What aspects of galaxy environment matter?

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\textbf{ABSTRACT}

We determine what aspects of the density field surrounding galaxies most affect their properties. For Sloan Digital Sky Survey galaxies, we measure the group environment, meaning the host group luminosity and the distance from the group center (hereafter, “groupocentric distance”). For comparison, we measure the surrounding density field on scales ranging from $100~h^{-1} \text{kpc}$ to $10~h^{-1} \text{Mpc}$. We use the relationship between color and group environment to test the null hypothesis that only the group environment matters, searching for a residual dependence of properties on the surrounding density. Generally, red galaxies are slightly more clustered on small scales ($\sim 100–300~h^{-1} \text{kpc}$) than the null hypothesis predicts, possibly indicating that substructure within groups has some importance. At large scales ($> 1~h^{-1} \text{Mpc}$), the actual projected correlation functions of galaxies are biased at less than the 5% level with respect to the null hypothesis predictions. We exclude strongly the converse null hypothesis, that only the surrounding density (on any scale) matters. These results generally encourage the use of the halo model description of galaxy bias, which models the galaxy distribution as a function of host halo mass alone. We compare these results to proposed galaxy formation scenarios within the Cold Dark Matter cosmological model.

\textit{Subject headings:} galaxies: fundamental parameters — galaxies: statistics — galaxies: clustering

1. Introduction: galaxy properties and environment

Galaxy properties are a strong function of their environment. In particular, galaxies in dense environments are older, redder, more concentrated, higher in surface brightness, and more luminous than galaxies in voids (Hubble 1936; Oemler 1974; Davis & Geller 1976; Postman & Geller 1984; Dressler 1980; Santiago & Strauss 1992; Hermit et al. 1996; Zehavi et al. 2002; Norberg et al. 2002; Hogg et al. 2003; Blanton et al. 2005a; Kauffmann et al. 2004; Weinmann et al. 2005; Maller et al. 2005; Martínez & Muriel 2006). Clearly, part of understanding galaxy formation must involve understanding why regions with different initial conditions (a different initial cosmological density field) result in such different galaxy populations.

Quantitative understanding of this variation of clumping with galaxy type has improved in the last twenty years or so with the advent of large extragalactic samples. Among the papers written on this subject, what the authors mean by “galaxy type” has varied considerably. For some “type” has meant a measure of its optical morphological properties — is it an elliptical, a dwarf elliptical, a lenticular, a spiral, or an irregular? Others have preferred measures of galaxy structure such as size or concentration, or measures of the galaxy star-formation history, such as color or emission line flux. A number of recent papers (Kauffmann et al. 2004; Blanton et al. 2005a; Quintero et al. 2006) have shown that star-formation related properties such as color and emission line flux are directly affected by environment, while structural properties such

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as surface brightness and concentration (which are more closely related to classical morphology) are not. In addition, Kauffmann et al. (2004) have shown that environment does not affect measures of very recent star-formation such as emission lines (the last 10 Myr) over and above its affect on longer time scale measures such as optical color (the last 1 Gyr). Whether other classical morphological measurements, such as spiral arm properties, are related to environment directly, remains to be seen. In this paper, we will simplify based on these results to only consider the relationship between environment and galaxy colors.

Astronomers have not only differed by what they mean by “galaxy type,” they also have differed in how they measure “environment.” Usually their choices have been motivated by practicality — after all, the ultimate measure of environment, the local mass density field, is currently observationally inaccessible. In some cases, astronomers have used distance from the center of a cluster or surface density within that cluster as a measure of environment (Oemler 1974; Dressler 1980; Postman & Geller 1984; Gomez et al. 2003; Quintero et al. 2006). In other cases, we have used field samples and measured the number of nearby galaxies relative to the mean density, using various measures (Hashimoto et al. 1998; Hashimoto & Oemler 1999; Balogh et al. 2004a; Hogg et al. 2004; Kauffmann et al. 2004; Blanton et al. 2005a). Sometimes, we do not measure the density around individual objects, but instead measure the average environments of classes of galaxies. For example, we can measure as a function of galaxy properties the mean environments around galaxies (Hogg et al. 2003; Blanton et al. 2005a) or their correlation functions (Davis & Geller 1976; Santiago & Strauss 1992; Hermit et al. 1996; Norberg et al. 2002; Zehavi et al. 2004). In this paper, we will consider all of these approaches to understand what description of the density field is most directly related to galaxy colors.

All of these analyses have found the same qualitative results. The “later type” galaxies — diffuse, low surface brightness, blue spiral or irregular galaxies — populate the low density regions. The “earlier type” galaxies — concentrated, high surface brightness, red elliptical or S0 galaxies — populate the high density regions. However, all of the measures of environment are correlated at least weakly to each other, so one expects them all to show the same qualitative trends. If we can determine what aspects of environment are most directly related to galaxy properties, it will be an important clue in determining the way in which environment affects galaxy formation. Making this determination is the goal of this paper.

