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LARGE-SCALE CLUSTERING OF GALAXIES IN THE CfA REDSHIFT SURVEY

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ABSTRACT

We use the Center for Astrophysics Redshift Survey, now complete to $m_B \leq 15.5$ over eleven 6° slices, to measure the power spectrum of the galaxy distribution up to wavelengths $\sim 200\ h^{-1}$ Mpc. The combination of large spatial and angular extent with high sampling density allows simultaneous measurement of the power spectrum on both large and small scales.

Comparison with large ($L \gtrsim 400\ h^{-1}$ Mpc) *N*-body simulations of cosmological models shows that the power spectrum of the standard CDM model ($\Omega h = 0.5$ and $\sigma_8 = 1$; see below for definitions) is inconsistent with the observed power spectrum at the 99% confidence level. The power spectrum of an open CDM model ($\Omega h = 0.2$ and $\sigma_8 = 1$) best approximates the observed power spectrum for wavelengths $< 125\ h^{-1}$ Mpc.

Subject headings: cosmology: observations — galaxies: clustering

1. INTRODUCTION

Cosmological models based on the canonical inflation scenario (Bardeen, Steinhardt, & Turner 1983; Bardeen et al. 1986) have Gaussian adiabatic, primordial density fluctuations completely described by their power spectrum [hereafter PS; $P(k) \propto k$ at large scales for the Zel'dovich PS]. The discovery of large-scale coherent features in galaxy redshift surveys (de Lapparent, Geller, & Huchra 1989; Haynes et al. 1988) prompts us to examine whether any such models are consistent with the observations.

Here we measure the PS of the galaxy distribution in the CfA Redshift Survey (Huchra et al. 1983; de Lapparent et al. 1986; Geller & Huchra 1989; Huchra et al. 1992). We compare the results with several cosmological simulations with Gaussian initial conditions. Although the galaxy formation process might have altered the statistics of the galaxy distribution relative to the mass distribution, measurement of the PS of the observed galaxy distribution provides a strong test of the standard models. In subsequent papers (Park et al. 1992b) we plan to examine higher order statistics of galaxy clustering which further differentiate among competing models.

Accurate measurement of the PS of the galaxy distribution requires a galaxy sample which covers a large enough volume to access wavelengths $\gtrsim 100\ h^{-1}$ Mpc *and* which densely traces structure on small scales. The large-scale PS of the galaxy distribution best reflects initial conditions. On small scales we most accurately determine the normalization of the PS. Redshift samples used in previous studies of the PS are typically sparse and the sampling noise introduces large uncertainties. Furthermore, the estimation of uncertainties in the PS and statistical hypothesis tests of conclusions are not based on realistic Monte Carlo simulations (one exception is Park, Gott, & da Costa 1992a).

2. POWER SPECTRUM OF CfA DATA

The extension of the CfA redshift survey (de Lapparent et al. 1986; Geller & Huchra 1989; Huchra et al. 1992) to $m_B \leq 15.5$ (hereafter CfA2) now includes $> 12{,}000$ galaxy redshifts and is complete over eleven 6° "slices" which cover large contiguous regions of both the north and south Galactic hemispheres. These slices sample the galaxy distribution densely out to $\sim 10{,}000$ km s^{-1}. Although not as deep as some pencil beam surveys (Broadhurst et al. 1990; Shectman et al. 1992), the sample has sufficient depth and angular extent to measure the PS on scales exceeding 100 h^{-1} Mpc. The high sampling density of structure also allows accurate measurement of the PS on small scales.

CfA2 North is complete over five 6° slices covering $8^h < \alpha < 17^h$, $20.5° < \delta < 44.5°$ and $8.5° < \delta < 14.5°$ and includes 5248 galaxies. CfA2 South (Huchra et al. 1992) is complete over six 6° slices covering $20^h < \alpha < 4^h$, $6° < \delta < 42°$ and includes 3045 galaxies. To reduce the possible effects of Galactic obscuration (Burstein & Heiles 1982), we limit analysis of CfA2 South to the region $21^h < \alpha < 3^h$ and $b < -25°$, leaving 2153 galaxies.

