast, are determined by a best-fit ellipse to 25 mag / sq. arcsec surface brightness around each galaxy. Unlike the matched galaxy models, the isophotal ellipse fit
is sensitive to a narrow and faint surface brightness region of each galaxy. As such, the
isophotal ellipses (and thus their measured PAs) are more susceptible to contamination by
nearby objects and image artifacts.

To explore the cause of these discrepant PA measurements in individual systems, we
obtained SDSS images of all high-fracDeV (fracDeV > 0.9) SGs hosted by high-fracDeV
HGs with discrepant hostward elongation signals. We visually compared the SDSS-reported
isophotal ellipses and de Vaucouleurs PAs and scale radii with the galaxy images. We
found that the great majority of discrepant PAs could be attributed to two causes: intrin-
sic variations in the PAs of isophotes with radius (∼ 70%) and PA misestimation due to
contamination (∼ 30%). Contamination was caused (in roughly equal numbers) either by a
nearby bright object or by a bright knot somewhere within the galaxy.

Figure 24 shows an example of an isolated galaxy for which the model and isophotal
PA differ by nearly 90° due to intrinsic isophotal twisting. Generally, the de Vaucouleurs
and exponential galaxy profiles fit to the brighter galaxy interior while the 25 magnitudes
/ arcsec² isophote traces the outer edge of each galaxy. This is particularly noticeable
in this example, where the de Vaucouleurs model fits primarily the central bar or bulge
region, while the isophotal ellipse traces the outer edge of the spiral arms. In this fashion,
isophotal twisting can lead to highly discrepant PA measurements. Given that the physical
mechanisms which give rise to galaxy alignments are not well understood, it is not clear
which PA determination is most relevant. This motivated our decision to exclude all galaxies
with highly discrepant (∆PA > 15°) isophotal and de Vaucouleurs PAs from this analysis.
Further study is required before these interesting objects can be properly incorporated into
an alignment analysis.

Figure 25 shows illustrative examples of isophotal contamination. In a number of cases,
failure to separate the light from other objects results in an isophotal PA which does not
physically reflect the system in question. Although not as prevalent as isophotal twisting,
such cases are responsible for a significant fraction of discrepant PA measurements.

Importantly, we note that we do not expect random (i.e., isotropic) PA contamination
for galaxies in groups and clusters. In such environments, galaxy spatial density is a rapidly
declining function of separation from the center (∆R). As a result, a given group or cluster
member is most likely to have an optical companion radially interior to its location. We thus
expect that isophotal contamination due to chance juxtaposition of galaxies will preferentially
skew isophotal PA in the radial (hostward) direction. The degree to which this occurs will
depend strongly on the how rapidly galaxy number density falls off with increasing separation
from the cluster center.
From this investigation we conclude that care is required to ensure that only accurate PA measurements are included in alignment analysis. This is particularly important for contamination cases where the best-fit isophotal ellipse is highly elongated, giving the illusion of high accuracy. Elimination of discrepant cases has a profound effect on the measured hostward alignment signal. We believe the use of different PA measurements may be responsible for several conflicting previous results (see discussion in §7.2).

6.2. Spectroscopic Survey Limitations

In some cases, the limitations of the SDSS spectroscopic sample restrict our ability to properly characterize alignment. Fiber collisions make it difficult to observe galaxies with small projected separations. On SDSS plates, the spectroscopic fibers (3” each) can be set no closer than 55” apart. Although this limit is mitigated somewhat by plate tiling, many of the closest neighbors in projection will be absent. In addition, the finite (640) number of fibers allowed per plate ultimately limits the fraction of galaxies that can be observed in dense fields. As a result, the completeness of a galaxy group generally decreases with increasing group size. The inability to fully sample the innermost regions of groups and clusters could systematically affect the measured alignment signal. Of importance to our exploration of the Holmberg Effect in the SDSS spectroscopic sample, some bright nearby neighbors may be absent because of these effects. If such omissions were common, we would incorrectly identify many objects as isolated galaxies. Whether or not the robust elimination of interlopers afforded by spectroscopic redshifts outweighs the potential statistical benefits of the larger photometric sample for detecting alignment trends is a difficult question which we do not attempt to answer here. It is likely, however, that exclusive use of galaxies from the spectroscopic sample will not provide the most accurate picture of galaxy alignment at separations approaching the fiber collision limit.

The magnitude limit of the spectroscopic survey may also affect our results. It was observed in early cluster studies (see Sastry 1968, Noonan 1972, Austin & Peach 1974) that the apparent shape of a cluster (isopleths) may vary as a function of the galaxy flux limit, so that the distribution of the brightest members may not be representative of the overall population. A similar effect due to either the spectroscopic magnitude limit or fiber collisions is possible with these data.

The survey magnitude limit also likely hinders our ability to properly reproduce the original selection criteria of Holmberg (1969) and robustly assess the existence of the Holmberg Effect. Holmberg (1969) mandated a host-satellite mass ratio of at least 25 (corresponding to a flux ratio of roughly 3.5 magnitudes). With the limiting SDSS survey magnitude of
17.77, only host galaxies of \( r <\lesssim 14 \) are bright enough to have spectroscopically-identified “Holmberg-like” companions. Of the 572,495 galaxies in our dataset, only 2,775 are this bright. We find only 1178 such HGs in our group catalog.

