A CONSTANT CLUSTERING AMPLITUDE FOR FAINT GALAXIES?

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ABSTRACT

The angular clustering of faint field galaxies is investigated using deep imaging (I ~ 25) obtained with the 10-m Keck-I telescope. The autocorrelation function is consistent with \( \omega(\theta) \propto \theta^{-0.8} \) and, although less steep correlation functions cannot be ruled out with high confidence, we find no compelling evidence for a systematic decrease in the power law index at the faintest magnitude limits. Results from a number of independent observational studies are combined in order to investigate the variation of the correlation amplitude with median I-magnitude. At \( I_{med} \sim 25 \) the results obtained by different studies are all in rough agreement and indicate that for \( I_{med} > 22 \) the correlation amplitude declines far less steeply than would be expected from an extrapolation of the trend in the brighter samples. In particular, at \( I_{med} \sim 24 \) our data indicate \( \omega(\theta) \) to be a factor \( \sim 7 \) higher than the extrapolation. A near-independence of magnitude is a general feature of the correlation amplitude in models in which the redshift distribution of the faint field population contains a substantial fraction of galaxies with \( z \gtrsim 1 \). In order to reproduce the apparent abrupt flattening of the amplitude of \( \omega(\theta) \) observed at faint limits, approximately 50% of the galaxies in a sample with a depth of \( I \sim 25 \) must be at \( z > 1 \).

Subject headings: cosmology: large-scale structure of the universe — cosmology: observations — galaxies: evolution

1. INTRODUCTION

The angular clustering of faint field galaxies has been studied extensively (e.g. Elstathoiu et al. 1991, hereafter EBKTG; Roche et al. 1993, 1996; Brainard, Small & Mould 1995, hereafter BSMH; Hudon & Lilly 1996; Lidman & Peterson 1996; Villumsen, Freudling & da Costa 1996; Woods & Fahman 1997). A prime motivation of these studies has been to investigate the nature of the faint field population. In particular, it is possible to infer the effective correlation length of the sample and the rate at which clustering evolves from a combination of the amplitude of the angular autocorrelation function, \( \omega(\theta) \), and the redshift distribution of the faint galaxies, \( N(z) \). These observations can then be used to link properties of the faint field population with samples of local galaxies. While the exact interpretation remains controversial, it is generally accepted that overall \( \omega(\theta) \) is fit well by a power law of the form \( \theta^{-0.8} \) (although see Infante & Pritchet 1995 for evidence of a flattening in the power-law coefficient at faint limits). Moreover, the amplitude of \( \omega(\theta) \) appears to decline strongly with apparent magnitude, although it remains significantly non-zero at the faintest limits.

Some knowledge of the redshift distribution of the galaxies is required in order to interpret the observed decline of the amplitude of \( \omega(\theta) \) with limiting magnitude in terms of the evolution of real-space clustering. Although their precise \( N(z) \) is not known, the majority of the faint field population to depths of \( I \sim 25 \) appear to have \( z \sim 1 \) (Kneib et al. 1996; Connolly et al. 1997). Given this constraint, the rate of clustering evolution inferred from \( \omega(\theta) \) is consistent with all “reasonable” theoretical possibilities. Similarly, the present-day correlation length of the descendents of the faint galaxy population is not constrained strongly. Some authors argue in favor of a value of \( r_0 \) close to that of local bright galaxies (e.g. Hudon & Lilly 1995; Villumsen, Freudling & da Costa 1996), while others argue for a smaller value, consistent with that seen for dwarf galaxies (e.g. BSM; Infante & Pritchet 1995).