To cover regions where CfA2 is not yet complete, we combine CfA2 North and South with the shallower CfA1 catalog (Huchra et al. 1983) ($m_B \leq 14.5$), which covers a larger solid angle. We use the CfA1 data exclusively in the incomplete regions of CfA2. CfA1 North includes 1845 galaxies over $b > 40°$ and $\delta > 0°$. CfA1 South includes 556 galaxies over $b < -30°$ and $\delta > -2.5°$. We limit analysis of CfA1 South to $21^h < \alpha < 3^h$, leaving 530 galaxies. From the combined catalog (hereafter CfA1+2) we draw two volume-limited subsamples: a sample of 1554 galaxies with absolute magnitudes $M < -19.5 + 5 \log h$ (hereafter CfA100) and a sample of 409 galaxies with $M < -20.3 + 5 \log h$ (CfA145). CfA100 has outer boundaries at distances of 100 h^{-1} Mpc within CfA2 and 63.1 h^{-1} Mpc within CfA1. The deeper CfA145 sample extends out to 144.5 h^{-1} Mpc within CfA2 and 91.2 h^{-1} Mpc within CfA1.

All analyses of the CfA data are in *redshift* space. We correct the heliocentric velocities for solar motion with respect to the centroid of the Local Group, $\Delta v = 300 \sin(l) \cos(b)$ km s^{-1}.

We use the technique described by Park et al. (1992a) (see also Baumgart & Fry 1991; Peacock & Nicholson 1991) to measure the PS directly from the galaxy distribution in CfA1+2. For a distribution of galaxies within a finite volume,

$$P(\boldsymbol{k}) = \left(\langle |\delta_{\boldsymbol{k}}|^2 \rangle - \frac{1}{N}\right) \Big/ \sum_{\boldsymbol{k}} |M_{\boldsymbol{k}}|^2 .$$

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Here $P(\mathbf{k})$ is the power per mode and $M_{\mathbf{k}}$ is the Fourier transform of the survey region. We refer to the directionally averaged quantity $P(k)$ as the PS. For a sample of N galaxies, the Fourier transform of the galaxy distribution (minus the contribution due to the survey geometry) is given by

$$\delta_{\mathbf{k}} = \frac{1}{N} \sum_{j=1}^{N} e^{i\mathbf{k} \cdot \mathbf{x}_j} - M_{\mathbf{k}} .$$

Thus $P(k)$ accounts for the contributions caused by Poisson noise (the $1/N$ term) and survey geometry, and corrects the normalization for the effects of observing the galaxy distribution through a finite window. Experiments with N-body simulations verify that the PS measured in this way is equal to the real PS for all but the largest wavelength mode. Unlike the two-point correlation function (CF hereafter), the PS should be unaffected by uncertainty in the mean density, measured by the $k = 0$ mode in the PS. However, because we observe the galaxy distribution through a finite window, this uncertainty may affect the measured PS for the largest wavelengths (Peacock & Nicholson 1991). Our correction to the normalization is accurate if the PS is flat or turns over on larger scales but underestimates the true PS if it increases.

We use a Monte Carlo technique to estimate the uncertainty in the CfA PS caused by the finite survey volume and demonstrate that our results are not limited by our use of volume-limited samples. From the variation in PS for 100 mock CfA1+2 surveys drawn from an open CDM simulation (described below), we estimate 95% confidence limits for the CfA100 and CfA145 PS. We linearly scale the uncertainty range in the simulations by the factor $P_{\text{obs}}/P_{\text{model}}$, where the Ps are the PS of the observation and the open CDM model. This random phase approximation (Peebles 1973) has been verified for cosmological simulations with different PS. When we double the number of "galaxies" in mock CfA100 surveys, the uncertainties decrease by less than 10% (by $\sim 1\%$ at high wavenumbers). Thus, the major source of uncertainty is the statistical fluctuation from one survey to another, rather than finite sampling of structures.

Figures 1 and 2 show the CfA1+2 PS as filled circles (CfA100) and filled triangles (CfA145). The PS scales with the survey volume; for straightforward comparison among different survey results we renormalize the PS to $V = (1\ h^{-1}\ \text{Mpc})^3$. Error bars for the CfA PS are 95% confidence limits. For $k > 0.1$, the CfA100 sample has a smaller uncertainty range than the CfA145 sample, while on large scales the CfA145 sample more accurately determines the PS. The arrows in Figure 1 indicate the Poisson noise levels for the CfA samples. The PS of our CfA100 sample has a slope of -2.1 at small scales ($k \geq 0.25$), and a slope of ~ -1.2 for $0.07 \leq k \leq 0.25$. The CfA145 results suggest a turnover at $k \approx 0.05$, but the uncertainties are large. We note an excess in the CfA145 PS at $k \sim 0.12$, or a wavelength scale $\sim 50\ h^{-1}$ Mpc. This feature may be a statistical fluke, but it is interesting to note that this scale corresponds to the diameter of the large voids seen in the CfA, Shectman et al. (1992), and Geller et al. (1992) surveys.

