THE CLUSTERING OF AGNs AND GALAXIES AT INTERMEDIATE REDSIFT

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ABSTRACT

Galaxies in the environments of 69 0.2 < z < 0.7, UBR-selected active galactic nuclei (AGNs) have been imaged to B_T ∼ 23.5. By applying photometric redshifts and color selection criteria to the galaxy catalog, the AGN-galaxy cross-correlation function has been measured as a function of galaxy type. The spatial cross-correlation of AGNs with red (early-type) galaxies is comparable to the autocorrelation function of elliptical galaxies at low redshift. In contrast, the cross-correlation of AGNs with blue (late-type) galaxies is weak and has been detected with low significance. Since blue galaxies dominate B_T ∼ 23.5 galaxy catalogs, the cross-correlation of UBR-selected AGNs with all galaxies is weak at intermediate redshifts.

Key words: galaxies: active — large-scale structure of universe — quasars: general

1. INTRODUCTION

The association of active galactic nuclei (AGNs) hosts with other galaxies is well established (Bahcall, Schmidt, & Gunn 1969; Yee & Green 1987; Hall & Green 1998; Laurikainen & Salo 1995; Smith, Boyle, & Maddox 1995, 2000) and provides constraints on the models for the formation and fueling of AGNs. In addition, since quasi-stellar objects (QSOs) can be used to trace large-scale structure at z ≥ 1 (Boyle et al. 1999), estimates of the QSO environments are required to estimate their bias with respect to galaxies that are used to trace large-scale structure at z < 1.

Several previous studies of AGN environments are summarized in Table 1. Radio-loud AGNs are typically found in environments comparable to galaxy clusters (Yee & Green 1987; Hall & Green 1998; Wold et al. 2000), while z < 0.3 radio-quiet AGNs appear to be associated with poorer environments similar to field galaxies (Laurikainen & Salo 1995; Smith et al. 1995; De Robertis, Yee, & Hayhoe 1998). While the z > 0.3 radio-quiet AGN-galaxy cross-correlation function is comparable to the clustering of field galaxies (Smith et al. 2000), it has only been detected with ∼2 σ significance (Ellingson, Yee, & Ghee 1991; Teplitz, McLean, & Malkan 1999; Smith et al. 2000), and no detailed information is available on the strength or evolution of galaxy clustering around radio-quiet AGNs at these redshifts.

Previous studies of AGN environments have typically used galaxy catalogs derived from single-band imaging. Galaxy evolution and k-corrections result in a changing morphological mix of galaxies as a function of redshift and depth. Since galaxy clustering is correlated with morphology and color, the clustering properties of galaxies are also a function of redshift and the observer’s bandpass. It is therefore plausible that estimates of AGN environments at z > 0.3 have been biased by the changing properties of the galaxy catalogs selected from single-band imaging. By using color selection, it is possible to select the same galaxy type as a function of redshift. By measuring the cross-correlation function of AGNs with early- and late-type galaxies, it is possible to determine if radio-quiet AGNs are in unusual environments.

2. DATA

2.1. Galaxy Sample

The galaxy sample has been previously used by Brown, Webster, & Boyle (2000) to measure the clustering of galaxies as a function of color, and a more detailed description of the catalog is provided by Brown et al. (2000) and Brown (2000). The image data consist of 5° × 5° images of the south Galactic pole (SGP) and UK Schmidt field 855 (F855). The images were produced by stacking SuperCOSMOS scans of UK Schmidt photographic plates in the U, B, J, R, and I bands. Object detection, instrumental photometry, and faint object star-galaxy classifications were determined with SExtractor (Bertin & Arnouts 1996). Photometric calibration of the data was determined with CCD images and published photometry. To prevent dust extinction from introducing spurious large-scale structure, magnitude estimates are corrected with the extinction estimates of Schlegel, Finkbeiner, & Davis (1998). The final galaxy catalogs are complete to B_T ∼ 23.5 and contain ∼2 × 10^5 galaxies per field.