To make matters worse, scattered light in the SDSS telescope increases sky brightness around bright galaxies (Adelman-McCarthy et al. 2008). This effect is believed to conceal fainter nearby galaxies, resulting in an observed dearth of faint galaxies near bright galaxies (Adelman-McCarthy et al. 2008). Several recent studies of weak lensing and SG anisotropy mask objects at very close separations to avoid these potential selection biases (for example, objects in the innermost 30 \( h^{-1} \) kpc and 35 \( h^{-1} \) kpc are excluded in Mandelbaum et al. 2005 and Bailin et al. 2007, respectively). In particular, this seriously complicates application of isolation criteria.

6.3. Isolation

Well-selected isolation criteria are of equal importance to major axis preference and to hostward elongation, both of which have now been observed to varying degrees in multiple independent investigations. Several of these studies (e.g., Brainerd 2005; Agustsson & Brainerd 2006; Yang et al. 2006) employ aggressive selection criteria in order to extract a sample of isolated objects. Among these isolated galaxy systems, they observe strong SG distribution anisotropy favoring the HG major axis. The aforementioned studies additionally report near-perfect SG isotropy around blue hosts (i.e., no sign of the Holmberg Effect).

Recently, Bailin et al. (2008) performed a systematic evaluation of the various selection criteria used in recent alignment studies. They conclude, based on examination of mock catalogs and simulations, that most previous efforts to select only isolated galaxy systems were ineffective. Objects people believed were truly isolated systems were statistically shown to include many group and cluster members. In reality, the SDSS spectroscopic survey alone does not, in general, include all potential neighbor galaxies, which makes application of isolation criteria very difficult. Based on our satellite anisotropy results (§5.2) and the HG and SG properties most closely associated with the alignment signal, we conclude that the alignment signal is largely due to the contribution of group and cluster members despite the ostensibly isolated nature of our group samples.
7. Previous Detections and Comparisons

7.1. Satellite Galaxy Anisotropy

The tendency for satellite galaxies to have anisotropic distributions favoring the major axis of their host galaxies has been observed by many authors using SDSS data (Brainerd 2005; Yang et al. 2006; Azzaro et al. 2007; Faltenbacher et al. 2007; Bailin et al. 2008). The enhancements of this signal among red HG-SG pairs (Yang et al. 2006; Azzaro et al. 2007; Bailin et al. 2008) and with decreasing radial separation (Yang et al. 2006) have been independently observed. Our results are consistent with these other recent findings in both in strength and nature with these other recent findings.

We build on these results by demonstrating the monotonic dependence of major axis preference on HG and SG light profile concentration, physical separation (both $\Delta V$ and $\Delta R$) and group size. In §5.2 we show that red, highly concentrated SGs of red, highly concentrated HGs preferentially reside near the projected major axis of their hosts. We also show that this effect increases in strength with decreasing physical separation. Lastly, but equally importantly, we observe that the alignment strength increases with increasing group size.

Galaxy clusters are known to produce a similar effect. Many past investigations have discovered elongated galaxy cluster isopleths which align strongly with the major axis of the brightest cluster galaxy (BCG) (e.g. Carter & Metcalfe 1980; Binggeli 1982). Indeed, BCG - cluster alignment is sufficiently strong that the BCG PA can be used as a proxy for the PA of the cluster galaxy distribution.

As would be expected in cluster environments, the galaxies which give rise to our measured anisotropy are mainly red, highly concentrated ellipticals. In the literature we find good agreement between our alignment findings and those from deep campaigns of individual galaxy clusters (e.g., the histograms of Carter & Metcalfe 1980 and Binggeli 1982). This further supports our suspicion that group and cluster members produce the majority, if not all, of the observed anisotropy signal.

7.2. Hostward Elongation

We observe hostward elongation in our SG sample (§5.3) at the few percent level (measured in fractional galaxy density change), in fair agreement with numerous previous studies. We find that the alignment signal is strongest among high fracDeV ($\text{fracDeV} > 0.9$) SGs irrespective of host type. We also observe an enhancement among red SGs (independent
of HG color). Most importantly, we report a connection between the type of PA used and the apparent alignment strength which may explain the variation among several previous results.

For some time, authors have suspected that intrinsic galaxy alignment effects may act as a contaminant in weak lensing surveys. Croft & Metzler (2000), Lee & Pen (2001) predicted that intrinsic alignments would dominate the weak lensing signal for spiral galaxies in SDSS. Bernstein & Norberg (2002) found no significant tangential elongation in a study of 1819 galaxies from the 2dFGRS, limiting the contamination to \( \sim 20\% \). Hirata et al. (2004) found no evidence for intrinsic alignment of satellite galaxies measured with the adaptive moments technique. Bernstein & Jarvis (2002), Mandelbaum et al. (2005) also concluded that contamination due to intrinsic galaxy alignment is minimal.

Using our entire SG sample, we find that the frequency of SGs oriented radially towards their hosts is 6% greater than that of SGs oriented perpendicular to their hosts (§5.3). This anisotropy is strongest among high-\( \frac{\text{fracDeV}}{h^{-1}} \)SGs, for which the fractional change steepens to \(-14\%\). These findings are generally consistent with those mentioned above. On the other hand, Pereira & Kuhn (2005) report a much stronger radial alignment in SDSS data with a sample of 85 X-ray selected clusters. They observe a \(-25.5\%\) change at 4\( \sigma \) significance. Agustsson & Brainerd (2006) also find a much stronger radial elongation effect. They find that SGs located at small projected separation (\( \Delta R < 100 h^{-1} \text{ kpc} \)) from relatively isolated hosts exhibit a \(-20\%\) density change between radial and tangential orientation. Faltenbacher et al. (2007) reports a similarly strong effect for red satellites at low projected separation.