To approximate PS-related quantities for these data, a useful fitting function for the CfA100 PS is given by $P(k) = 2.25P^L_{0.5}/[2.25\alpha P^L_{0.5}\,k^{2.1}(1 - e^{-k/0.1}) + \beta]$. Here $P^L_{0.5} = 335100kT(k, \Omega h = 0.5)$ is the linear CDM PS, $T(k, \Omega h)$ is the CDM transfer function (Bardeen et al. 1986), $\alpha = 0.005$, and $\beta = 1/1.3$. Note that $k = 1$ corresponds to the wavelength $2\pi h^{-1}$ Mpc.

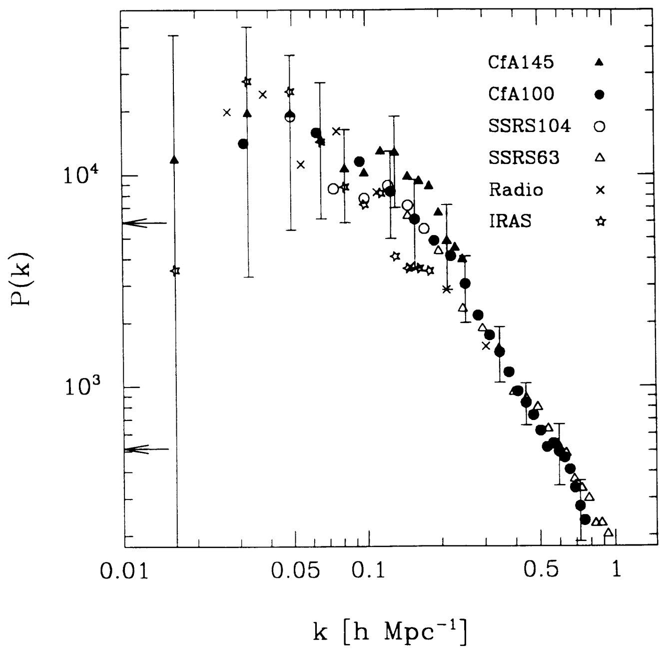

FIG. 1.—Power spectra of galaxy distributions in the CfA1+2 samples (CfA145: $M_{\text{abs}} < -20.3 + 5 \log h$; CfA100: $M_{\text{abs}} < -19.5 + 5 \log h$), the SSRS (Park et al. 1992a) (SSRS104: absolute diameter $D > 38\ h^{-1}$ kpc; SSRS63: $D > 23\ h^{-1}$ kpc), a radio galaxy sample (Peacock & Nicholson 1991), and the *IRAS* QDOT sample (Kaiser 1991). Error bars are 95% confidence limits. The arrows indicate the Poisson noise levels for the CfA145 (*upper arrow*) and CfA100 results. The power spectra are rescaled to a nominal volume of $(1\ h^{-1}\ \text{Mpc})^3$ and $k = 1$ corresponds to the wavelength $2\pi\ h^{-1}$ Mpc.

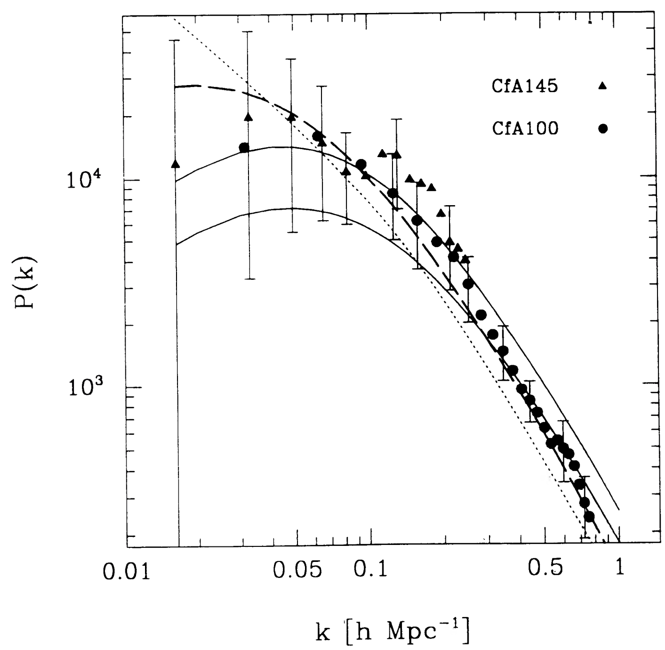

FIG. 2.—Comparison of the observed galaxy power spectra with those of cosmological models in redshift space. Lower and upper solid lines are the $\Omega h = 0.5$ biased CDM models with $\sigma_8 = 1$ and 1.4, respectively, the dashed line is an open CDM model with $\Omega h = 0.2$ and $\sigma_8 = 1$, and the dotted line is a power-law power spectrum model with the spectral index $n = -1$ and $\Omega = 1$. Error bars on observed power spectra are 95% confidence limits.