We choose here two classes of environmental measurements: “group environment” measurements and “surrounding density measurements” on varying scales. Here, we repeatedly use the term “group environment” to refer to two parameters regarding the galaxy environment: the luminosity of the host group or cluster (group luminosity) and the radius from the center of that group (groupocentric distance). By “surrounding density” we mean the density with respect to the mean in a cylinder around each galaxy, where the cylinder is aligned in the redshift direction to integrate over nonlinear redshift space distortions. The radius of the cylinder in the transverse direction determines the scale. We explain these density measurements in more detail below.

These results yield insights into how the spatial distribution of galaxies is related to that of the dark matter. In particular, a recently developed way of describing the relationship between galaxies and mass is by using the “halo occupation distribution” (HOD), which quantifies the distribution of galaxies as a function of host dark matter halo mass (see Berlind & Weinberg 2002 and references therein). The HOD description is an extremely convenient way of parameterizing the physics that relates galaxies and mass, and of marginalizing over the possible relationships when trying to use galaxy clustering to constrain cosmology (Abazajian et al. 2005). It typically assumes that the distribution of galaxy luminosities and types depends only on the mass of the host halo, and not on the larger scale density field. We test this assumption here by associating galaxy groups in the observations with dark matter halos, and asking whether indeed the masses
of these groups are the only quantities that are relevant to galaxy properties.

In Section 2 we describe the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Berlind et al. (2006) group catalog resulting from it. In Section 3, we find that both group luminosity and groupcentric distance are independently related to galaxy properties. We then consider whether the mean density around galaxies is related to galaxy colors over and above the dependence expected to result just from the dependence on group environment. We only find a large residual dependence on very small scales ($\sim 300 h^{-1}$ kpc). Meanwhile, even in regions with very different densities on large scales, the galaxy population is similar as long as the group environment is similar. In Section 4 we demonstrate the same results in terms of the correlation functions of red and blue galaxies. In Section 5 we compare our results to similar studies of others, finding agreement. In Section 6, we compare our results to similar investigations in the theoretical realm. In Section 7 we discuss the implications of our results for theories of galaxy formation and for interpreting large-scale structure statistics.

2. The SDSS spectroscopic sample of galaxies

In order to investigate the questions posed above, we use the SDSS spectroscopic sample. It is a large, homogeneously selected sample of galaxies in the local Universe, and is ideal for studying the relationship between galaxy properties and environment.

The SDSS is taking $ugriz$ CCD imaging of $10^4$ deg$^2$ of the Northern Galactic sky, and, from that imaging, selecting $10^6$ targets for spectroscopy, most of them galaxies with $r < 17.77$ mag (e.g., Gunn et al. 1998; York et al. 2000; Abazajian et al. 2003). Automated software performs all of the data processing: astrometry (Pier et al. 2003); source identification, deblending and photometry (Lupton et al. 2001); photometricity determination (Hogg et al. 2001); calibration (Fukugita et al. 1996; Smith et al. 2002); spectroscopic target selection (Eisenstein et al. 2001; Strauss et al. 2002; Richards et al. 2002); spectroscopic fiber placement (Blanton et al. 2003); and spectroscopic data reduction. Descriptions of these pipelines also exist in Stoughton et al. (2002). An automated pipeline called $\text{idlspec2d}$ measures the redshifts and classifies the reduced spectra (Schlegel et al., in preparation).

The spectroscopy has small incompletenesses coming primarily from (1) galaxies missed because of mechanical spectrograph constraints (6 percent; Blanton et al. 2003), which leads to a slight under-representation of high-density regions, and (2) spectra in which the redshift is either incorrect or impossible to determine (< 1 percent). In this context, we note that the mechanical constraints are due to the fact that fibers cannot be placed more closely than $55''$; when two or more galaxies have a separation smaller than this distance, one member is chosen independent of its magnitude or surface brightness. Thus, this incompleteness does not bias the sample with respect to luminosity. In addition, there are some galaxies ($\sim 1$ percent) blotted out by bright Galactic stars, but this incompleteness should be uncorrelated with galaxy properties.