The last three studies, mentioned above, relied exclusively on isophotal PA measurements, which, we believe, are suspect. We demonstrated the impact of PA type (isophotal or model-based) on the measured hostward elongation signal in §6.1. By varying our PA selection, we can recover results from a wide range of recent investigations. We conclude specifically that relying solely on SDSS isophotal PA produces a stronger radial (hostward) elongation signal than does the exclusive use of matched models or adaptive moments. We present our interpretations and further discussion in §9.

8. In Search of the Holmberg Effect

Holmberg (1969) observed that the distribution of nearby (projected radial separation < 40 \( h^{-1} \) kpc) satellite galaxies (SGs) around inclined, isolated spiral host galaxies (HGs) was heavily concentrated near the HG projected minor axis. In fact, after statistically
subtracting the expected isotropically-distributed field galaxies, Holmberg found effectively no SGs within $30^\circ$ of the projected HG major axis ($\theta < 30^\circ$). Since the host galaxies were inclined spirals, this suggested that SGs of such hosts have primarily polar orbits.

Holmberg (1969) selected isolated systems for several reasons. First, such systems are dynamically simple in comparison to larger groups. In addition, stringent isolation criteria could be used to decrease the frequency of interlopers in the SG sample. To evaluate a galaxy’s degree of isolation, Holmberg (1969) first defined a circular survey region of $40\, h^{-1}$ kpc projected radius around each HG. Next, he estimated the (stellar) mass of each HG and SG companion from luminosity and morphological type. Isolation required that all SGs within twice the survey radius ($80\, h^{-1}$ kpc) have less than $1/5$ the mass of the HG and all SGs within the survey radius ($40\, h^{-1}$ kpc) have less than $1/25$ the HG mass. Systems which passed those criteria and were sufficiently inclined ($q \leq 0.53$) were included in the analysis.

In practice, exactly replicating these conditions using the SDSS spectroscopic galaxy sample is essentially impossible, primarily because of spatial sampling constraints (i.e., “fiber collisions,” see §6.2). Insufficient spatial sampling causes multiple problems. Firstly, the very small typical separations of Holmberg’s original SG sample ($40\, h^{-1}$ kpc is roughly $4 \times$ the HG semi-major axis length) greatly intensifies the incompleteness of the sample due to the fiber collision effect. After removing likely blends and misidentifications (SGs with $\Delta R < r_p$ or $\Delta R < \text{iso}R$) we find only 132 SGs around 130 inclined ($q_{\text{iso}} < 0.53$ and $q_{\text{mom}} < 0.53$) HGs in our original group sample (i.e. without any isolation criteria applied) with $\Delta R < 40\, h^{-1}$ kpc. Without the ability to identify all nearby galaxies of comparable size and brightness, it is impossible to properly apply Holmberg’s isolation criteria to our galaxy sample.

8.1. An Isolated Sample

We first attempt to apply Holmberg’s selection criterion (approximately) to our group sample in order to demonstrate the difficulties with reproducing his analysis precisely with the SDSS spectroscopic sample. Unable to exactly reproduce his galaxy mass estimates, we apply the same cuts using bolometric luminosity (calculated with the LRT codes). The modified group selection procedure incorporates the following criteria:

$$ (L_{\text{bol}})_{\text{HG}} \geq 25 \left( L_{\text{bol}} \right)_{\text{SG}} \text{ for } \Delta R \leq 40\, h^{-1} \text{ kpc} \quad (12) $$

$$ (L_{\text{bol}})_{\text{HG}} \geq 5 \left( L_{\text{bol}} \right)_{\text{SG}} \text{ for } \Delta R \leq 80\, h^{-1} \text{ kpc}. \quad (13) $$

All hosts which fail these tests are removed from the HG list. The remaining groups comprise our ‘isolated’ sample. We identify inclined HGs by axis ratio, requiring that $q_{\text{mom}} < 0.53$ and
Unfortunately, this procedure yields only 2 SGs of 2 HGs within the neighbor volume employed by Holmberg (1969).

### 8.2. More Distant Companions: a Marginal Effect

Unable to replicate the analysis of Holmberg (1969) with SDSS spectroscopic data, we instead proceed with an examination of more distant SG companions. We select SGs of inclined isolated systems as above but relax the radial separation constraint, including SGs as distant as $500 \, h^{-1} \text{kpc}$. In the spirit of selecting relatively isolated HGs, we exclude SGs from systems with more than 25 detected satellites within $1 \, h^{-1} \text{Mpc}$. From among these, we select the SGs with $15 \times \text{SG} \, L_{\text{bol}} < \text{HG} \, L_{\text{bol}}$ and $\text{SG} \, \text{fracDe} \, V < 0.10$. These last few criteria specifically pick out smaller SGs while avoiding clusters and big groups.