Figure 1 compares the CfA1 + 2 PS with PS measured from a variety of galaxy redshift surveys. Baumgart & Fry (1991) measure the PS from the CfA1 (Huchra et al. 1983) and the Perseus-Pisces samples (Haynes et al. 1988), but the normalization of their PS is probably incorrect (Peacock & Nicholson 1991; Park et al. 1992a). Because of this uncertainty, we do not plot their results in Figure 1. Kaiser (1991) shows that the large-scale PS (stars in Fig. 1) of the *IRAS* QDOT sample (Rowan-Robinson et al. 1990) (2163 galaxies) differs in slope and amplitude from that of the standard CDM model (Bardeen et al. 1986; Blumenthal et al. 1984). The sparse sampling of the QDOT survey does not allow simultaneous measurement of the small-scale PS. Peacock & Nicholson (1991) measure the PS (crosses in Fig. 1) of 329 radio galaxies with redshifts $z < 0.1$ and claim detection of a break in the PS to a spectral index $n \geq -0.5$ for wavelengths $\lambda \geq 200\ h^{-1}$ Mpc (see also Peacock 1991). However, Figure 1 shows that the turnover at small k may not be statistically significant. Park et al. (1992a) measure the PS from volume-limited samples drawn from the SSRS (da Costa et al. 1988), a diameter-limited sample of 1657 optical galaxies (open circles and open triangles in Fig. 1 for absolute diameter–limited samples SSRS104 and SSRS63, respectively). They also find that the PS has a slope of ~ -2 at $\lambda \leq 30\ h^{-1}$ Mpc and ~ -1 at $30 < \lambda < 128\ h^{-1}$ Mpc.

The PS of the magnitude-limited optical galaxy samples (CfA) agree well with those for diameter-limited optical (SSRS), flux-limited radio, and infrared galaxy samples (note that the radio and *IRAS* QDOT samples are very sparse; thus the high-frequency ranges of their PS are uncertain). This result differs from Peacock & Nicholson's assertion that radio galaxies are more clustered than optical galaxies. This discrepancy may occur because Peacock & Nicholson compare the radio galaxy CF in *redshift space* with Davis & Peebles's (1983, hereafter DP83) estimate of the CF for optical galaxies in *real space*. Furthermore, DP83 derive their CF from the shallower CfA1 sample (which does not include structures like the "Great Wall" in the CfA2 sample).

To demonstrate that our PS is accurate, we compare the Fourier transform (Fig. 3, *solid curve*) of the CfA PS with the CF calculated directly from the full magnitude-limited sample, including galaxies with velocity $v \leq 15{,}000$ km s^{-1} (*open circles*: all galaxies equally weighted; *filled triangles*: selection function weighted). The three functions agree well up to $r \simeq 15$ h^{-1} Mpc. On larger scales, the uncertainty in the mean density causes the discrepancy in the CF for different weightings.

3. ANALYSIS: COMPARISON WITH SIMULATIONS

In Figure 2 we compare the PS of our CfA1 + 2 samples with those measured for simulations of four cosmological models: (1) the canonical biased CDM model with $\Omega h = 0.5$, bias factor $b = 1.5$, and $\sigma_8 = 1$ (*lower solid curve*); (2) a biased CDM model with higher normalization $\sigma_8 = 1.4$, and $b = 1.4$ (*upper solid curve*); (3) an open CDM model with $\Omega h = 0.2$ and $\sigma_8 = 1$ (*dashed curve*); and (4) a power-law PS model with the spectral index $n = -1$, and $\Omega = 1$ (*dotted curve*). Here Ω is the density parameter, h is the Hubble constant divided by 100 km s^{-1} Mpc^{-1}, and σ_8 is the rms "galaxy" density fluctuation in an 8 h^{-1} Mpc radius sphere.

The $\Omega = 1$, $h = 0.5$ CDM simulations were run on a 324^3 mesh corresponding to a physical comoving volume of (388.8 h^{-1} Mpc)^3 by moving 162^3 CDM and 1,201,320 biased particles (see Park 1991 for the biasing scheme) using a particle-mesh N-body code (Hockney & Eastwood 1981; Melott 1986).