2.2. AGN Sample

The AGN sample consists of 69 0.2 < z < 0.7, UBR-selected broad emission line AGNs from La Franca et al. (1999). The survey area is the SGP field, and while the catalog does not have homogeneous sky coverage, it is not strongly concentrated in any one part of the field. As the F855 field only contains seven 0.2 < z < 0.7 AGNs with published positions (Verón-Cetty & Verón 2000), the F855 field has not been used to measure AGN-galaxy clustering. AGN positions were determined by selecting B_T < 23.5 objects in the stacked SuperCOSMOS scans within 5° of the published positions. The resulting catalog of AGNs contained 69 B_T < 21 objects with U − B_T < 0.1 colors. The B_T
| Reference                  | AGN Type | Number of AGNs | AGN Redshift Range | AGN Magnitudes | Galaxy Magnitude Limit | Correlation Function Estimate |
|----------------------------|----------|----------------|--------------------|----------------|------------------------|-------------------------------|
| De Robertis et al. 1998    | Seyferts | 33             | $z < 0.04$         | $-23.0 < M_R < -18.5$ | $M_R < -19.5$            | $r_0 \sim 5.4$                |
| Laurikainen & Salo 1995    | Seyfert 1 | 55             | $z < 0.05$         | $-22.0 < M_V < -17.0$ | $B_J < 21$              | $r_0 \sim 5$                  |
|                            | Seyfert 2 | 49             | $z < 0.05$         | $-21.5 < M_V < -21.5$ | $B_J < 21$              | $r_0 > 5$                     |
| Yee & Green 1987           | RQ QSOs  | 33             | $z < 0.3$          | $-26.0 \leq M_R \leq -23.5$ | $r \leq 21.5$          | $r_0 \sim 8$                  |
| Smith et al. 1995          | X-ray QSOs | 169          | $z < 0.3$          | $-23.5 < M_R < -17.0$ | $B_J < 20.5$            | $r_0 \sim 5$                  |
| Yee & Green 1987           | RQ QSOs  | 7              | $0.3 < z < 0.6$    | $-26.5 \leq M_R \leq -23.5$ | $r \leq 21.5$          | $r_0 \sim 6$                  |
| Ellingson et al. 1991      | RQ QSOs  | 46             | $0.3 < z < 0.6$    | $-24.0 < M_R < -18.5$ | $r \sim 23.5$          | $r_0 \sim 6$                  |
| This work (AGN-early)      | UBR AGN  | 69             | $0.2 < z < 0.7$    | $-24.0 < M_V < -19.0$ | $B_J < 23.5$            | $r_0 \sim 8$                  |
| Smith et al. 2000          | X-ray QSOs | 83           | $0.3 < z < 0.7$    | $-26.0 < M_V < -17.5$ | $V = 23$                | $r_0 \sim 3$                  |
| Boyle & Couch 1993         | QSOs     | 27             | $0.9 < z < 1.7$    | $-24.0 < M_R < -22.0$ | $R < 23$                | No correlation                |
| Teplitz et al. 1999        | RQ QSOs  | 30             | $0.9 < z < 2.1$    | $-26.5 < M_V < -20.6$ | $I, J, H \sim 21, K$   | $2 \sigma$ correlation         |
| Croom & Shanks 1999        | RQ QSOs  | 150            | $0.0 < z < 3.2$    | $B \lesssim 22$     | $B_J < 23$              | No correlation                |
| Yee & Green 1987           | RL QSOs  | 10             | $0.3 < z < 0.5$    | $-25.0 \leq M_V \leq -23.5$ | $r \leq 21.5$          | $r_0 \sim 9$                  |
| Wold et al. 2000           | RL QSOs  | 9              | $0.55 < z < 0.82$  | $-25.5 \leq M_V \leq -23.5$ | $r \leq 21.5$          | $r_0 \sim 17$                 |
| Hall & Green 1998          | RL QSOs  | 31             | $1.0 < z < 2.0$    | $-27.5 < M_V < -24.0$ | $V, R \sim 23.5, I$    | $r_0 \sim 11.7$               |

TABLE 1
SAMPLE OF STUDIES OF AGN ENVIRONMENTS
absolute magnitudes and redshifts of the AGNs are plotted in Figure 1. The catalog contains 36 QSOs \( M_{b_j} < -21.5 + 5 \log h \), where \( H_0 = 100 \ \text{km s}^{-1} \ \text{Mpc}^{-1} \) and 33 Seyfert 1 galaxies. Five of the AGNs are within 20° of the 1.4 GHz sources detected by the NRAO VLA Sky Survey (Condon et al. 1998), but all have fluxes less than 60 mJy and 1.4 GHz luminosities less than \( 10^{26} \ \text{W Hz}^{-1} \).

2.3. Photometric Redshifts

Approximately 700 \( 0 < z < 0.8 \) galaxy redshifts in the SGP and F855 fields are available from the NED.1 Spectroscopic redshifts are available for galaxies as faint as \( B_j \sim 22 \), so it is possible to use multicolor photometry and spectroscopic redshifts of galaxies in the SGP and F855 fields to calibrate the photometric redshifts. The relationship between the multicolor photometry and the galaxy redshift was determined by fitting quadratic functions to the data (Connolly et al. 1995). The relationship was determined for \( U_B R I \), \( U B_j R \), \( B_j R I \), and \( B_j R \) photometry, since only a small fraction of the catalog is detected in all four bands. Figure 2 shows a comparison of the photometric and spectroscopic redshifts for galaxies in the two fields. While \( B_j R \) photometric redshifts are poorer than the photometric redshifts derived in three or more bands, they do place useful constraints on the redshifts. Error estimates for the photometric redshifts have been determined by measuring the rms of the residuals as a function of photometric redshift and color. The accuracy of the photometric redshifts is a function of galaxy color and, as shown in Figure 3, red galaxies have comparatively small errors.

2.4. Color Selection

A significant bias present in most studies of the AGN environment is that they have relied on small samples or single-band imaging. Galaxy evolution and \( k \)-corrections result in a changing morphological mix of galaxies as a function of limiting magnitude with single-band imaging. Galaxy catalogs in bands bluer than \( R \) are dominated by weakly clustered (blue) late-type galaxies at magnitudes fainter than \( B_j \sim 22 \) (Efstathiou et al. 1991).

Multicolor imaging provides significant advantages for the study of the AGN host environment. Colors and photo-

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1 The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Fig. 4.—Colors and photometric redshifts of galaxies with morphological classifications from Abraham et al. (1996) and Smail et al. (1997). The solid line is an estimate of the color of a nonevolving Sbc determined with a polynomial fit to the $k$-corrections from Coleman et al. (1980). Most early-type galaxies are redder than the nonevolving Sbc’s.

Fig. 5.—$18.0 < B_J < 22.5$ galaxy angular correlation functions for the SGP and F855 fields. The autocorrelation function of early-subsample galaxies is significantly stronger than the autocorrelation function of late-subsample galaxies. Power laws fitted to the less than 0.3 data are good approximations to the observed clustering on most angular scales.

Fig. 6.—Photometric redshifts of galaxies with morphological classifications from Abraham et al. (1996) and Smail et al. (1997). The solid line is an estimate of the color of a nonevolving Sbc determined with a polynomial fit to the $k$-corrections from Coleman et al. (1980). Most early-type galaxies are redder than the nonevolving Sbc’s.

photometric redshifts can be used to select particular galaxy types at faint magnitudes. Since galaxy clustering is strongly correlated with color (Brown et al. 2000) and morphology (Davis & Geller 1976; Loveday et al. 1995), studying the cross-correlation of AGNs with particular galaxy types should help determine whether AGN hosts are in unusual galaxy environments.