A feature which has emerged from the studies of \( \omega(\theta) \) for faint galaxies in blue passbands is a slowing of the decline of the correlation amplitude with apparent magnitude beyond \( B \sim 24.5-25 \), equivalent to a median \( I \) magnitude of \( I_{med} \sim 22.5 \) (Roche et al. 1996). A change in the slope of the differential number counts is also seen in blue passbands at a similar magnitude (Metcalfe et al. 1995; Smail et al. 1995). One interpretation of these features is that they arise from a steepening in the faint-end slope of the luminosity function at high redshift, \( z \gtrsim 1 \) (Metcalfe et al. 1995). Clearly it is important to confirm and extend these observations to test this proposal.

Here we present an analysis of \( \omega(\theta) \) obtained from deep imaging (\( I \sim 25 \)), sufficient to probe the strength and evolution of galaxy clustering from \( z \sim 1 \). By combining these observations with results from clustering analyses of other, brighter, \( I \)-selected samples we investigate the variation of \( \omega(\theta) \) with magnitude. Using a modest extrapolation of the observed magnitude-redshift relation of brighter \( I \)-selected galaxies we then compare the observed clustering behavior to theoretical predictions.

2. OBSERVED GALAXY CLUSTERING

The data consist of deep \( I \)-band imaging of two independent fields (1640+22 and 2229+26) obtained in good conditions with the Low Resolution Imaging Spectrograph (LRIS, Oke et al. 1995) on the 10-m Keck-I telescope. The fields are centered on two high galactic latitude pulsars and thus provide essentially random samples of faint field galaxies. Details of the observations, the reduction and cataloging of the galaxies, and the number counts of the galaxies are discussed in Smail et al. (1995); Reid et al.
(1996) discuss the analysis of the faint stars in these fields. These frames constitute a superb dataset for the study of the clustering properties of faint galaxies due to both the excellent seeing (0.53′′ and 0.58′′ FWHM for 1640+22 and 2229+26 respectively) and depth (50% completeness limits of $I = 26.0$ and $I = 25.6$ for 1640+22 and 2229+26 respectively). To reduce stellar contamination we consider only objects with $I \geq 22$ in our analysis.

The direct pair-counting method proposed by Landy & Szalay (1993), $\omega(\theta) = (DD - 2DR + RR)/RR$, was used to estimate $\omega(\theta)$ for all objects with $22 \leq I \leq I_{\text{lim}}$. Here $DD$, $DR$, and $RR$ are the number of unique data-data, data-random, and random-random pairs within a given angular separation bin centered on $\theta$. To determine $DR$ and $RR$, mask frames defining areas around bright stars and galaxies ($I < 20$) were constructed for each field and these regions were excluded from the analysis. Also excluded was a generous border (15 arcsec) along the frame boundaries, resulting in field sizes of order 30 sq. arcmin.

Raw measurements of $\omega(\theta)$ were computed independently for each field and error bars were assigned to the functions using bootstrap resampling of the data. Since the areas of the fields are almost identical and the residual stellar contamination is similar, it is fair to compute a mean of the two independent raw measurements of $\omega(\theta)$ directly. The result is shown in Fig. 1 where the data points and error bars are the formal values obtained via a weighted mean of the corresponding individual functions.

The observed number of objects is used to compute $DD$ and $DR$. Since the area of the detector is small, $\omega(\theta)$ is therefore underestimated by an amount: IC $= \Omega^{-2} \int \int \omega(\theta)d\Omega_1 d\Omega_2$ (e.g. Groth & Peebles 1977), the so-called “integral constraint”. Assuming a power law correlation function, $\omega(\theta) = A_\omega \theta^{-\delta}$ with $\delta = 0.8$ as suggested by previous studies, we find IC$_{1640+22} = (0.021 \pm 0.002)A_\omega$ and IC$_{2229+26} = (0.023 \pm 0.002)A_\omega$.