For the purposes of computing large-scale structure and galaxy property statistics, we have assembled a subsample of SDSS galaxies known as the NYU Value Added Galaxy Catalog (NYU-VAGC; Blanton et al. 2005b). For most of this paper we use the group catalog described in Berlind et al. (2006), based on a volume-limited sample of galaxies from the NYU-VAGC complete down to $M_{0, r} - 5 \log_{10} h < -19$ within the redshift range $0.015 < z < 0.068$. For additional tests we will use two alternate group catalogs complete to $M_{0, r} - 5 \log_{10} h < -18$ and to $M_{0, r} - 5 \log_{10} h < -20$, and spanning redshift ranges of $0.015 < z < 0.045$ and $0.015 < z < 0.10$ respectively. Berlind et al. (2006) identify these groups using a friends-of-friends algorithm (see e.g., Geller & Huchra 1983; Davis et al. 1985) with perpendicular and line-of-sight linking
lengths equal to 0.14 and 0.75 times the mean inter-galaxy separation, respectively. Mock galaxy catalogs demonstrate that these parameters produce galaxy groups that most closely resemble the underlying dark matter halos. We have included groups with $N_{\text{gals}} = 1$ or 2 (singles and pairs) for some of our investigations here, but for most test simply use those with $N_{\text{gals}} \geq 3$.

We define the group luminosity to be the sum of the luminosities of all the galaxies in the group that appear in the volume-limited catalog (in this case those with $M_{0,r} - 5 \log_{10} h < -19$). We calculate rough mass estimates for the clusters using the group luminosity function and assuming a monotonic relation between a group’s luminosity and the mass of its underlying dark matter halo. By matching the measured space density of clusters to the theoretical space density of dark matter halos (given the concordance cosmological model and a standard halo mass function), we assign a virial halo mass to each cluster luminosity. This determination ignores the scatter in mass at fixed cluster luminosity and is only meant to yield rough estimates. By these estimates, the minimum group mass than can host any galaxy in our sample is about $5 \times 10^{11} h^{-1} M_\odot$.

Each group has an associated “virial radius” related to this mass of

$$r_{\text{vir}} = \left( \frac{3}{4 \pi} \frac{M}{200 \rho_0} \right)^{\frac{1}{3}},$$

where $M$ is the estimated mass of the cluster and $\rho_0$ is the current mean density of the Universe. We use the group centers given by Berlind et al. (2006), which are the mean of the member galaxy positions. We define the groupocentric distance $r_P$ as the projected distance measurement from each galaxy to the center of its host group. We then scale each groupocentric distance by $r_{\text{vir}}$. We have also tested the effect of using a group center defined by the densest location in the group on 300 $h^{-1}$ kpc scales, finding no significant difference in our conclusions.

In this study, we will also also the surrounding densities of each galaxy. We do so by counting galaxies in annuli extended 2000 km s$^{-1}$ long in the redshift direction, centered on the galaxy of interest. The five annuli we use are: $0.01 < r_T < 0.1$, $0.1 < r_T < 0.3$, $0.3 < r_T < 1$, $1 < r_T < 6$, and $6 < r_T < 10 h^{-1}$ Mpc. We use random catalogs to estimate how many galaxies we expect in each cylinder, accounting for holes in the survey and the edges of the sample (described using the geometry information in the NYU-VAGC). The ratio of these two is then $N/N_{\text{exp}} = 1 + \delta$, where each annulus above we denote $\delta_{0.1}$, $\delta_{0.3}$, $\delta_{1}$, $\delta_{6}$, and $\delta_{10}$ respectively.

3. Galaxy colors and environment

3.1. Color correlates with group luminosity

We find that galaxy colors are a strong function of their group luminosity. Figure 1 shows the color-magnitude diagram of galaxies in our catalog in several bins of group $0.1$-band absolute magnitude. We use a definition of “blue” and “red” according to whether a galaxy is bluer or redder than the solid line in each panel, which follows the blue edge of the red sequence using the formula:

$$(0.1)_{g-r} = 0.80 - 0.03(M_{0,r} + 20).$$

According to this definition, the blue fraction (listed in each panel) decreases with increasing group luminosity.
In addition to the blue fraction we can fit the blue and red sequence positions as a function of luminosity. We do so as follows: in bins of luminosity we fit the color distribution with a mixture of two gaussians, in the manner of Baldry et al. (2004). The top row of diamonds in each panel of Figure 1 shows the mode of the redder gaussian of each fit, the bottom row shows the mode of the bluer gaussian. In the smallest groups, the mode of the bluer gaussian has a clear significance, since it corresponds to a mode of the full distribution. In the largest groups, the significance of the blue mode is less clear, though we still include the second gaussian in the fit to model the blue tail of galaxies in the large groups. The dashed lines in each panel show a linear regression on absolute magnitude for each sequence independently. The dotted lines in each panel are all identical and show the fit for the lowest luminosity groups.

For the blue galaxies, there is a change in the slope of the blue sequence such that the highest luminosity blue galaxies are fixed in color as a function of environment, but the lower luminosity blue galaxies become redder in large groups by about 0.1 mag. For the red galaxies, the red sequence is almost fixed. There is a trend of about 0.02 mag in color across this range of environment, which is statistically significant, but we believe verifying this trend requires a better understanding of the galaxy photometry in SDSS than currently exists. For example, in rich clusters the colors of the smaller galaxies may be contaminated by overlapping larger galaxies (Masjedi et al. 2006). Without a more careful examination than space affords here, we do not make much of this trend. Hogg et al. (2004) and Balogh et al. (2004b) have previously noted these trends in very similar data sets.