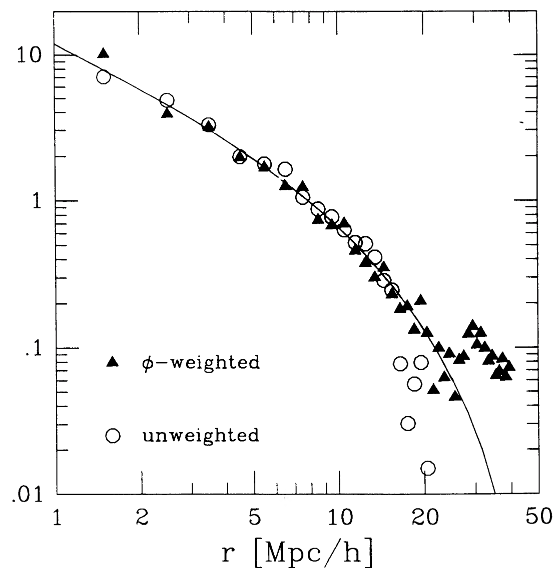

FIG. 3.—Two-point spatial correlation functions in redshift space directly calculated from the CfA data (*open circles*: all galaxies equally weighted; *filled triangles*: selection function weighted). The solid curve is the Fourier transform of the observed (CfA1 + 2) power spectrum.

The open CDM and the power-law model simulations were run on a 480^3 mesh [comoving volume = (576 h^{-1} Mpc)^3] by moving 240^3 particles.

We extract 100 mock CfA1 + 2 surveys from each of these simulations. We include the peculiar motion of particles and measure their PS. Each of the PS in Figure 2 is the average of the PS for 100 mock CfA1 + 2 surveys. We always compare the CfA data with the simulations in *redshift space*.

At large wavenumbers, the PS for all the simulations have a slope of ~ -2.1, in excellent agreement with the observed PS. In real space the PS have a slope of ~ -1.2 over the same range of wavenumber. This change in slope is caused by the strong "fingers of God" along the line of sight (this radial smoothing effect is similar to the radial projection effect from the spatial CF to the angular CF [Peebles 1980; J. R. Gott III 1991, private communication]).

The observed PS at $k < 0.2$ is significantly higher than the flat CDM PS (*lower solid curve*) with the conventional normalization (DP83; Bardeen et al. 1986; Hoffman 1987). None of the statistics $\sigma^2 = \int_{0.05}^{0.2} P(k)k^2\,dk$ measured from 100 mock CfA1 + 2 surveys in this model reached the observed values. If we change the normalization to $\sigma_8 = 1.4$ (*upper solid curve*), we can reduce the discrepancy at large scales, but the disagreement shifts to small scales. The PS of the $n = -1$ power-law model (*dotted curve*) is a bit high at $k \leq 0.03$ and is too low at small scales because of large peculiar motions.

Of the models examined here, the open CDM PS agrees best with the CfA100 results for $k \geq 0.05$. This model has also been used to better explain the appearance of large-scale structure (Park 1990) and the APM angular CF (Efstathiou, Sutherland, & Maddox 1990). For $k < 0.05$, we note a discrepancy between this model and the CfA data but the statistical significance of this result is small. Deeper samples are needed to examine the discrepancy at larger scales.

4. CONCLUSIONS

The redshift space power spectrum for the galaxy distribution in the CfA survey has an index $n = -2.1$ for $k > 0.25$ and

$n \approx -1.2$ for $0.07 \leq k \leq 0.25$. We detect a turnover in the power spectrum on a scale $\lambda \sim 150\ h^{-1}$ Mpc, but the statistical significance is small. If the turnover in the PS indicated is real, then a sample twice as deep as ours (Shectman et al. 1992; Geller et al. 1992) might be a fair sample of the universe and thus more accurately measure the large-scale PS. The "bump" in the CfA145 PS on a scale $\sim 50\ h^{-1}$ Mpc, while of low significance is intriguing because it occurs at the scale of the large voids in the CfA, Shectman et al. (1992), and Geller et al. (1992) surveys.

Comparison of the CfA survey PS with the PS of simulations in redshift space reveals that the standard ($\Omega h = 0.5$, $\sigma_8 = 1$) CDM model is incompatible with the observations at the 99% confidence level. None of 100 mock CfA surveys extracted from the standard CDM simulation match the large-scale PS of the CfA data. A CDM model with higher normalization ($\sigma_8 = 1.4$) better matches the large-scale power, but fails on small scales. An open CDM model ($\Omega h = 0.2$) agrees well for $\lambda < 125\ h^{-1}$ Mpc. However, this model is only marginally consistent with limits on the cosmic microwave background anisotropy (Smoot et al. 1991).

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