Some stellar contamination remains in our catalogs and results in the inferred amplitude of $\omega(\theta)$ being lowered from its actual value. Fortunately the excellent seeing allowed a detailed study of the star counts in these fields at somewhat brighter magnitudes and from that analysis a mean stellar contamination can be estimated. Extrapolating the star counts obtained by Reid et al. (1996) under the assumption that beyond $I \sim 22$ they remain fairly flat (e.g. Fig. 1 of Reid et al.), we determine a stellar contamination in our catalogs of $\sim 10\%$ for $I = 22.0 - 24.0$, $\sim 9\%$ for $I = 22.0 - 24.5$, and $\sim 7\%$ for $I = 22.0 - 25.0$. The final corrected amplitude of $\omega(\theta)$ is then given by $A_\omega = A_\omega^{\text{IC}} N_{\text{obj}}^2 (N_{\text{obj}} - N_s)^{-2}$, where $N_{\text{obj}}$ is the number of objects, $N_s$ is the number of stars, and $A_\omega^{\text{IC}}$ is the inferred amplitude of $\omega(\theta)$ after correcting for the IC.

The functions in Fig. 1 are consistent with power laws in which $\delta = 0.8$, as are the individual $\omega(\theta)$ computed for each field. Formally the index of the best-fitting power law, $\delta_{\text{best}}$, ranges from 0.6 to 1.1 for the correlation functions computed from the two fields independently (Table 1) and from 0.7 to 0.9 for the combined fields. There is, however, no clear trend of $\delta_{\text{best}}$ with limiting magnitude, nor is the formal best fit significantly better than that with $\delta = 0.8$. We therefore adopt $\omega(\theta) = A_\omega \theta^{-0.8}$ for all further analysis.

![Figure 1](image_url)

Figure 1. Mean correlation functions obtained by weighted averaging of the raw functions computed from the two independent fields. Solid lines indicate the best-fitting power law of the form $\omega(\theta) = A_\omega \theta^{-0.8}$, including suppression due to the IC. Dotted lines show the power law that is formally the best fit to the observed $\omega(\theta)$. See Table 1 for details of the individual fits.

Table 1 lists values of $\omega(\theta)$ evaluated at $\theta = 1$′ for the two individual fields and the combined sample. The errors listed are the formal errors derived from the fit of the power law, $\omega(\theta) \propto \theta^{-0.8}$, to the raw correlation functions. From the table, $\omega(1)$ is nearly independent of limiting magnitude and the galaxies in 2229+26 are slightly more clustered than the 1640+22 galaxies, although the amplitudes from the two fields agree at better than $1\sigma$. Results for $\omega(1)$ as a function of median $I$-magnitude are plotted in Fig. 2, along with those from other studies of the clustering of $I$-selected galaxy samples.

### 3. Results and Interpretation

We start by noting that the clustering amplitudes of the brightest samples in both our fields are in reasonable agreement with the clustering of $22 < I < 24$ galaxies reported by EBKGTG who find $\omega(1) = 0.024 \pm 0.006$ (corrected for their IC, but not stellar contamination). Allowing a mean stellar contamination of order 5% in the EBKGTG data increases their value to $\omega(1) = 0.027 \pm 0.006$ (Fig. 2).

Performing a weighted linear least squares fit to the data of Lidman & Peterson (1996) shown in Fig. 2, we find $\omega(1) \propto I^{-0.29}$ at bright magnitudes. At our faintest limits, however, $\omega(1)$ is $\sim 7$ times larger than the expectations based on an extrapolation of the linear fit to the Lidman & Peterson data. Moreover, for $I_{\text{med}} = 22$, $\omega(1)$ appears to be nearly independent of magnitude, both internally within our sample and in comparison to slightly brighter studies. Thus we conclude that the amplitude of $\omega(\theta)$ for $I$-selected samples of galaxies ceases to decline steeply with apparent magnitude at $I_{\text{med}} \sim 22$ and remains roughly constant at fainter magnitudes, although a
modest rise or fall in the amplitude at the faintest magnitudes cannot be ruled out.