Applying the above criteria, we observe a preference for the minor axis among the remaining SGs (Fig. 19). Among SGs with $\Delta R < 500 \, h^{-1} \text{kpc}$ and $\Delta V < 500 \, \text{km/s}$ (51 galaxies), we find few galaxies (4 galaxies per 15° bin) near the HG major axis ($\theta < 30^\circ$). The density increases to 9 galaxies per bin for $30^\circ < \theta < 60^\circ$ and to 12 and 13 galaxies per bin for $60^\circ < \theta < 75^\circ$ and $75^\circ < \theta < 90^\circ$, respectively. This roughly 3-fold increase indicates anisotropy at $3\sigma$ significance. For SGs with $\Delta R < 300 \, h^{-1} \text{kpc}$ and $\Delta V < 300 \, \text{km/s}$ (27 galaxies), we find a low, constant galaxy density (2 galaxies per 15° bin) for $\theta < 45^\circ$. For $\theta > 45^\circ$, we find that galaxy density rises steeply, such that galaxies with $75^\circ < \theta < 90^\circ$ are 4.5 times as numerous (9 galaxies) as those with $\theta < 45^\circ$. For the latter case, although the fractional slope is quite large, the dwindling galaxy counts ultimately reduce the significance of the deviation from isotropy to approximately $2.5\sigma$. Keep in mind that rather than including all of the satellites in the galaxy systems, we have selectively included and excluded SGs with different properties to obtain this behavior. We caution that that our results depend quite sensitively on the specific selection criteria we use. With so few objects, further subdivision is not practical.

In summary, we observe that a subset of SGs with certain properties favor the HG minor axis within $500 \, h^{-1} \text{kpc}$ projected radius at marginal significance. The strength of this trend may increase with decreasing $\Delta R$, but the accompanying decrease in the total number of SGs decreases the significance of this result. Whether or not this apparent anisotropy and preference for the HG minor axis is due entirely to selection effects remains to be seen.
8.3. Difficulties and Discussion

Although we observe a trend that resembles the Holmberg Effect, we are unable to confirm or refute the findings of Holmberg (1969) in the present work. Holmberg (1969) enforced isolation criteria using a mass cut. In practice, his mass determination is difficult to reproduce. As a substitute, we impose the same cuts in bolometric luminosity ($L_{bol}$ computed with LRT). We also use SDSS fracDeV and K-corrected galaxy colors in lieu of confirmed morphological type.

A more important difference is the spatial extent of satellite survey regions. The Holmberg (1969) sample is restricted to faint nearby (typically within 4 galaxy radii) companions. Very few such galaxies even exist in the SDSS spectroscopic sample (only find 2 after imposing criteria of Holmberg 1969). At close separations, Holmberg (1969) requires a host-satellite mass ratio of at least 25. In practice, many such galaxies will be near the magnitude limit of the spectroscopic survey. Those that are sufficiently bright may be undersampled because of fiber collisions (see §6.2).

Zaritsky et al. (1997b) detect a Homberg-like SG anisotropy using their own independent sample (Zaritsky et al. 1997a) at larger radii ($\geq 200$ kpc). They find inconsistency with isotropy at the 99% confidence level, reporting that 72 of their 115 SGs (63%) reside at $\theta > 45^\circ$. This corresponds to a 217% fractional increase in the number of SGs aligned with the minor axis relative to the major axis, assuming the underlying distribution is linear in $\theta$.

We find an alignment signal resembling that of Holmberg (1969), albeit at larger projected separations. In magnitude and radial extent, our results are generally consistent with those of Zaritsky et al. (1997b), although at marginal significance. We further caution that our findings are highly sensitive to selection criteria and may be the result of selection effects.

9. Discussion and Conclusions

We conclusively observe an anisotropy in the distribution of satellite galaxies (SGs) in systems with red, highly concentrated (chiefly elliptical) host galaxies (HGs). Within these systems, the alignment trend strength is further enhanced by nearly a factor of two for red, high-concentration SGs (also mainly ellipticals). We find conclusive evidence of increasing alignment strength with decreasing physical separation (both in projected radius $\Delta R$ and velocity separation $\Delta V$), noting that the fractional anisotropy among the closest satellites ($\Delta R < 250 h^{-1}$ kpc) is 40% greater than that seen among more distant ($500 h^{-1}$ kpc < $\Delta R < 1000 h^{-1}$ kpc) companions. In addition, the strength of the alignment trend increases with
spectroscopically-identified group size (see §5.2).

Although these results agree well with several other recent studies (see §7.1), we offer a slightly different interpretation. Based on the nature of the galaxies which give rise to this effect, we suspect that members of large groups and clusters contribute significantly to, or even dominate, this alignment trend. The well-known alignment of the members of galaxy clusters with the orientation of the brightest member has a comparable magnitude and sign. A recent thorough inspection of popular selection criteria (Bailin et al. 2008) determined that extremely stringent criteria are required to generate a sample of truly isolated hosts and satellites. They find that with less stringent criteria, group and cluster members will be ubiquitous in ostensibly isolated SDSS galaxy samples.

