The Astrophysical Journal, 469:L85–L88, 1996 October 1

STRONG CLUSTERING OF FAINT GALAXIES AT SMALL ANGULAR SCALES

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Received 1996 May 16; accepted 1996 July 22

ABSTRACT

The two-point angular correlation function of galaxies, $\omega(\theta)$, has been computed on equatorial fields observed with the Cerro Telolo Inter-American Observatory 4 m prime focus, within a total area of 2.31 deg^2. In the magnitude range $19 \leq m_R \leq 21.5$, corresponding to $\langle z \rangle \approx 0.35$, we find an excess of power in $\omega(\theta)$ at scales $2'' \leq \theta \leq 6''$ over what would be expected from an extrapolation of $\omega(\theta)$ measured at larger θ. The significance of this excess is $\approx 5\ \sigma$. At larger scales, $6'' < \theta \leq 24''$, the amplitude of $\omega(\theta)$ is 1.6 times smaller than the standard nonevolutionary model. At these scales there is remarkable agreement between the present data and Infante & Pritchet (1995).

At large angular scales ($6'' < \theta \leq 24''$) the data are best described by a model where clustering evolution in $\xi(r, z)$ has taken place. Strong luminosity evolution cannot be ruled out with the present data. At smaller scales, $2'' \leq \theta \leq 6''$, our data are formally fitted by models where $\epsilon = -2.4(\Omega = 0.2, r_0 = 5.1\ h^{-1}$ Mpc) or $r_0 = 7.3\ h^{-1}$ Mpc ($\Omega = 0.2$, $\epsilon = 0$). If the mean redshift of our sample is 0.35, then our data show a clear detection of the scale ($\approx 19\ h^{-1}$ kpc) where the clustering evolution approaches a highly nonlinear regime, i.e., $\epsilon \leq 0$.

The rate at which galaxies merge has been computed. If this rate is proportional to $(1 + z)^m$, then $m = 2.2 \pm 0.5$.

Subject heading: galaxies: evolution — galaxies: formation — galaxies: interactions

1. INTRODUCTION

The two-point angular correlation function has been extensively used to study the clustering properties of galaxies. At large angular separations, $\theta > 10''$, it is well established that faint galaxies are less clustered compared to galaxies observed locally. Infante & Pritchet (1995) using observed redshift distributions and straightforward calculations with little model dependency found that predicted angular correlation amplitudes are about a factor of 2 higher than those observed over a wide range from $20 < m_B < 24$. The blue galaxy excess in the counts $N(m)$ and the correlation deficiency can be neatly resolved by introducing a "new," weakly clustered population at low redshifts of $0.2 < z < 1$ (Efstathiou et al. 1991; Infante & Pritchet 1995). However, luminosity-dependent evolution must be invoked in order to brighten up invisible low-L galaxies at $z = 0$ to $\sim L^*$ at $z \approx 0.3$, while still maintaining the nonevolutionary shape of $N(z)$ (Colless et al. 1990; Lilly, Cowie, & Gardner 1991; Broadhurst, Ellis, & Shanks 1988).

At small angular scales, $\theta \leq 10''$, the situation is different, and there is no consensus yet. A limited number of studies have been successful in measuring the angular correlation function at small separations ($\theta < 6''$, physical separation less than $\sim 20\ h^{-1}$ kpc at $z \approx 0.3$)(Carlberg, Pritchet, & Infante 1994; Neuschaefer et al. 1995; Woods et al. 1995). The main difficulty in such determinations is poor statistics on scales $\leq 10''$. The results range from a strong excess to a deficiency of pairs with respect to an inward extrapolation of $\omega(\theta) \propto \theta^{-0.8}$ at larger separations. This excess in $\omega(\theta)$ may be due to a population of "companions" not present at the current epoch or luminosity enhancement of intrinsically faint galaxies in pairs.

In this Letter we present the first clear detection of a break from a power law observed at larger separations in the angular two-point correlation function, $\omega(\theta)$, at $\theta < 6''$. We have measured $\omega(\theta)$ at separations $2'' < \theta \leq 68''$ on a 2.31 deg^2 field at $19 \leq m_R \leq 21.5$ ($\langle z \rangle \approx 0.35$) from a recently selected catalog of faint galaxy pairs and groups (de Mello, Infante, & Menanteau 1996a, 1996b, hereafter Paper I and Paper III). Special care was taken in this work to resolve galaxies at small separations.

2. THE DATA

The data set is comprised of 96 equatorial images of $15' \times 15'$ ($0\overset{''}{.}44$ pixel^{-1}) making a total area of 5.25 deg^2 taken at the Cerro Telolo Inter-American Observatory (CTIO) 4 m prime focus camera by the High-z Supernovae Search Group (Leibundgut et al. 1995) over two nights in 1995 March and November. The fields are all equatorial within $0^h \leq$ R.A. $\leq 4^h$ and $10^h \leq$ R.A. $\leq 14^h$. Center field coordinates will be given in a forthcoming paper. Five minute exposures through a redshifted B filter which is almost equivalent to a regular Kron-Cousin R filter [$B/(z = 0.4)$, hereafter m_R] were sufficient to provide good quality images. After a careful inspection of the images we decided to run our analysis on the best images. Our selection criteria were based on seeing, low number of bright stars, and photometric conditions. The total effective angular area on which we have computed the angular correlation function is 2.31 deg^2.