Thus, galaxy colors are a strong function of their group luminosity, with the most dramatic change being the reduction of the blue fraction, and more minor changes occurring in the actual location of the sequences. We also note that the reduction in blue fraction occurs even for the smallest groups, where ram pressure stripping of the cold disk gas is highly unlikely to affect galaxies of these luminosities.

3.2. Color correlates with groupcentric distance

Galaxy colors are also a function of their groupcentric distance. Figure 2 shows the color-magnitude diagram in bins of $r_p/r_{vir}$, in groups with total absolute magnitudes $M_0 - 5 \log_{10} h < -23$. For such groups, we see a dependence of galaxy colors on the groupcentric radius. In less luminous groups there are weaker trends of color with radius, mostly because single-member groups become important in this regime, and such galaxies tend to be blue (and are by definition at the centers of their groups). The dotted lines in this figure are the same as for Figure 1, the fit to the sequences of the low luminosity groups. The changes with groupcentric distance of the positions of the red and blue sequences are similar to the changes with group luminosity. Thus, at least in luminous groups the trends with groupcentric distance are similar to the trends with group luminosity: the blue fraction decreases significantly in the centers of the groups and the positions of the sequences change slightly.

Figure 3 shows the same results, but simply as the blue fraction as a function of $r_p/r_{vir}$ for the same ranges of group luminosities from Figure 1. We here limit the groups to those with three or more members, since for singles and pairs the groupcentric radius is close to meaningless. Thus, both group luminosity and radius from the center of the group are closely (and independently) related to galaxy colors, similar to previous findings (Dressler 1980; Whitmore et al. 1993; Lewis et al. 2002; Gomez et al. 2003; Weinmann et al. 2005; Quintero et al. 2006).
3.3. How to test whether only group environment matters

Neither of the previous subsections have surprising results: they are consistent with the decades-old understanding of the distribution of galaxy properties. However, we would like to explore whether the group environment is the only thing that matters. Does the surrounding density field, per se, matter at all? For example, does the position of the group in the larger scale density field matter? In this and the following sections we will be testing this simple null hypothesis: can the relationship between galaxy colors and group environment predict the dependence of galaxy colors on the surrounding density field at all scales?

If the surrounding density really were an important variable, the residual surrounding density relative to the mean at each group luminosity and radius would be related to galaxy colors. Consider Figure 4, showing the mean density on \(100 \, h^{-1} \, \text{kpc}\) scales as a function of radius for groups of various luminosities. That is, it shows the mean density as a function of group environment. Obviously, since we know that color correlates with radius and luminosity, color will correlate with density as well, even under our null hypothesis. However, if the surrounding density is independently important, then a region within a group which is particularly dense relative to the mean for its group environment shown in Figure 4 might have a redder (or bluer) population. Similarly, if the large scale density field is an important variable, a group surrounded by many other groups would have a different galaxy population to a similarly sized one that is not.

In the rest of this paper, we compare the actual relationship between galaxy colors and density field to that predicted by the null hypothesis. We construct these predictions by classifying the environments of galaxies according to their group luminosity and groupocentric distance, and then shuffling the colors of galaxies with similar group environments. This procedure leaves the relationship between group environment and color intact, and leaves the relationship between group environment and density intact, but scrambles the direct relationship between the density field and color. Then, whatever analysis we perform on the actual galaxy catalogs we can similarly perform on this shuffled catalog to produce the null hypothesis prediction.

Note that for small groups (singles and pairs) the group luminosity is very uncertain, since adding or subtracting a single galaxy from the group has a large effect. Additionally, the groupocentric distance is poorly defined in these cases. For these reasons, in many of the tests below we exclude galaxies in singles and pairs, and concentrate on galaxies in groups with \(N_{\text{gals}} \geq 3\).

3.4. The large-scale density field matters only a little

Figure 5 shows the mean density on various scales around galaxies as a function of color. The dashed line shows the expected mean density under the null hypothesis, assuming that the galaxy population depends only on group environment and not independently on the density. Here we have restricted the sample to galaxies in groups with \(N_{\text{gals}} \geq 3\), because the shuffling test is less appropriate for singlets and pairs, whose groupocentric distances mean very little and whose group luminosities can be greatly affected by misclassifying group membership.