The color criteria applied to the galaxy catalog select galaxies redder or bluer than a nonevolving Sbc in $B_J-R$, where the color as a function of redshift is determined with $k$-corrections from Coleman, Wu, & Weedman (1980). The use of $B_J-R$ rather than shallower $U-B_J$ or $R-I$ allows the selection of $B_J = 23.5$ early-type galaxies at $z \sim 0.5$. Since the $B_J-R$ selection criteria are a function of redshift, photometric redshifts are used to determine the correct value of $B_J-R$ when selecting galaxies. For the remainder of this paper, the early and late subsamples will refer to galaxies redder or bluer than the $B_J-R$ selection criteria. Figure 4, a plot of the colors and photometric redshifts of galaxies in the SGP with HST morphologies (Abraham et al. 1996; Smail et al. 1997), shows that the color selection criteria are capable of selecting different types of galaxies.

3. ANGULAR AND SPATIAL CORRELATION FUNCTIONS

The angular correlation function estimates the fractional excess of object pairs at a given angular separation compared with what would be expected for a random distribution of objects. The estimators of the angular correlation function used in this paper require random object catalogs, which are produced by making copies of the galaxy catalog and randomly repositioning the copied galaxies across the field.
The angular autocorrelation function of galaxies is estimated with

\[ \hat{\omega}(\theta) = \frac{DD - 2DR + RR}{RR} \]

(Landy & Szalay 1993), where DD, DR, and RR are the number of galaxy-galaxy, galaxy-random, and random-random pairs at angular separation \( \theta \pm \delta \theta \). The Landy & Szalay (1993) estimator is only applicable to the autocorrelation function, so the AGN-galaxy (and early-late) cross-correlation function is determined with

\[ \hat{\omega}(\theta) = \frac{AG}{AR} - 1, \]

where AG and AR are the number of AGN-galaxy and AGN-random pairs at angular separation \( \theta \pm \delta \theta \). The random errors of AR, DR, and RR are reduced by taking the average of multiple estimates of each parameter, where each estimate has been determined with a different random object catalog. Both estimators of the angular correlation function satisfy the integral constraint,

\[ \int \int \hat{\omega}(\theta) d\Omega_1 d\Omega_2 \approx 0 \]

(Groth & Peebles 1977), resulting in an underestimate of the angular correlation function. To remove this bias from the correlation function, the term

\[ \omega(\theta)_{\Omega} = \frac{1}{\Omega^2} \int \int \omega(\theta) d\Omega_1 d\Omega_2 \]

is added to the estimate of the correlation function. The term \( \omega(\theta)_{\Omega} \) does require an assumption of the form of the correlation function to correctly estimate the value of the correlation function.

Galaxy angular correlation functions are typically approximated by power laws of the form

\[ \omega(\theta) = A \theta^{1-\gamma}, \]

where \( A \) is a constant and \( \gamma \sim 1.7 \). The corresponding spatial correlation function is given by

\[ \xi(r, z) = (r/r_0)^{-\gamma}(1 + z)^{-(3+\epsilon)}, \]

where \( r \) is the separation of the galaxies in physical coordinates and \( r_0 \) and \( \epsilon \) are constants. For \( \epsilon = 0 \) and \( \epsilon = \gamma - 3 \), the clustering properties are fixed in physical and comoving coordinates, respectively. The relationship between the angular and spatial correlation functions is given by Limber’s equation (Limber 1954). If \( \xi(r, z) \sim 0 \) when \( r \geq 0.1z \), then Limber’s equation is given by

\[ \omega(\theta) = \int \frac{dN_1}{dz} \left\{ \int \xi[r(\theta), z] \frac{dN_2}{dz'} dz' \right\} dz / \int \frac{dN_1}{dz} \int \frac{dN_2}{dz} dz \]

(Phillipps et al. 1978), where \( dN_1/dz \) and \( dN_2/dz \) are the redshift distributions of each set of objects (e.g., the early and late subsamples), and \( r(\theta) \) is the distance between two objects at \( z \) and \( z' \), separated by angle \( \theta \) on the sky. For the AGN-galaxy correlation function, the redshifts of each AGN are known, so Limber’s equation can be written as

\[ \omega(\theta) = \sum_i^n \left\{ \int \xi_{ag}[r(\theta), z] \frac{dN_1}{dz} dz \right\} / \sum_i^n \left( \int \frac{dN_1}{dz}^2 dz \right), \]

where \( n \) is the number of AGNs, \( dN_1/dz \) is the number of galaxies per unit redshift, and \( r(\theta) \) is the distance in physical coordinates between an AGN at redshift \( z_i \) and a galaxy at redshift \( z \), separated by angle \( \theta \) on the sky.

4. CLUSTERING OF FAINT GALAXIES

Estimates of the clustering of \( z \sim 0.5 \) galaxies are required if the environment of AGN hosts is to be compared with the “normal” galaxy environment. To make the comparison valid, the same galaxy selection criteria are applied to the study of galaxy-galaxy clustering as AGN-galaxy clustering. The early- and late-subsample autocorrelation functions and the early-late cross-correlation functions have been determined in the SGP and F855 fields. Plots of the 18.0 < \( B_j < 22.5 \) angular correlation functions are shown in Figure 5. The amplitudes and values of the \( \gamma \) as a function of magnitude are summarized in Tables 2–4. The value of \( \gamma \) and the amplitude of the clustering strongly depend on color (Brown et al. 2000). The observed clustering in the SGP is consistently stronger than the observed clustering in F855 at bright magnitudes. However, at fainter magnitudes the difference between the clustering properties in the two fields is significantly reduced and the late-subsample autocorrelation functions are comparable. At faint magnitudes, the estimates of \( \gamma \) for the early-late cross-correlation function in the SGP and F855 fields differ by \( \sim 2 \sigma \). It is possible that this is due to the cross-correlation function estimator having larger errors than predicted by the Poisson estimate (Landy & Szalay 1993). In addition, at faint magnitudes in the F855 field, the early-late cross-correlation function is comparable to the expected variations in the galaxy number counts introduced by errors in the dust extinction estimates.