The cluster origin offers a natural explanation for this alignment effect. Cluster shape is defined by the spatial distribution of member galaxies. These members form in the high-density filaments, creating an anisotropy in the distribution of satellites during the formation process. Although dynamical processes may alter the distribution somewhat as time passes, numerical work indicates that the cluster shape will retain the memory of the initial member galaxy distribution (see e.g., Knebe et al. 2004 and Libeskind et al. 2005). The brightest cluster galaxies (BCGs) could acquire their alignment with this anisotropic distribution of member satellites through tidal forces exerted by the large-scale structure during their formation. Alternatively, mergers and accretion events drawing from the already-anisotropic SG distribution could create this alignment. See Bailin et al. (2008) for further details and discussion of this scenario.

We also find significant evidence of hostward elongation among satellite galaxies (SGs). Although this effect has been observed before, we are able to reconcile many previously conflicting results. Among the attributes we investigate, hostward elongation depends most strongly on SG concentration and color. We find effectively no significant direct dependence on HG properties. Ultimately we conclude that the hostward elongation is real, but not nearly as strong an effect as the major axis anisotropy mentioned above.

More importantly, we find that the detection of hostward elongation is a strong function of the method used to measure and define position angle of the galaxy. We find that, at low projected separation ($\Delta R < 100 h^{-1} \text{kpc}$), the radial alignment signal calculated with isophotal PA sharply increases in strength. We observe no such increase among the same galaxies using de Vaucouleurs PA. We further find that excluding objects whose PA measurements differ by more than 15° eliminates this discrepancy. This explains why some authors (e.g., Pereira & Kuhn 2005, Agustsson & Brainerd 2006, & Faltenbacher et al. 2007), who relied solely on isophotal PA for galaxy orientation, observed a stronger radial alignment effect than those who used galaxy moments (e.g., Bernstein & Norberg 2002, Hirata et al.
Given that PA determination plays such a crucial role in galaxy alignment studies, we stress the prevalence of these discrepant PAs and their significant potential impact.

At the same time, this observed discrepancy raises new questions. Host galaxies (HGs) in our group sample appear immune to this phenomenon (§6.1). The rate at which SGs are affected by this appears to increase dramatically at small projected separations from the HG. Observing the anomalous objects by eye, we find that most exhibit strong isophotal twisting (e.g. barred spiral galaxies), although there is a significant (nearly 1/3) contribution from isophotal contamination. As outlined previously, isophotal contamination may induce a radial alignment bias if spatial galaxy density is a decreasing function of projected separation.

For cases of severe isophotal twisting, position angle is an ill-defined quantity. Since the mechanisms of galaxy production and alignment within their haloes is still highly uncertain, it is not clear how to best incorporate galaxies with extreme isophotal twisting into an alignment investigation such as this. For the same reason, we are unsure how to interpret a radial elongation tendency. Some numerical simulations (e.g. Faltenbacher et al. 2008) show a strong tidally-induced radial alignment effect in dark matter haloes. Whether or not such orientations would also apply to the luminous regions of galaxies within these haloes is unclear.

Regardless of the cause, measuring the intrinsic radial elongation signal of galaxy systems is an important step in the application of weak lensing to precision cosmology. In general agreement with other authors (e.g. Bernstein & Norberg 2002; Mandelbaum et al. 2005), we believe that a radial elongation signal with the magnitude we have found in SDSS spectroscopic galaxy sample will minimally influence galaxy-galaxy lensing at the levels of precision currently required. Further investigation, however, will be required to determine whether or not this hostward elongation is observed among fainter galaxy populations (i.e., in the SDSS photometric galaxy sample).

A third alignment trend, the Holmberg Effect, remains improperly tested. The magnitude and spatial sampling limitations of the SDSS spectroscopic survey combined with systematic effects in the vicinity of bright galaxies effectively preclude implementation of Holmberg’s original selection criteria. Instead, we explore the distribution of SGs at larger projected separation. We find that, although the whole SG population around inclined, isolated spirals shows no detectable anisotropy, specific SG subsets do. SGs from smaller systems ($N_{SG} < 25$) with $fracDeV < 0.15$ and $L_{bol} < 1/15$ that of their host overwhelmingly prefer the HG minor axis, albeit at marginal ($3.4\sigma$) significance owing to the relatively small number of objects that satisfy these criteria.
Through improved convergence of independent observational results, we have uncovered and characterized several different galaxy alignment trends. However, further refinement is required before high-accuracy alignment prescriptions are available for weak lensing and simulations of galaxy formation and evolution. Importantly, much of this remaining work pertains to identification and removal of systematic effects such as position angle uncertainty that currently prevent a more thorough understanding of intrinsic galaxy alignment effects.

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A. Expected Signal-to-Noise

Here we derive the expected signal-to-noise ratio (S/N) of a trend detection using our histogram-fitting method (§5.1). Here S/N is the square root of the $\Delta \chi^2$ improvement of a weighted linear least-squares fit relative to a constant value (mean). Larger $\Delta \chi^2$ values constitute stronger evidence for anisotropy. We define:

$$S/N = \sqrt{|\Delta \chi^2|}. \quad (A1)$$

In our linear model, the histogram has $n_b$ bins in the angle $\theta$. Each bin $i$ contains

$$N_i = A \theta_i d\theta + \bar{N} \quad (A2)$$
galaxies, where $\bar{N} = N_{tot}/n_b$ is the mean number of galaxies per bin, $d\theta$ is the bin width, $N_{tot} = \sum_{i=1}^{n_b} N_i$ is the total number of galaxies in the sample, and $A$ is the best-fit slope of a linear fit to the histogram bins. The constant model assumes that $N_i = \bar{N}$.