Consider the scales \(r_T \geq 1 \, h^{-1} \, \text{Mpc}\) and greater. On these scales the solid and dashed lines generally agree better than about 5%. Thus, the density on these scales is only weakly related to galaxy colors, once the group environment is known. It is therefore clear that once we know the group environment, the large-scale environment (e.g., at \(6 \, h^{-1} \, \text{Mpc}\)) is not closely related to galaxy colors. We have also examined the positions of the blue and red sequences as a function of the large scale environment, and find only very small
changes in those positions ($<0.03$ mag in color). From the point of view of understanding galaxy formation, these results indicate that the large-scale density field has only a small effect on galaxy properties.

### 3.5. The small-scale density field matters a little bit more

The small-scale density field is generally less important than the position of the galaxy within the group. For example, Figure 4 shows that $\delta_{0.1} \sim 50$ is typical of the centers of small groups and the outskirts of large groups. However, the outskirts of large groups are much redder ($f_{\text{blue}} \sim 0.35$) than the centers of the smallest groups ($f_{\text{blue}} \sim 0.5$). Nevertheless, at a fixed group environment, there can be considerable variation in the small-scale surrounding density field, because of clumping within the group. Does this clumping on small scales matter? As we show here, yes, a little.

Consider the scales $r_T \leq 300$ $h^{-1}$ kpc in Figure 5. On these scales it is clear that the surrounding density is important even given the group environment. The sense is that very red galaxies tend to be in dense environments on small scales (relative to the density expected for their groupocentric distance and a particular group luminosity). Several possible explanations of this result exist. One is that there is surviving substructure in the groups from accretion of smaller groups, and that such substructures have the reddest galaxy populations. A second is that our group centers (which are associated with the mean positions of the galaxies) are inappropriate and a more appropriate center would be the density peak of the group. In fact, we have tested this possibility by defining the center of the group as the densest location in the group (instead of the geometric center); our results do not change significantly with this change in definition, indicating that this explanation does not account for the effects we see. A final possibility is that because our shuffling procedure mixes true groupocentric radii due to projection effects, some of this extra information in the density field is because it can be a better indicator of whether the galaxies are near the true group center.

### 3.6. Blue fraction as a function of environment shows the same

The mean density is a crude measurement — there could be large effects that only happen in the densest regions or in the voids that leave the mean density relatively unperturbed. To investigate this possibility, Figure 6 shows the blue fraction for groups of different luminosity classes as a function of large scale density, here calculated around the center of each group for $6 < r_T < 10$ $h^{-1}$ Mpc. The typical number of tracer galaxies in this annulus is $\sim 50$, suggesting that the errors in the density estimate are about 15%, smaller than our bin widths in this figure. There is very little statistically significant dependence on density. In fact, we can test explicitly for a difference between what we would expect by performing the shuffling described above. The dashed line shows this null hypothesis prediction, which is no trend — unsurprisingly, on these large scales. For the actual galaxies, the only significant trend is in the most luminous groups, which is inconsistent with no trend at about $2\sigma$. This signal is due mostly to two groups with high blue fractions ($\sim 40\%$) which are in underdense regions. We note that when using a brighter volume limited sample (with $M_{0.1 \nu} - 5 \log_{10} h < -20$), which has a larger number of large clusters, we do not find any such trend.

In Figures 7 and 8 we perform these tests using the smaller scale density estimate $\delta_1$ and $\delta_{0.3}$. Here the null hypothesis expectation is no longer flat, since there is a trend of surrounding density with groupocentric distance at these scales. At $1$ $h^{-1}$ Mpc we find our results are very close to the null hypothesis expectation, indicating that the $1$ $h^{-1}$ Mpc density field still adds very little information over and above the group environment. At $300$ $h^{-1}$ kpc, we begin to see a dependence of blue fraction on density that exceeds the
null hypothesis expectation. This last result is consistent with what we found in the previous subsection: the smallest scale densities do matter somewhat over and above the group environment indicators.

Figures 6–8 make an additional point. In each case, at fixed density, the blue fraction is still a strong function of group luminosity. Thus, on no scale is the surrounding density a sufficient description of environment to explain the trends of galaxy colors with group environment.

4. Group environment and the correlation function

How does all of this affect the galaxy correlation function? After all, as we explain further below, one of the possibilities we want to test is how adequately we can model the relationship between environment and colors using the HOD description, and one of the main uses of that description is to model correlation functions (e.g., Seljak 2000; Scoccimarro et al. 2001; Berlind & Weinberg 2002; Zheng et al. 2005). On the other hand, if our null hypothesis is incorrect and one needs to know more than the dependence of galaxy color on group/halo environment in order to understand the relative correlation functions of galaxies of different types, then the halo model technique either does not make much sense or needs to be augmented. In this section, we directly test the possibility that we need to know more than the group environment.