To determine the spatial correlation function, an estimate of the redshift distribution is required. Estimates of the redshift distribution derived from luminosity functions, \( k \)-corrections, and evolution models are subject to uncertainties, since a range of models can reproduce the observed number counts. Models that assume a shape for the redshift distribution (Baugh & Efstathiou 1993) are useful for single-band imaging of low-redshift galaxies but are not as effective for multicolor-selected samples at higher redshifts, for which the selection criteria and \( k \)-corrections skew the redshift distribution.

Photometric redshifts contain information on the redshift distribution but assume that galaxies with the same colors and magnitudes are at the same redshifts. If the errors of the photometric redshifts are dominated by the redshift distribution of galaxies with the same multicolor photometry, it should be possible to derive a redshift distribution using the measured errors of the photometric redshifts. The redshift distribution has been estimated by smoothing the photometric redshift distribution with a Gaussian, where the \( \sigma \) of the Gaussian is given by the rms of the errors of the redshift estimates. At \( z < 0.05 \), the redshift distribution has been multiplied by \( z/0.05 \) to prevent an infinite density of galaxies at \( z = 0 \). Figure 6 shows the observed redshift distribution of galaxies from Glazebrook et al. (1995) detected in the stacked scans and models derived from their photometric redshifts. There is reasonable agreement between the measured and model distributions, although the galaxy number counts are limited. While the exact redshift distributions have not been determined, it is unlikely that large errors dominate the model redshift distributions.
The estimated redshift distributions of the early and late subsamples are plotted in Figure 7. The photometric redshifts of blue galaxies have large error estimates, and this results in the late-subsample redshift distribution being significantly broader than the early-subsample redshift distribution. The width of the distribution is consistent with late-type galaxies having smaller k-corrections and a higher fraction of dwarf galaxies than early-type galaxies. It should be noted that while the photometric redshifts are complete to \(B_J = 23.5\) for the early subsample, photometric redshifts for \(B_J > 22.5\) late-subsample galaxies are incomplete, and this may slightly skew the redshift distribution.

The amplitudes of the early and late autocorrelation functions and early-late cross-correlation function have

**TABLE 2**  
**Early-Sample Angular Correlation Function**

| Field Magnitude Range | \(N_{gal}\) | \(\gamma\) | \(\alpha(\ell) \times 10^3\) | \(N_{gal}\) | \(\gamma\) | \(\alpha(\ell) \times 10^3\) |
|-----------------------|-------------|-------------|-----------------------------|-------------|-------------|-----------------------------|
| 18.0 \(\leq B_J \leq 20.0\) ............... | 2206 | 1.70 ± 0.11 | 1352 ± 233 | 2599 | 1.79 ± 0.31 | 782 ± 196 |
| 18.0 \(\leq B_J \leq 21.0\) ............... | 5187 | 1.79 ± 0.08 | 830 ± 83 | 5553 | 2.02 ± 0.19 | 525 ± 78 |
| 18.0 \(\leq B_J \leq 22.0\) ............... | 11056 | 1.74 ± 0.04 | 510 ± 51 | 11303 | 1.94 ± 0.09 | 326 ± 34 |
| 18.0 \(\leq B_J \leq 23.0\) ............... | 21833 | 1.81 ± 0.05 | 283 ± 28 | 21652 | 1.87 ± 0.07 | 194 ± 19 |
| 18.0 \(\leq B_J \leq 23.5\) ............... | 29290 | 1.84 ± 0.06 | 221 ± 22 | 27915 | 1.89 ± 0.05 | 169 ± 17 |

**TABLE 3**  
**Late-Sample Angular Correlation Function**

| Field Magnitude Range | \(N_{gal}\) | \(\gamma\) | \(\alpha(\ell) \times 10^3\) | \(N_{gal}\) | \(\gamma\) | \(\alpha(\ell) \times 10^3\) |
|-----------------------|-------------|-------------|-----------------------------|-------------|-------------|-----------------------------|
| 18.0 \(\leq B_J \leq 20.0\) ............... | 3854 | 1.35 ± 0.27 | 443 ± 257 | 4648 | 1.57 ± 0.37 | 289 ± 87 |
| 18.0 \(\leq B_J \leq 21.0\) ............... | 11952 | 1.39 ± 0.13 | 260 ± 25 | 13866 | 1.62 ± 0.16 | 157 ± 21 |
| 18.0 \(\leq B_J \leq 22.0\) ............... | 37785 | 1.33 ± 0.10 | 120 ± 9 | 43047 | 1.42 ± 0.15 | 76 ± 7 |
| 18.0 \(\leq B_J \leq 23.0\) ............... | 128278 | 1.29 ± 0.09 | 44 ± 8 | 134331 | 1.31 ± 0.18 | 37 ± 16 |
| 18.0 \(\leq B_J \leq 23.5\) ............... | 207390 | 1.34 ± 0.12 | 28 ± 4 | 183347 | 1.33 ± 0.12 | 27 ± 5 |

**TABLE 4**  
**Early-Late Angular Cross-Correlation Function**

| Field Magnitude Range | \(\gamma\) | \(\alpha(\ell) \times 10^3\) | \(\gamma\) | \(\alpha(\ell) \times 10^3\) |
|-----------------------|-------------|-----------------------------|-------------|-----------------------------|
| 18.0 \(\leq B_J \leq 20.0\) ............... | 1.43 ± 0.25 | 430 ± 105 | 1.33 ± 0.35 | 202 ± 70 |
| 18.0 \(\leq B_J \leq 21.0\) ............... | 1.67 ± 0.08 | 322 ± 30 | 1.48 ± 0.14 | 204 ± 22 |
| 18.0 \(\leq B_J \leq 22.0\) ............... | 1.73 ± 0.06 | 183 ± 10 | 1.58 ± 0.08 | 102 ± 8 |
| 18.0 \(\leq B_J \leq 23.0\) ............... | 1.76 ± 0.04 | 85 ± 4 | 1.59 ± 0.08 | 52 ± 3 |
| 18.0 \(\leq B_J \leq 23.5\) ............... | 1.65 ± 0.04 | 56 ± 3 | 1.46 ± 0.09 | 40 ± 2 |