The improvement of a linear least-squares fit over the constant value is the squared difference between the two models divided by the individual bin counts, summed over all histogram bins. The $\bar{N}$ terms in the linear and constant models cancel, leaving:

$$\Delta \chi^2 = \sum_{i=1}^{n_b} \frac{(A \theta_i d\theta)^2}{N_i}. \quad (A3)$$

To simplify the calculation, we assume that the $N_i$ are roughly equal and that $N_i \approx \bar{N}$. Removing bin-independent terms from the summation, we have:

$$\Delta \chi^2 = \frac{A^2}{\bar{N}} d\theta \sum_{i=1}^{n_b} \theta_i^2 d\theta. \quad (A4)$$

To simplify the calculation, we define $\Delta \theta$ to be half the histogram width ($\Delta \theta = 45^\circ$ in this case). We can relate this to bin width ($d\theta$) by noting that $2\Delta \theta = n_b d\theta$. Substituting this outside the summation, we have:

$$\Delta \chi^2 = \frac{A^2}{\bar{N}} \frac{2\Delta \theta}{n_b} \sum_{i=1}^{n_b} \theta^2 d\theta. \quad (A5)$$

We convert this to an integral in the limit $n_b \to \infty$, leaving

$$\Delta \chi^2 = \frac{A^2}{\bar{N}} \frac{2\Delta \theta}{n_b} \int_{-\Delta \theta}^{\Delta \theta} \theta^2 d\theta = \frac{A^2}{\bar{N}} \frac{2\Delta \theta}{n_b} \frac{2}{3} \Delta \theta^3 = \frac{A^2}{\bar{N}} \frac{4\Delta \theta^4}{3n_b} = \frac{4A^2\Delta \theta^4}{3N_{tot}}. \quad (A6)$$

Finally we have,

$$\frac{S}{\bar{N}} = \sqrt{\Delta \chi^2} = \sqrt{\frac{4}{3} \frac{A\Delta \theta^2}{\sqrt{N_{tot}}}}. \quad (A7)$$
Fig. 1.— Characteristics of SDSS galaxy parameter $fracDeV$. Panel (a) shows the $fracDeV$ distribution of red and blue galaxies separately as fractions of the total sample (572495 objects total). The red and blue curves represent red and blue galaxies, respectively. The green curve is the total of all galaxies. All galaxies in the initial sample are represented. Panel (b) presents the full range of values for inverse concentration ($R_{50}/R_{90}$). Different values of $fracDeV$ are isolated to illustrate the distinct groups that form the overall curve. The sharp cutoff towards low inverse concentration is partially caused by the effects of seeing. Panel (c) shows the strong correlation between $fracDeV$ and inverse concentration among galaxies of $0 \leq fracDeV \leq 1$. 
Fig. 2.— Galaxy sample color properties. We adopt the locus $0.1(g - r) = 0.78 - 0.0325(M_r - 5 \log h + 19)$ of Bailin et al. (2007) (shown in red) as the color division between blue cloud and red sequence galaxies. Panel (a): all galaxies in our sample (panels b, c, & d combined). Panel (b): pure de Vaucouleurs galaxies ($fracDeV = 1$). Panel (c): pure exponential galaxies ($fracDeV = 0$). Panel (d): combined-profile objects ($0 < fracDeV < 1$). The gray scale is normalized separately in each panel.
Fig. 3.— Left: Neighbor volume cylinder diagram. Satellite galaxies have $\Delta R < 1\ h^{-1}\text{Mpc}$ and $\Delta V < 1200\text{ km/s}$ relative to their host galaxies. Right: schematic diagram illustrating the angles $\theta$ and $\phi$ we use to characterize the relative positions and orientations of host and satellite galaxies. The angle $\theta$, also called location angle, measures the angular position of a satellite galaxy relative to the direction of the host galaxy major axis. $\phi$ measures the orientation of the satellite major axis relative to “hostward” (radial).
Fig. 4.— Properties of the galaxy group sample. Panel (a): satellite galaxy (SG) counts as a function of projected radius ($\Delta R$). Panel (b): SG density as a function of velocity separation ($\Delta V$). Panel (c): host galaxy (HG) and SG fracDeV relative to the ungrouped data set. Panel (d): isophotal and moments axis ratios ($q_{iso}$, $q_{mom}$) for both HG and SG populations.
Fig. 5.— Illustration of our histogram condensation analysis technique. The original subsample, consisting of hosts and satellites with high concentration \( \text{frac}DeV > 0.9 \), is further subdivided into 10 bins of radial host-satellite separation \( (100 \, h^{-1} \text{kpc} \text{ per bin, panels b1-b10}). \) We fit a linear model to this histogram within each subdivision and compute the fractional change and its uncertainty. These fractional changes are then reproduced in the panel (a) as a function of radial separation. The error bars are the slope uncertainties from the fitting procedure.
Host Major Axis Preference: host galaxy concentration

| HG fracDeV   | N_{gals} | ΔN [0:90] | σ_{ΔN} | |A|/σ_{A} |
|--------------|----------|-----------|---------|---------|
| Total        | 162954   | -12.4%    | ± 0.8%  | 15.36   |
| HG fracDeV > 0.9 | 73395    | -23.9%    | ± 1.1%  | 21.16   |
| 0.5 < HG fracDeV < 0.9 | 44319    | -6.8%     | ± 1.6%  | 4.26    |
| 0.1 < HG fracDeV < 0.5 | 27722    | 3.0%      | ± 2.1%  | 1.44    |
| HG fracDeV < 0.1 | 17518    | 4.8%      | ± 2.7%  | 1.80    |