The correlation function \( \xi(r) \) is the excess probability relative to a Poisson distribution of finding a galaxy a distance \( r \) away from a given galaxy. Because of peculiar velocities distorting the Hubble flow in the redshift direction, it is often useful to study this probability as a function of two variables: \( \xi(r_p, \pi) \), where the separation parallel to the line of sight is \( \pi \) and the transverse separation is \( r_p \). Here we will not be interested in the dependence on the redshift separation so we will measure a projection of this function onto the transverse direction (Davis & Peebles 1983):

\[
  w_p(r_p) = 2 \int_0^\infty d\pi \xi(r_p, \pi).
\]

(3)

In practice we integrate out to \( \pi = 40 \, h^{-1} \) Mpc, following Zehavi et al. (2005). To estimate \( \xi(r_p, \pi) \) we use the Landy & Szalay (1993) estimator of the correlation function.

In order to ask whether the relative correlation function of red and blue galaxies is explained by group environments alone, we execute the same shuffling test we used above, shuffling the colors among galaxies with similar group environments. Unlike in the previous section, we include all galaxies in the shuffling, even singles and pairs. Figure 9 shows the results. In the top panel, the solid, long-dashed, and thick solid lines are the actual correlation functions of blue (lowest), red (highest), and all (middle) galaxies. The dotted and short-dashed lines are the null hypothesis predictions of the correlation functions of blue and red galaxies, resulting when we shuffle galaxies with similar groupcentric radii and host group luminosities. In fact, we have shuffled twenty independent times and here plot the mean of those twenty different shuffles. The error bars in Figure 9 are simply the variance among the twenty realizations. The bottom panel shows the square root of the ratios of the actual correlation functions to the shuffled correlation functions.

In all cases, the biases are less than 5% on scales greater than 1 \( h^{-1} \) Mpc. These results are consistent with those in the previous section: the relative strength of the large scale correlation functions of red and blue galaxies contains very little information that is not already in the variation of color with group environment.

At smaller scales, the shuffled correlation functions begin to differ somewhat from the actual ones by small amounts, with up to a 10% bias on the smallest scales. The blue correlation function is smaller than shuffled version, while the red correlation function is larger. This difference is probably related to the
deviations in Figure 5 and Figure 8 at small scales, and also indicates that either clumps on small scales within groups have redder galaxy populations, or that our measurements of projected groupocentric radius are mixing true groupocentric radii.

We have measured the difference between accounting for the groupocentric distance when shuffling and not doing so. The difference is negligible on large scales, and minor on small scales. Thus, at least for large scale clustering, halo occupation models probably do not have to account for the radial dependence of halo occupation.

We have explored how these results vary with our choice of color cut and with galaxy luminosity. If we vary the first term on the right hand side of Equation 2 between 0.7 and 0.9, the changes to our results are only 2–3%. If we use group catalogs including different ranges of galaxy luminosity ($M_v - 5 \log_{10} h < -18$ and $-20$), the results are in Figure 10, showing the relative bias averaged between 4 and 20 $h^{-1}$ Mpc. Both the higher and lower luminosity samples show more of a relative bias, but the effects are still smaller than 5% in each case.

5. Comparison to previous results

How do our results compare with similar previous work? Kauffmann et al. (2004) found similar results for the relationship between D4000 and the large-scale density field at fixed density on scales of 1 $h^{-1}$ Mpc. Blanton et al. (2006) found similar results for color and Hα equivalent width. Balogh et al. (2004a) found a contradictory result that Blanton et al. (2006) demonstrated was due to the sparseness of the catalog used for their density estimators. None of these tests were as sensitive as those we use here.

Meanwhile, for samples of large clusters Gomez et al. (2003) and Lewis et al. (2002) found that the emission line indicators of star-formation were significantly reduced far outside clusters, around two to three virial radii. This result suggests that environmental effects extend very far. As Quintero et al. (2006) show using the group catalog we use here, our estimated virial radii tend to be about twice theirs, which partly explains the difference in our result. However, it is also the case that the test in Gomez et al. (2003) does not cleanly separate the effect of small and large-scale environment. The mean density two to three virial radii away from a large cluster is larger than the mean density of the universe and tends to be populated by large groups. As Lewis et al. (2002) show, the star-formation rates at these distances from clusters correlate well with the local density field (from our point of view here, they correlate with whether galaxies are in a moderately-sized group or not). Thus, correlations of galaxy properties with clustocentric distance, even at large distances, may still be due to very local physical effects. As we noted above, in agreement with Lewis et al. (2002), this result indicates that effects that can only be important in very large clusters such as ram pressure stripping of the cold disk gas, cannot explain the relationship between environment and properties observed in less dense environments.