**TABLE 5**  
**Spatial Autocorrelation and Cross-Correlation Functions of Galaxies**

| Correlation Function Samples | Galaxy Magnitude Range | Field | \(\gamma\) | \(r_0 (h^{-1}\text{Mpc})\) | \(r_0 (h^{-1}\text{Mpc})\) |
|-----------------------------|-----------------------|-------|-------------|-----------------------------|-----------------------------|
| Early-Early ................. | 18.0 \(\leq B_J \leq 22.5\) | SGP | 1.90 | 6.6 ± 0.3 | 7.7 ± 0.3 |
| Late-Late .................... | 18.0 \(\leq B_J \leq 22.5\) | SGP | 1.35 | 4.5 ± 0.2 | 5.9 ± 0.3 |
| Early-Late ................... | 18.0 \(\leq B_J \leq 22.5\) | F855 | 1.65 | 5.0 ± 0.2 | 6.1 ± 0.2 |
| Early-Early .................. | 18.0 \(\leq B_J \leq 23.5\) | SGP | 1.90 | 5.8 ± 0.2 | 7.0 ± 0.2 |
| Late-Late .................... | 18.0 \(\leq B_J \leq 23.5\) | SGP | 1.35 | 2.5 ± 0.2 | 3.6 ± 0.3 |
| Early-Late ................... | 18.0 \(\leq B_J \leq 23.5\) | F855 | 1.65 | 4.0 ± 0.1 | 5.1 ± 0.2 |
| Early-Late ................... | 18.0 \(\leq B_J \leq 23.5\) | F855 | 1.65 | 3.0 ± 0.2 | 4.0 ± 0.2 |
been plotted in Figure 8. To allow the comparison of the amplitude at different magnitudes, \( \gamma \) has been fixed for all magnitudes to the average value of \( \gamma \) for the SGP and F855 18.0 < \( B_J \) < 22.5 correlation functions. Models with the clustering fixed in comoving coordinates have been fitted to the 18.0 < \( B_J \) < 22.5 mag range for the SGP and F855 fields. The models have been fitted to this magnitude range, since it includes a large number of galaxy-galaxy pairs, while avoiding systematic errors that could be present near the magnitude limits of the data. Additional estimates of \( r_0 \) with clustering fixed in comoving and physical coordinates are provided in Table 5.

Figure 8 shows that the clustering in the SGP is consistently stronger than the clustering in F855 for 18.0 < \( B_J \) < 22.5 galaxies. Before concluding that large-scale structure is responsible for the observed difference between the clustering in the two fields, it is useful to exclude the most plausible sources of error. Systematic errors in the \( B_J - R \)
Fig. 8a

Fig. 8b

Fig. 8c

Fig. 8.—Amplitudes of the early and late autocorrelation functions and the early-late cross-correlation function. Models fitted to the $B_J = 22.5$ data points with clustering fixed in comoving coordinates are shown. The median redshifts of the early and late subsamples as a function of depth are listed at the top of (a) and (b). The difference between the observed clustering in the two fields generally decreases as a function of magnitude.

colors of $\sim 0.2$ mag in the two fields only slightly alter the observed clustering in each field and are inconsistent with galaxy number counts, color-color diagrams, and published photometry. Large uniform errors in the photometry in all four bands can bring the clustering at bright magnitudes into agreement, but they are also inconsistent with galaxy number counts and published photometry. The Schlegel et al. (1998) dust maps estimate $E(B - V) \sim 0.05$ in the F855 field, and errors in the dust extinction estimates could introduce systematic errors. However, errors in the dust extinction estimates should produce the largest discrepancies at faint magnitudes, where the amplitude of the angular correlation function is small rather than at bright magnitudes.

It is therefore not implausible that the difference between the two fields is due to large-scale structure. The distribution of galaxy clusters in both fields shows evidence of structures comparable to the field of view (Brown et al. 2000; Brown 2000), and the SGP may contain several “sheets” of galaxies (Broadhurst et al. 1990), although it is uncertain if this is particularly unusual (Kaiser & Peacock 1991). The effects of large-scale structure on estimates of the correlation function should decrease with increasing survey volume, and this is consistent with the observed difference between the clustering in the two fields decreasing with increasing depth. While it is unexpected to see weakly clustered late-subsample galaxies showing the effects of large-scale structure, the discrepancy between the two fields disappears for bluer galaxies selected with $U - B_J < 0.4$ (Brown et al. 2000). Since it is uncertain which field is more representative of the universe, the discussion of AGN-galaxy clustering in the SGP assumes that estimates of $r_0$ could have systematic errors comparable to the difference between the estimates of $r_0$ in the SGP and F855 ($\sim 1 h^{-1}$ Mpc).

Models for the clustering of early-subsample galaxies in each field are a reasonable approximation to the observed clustering, and the estimates of the spatial correlation function are comparable to the clustering of early-type galaxies in the local universe (Loveday et al. 1995; Guzzo et al. 1997). In contrast, the observed amplitude of the late-subsample autocorrelation function is an order of magnitude weaker, and the models are a poor fit to the data. At $B_J > 22$, the amplitude of the correlation function rapidly decreases because of the increasing number of weakly clustered faint blue galaxies (Efstathiou et al. 1991; Brown et al. 2000). The amplitude of the early-late cross-correlation function also decreases at faint magnitudes, although...
Fig. 9.—AGN-early and AGN-late angular cross-correlation functions. The AGN-early correlation function is significantly stronger than the AGN-late correlation function. While a power law is a good approximation to the observed AGN-early cross-correlation function, a power-law fit to the AGN-late cross-correlation function is a poor fit to the data.