Fig. 6.— Satellite location angle (θ) for different subsamples of host galaxy fracDeV with 1σ Poisson error bars. The upper panel provides the following subsample-specific data: the number of galaxies (N_{gals}), the fractional slope as a percent decrease (ΔN[0 : 90]), uncertainty in the percentage slope (σ_{ΔN}), and anisotropy significance (|A|/σ_{A}). The inset directly compares the normalized fractional slopes of the different subsamples. N/N_0 is normalized galaxy density, where N_0 is the galaxy density along the host galaxy projected major axis N(θ = 0). The dashed black line indicates zero slope (isotropy).
Fig. 7.— Satellite location angle ($\theta$) for different subsamples of satellite galaxy $fracDeV$ (concentration). The format of this figure is identical to that of Figure 6. All four subsamples show some preference for the host major axis. de Vaucouleurs profile-dominated satellite galaxies ($fracDeV > 0.5$) prefer the major axis most strongly.
Fig. 8.— Satellite location angle ($\theta$) as a function of host galaxy (HG) and satellite galaxy (SG) colors. The format of this figure is identical to that of Figure 6. We perform color separation using the division of Bailin et al. (2007) (Fig. 2). Major axis preference is restricted to satellite galaxies of red hosts and is strongest specifically for red satellites of red hosts. Satellites of blue host galaxies are generally consistent with isotropy.
Fig. 9.— Satellite location angle ($\theta$) for different subsamples of host-satellite velocity separation ($\Delta V$). The format of this figure is identical to that of Figure 6. Major axis preference is restricted to the two lower $\Delta V$ bins ($\Delta V < 600$ km/s). At large $\Delta V$ (> 900 km/s), the satellite galaxy distribution is consistent with isotropy.
Fig. 10.— Satellite location angle ($\theta$) for different subsamples of projected host-satellite radial separation ($\Delta R$). The format of this figure is identical to that of Figure 6. Major axis preference is strongest and most significant at close separations ($\Delta R < 250 h^{-1} \text{kpc}$). Despite increasing subsample size, this anisotropy decreases steadily in strength and significance with increasing radial separation.
Fig. 11.— Satellite location angle (θ) for different galaxy group sizes (satellites per system, $N_{SG}$). The format of this figure is identical to that of Figure 6. Most satellites exist in small systems ($N_{SG} \leq 5$). Alignment strength (fractional slope) increases with increasing group size. The subsample with the largest groups ($21 \leq N_{SG} \leq 1000$) has the highest trend significance despite having the fewest member objects, suggesting that major axis preference is more prevalent in larger galaxy groups.
Fig. 12.— Differential distribution of satellite galaxy (SG) angular position ($\theta$) relative to host galaxies (HGs). Each panel column contains a different range of satellite galaxy fracDeV. Similarly, each panel row hosts a different range of host galaxy fracDeV. Projected radial separation ($\Delta R \leq 1 \, h^{-1} \text{Mpc}$), in 10 bins of width $100 \, h^{-1} \text{kpc}$, spans the horizontal axis. See Fig. 5 for an example of this plotting technique. High significance (fractionally small error bars) detections of SG preference for HG major axes (values below 0) are markedly concentrated towards the upper-right (high fracDeV). All objects have velocity separation $\Delta V < 500 \, \text{km/s}$ and good agreement between isophotal and model position angles ($\Delta PA \leq 15^\circ$).
Fig. 13.— Hostward elongation ($\phi$) for different subsamples of satellite galaxy fracDeV (concentration). The format of this figure is identical to that of Figure 6. The observed hostward elongation trend is restricted to high-fracDeV (> 0.9) satellite galaxies.
Fig. 14.— Hostward elongation ($\phi$) for different subsamples of host galaxy $\text{fracDeV}$ (concentration). The format of this figure is identical to that of Figure 6. All four subsamples are statistically consistent with each other and with the total group sample. Hostward alignment strength thus appears to be independent of host galaxy concentration.
Fig. 15.— Hostward elongation (φ) as a function of host and satellite galaxy colors. The format of this figure is identical to that of Figure 6. We perform color separation using the division of Bailin et al. (2007) (Fig. 2). Hostward elongation is restricted to the two subsamples with red satellite galaxies. Host galaxy color has no discernible effect on hostward elongation trend strength.
Satellite galaxy hostward elongation ($\phi$) as a function of velocity separation ($\Delta V$). The format of this figure is identical to that of Figure 6. Each $\Delta V$ subsample is statistically consistent with the total group sample. The subsamples are also loosely consistent with each other. The high significance in the lowest velocity bin ($|\Delta V| < 300$ km/s) is a result of subsample size. On its own, host-satellite $\Delta V$ does not influence the degree of hostward alignment.
Fig. 17.— Satellite galaxy hostward elongation ($\phi$) as a function of projected radial separation ($\Delta R$). The format of this figure is identical to that of Figure 6. No subsamples show anisotropy at very high significance. Hostward alignment is strongest in the innermost ($\Delta R < 250$ $h^{-1}$ kpc) radial bin.
Fig. 18.— Satellite location angle as a function of the number of satellites per host (i.e., group size). The format of this figure is identical to that of Figure 6. All four group size subsamples are consistent with other and with the total group population. There is no obvious dependence of hostward elongation on group size.
Fig. 19.— Holmberg-like effect seen among select satellite galaxies (SGs). In the above histograms we include only groups with inclined ($q_{mom} < 0.53$ and $q_{iso} < 0.53$), blue host galaxies (HGs) with fewer than 25 identified satellites within $1 \, h^{-1} \text{Mpc}$. We further require that isophotal and model HG position angle (PA) agree well ($\Delta \text{PA} < 15^\circ$). Within these systems, we keep SGs that are $15 \times$ less luminous than their hosts and satisfy $|\Delta V| < 500 \, \text{km/s}$. We eliminate all SGs within 5 Petrosian radii of the host to exclude mis-detected bright knots in the host galaxy. The red curve above includes objects with $\Delta R < 500 \, h^{-1} \text{kpc}$ and $\Delta V < 500 \, \text{km/s}$ while the blue curve extends only to $\Delta R < 300 \, h^{-1} \text{kpc}$ and $\Delta V < 300 \, \text{km/s}$. 