We construct a simple theoretical model to predict the angular clustering in our samples and compare this to the observations. On small scales ($\theta \ll 1$ rad.) an angular correlation function of the form $\omega(\theta) = A_\theta \theta^{-\delta}$ corresponds to a spatial correlation function of the form $\xi(r) = (r/r_0)^{-\gamma}$, where $\gamma = 1 + \delta$. Observations of local bright galaxies suggest that $\xi(r)$ is fit well by a power law with index $\gamma \sim 1.8$ and a correlation length, $r_0$, which varies significantly with both morphology and luminosity (e.g. Loveday et al. 1995 and references therein). Following Peebles (1980), $\omega(\theta)$ and $\xi(r)$ are related through

$$\omega(\theta) = \sqrt{\frac{\Gamma[(\gamma - 1)/2]}{\Gamma(\gamma/2)}} \frac{A}{\theta^{\gamma - 1}} r_0^\gamma$$

where $A$ is an amplitude factor dependent upon both the shape of $N(z)$ and the evolution of $\xi(r)$ (see, e.g. EBKTG). The evolution of $\xi(r)$ can be parameterized by $\xi(r, z) = (r_0/r)^\gamma (1+z)^{-3+\epsilon}$, where $\epsilon = 0.0$ corresponds to clustering fixed in proper coordinates and $\epsilon = -1.2$ corresponds to clustering fixed in comoving coordinates. Recent measurements of $\xi(r, z)$ for $I < 22$ galaxies with known redshifts suggest, however, that the evolution of clustering may have been moderately rapid and that $\epsilon > 0$. Le Fèvre et al. (1996) obtain $0 < \epsilon < 2$ for the CFRS galaxies and Shepherd et al. (1997) obtain $\epsilon \sim 1.5$ for a sample of CNOC field galaxies.

A redshift distribution, $N(z)$, is required in order to make a theoretical prediction of the clustering amplitude of the faint galaxies. As a basis for this we extrapolate from the $N(z)$ observed for the CFRS galaxies (e.g. Le Fèvre et al. 1996). For $19 \leq I \leq 22$, $N(z)$ for the CFRS galaxies is fit well by $N(z) \propto z^2 \exp[-(z/z_0)^2]$ where $z_0$ is approximately equal to the median redshift. Under the assumption that the shape of $N(z)$ does not change appreciably with depth, median redshifts for our faint galaxies can be obtained from a linear extrapolation of the CFRS $I_{med}$–$z$ relation. For galaxies with $22 \leq I \leq I_{lim}$ we expect $z_{med} = 0.81, 0.86, 0.91$ for $I_{lim} = 24.0, 24.5, 25.0$ (corresponding to $I_{med} = 23.2, 23.6, 24.0$). These predictions are similar to the limits obtained from lensing analyses of arclets seen through rich clusters of galaxies, which yield $z_{med} \sim 0.8 \pm 0.1$ for $I < 25$ (Kneib et al. 1996).

Using the above shape for $N(z)$ with $z_{med}$ extrapolated from the CFRS $I_{med}$–$z$ relation, theoretical predictions for $\omega(1')$ were computed for galaxies with $19 \leq I \leq I_{lim}$.
universe). In the EdS universe, the normalizations correspond to $r_0 = 4.0, 5.0, 5.9 h^{-1}\mathrm{Mpc}$ for $\epsilon = -1.2, 0.0, 1.0$. To obtain identical normalizations in the open model, the correlation lengths are $r_0 = 4.4, 5.5, 6.5 h^{-1}\mathrm{Mpc}$. Although none of the models provide a good fit to all of the data points, the general flattening trend of the data is reproduced fairly well.