Fig. 10.—Amplitude of the AGN-early angular cross-correlation function. Models with clustering fixed in comoving and physical coordinates have been fitted to the $B_J = 22.5$ data point. The clustering is significantly stronger than the autocorrelation function of early-subsample galaxies.

Fig. 11.—Angular cross-correlation of AGNs and $B_J < 22.5$ early-subsample galaxies, with photometric redshift constraints applied to the pair counts. Poisson statistics have been used to determine the 1$\sigma$ errors shown with the data points. A power law with $\gamma = 1.90$ is a good fit to the data.

**Table 7**

| Magnitude Range | Angle (arcsec) | AG | $AR \times 20$ | $\omega(\theta)$ |
|-----------------|----------------|----|----------------|------------------|
| $18.0 \leq B_J \leq 22.5$ | $10 \leq \theta < 20$ | 15 | 320 | $-0.06 \pm 0.35$ |
| | $20 \leq \theta < 40$ | 53 | 1183 | $-0.10 \pm 0.12$ |
| | $40 \leq \theta < 80$ | 263 | 4680 | $0.13 \pm 0.07$ |
| | $80 \leq \theta < 160$ | 949 | 1911 | $0.00 \pm 0.03$ |
| | $160 \leq \theta < 320$ | 3812 | 76187 | $0.00 \pm 0.02$ |
| | $320 \leq \theta < 640$ | 15602 | 303404 | $0.03 \pm 0.01$ |
| $18.0 \leq B_J \leq 23.5$ | $10 \leq \theta < 20$ | 42 | 905 | $-0.07 \pm 0.14$ |
| | $20 \leq \theta < 40$ | 175 | 3333 | $0.05 \pm 0.08$ |
| | $40 \leq \theta < 80$ | 751 | 13747 | $0.09 \pm 0.04$ |
| | $80 \leq \theta < 160$ | 2805 | 55104 | $0.02 \pm 0.02$ |
| | $160 \leq \theta < 320$ | 11166 | 221132 | $0.01 \pm 0.01$ |
| | $320 \leq \theta < 640$ | 45032 | 880067 | $0.03 \pm 0.01$ |
models of the spatial correlation function are better approximations to the observed clustering. While the values of $r_0$ for the early-late cross-correlation function are similar to those for the late-subsample autocorrelation function, the larger value of $c$ results in significantly stronger clustering on scales of $\lesssim 1 \, h^{-1} \text{Mpc}$.

5. AGN-GALAXY CLUSTERING

Estimates of the cross-correlation of AGNs with the early and late subsamples are summarized in Tables 6–8. The AGN-early cross-correlation is significantly stronger on scales $\gtrsim 1'$, while on smaller scales the signal-to-noise ratio is poor. Despite the strength of the AGN-early cross-correlation, inspection of Tables 6 and 7 shows most AGN-galaxy pairs are AGN-late pairs, and the cross-correlation of AGNs with all galaxies will be similar to the AGN-late cross-correlation function.

The AGN-early and AGN-late angular cross-correlation functions for $B_J < 22.5$ galaxies are shown in Figure 9. Power laws with $\gamma$ fixed to 1.90 and 1.65 have been fitted to the AGN-early and AGN-late data on angular scales less than 0.3. The AGN-early cross-correlation function is strong, and the power-law fit is a good approximation to the observed clustering, although most of the data points are $\gtrsim 1 \sigma$ from the fit. In contrast, the AGN-late cross-correlation is weak, and a power law is a poor fit to the data. From the available data, the amplitude of the AGN-late cross-correlation function cannot be reliably measured.

The amplitude of the AGN-early cross-correlation function is plotted in Figure 10, along with models of the cross-correlation, with evolution fixed in comoving and physical coordinates. While the amplitude of the angular cross-correlation function is typically less than the early-subsample autocorrelation function, the difference between the early subsample and AGN-redshift distributions results in the estimates of being significantly higher than that of the early-subsample autocorrelation function.

The errors of the $\phi(\theta)$ estimates are dominated by galaxies along the line of sight that are not associated with the

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**TABLE 8**

| Magnitude Range | Angle (arcsec) | AG | AR x 20 | $\phi(\theta)$ |
|-----------------|---------------|----|---------|----------------|
| $18.0 \leq B_J \leq 22.5$ | 10 $\leq \theta < 20$ | 1 | 20 | $0.07 \pm 0.20$ |
| | 20 $\leq \theta < 40$ | 10 | 133 | $0.51 \pm 0.45$ |
| | 40 $\leq \theta < 80$ | 40 | 518 | $0.48 \pm 0.23$ |
| | 80 $\leq \theta < 160$ | 80 | 2104 | $0.21 \pm 0.10$ |
| | 160 $\leq \theta < 320$ | 160 | 7947 | $0.11 \pm 0.05$ |
| | 320 $\leq \theta < 640$ | 320 | 31708 | $0.08 \pm 0.03$ |
| $18.0 \leq B_J \leq 23.5$ | 10 $\leq \theta < 20$ | 10 | 71 | $0.41 \pm 0.91$ |
| | 20 $\leq \theta < 40$ | 20 | 373 | $0.24 \pm 0.26$ |
| | 40 $\leq \theta < 80$ | 40 | 1388 | $0.28 \pm 0.13$ |
| | 80 $\leq \theta < 160$ | 80 | 5637 | $0.21 \pm 0.07$ |
| | 160 $\leq \theta < 320$ | 160 | 21818 | $0.08 \pm 0.03$ |
| | 320 $\leq \theta < 640$ | 320 | 87823 | $0.08 \pm 0.02$ |

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**FIG. 12**—Amplitude of the AGN-early cross-correlation function with photometric redshift constraints applied. The errors are significantly reduced, and the best fits to the data are slightly decreased. However, the amplitude of the clustering is consistent with the AGNs being in environments comparable to elliptical galaxies. The estimated median redshifts are for early-subsample galaxies that satisfy the photometric redshift constraints rather than the entire early subsample.

