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Early-type Galaxy Clustering in the NOAO Deep Wide-field Survey

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Abstract

We have measured the clustering of $0.30 < z < 0.84$ early-type galaxies with the initial data release of the NOAO Deep Wide-Field Survey (NDWFS). We have used the spectral synthesis models and photometric redshifts to connect, as an evolutionary sequence, related galaxy populations at different redshifts. The spatial clustering of early-type galaxies is found to be a strong function of luminosity and a weaker function of rest-frame color. We do not detect significant evolution of the spatial correlation function of $M_R - 5\log h \sim -21$ early-type galaxies at $z < 0.84$. This is consistent with recent ΛCDM models of galaxy clustering.

1.1 Introduction

The strength and evolution of the spatial clustering of galaxies is a function of cosmology, galaxy mass and galaxy formation scenarios in Cold Dark Matter models. While the underlying dark matter distribution is predicted to undergo rapid evolution, the clustering of early-type galaxies formed in massive halos is predicted to undergo mild evolution at $z < 2$ (Kauffmann et al. 1999, Benson et al. 2001).

At $z < 0.2$, strong constraints on galaxy clustering as a function spectral type and absolute magnitude are provided by the 2dFGRS and SDSS wide-field spectroscopic surveys (Norberg et al. 2002, Zehavi et al. 2002). At higher redshifts, constraints are provided by the angular correlation function measured from imaging data. However, many previous estimates of spatial clustering derived from the angular correlation function rely on models of the galaxy redshift distribution which were constrained with limited data (e.g., number counts in 1 or 2 bands). In addition, the distribution of galaxy types and luminosities can be a strong function of apparent magnitude and redshift. As the clustering of low z galaxies is a function of galaxy type and luminosity, measurements of the evolution of the spatial clustering can be dominated by selection effects.

Using spectral synthesis models and photometric redshifts, we have measured the clustering of $0.30 < z < 0.84$ early-type galaxies as a function of their rest-frame color, luminosity and redshift. By verifying the photometric redshifts with spectroscopy and simulations, we estimated the spatial clustering of galaxies with angular correlation functions and well constrained model redshift distributions.

1.2 The NDWFS Red Galaxy Sample

To measure the evolution of galaxy clustering, we have used the initial $B_W RI$ data release of the NOAO Deep Wide-Field Survey (Jannuzi & Dey 1999). We have used photometric redshifts and the GISSEL01 τ galaxy spectral evolution models (Bruzual & Charlot 1993) to estimate galaxy redshifts, luminosities and rest-frame colors. The accuracy of the photometric redshifts, luminosities and rest-frame colors were verified with spectroscopic redshifts and simulated data. Red galaxies at $0.30 < z < 0.84$ (which have a strong 4000 break) have $B_W RI$ photometric redshifts with 1σ uncertainties of $\approx 15\%$.

We used the photometric redshifts and τ models to connect, as an evolutionary sequence, related populations of galaxies at different redshifts. For galaxies with $z = 0$ colors comparable to ellipticals, the expected luminosity evolution is ≈ 1 magnitude in R by $z = 1$. We selected two samples with present-day rest-frame colors of $B_W - R > 1.31$ and $B_W - R > 1.58$, allowing direct comparison with the 2dFGRS and SDSS measurements of low z early-type galaxy clustering. A detailed description of this work is provided by Brown et al. (2003).

1.3 The Correlation Function

The angular correlation function of $0.30 < z < 0.84$ early-type galaxies as a function of photometric redshift, absolute magnitude and rest-frame color was determined with the Landy & Szalay estimator (1993). The covariance for the correlation function was determined using the method of Eisenstein & Zaldarriaga (2001) with the contribution of shot-noise included. Example angular correlation functions are plotted in Figure 1.1. We assumed the correlation function is a power-law given by

$$\omega(\theta) = \omega(1')\theta^{1-\gamma}, \tag{1.1}$$

where θ is the angular scale and $\gamma \equiv 1.87$, the value of γ for the clustering of low z early-types (Norberg et al. 2002, Zehavi et al. 2002). Power-law fits, also plotted in Figure 1.1, are in excellent agreement with the observed clustering.

The spatial clustering of early-type galaxies was determined with Limber's (1954) equation and the galaxy redshift distribution. For this work, we assumed the spatial correlation function was a power-law given by

$$\xi(r,z) = [r/r_0(z)]^{-\gamma}, \tag{1.2}$$

where r is the distance scale in comoving coordinates. We estimated the redshift distribution for Limber's equation by summing the redshift likelihood distributions of the individual galaxies from the photometric redshift code. The spatial clustering of early-type galaxies as a function of absolute magnitude and photometric redshift is plotted in Figures 1.2 and 1.3.