Recently, Yang et al. (2006) have performed a similar test, using the cross-correlation of groups of fixed mass with galaxies, as a function of the spectral type of the central group galaxy. For groups with estimated masses $M > 10^{12} M_\odot$ they find a strong bias on large scales between the youngest and oldest central galaxies. Their results indicate that for the central galaxies of large groups the large-scale density field may indeed be important, while our results here suggest that the satellites are left relatively affected. In any case, the changes to the central galaxies do not seem to affect the correlation function of all galaxies on large scales at more than the 5% level.
6. Comparison to theoretical results

One assumption certain models of galaxy formation make is that the mass of a host halo fully determines the statistical properties of the galaxies within it. That is, they assume that the assembly time of the halo and its overall merger history are independent of the larger scale environment. The results of Lemson & Kauffmann (1999) lent support to this approximation. However, recent results found correlations to this effect (Gao et al. 2005). Wechsler et al. (2005) explored the effect more fully and found that these correlations were also related to the concentration of the halos. They demonstrated that at halos around $10^{13} \, M_\odot$ at $z = 0$ there is little effect, but at larger masses, early forming (or high concentration) halos are less clustered, while at smaller masses early forming halos are more clustered.

Clearly, our results here mean either: that for the typical masses of halos in our sample (probably around $10^{12} - 10^{13} \, M_\odot$) the assembly time and other properties are not related to the large scale density field; or, that the assembly time has little to do with the whether galaxies in the halo are red or blue. The fact that there is no dependence even for different ranges of group luminosity (Figure 6) suggests the latter.

Croton et al. (2006) have extended the theoretical work to include models of galaxy formation and follow the consequences of this “halo assembly bias.” For their sample most comparable to ours ($M_{bj} - 5 \log_{10} h < -18$) their red galaxy correlation function on large scales is higher than would be expected based on just the host halo environment, with a bias of 10%, while their blue galaxy correlation function is consistent. While this result is a bit at odds with ours, we note that there are a number of differences in analysis. For example, rather than shuffling based on observable properties, they shuffle based on the predicted halo masses. In addition, they use the three-dimensional correlation function rather than the projected correlation function we use here. A fairer comparison would bring their results fully into observable quantities to test whether our results here are indeed inconsistent with their hierarchical models.

7. Conclusions

We have described the relationship between galaxy colors and their group environments, in terms of the luminosity of their host group and their distance from the center of that group (groupocentric distance). Furthermore, we have searched for any residual relationship between galaxy color and measures of the surrounding environment on various scales, finding only a slight dependence at large scales ($> 1 \, h^{-1} \text{Mpc}$) and a stronger dependence at the smallest scales ($< 300 \, h^{-1} \text{kpc}$). Measured at any scale, the variation of galaxy colors with the surrounding density field does not explain the variation of color with group environment: the group environment always yields extra information.

Since other properties, such as concentration and surface brightness, do not appear to correlate with the density field independently of color (Blanton et al. 2005a; Kauffmann et al. 2004; Quintero et al. 2006) these results likely extend to other galaxy properties as well. In fact, we have checked this proposition explicitly for concentration and found no dependence of concentration on the larger scale density field once the color and group environment is fixed.

When interpreting these results, keep in mind that we have considered for the most part only galaxies with $M_r - 5 \log_{10} h < -19$ (though in Figure 10 we also look at slightly lower luminosity galaxies), which limits us to dark matter halos of $\sim 5 \times 10^{11} \, h^{-1} \, M_\odot$ or greater. Whether the assembly time or large-scale density affects galaxies in smaller halos is an open question.

These results have important consequences for the study of galaxy formation:
1. That the blue fraction has no residual relationship with the large scale density field (such as $1\, h^{-1}$ Mpc and above) demonstrates that galaxy formation is closely tied to physics within each halo. The location of that halo in the large-scale density field appears not to be important, nor (if CDM is correct) the assembly time of the host halos (at fixed halo mass).

2. The residual dependence of color on small scale density may indicate the importance of surviving substructure within the group (though it is hard to disentangle possible projection effects causing this dependence). If so, it may be a signature of the processing of blue galaxies into red galaxies in moderately sized groups prior to infall into large groups.

These results are also important for studies of large-scale structure that depend on the use of the halo occupation distribution formalism to model small-scale clustering. A typical simplification (not a necessary one) of those models is that how galaxies occupy halos depends only on their mass, not their larger scale environment. By showing that the relative distribution of different types of galaxies is not affected by the larger scale environment (while it manifestly is affected by the group luminosity) we lend credence to this assumption. Furthermore, theoretically speaking, the large-scale density field is related to the assembly time of the halos, and we might expect assembly times to be related to the ages of the galaxies. Either the halos containing our $L_*$ galaxy sample do not have much relationship between their assembly time and large-scale clustering, or the process of galaxy formation is not much affected by the assembly time of the halo at a given halo mass. Either possibility is encouraging to those trying to use the halo model to interpret the medium-scale correlation functions of similar samples in terms of cosmological models.