**FIG. 13**—Amplitude of the Seyfert 1 and QSO cross-correlation functions with photometric redshift constraints. There is no evidence for a strong correlation between AGN luminosity and host environment.
AGNs. The signal and significance of the correlation function can be improved if the number of unassociated galaxies included in the estimate of $\omega(\theta)$ is reduced. Early-type galaxies have comparatively small photometric redshift errors, so it is possible to define a narrow range of photometric redshifts that could be associated with the AGNs. Figure 11 shows the AGN-early cross-correlation function for galaxies with photometric redshifts within 2 $\sigma$ of the AGN redshift. The inclusion of photometric redshift constraints has significantly improved the signal-to-noise ratio, and the observed correlation function is more consistent with a power law than Figure 9. While deviations from a power law have been seen in some estimates of AGN-galaxy correlation functions (Hall & Green 1998; Croom & Shanks 1999), there are no statistically significant breaks from a power law on scales less than 0.3 $\text{Mpc}$ in Figure 11.

The spatial AGN-early cross-correlation can be determined by deriving the redshift distribution of galaxies with photometric redshifts within 2 $\sigma$ of each AGN, when applying Limber’s equation. The amplitude of the AGN-early cross-correlation and models of the spatial cross-correlation are shown in Figure 12, and the fit to the $B_J = 22.5$ data point is weaker than in Figure 10. However, the estimate of $r_0$ and the power law form of the angular correlation function in Figure 11 are consistent with AGN environments being similar to the environments of strongly clustered galaxies, such as the early subsample and low-redshift ellipticals (Guzzo et al. 1997).

The estimates of $r_0$ are dependent on the assumed value of $\gamma$, and it is possible that $\gamma \ll 1.90$. If radio-quiet AGNs were in spiral galaxies (Hutchings, Crampton, & Campbell 1984; Malkan, Margon, & Chanan 1984) and had similar clustering properties to late-subsample galaxies, the value of $\gamma$ for the AGN-early cross-correlation function would be $\sim 1.65$. However, when the AGN-early cross-correlation function was fitted with power laws with $\gamma \leq 1.65$, the estimates of $r_0$ increased to greater than 11 $h^{-1}$ Mpc, which is approximately double the estimate of $r_0$ for the early-late spatial cross-correlation function.

There may be a correlation between AGN luminosity and host galaxy, if luminous AGNs occur more frequently in early-type galaxies than Seyferts (McLure et al. 1999). If this is the case, the correlation between galaxy morphology and environment may result in a correlation between AGN luminosity and environment. Figure 13 compares the amplitudes of the Seyfert 1 ($M_{B_J} < -21.5$) and QSO ($M_{B_J} > -21.5$) cross-correlation functions with the early subsample. Fits to the $B_J = 22.5$ data point show Seyfert 1’s are correlated with slightly richer environments, but the difference between the $r_0$ estimates has less than 1 $\sigma$ significance.

6. DISCUSSION

While the detection of radio-quiet AGNs in environments similar to early-type galaxies may appear to contradict previous studies at similar redshifts (Yee & Green 1987; Boyle & Couch 1993; Croom & Shanks 1999; Teplitz et al. 1999; Smith et al. 2000), this assumes all studies of AGN-galaxy clustering have used the same galaxy population to measure AGN environments. However, as color selection has been used to select galaxies for this study, the properties of the early and late subsamples will differ significantly from catalogs of galaxies that are selected by observed broadband flux.

Early-subsample galaxies contribute $\sim 30\%$ of the total galaxy counts at $B_J < 21$ and only $\sim 15\%$ of the counts at $B_J > 22$. If the AGN-late cross-correlation function is assumed to be negligible and the AGN-early cross-correlation function is a power law with $r_0 \sim 9 h^{-1}$ Mpc, then the AGN-galaxy cross-correlation function should be a power law with $r_0 \sim 5 h^{-1}$ Mpc at $B_J < 21$ and $r_0 \sim 3 h^{-1}$ Mpc at $B_J > 22$. In redder bands, where the early-type galaxies make up a larger fraction of the total galaxy number counts, stronger clustering will be measured. Early-subsample galaxies make up $\sim 25\%$ of the total $R < 21.5$ galaxy counts, and the AGN-galaxy correlation function would be expected to be $r_0 \sim 4 h^{-1}$ Mpc, even though the redshift range sampled is comparable to that of $B_J \sim 23$ galaxies. These estimates of $r_0$ for $B_J$- and $R$-limited samples are consistent with measurements of the AGN-galaxy cross-correlation function derived from single-band imaging by Yee & Green (1987), Ellingson et al. (1991), and Smith et al. (1995, 2000).

While radio-quiet AGNs occur in environments comparable to early-type galaxies, this should not be interpreted as a direct correlation between richness and AGN activity. As shown in Figure 13, there is no evidence for a strong correlation between AGN luminosity and environment. HST imaging of radio-quiet QSOs and X-ray–selected AGNs indicates $\sim 75\%$ of host galaxies have morphologies earlier than Sbc galaxies (McLure et al. 1999; Schade, Boyle, & Letawsky 2000). It is therefore plausible that AGN activity is not significantly affected by the host environment and that the observed strength of the AGN-early cross-correlation function is due to the correlation between galaxy morphology and clustering properties.

The strength of the AGN-early cross-correlation function implies that it should be detectable at $z > 0.5$. Using samples of early-type galaxies obtained with CCD mosaics on 4 m class telescopes, it will be possible to measure the evolution of the AGN-early cross-correlation function at $z > 1$. This will provide an estimate of the bias of AGNs with respect to galaxies that are used to measure large-scale structure at lower redshifts. If the clustering properties of AGNs are due to the distribution of host galaxy morphologies, the evolution of the AGN-early cross-correlation function will also place strong constraints on the properties of AGN host galaxies as a function of redshift.