![Diagram](image)

Figure 2. Observed variation of $\omega(1')$ with median $I$ magnitude. All data points have been corrected for the IC and stellar contamination. The thick solid line is a weighted linear least squares fit to the data of Lidman & Peterson (1996). Note that systematic offsets can be introduced into the measured values of $\omega(1')$ by a number of effects, including atmospheric seeing differences between datasets, object deblending algorithms, the definition of mask regions, and stellar contamination corrections. Such offsets would typically be comparable in magnitude to the amplitudes, the definition of mask regions, and stellar contamination corrections. Such offsets would typically be comparable in magnitude to the atmosphere sampling differences between datasets, object deblending algorithms, the definition of mask regions, and stellar contamination corrections. Such offsets would typically be comparable in magnitude to the amplitude of $\omega(\theta)$ accurately at very faint magnitudes and, hence, provide strong conclusions about the clustering properties of the faint field population and the reality of any features in the relationship of $\omega(\theta)$ and $I_{\text{med}}$.

Here we have measured $\omega(\theta)$ for faint galaxies in two independent random fields to $I \sim 25$ using high resolution imaging obtained with the Keck–I telescope. The angular clustering of the galaxies is consistent $\omega(\theta) \propto \theta^{-0.8}$, though power laws which are either somewhat steeper or somewhat shallower cannot be ruled out with high confidence. Additionally, the observed clustering amplitude at our faint limit is consistent with that expected from local bright galaxies, $r_0 \sim 4-6h^{-1}\mathrm{Mpc}$, provided clustering evolves in a reasonable manner and the redshift distribution extends beyond $z \sim 1$. This conclusion echoes that of Woods & Fahlman (1997) from their analysis of an $I_{\text{med}} \lesssim 23$ sample.

Fainter than $I_{\text{med}} \sim 22$ the amplitude of $\omega(\theta)$ is approximately independent of median magnitude. This result supports claims of a flattening in the amplitude of $\omega(\theta)$ obtained in blue samples at a comparable depth (Roche et al. 1996). The apparent abruptness of the flattening of the amplitude of $\omega(1')$ is not reproduced well by a model based upon a simple extrapolation of the $N(z)$ observed for the CFRS galaxies. We interpret this as evidence for a modest increase in the fraction of the galaxies at this depth lying in a high–$z$ tail compared to the extrapolation of the CFRS $N(z)$. Such a population has also been used to explain the flattening of the differential number counts in the blue passbands at a depth equivalent to $I_{\text{med}} \sim 22.5$ (Metcalfe et al. 1995; Small et al. 1995). The appearance of this feature at the equivalent apparent magnitude in both blue and red passbands rules out the possibility that it is caused by a population of very distant galaxies, $z \geq 4$, which fall out of the sample as the Lyman-limit moves into the $B$-band.

4. DISCUSSION AND CONCLUSIONS

The interpretation of the observed amplitude of $\omega(\theta)$ in terms of a correlation length of the galaxy sample is complicated by both a lack of direct knowledge of the redshift distribution of these galaxies and the fact that at different limiting magnitudes the sample may be dominated by different galaxy populations. It is entirely likely that the morphological composition of a sample will vary with depth due to both the shift of the restframe wavelengths sampled by the filter and the possibility that different galaxy populations may evolve differently. This may contribute to the different conclusions drawn from clustering studies of faint galaxies in different passbands. At best all that can be concluded based on $\omega(\theta)$ analyses of deep fields is an effective correlation length and an effective rate of clustering evolution since it is clear that the observed clustering is inextricably linked to the evolution of the galaxy population as a whole. Moreover, where fields are specifically chosen to avoid bright foreground galaxies (e.g. BSM) the inferred $r_0$ may be far lower than the true “universal” value since these lines of sight may be biased toward regions of the sky containing voids and, hence, would have an uncharacteristically low galaxy clustering amplitude. Deep wide-field imaging (sufficient to average over significant amounts of large-scale structure) is therefore necessary to determine the mean amplitude of $\omega(\theta)$ accurately at very faint magnitudes and, hence, provide strong conclusions about the clustering properties of the faint field population and the reality of any features in the relationship of $\omega(\theta)$ and $I_{\text{med}}$.

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