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### Holmberg Effect

| Neighbor Volume ($\Delta R$, $\Delta V$) | $N_{\text{gal}}$ | $\Delta N$ [0:90] | $\sigma_{\text{AN}}$ | $|\Delta|/\sigma_A$ |
|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|
| $500 \, h^{-1} \text{kpc}$, $500 \, \text{km/s}$ | 51 | 511.5% | $\pm 167.9\%$ | 3.05 |
| $300 \, h^{-1} \text{kpc}$, $300 \, \text{km/s}$ | 27 | 2129.8% | $\pm 840.3\%$ | 2.53 |
Fig. 20.— Satellite galaxy (SG) distribution ($\theta$) trends of the same hosts and satellites using isophotal position angle (blue) and galaxy model PA (red). We exclude round objects ($q_{\text{iso}} > 0.9$ or $q_{\text{mom}} > 0.9$) for which PA may be inaccurate. The isophotal slope error bars, comparable in magnitude to those of the de Vaucouleurs slopes, have been omitted for clarity. Comparing these two cases, we observe little difference for any profile type or radius, suggesting that the HG population is unaffected by discrepant PAs.
Fig. 21.— Hostward elongation ($\phi$) in different bins of host galaxy (HG) $\text{fracDeV}$, satellite galaxy (SG) $\text{fracDeV}$, and projected radius ($\Delta R$). The isophotal slope error bars, comparable in magnitude to those of the de Vaucouleurs slopes, have been omitted for clarity. We observe a marked difference between $\phi_{\text{iso}}$ (blue) and $\phi_{\text{deV}}$ (red) among the same high $\text{fracDeV}$ SGs (rightmost column). In particular, we observe a striking disparity between isophotal and de Vaucouleurs hostward elongation among highly concentrated ($\text{fracDeV} > 0.9$) SGs of highly concentrated ($\text{fracDeV} > 0.9$) HGs (top-right panel). We examine this subsample in greater detail in Fig. 22. The discovery of this discrepancy motivated our $\Delta PA < 15^\circ$ requirement.
Closer inspection of hostward elongation ($\phi$) in the subsample of host-satellite pairs with HG $\frac{\text{DeV}}{0.9}$, SG $\frac{\text{DeV}}{0.9}$, $|\Delta V| < 500 \text{ km/s}$, and $\Delta R < 100 \ h^{-1} \text{ kpc}$, in which we find the greatest discrepancy between results based on isophote- and de Vaucouleurs model-based PAs (see Fig. 21). We further separate the galaxies with good PA agreement ($\Delta PA < 15^\circ$, blue) from those with poor agreement ($\Delta PA > 15^\circ$, red). The whole subsample (no $\Delta PA$ requirements, black) is the sum of the red and blue histograms. In the figures above, we have excluded all satellites falling within 1 Petrosian radius ($r_p$) of the host galaxy which are very likely misidentified bright knots within the host itself. Without the $\Delta PA < 15^\circ$ requirement, the hostward elongation signal from isophotal PA fractional slope is 4 times that we obtain from de Vaucouleurs model PAs.
Fig. 23.— The exponential and de Vaucouleurs model-fitting procedures have several known flaws. Above, the distribution of position angle (PA) is shown for exponential model fits (left) and isophotes (right). While the isophotal PAs have an effectively random distribution, the model-based PA suffers from significant anisotropy. For reference, we provide the $\Delta \chi^2$ between the observed distribution and an isotropic (constant) model.
Fig. 24.— Spiral structure causes isophotal twisting, which can lead to highly discrepant de Vaucouleurs and isophotal position angles. Above, the galaxy models seek out the light in the bulge and/or bar, whereas the 25 mag / sq. arcsec isophote roughly detects where the spiral arms fade into the sky (on much larger scales).
Fig. 25.— Position angles measured with isophotes and galaxy models can provide highly discrepant results. Unlike the previous example (Figure 24) where two discrepant position angles both correspond to obvious galactic features, the objects above have nearby neighbors which distort the appearance of the isophotes nearby. In several of the cases above, this systematic effect could easily mimic a hostward elongation signal.