1.4 Clustering as a Function of Absolute Magnitude

The clustering of the rest-frame $B_W - R > 1.31$ and $B_W - R > 1.58$ galaxy samples as a function of present-day absolute magnitude is plotted in Figure 1.2. For comparison, low z data from the 2dFGRS and ΛCDM models are also shown in Figure 1.2. While the clustering of galaxies is a function of color, the striking correlation is between r_0 and absolute magnitude. While there is little or no correlation with luminosity at $M_R - 5\log h \sim$

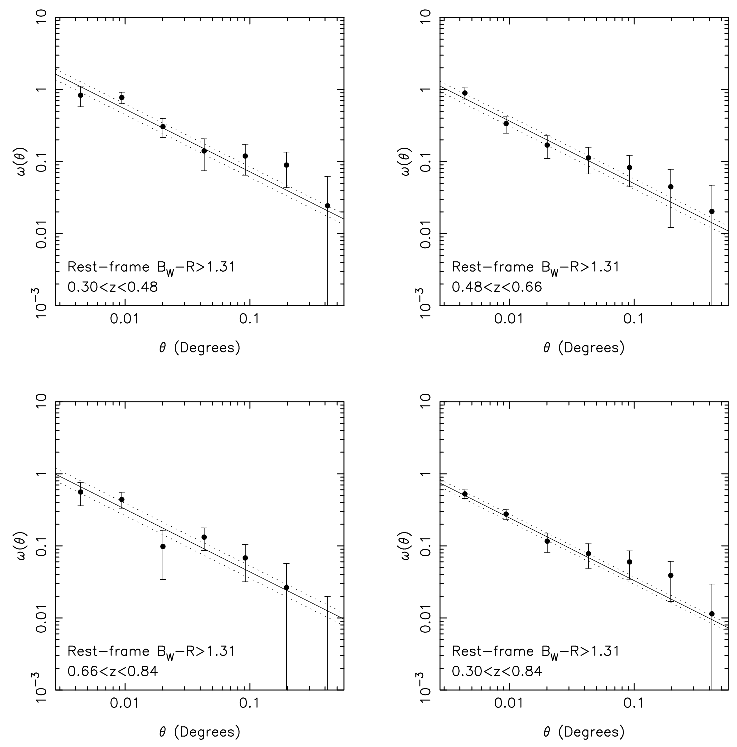

Fig. 1.1. The angular correlation functions of $B_W - R > 1.31$, $-21.5 < M_R - 5\log h < -20.5$ galaxies for a series of photometric redshift bins. Power-law fits to the data are shown along with $\pm 1\sigma$ errors (dotted lines). For reference, 0.1° corresponds to a transverse comoving distance of $3h^{-1}$Mpc at $z \approx 0.7$.

-20.0^*, the value of r_0 rapidly increases from $r_0 \approx 6h^{-1}$Mpc at $M_R - 5\log h = -21$ to $r_0 \approx 10h^{-1}$Mpc at $M_R - 5\log h = -22$.

The clustering of $> L^*$, $0.30 < z < 0.84$ galaxies is slightly stronger than at low z in the 2dFGRS. However, as $> L^*$ galaxies are more strongly clustered than L^* galaxies, they are more susceptible to cosmic variance. The distribution of the $M_R - 5\log h \sim -22$ galaxies does show evidence of structures with sizes comparable to the area of the initial NDWFS data release. In addition, as r_0 is strongly correlated with absolute magnitude at $M_R - 5\log h < -21.5$, clustering evolution estimates using the most luminous galaxies are sensitive to small errors in the photometric redshifts and spectral evolution models. It is therefore advisable to use $M_R - 5\log h \sim -21$ galaxies to measure the evolution of galaxy clustering.

1.5 Clustering as a Function of Redshift

The clustering of $-21.5 < M_R - 5\log h < -20.5$ galaxies as a function of photometric redshift is plotted in Figure 1.3. For comparison, the low redshift 2dFGRS and SDSS measurements are also plotted along with ΛCDM models. There is no significant evolution of the early-type correlation function (in comoving coordinates) at $z < 0.84$. The ΛCDM

* $H_0 = 70$km s^{-1}Mpc^{-1}, $h \equiv \frac{H_0}{100\text{km s}^{-1}\text{ Mpc}^{-1}}$, $\Omega_m = 0.3$ and $\Lambda = 0.7$