7. SUMMARY

The environments of galaxies and $69 \% < z < 0.7$ AGNs have been measured using photometric redshifts and color criteria to select galaxy types to $B_J \sim 23.5$. The key conclusions are as follows: (1) The clustering of early-subsample galaxies is strong across the observed magnitude range with $r_0 \sim 7 h^{-1}$ Mpc and $\gamma \sim 1.90$. (2) The autocorrelation function of late-subsample galaxies is weak and decreases to $r_0 \leq 4 h^{-1}$ Mpc at $B_J \sim 23.5$. This is probably due to the increasing fraction of weakly clustered blue galaxies at faint apparent magnitudes. (3) The cross-correlation function of radio-quiet, $-24 < M_B < -19$ AGNs with early-subsample galaxies has been detected with high significance on scales $\lesssim 1$. The AGN-early spatial cross-correlation function is stronger than the early-subsample autocorrelation function and is comparable to the clustering of elliptical galaxies at $z \sim 0$. (4) The AGN-late cross-correlation function is very weak and has been detected with low sig-
significance. As the fraction of late-type galaxies in magnitude-limited samples increases with survey depth, the cross-correlation function of AGNs with all galaxies decreases with increasing magnitude. (5) The signal-to-noise ratio of AGN-galaxy cross-correlation functions is significantly improved by using photometric redshifts to reject galaxies that cannot be associated with the AGNs from the correlation function estimate. (6) The correlation between AGN optical luminosity and host environment is weak and has not been detected at a significant level in this work.

REFERENCES

Abraham, R. G., van den Bergh, S., Glazebrook, K., Ellis, R. S., Santiago, B. X., Surma, P., & Griffiths, R. E. 1996, ApJS, 107, 1
Bahcall, J. N., Schmidt, M., & Gunn, J. E. 1969, ApJ, 157, L77
Baugh, C. M., & Efstathiou, G. 1993, MNRAS, 265, 145
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Boyle, B. J., & Couch, W. J. 1993, MNRAS, 264, 604
Boyle, B. J., Croom, S. M., Smith, R. J., Shanks, T., Miller, L., & Loaring, N. 1999, in Looking Deep in the Southern Sky, ed. R. Morganti & W. J. Couch (New York: Springer), 16
Broadhurst, T. J., Ellis, R. S., Koo, D. C., & Szalay, A. S. 1990, Nature, 343, 726
Brown, M. J. I. 2000, Ph.D thesis, Univ. Melbourne
Brown, M. J. I., Webster, R. L., & Boyle, B. J. 2000, MNRAS, 317, 782
Coleman, G. D., Wu, C. C., & Weedman, D. W. 1980, ApJS, 43, 393
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Connolly, A. J., Csabai, I., Szalay, A. S., Koo, D. C., Kron, R. G., & Munn, J. A. 1995, AJ, 110, 2655
Croom, S. M., & Shanks, T. 1999, MNRAS, 303, 411
Davis, M., & Geller, M. J. 1976, ApJ, 208, 13
De Robertis, M. N., Yee, H. K. C., & Hayhoe, K. 1998, ApJ, 496, 93
Efstathiou, G., Bernstein, G., Katz, N., Tyson, J. A., & Guhathakurta, P. 1991, ApJ, 380, L47
Ellingson, E., Yee, H. K. C., & Green, R. F. 1991, ApJ, 371, 49
Glazebrook, K., Ellis, R., Colless, M., Broadhurst, T., Allington-Smith, J., & Tanvir, N. 1995, MNRAS, 273, 157
Groth, E. J., & Peebles, P. J. E. 1977, ApJ, 217, 385
Guzzo, L., Strauss, M. A., Fisher, K. B., Giovanelli, R., & Haynes, M. P. 1997, ApJ, 489, 37
Hall, P. B., & Green, R. F. 1998, ApJ, 507, 558
Huchtings, J. B., Crampton, D., & Campbell, B. 1984, ApJ, 280, 41
Kaiser, N., & Peacock, J. A. 1991, ApJ, 379, 482
La Franca, F., Lissandrini, C., Cristiani, S., Miller, S., Hawkins, M. R. S., & MacGillivray, H. T. 1999, A&AS, 140, 351
Landy, S. D., & Szalay, A. S. 1993, ApJ, 412, 64
Laurikainen, E., & Salo, H. 1995, A&A, 293, 683
Limber, D. N. 1954, ApJ, 119, 655
Loveday, J., Maddox, S. J., Efstathiou, G., & Peterson, B. A. 1995, ApJ, 442, 457
Malkan, M. A., Margon, B., & Chanan, G. A. 1984, ApJ, 280, 66
McLure, R. J., Kukula, M. J., Dunlop, J. S., Baum, S. A., O'Dea, C. P., & Hughes, D. H. 1999, MNRAS, 308, 377
Phillips, S., Fong, R., Ellis, R. S., Fall, S. M., & MacGillivray, H. T. 1978, MNRAS, 182, 673
Schade, D., Boyle, B. J., & Letawsky, M. 2000, MNRAS, 315, 498
Schlegel, D., Finkbeiner D. P., & Davis, M. 1998, ApJ, 500, 525
Smail, I., Dressler, A., Couch, W. J., Ellis, R. S., Oemler, A., Butcher, H., & Sharples, R. M. 1997, ApJS, 110, 213
Smith, R. J., Boyle, B. J., & Maddox, S. J. 1995, MNRAS, 277, 270
—. 2000, MNRAS, 313, 252
Teplitz, H. I., McLean, I. S., & Malkan, M. A. 1999, ApJ, 520, 469
Veron-Cetty, M. P., & Veron, P. 2000, A Catalog of Quasars and Active Galactic Nuclei (ESO Sci. Rep. 19/9th ed.; Garching: ESO), 1
Wold, M., Lacy, M., Lilje, P. B., & Sergeant, S. 2000, MNRAS, 316, 267
Yee, H. K. C., & Green, R. F. 1987, ApJ, 319, 28