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Fig. 1.— Group luminosity affects the color-magnitude distribution of galaxies. In each panel, grey scale is related to number density of galaxies with a given color and absolute magnitude. The solid line is the same in each panel and represents our division between “red” and “blue.” The fraction $f_{\text{blue}}$ we consider blue by this criterion is listed in each panel. The dashed lines and diamonds are the fits to the red and blue sequences described in the text (the dotted lines are identical in each panel and equal to the dashed lines in the lowest luminosity set of groups). Each panel corresponds to groups of the listed range of total absolute magnitudes. As one goes from smaller to larger groups, the blue fraction decreases, though the positions of the red and blue sequences do not change much. Note that the cut-off seen on the right-hand side of the panels (most prominently in the $-21.0 < M_{0.1r} - 5 \log_{10} h < -19.8$ panel in the lower right) is imposed by the lower limit on the absolute magnitude in each panel.
Fig. 2.— For high luminosity groups, the groupocentric distance affects the color-magnitude distribution. Similar to Figure 1, but now concentrating on high luminosity groups ($M_{0.1r} - 5 \log_{10} h < -23$), and dividing galaxies by the projected distance $r_p$ from the center of the group relative to the virial radius $r_{\text{vir}}$. The dotted lines here are again the dotted lines for the low luminosity set of groups.
Fig. 3.— The galaxy population is redder at the centers of groups for all group sizes. Blue fraction as a function of distance from the center of groups, for four ranges of group luminosity (same four as used in Figure 1. (The innermost point includes galaxies all the way to the center of each group). At all group luminosities, there is a smaller blue fraction for galaxies near the centers of the groups. For this figure, we have included only groups with three or more members (otherwise the distance from the “center” is meaningless to consider).
Fig. 4.— Density increases towards the centers of groups. Mean relative density $1 + \delta_{0.1}$ on scales of 100 $h^{-1}$ kpc as a function of distance from the center of groups, for four ranges of group luminosity (same four as used in Figure 1. For this figure, we have included only groups with three or more members (otherwise the distance from the “center” is meaningless to consider).
Fig. 5.— On very small scales ($\sim 300 \, h^{-1} \text{kpc}$), but not on larger scales, the local density contains information over and above that predicted by the relationship between group environment and color. In each panel, the solid line shows the mean density as a function of color for galaxies in the sample, at the scale noted in each panel. We restrict to galaxies in groups with $N_{\text{gals}} \geq 3$, for which the group identifications and groupocentric distances are most secure. The dashed line is the result after shuffling the colors of galaxies with approximately the same group environment. On large scales ($r_T > 1 \, h^{-1} \text{kpc}$), the two curves agree well, meaning that galaxy colors are not affected by the density field (except insofar as different group environments correspond to different densities). On small scales ($r_T \sim 300 \, h^{-1} \text{kpc}$), on the other hand, the effects can be as high as 50%, indicating that the small scale clumping within the groups may directly relate to galaxy colors.
Fig. 6.— Blue fraction as a function of large-scale density (in the annulus $6 < r_T < 10 \, h^{-1} \, \text{Mpc}$), for galaxies in groups of various luminosities, for $N_{\text{gals}} \geq 3$. The blue fraction is a very weak function (at best) of the large-scale density. The dashed line shows the null hypothesis expectation if only the group luminosity and groupocentric distance matter.
Fig. 7.— Similar to Figure 6, but for the annulus $0.3 < r_T < 1 \, h^{-1} \, \text{Mpc}$.
Fig. 8.— Similar to Figure 6, but for the annulus $0.1 < r_T < 0.3 \, h^{-1} \, \text{Mpc}$. 

Groups with:

- $-26.0 < M_{a,r} - 5 \log_{10} h < -24.0$
- $-24.0 < M_{a,r} - 5 \log_{10} h < -22.5$
- $-22.5 < M_{a,r} - 5 \log_{10} h < -21.5$
- $-21.5 < M_{a,r} - 5 \log_{10} h < -20.5$
Fig. 9.— Demonstration that group environment explains most of the relative bias between galaxy types. 
Top panel: correlation function of red galaxies (upper lines), blue galaxies (lower lines) and all galaxies (thick middle line). The solid line for the red galaxies and the long-dashed line for the blue galaxies are the actual correlation functions. The short-dashed line for the red galaxies and the dotted line for the blue galaxies are the correlation functions of the shuffled samples. The error bars indicate the variance among twenty independent shuffles. The short-dashed and dotted lines correspond to shuffling the galaxy colors among galaxies in groups of similar mass. Bottom panel: dashed and dotted lines are the bias of the original correlation function with respect to the shuffled correlation function.
Fig. 10.— Relative bias of the actual galaxy clustering relative to the “shuffled” galaxy clustering, for three volume-limited catalogs. $b$ is averaged between 4 and 20 $h^{-1}$ Mpc. Solid symbols are the red galaxies, open symbols are the blue galaxies.