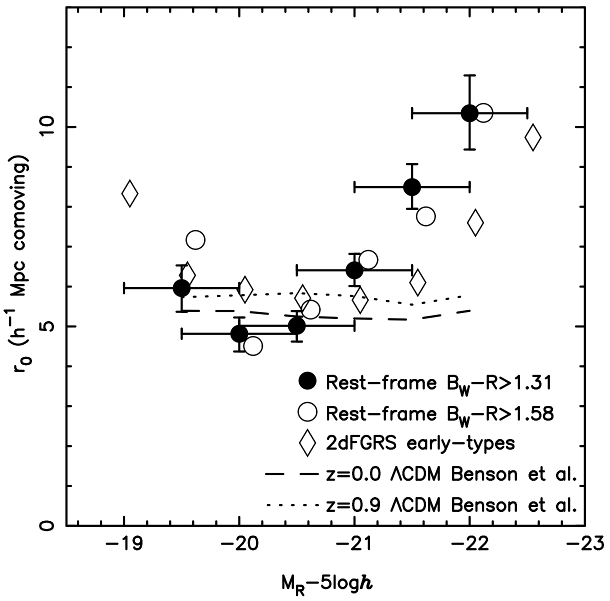

Fig. 1.2. The spatial clustering of red galaxies as a function of present-day absolute magnitude. For clarity, only the $B_W - R > 1.31$ data are shown with error bars and the $B_W - R > 1.58$ data has been shifted slightly to the right. The clustering of red galaxies is a strong function of luminosity and a weaker function of spectral type. A ΛCDM simulation of the clustering $B - R > 1.24$ galaxies (Benson et al. 2001, Benson private communication) reproduces the clustering of L^* galaxies but the $141^3 h^{-3}\mathrm{Mpc}^3$ simulation volume is insufficient to measure the clustering of the most luminous galaxies.

models of Kauffmann et al. (1999) and Benson et al. (2001) provide surprisingly good approximations to the observed clustering evolution. If the evolution of the underlying dark matter distribution at $z < 1$ is well described by the linear or quasi-linear growth of density perturbations, the bias of early-type galaxies must be rapidly evolving with redshift.

1.6 Conclusions

We have used the NOAO Deep Wide-Field Survey to measure the clustering of $0.30 < z < 0.84$ early-type galaxies. Samples with present-day rest-frame colors of $B_W - R > 1.31$ and $B_W - R > 1.58$ were selected to allow direct comparison with low redshift early-type samples from the 2dFGRS and SDSS. The clustering of early-type galaxies is strongly correlated with luminosity at $M_R - 5\log h < -21.5$. Clustering evolution measurements with samples where the distribution of spectral types and luminosities are a function of redshift will be dominated by selection effects. The clustering of $M_R - 5\log h \approx -21$ early-type galaxies undergoes little or no evolution at $z < 0.84$. The value of r_0 at $0.30 < z < 0.84$ is $6.3 \pm 0.4 h^{-1}\mathrm{Mpc}$ for $-21.5 < M_R - 5\log h < -20.5$, $B_W - R > 1.31$ galaxies, the largest sample studied. The lack of detectable evolution is consistent with recent ΛCDM models where the bias undergoes rapid evolution and r_0 undergoes little evolution at $z < 2$.

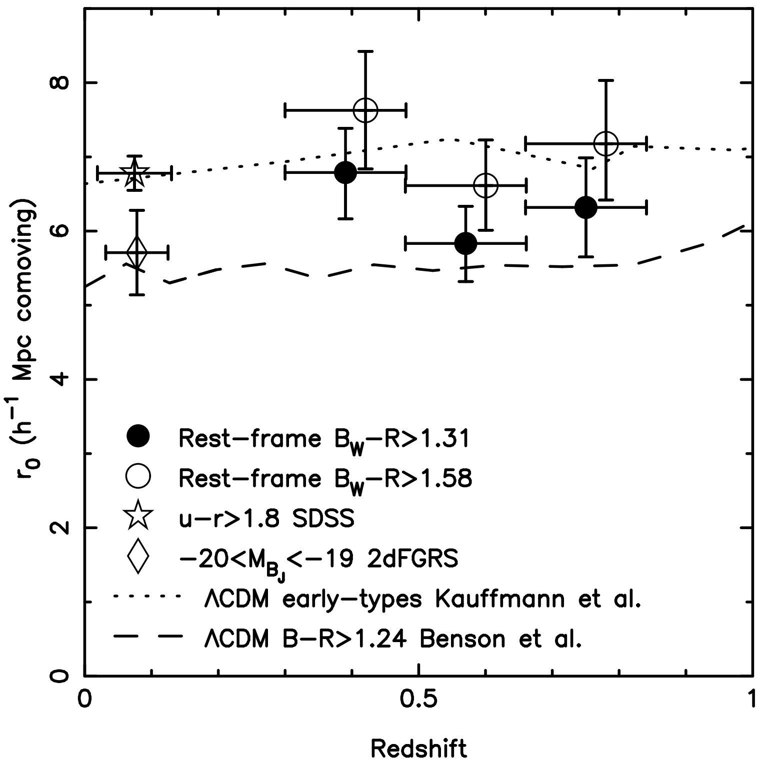

Fig. 1.3. The clustering of early-type galaxies as a function of redshift from the NDWFS, SDSS and 2dFGRS. The horizontal bars indicate the photometric (NDWFS) and spectroscopic (2dFGRS, SDSS) redshift ranges. The clustering of early-type galaxies is well approximated by ΛCDM simulations of the clustering of early-type and $B-R > 1.24$ galaxies (Kauffmann et al. 1999, Benson et al. 2001, Benson private communication). From the plot, it is clear the value of r_0 (in comoving coordinates) undergoes little or no evolution over the redshift range observed.

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