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The observations, reductions, calibrations, and selection criteria are described in Paper I. Coordinates of each pair/group are also given in Papers I and III. A number of tests were conducted in order to determine detection performance and limiting magnitudes. We claim in Paper I that our catalog is 99% complete at $m_R < 22$ and that the two components of a pair separated by more than 2″ were always detected for 1″.0 ≤ seeing ≤ 1″.6. Star/galaxy separation was done using Kron photometry (Kron 1980) and the properties of the inverse first and second moments of the images which gives a measure of intrinsic size and central compactness (see Paper III for more details). Results were tested by eye inspection.

3. ANALYSIS AND RESULTS

The angular correlation function, $\omega(\theta)$, was computed using a method that is more fully described in Infante (1994; see also Infante & Pritchet 1995, hereafter IP95). An artificial catalog of randomly distributed objects was created, and areas contaminated by defects, bright stars, etc. were masked from both the artificial catalog and the real catalog. The estimator used was

$$\omega(\theta) = \frac{N_{gg} N_r}{B N_{gr}(N_g - 1)} - \frac{N_{rr} N_{r1}}{N_{rr_1}(N_r - 1)}, \quad (1)$$

where N_{gg} is the number of galaxy pairs in a given range of separations summed over all CCD fields, N_{gr} is the number of random pairs using galaxies as centers, N_g is the number of galaxies, N_r is the number of random objects, N_{rr} is the number of random pairs, and N_{rr_1} is the same as N_{rr} but an independent set of random counts. B is the "integral constraint" correction factor (e.g., Peebles 1980; Koo & Szalay 1984). At the relevant scales in this Letter, $\theta < 24''$, the uncertainties are limited by Poisson noise rather than by variations in B. We have used $B = 1$ for our clustering at small separation analysis.

The angular correlation function $\omega(\theta)$ was derived in a 2.31 deg^2 area. Figure 1 gives the angular correlation function at separations $\theta < 2'$, for the magnitude interval $19 \leq m_R \leq 21.5$. Also, the canonical $\omega = 2.3\theta^{-0.8}$, as derived in IP95, is given for comparison in Figure 1 (*thick solid line*). The uncertainties, δ_ω, are 65% confidence intervals computed using the bootstrap resampling method as described in Efron & Tibshirani (1986). Five hundred resamplings were carried out in each computation. We note that Poisson errors are ~2.5 times smaller than bootstrap errors. In most data points the 2 σ Poisson error bars are smaller than the symbol.

Using least squares to fit $\omega(\theta)$ we obtain $\omega = (2.06 \pm 0.02)\theta^{-0.79 \pm 0.02}$ in the range $6'' < \theta \leq 67''.6$. A K-S significance test shows that in this range, both the canonical IP95 and $\omega(\theta)$ for our data, are drawn from the same distribution with a 90% significance level.

Table 1 shows the number, N, of pairs at separations $2'' < \theta \leq 6''$ and $6'' < \theta \leq 24''$ for the real and random catalogs. The fractional excess,

$$\left(\frac{\Delta N}{N}\right)_{\rm pairs} = \frac{\Delta\omega}{1 + \omega}, \quad (2)$$

in the number of pairs with respect to the random catalog are 0.637 and 0.200, respectively, while $(\Delta N/N)_{\rm pairs}$ over what would be expected from IP95 are 0.361 and −0.011, respectively. We also show in Table 1 the number of isolated groups, with 2, 3, 4, 5, and 6 members, found in our catalog and the number of groups found in the random catalog.

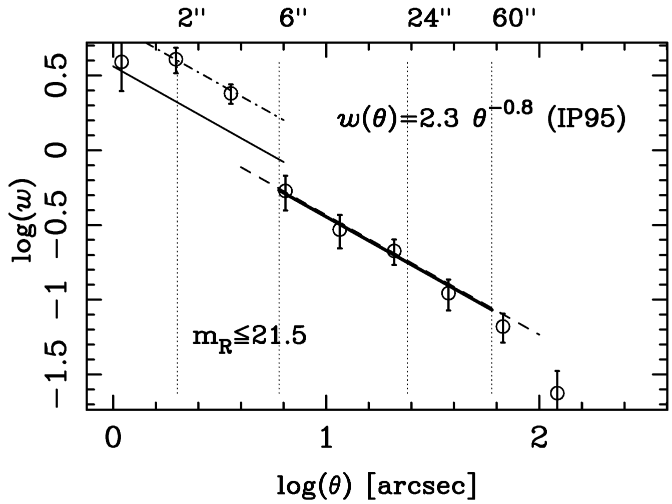

FIG. 1.—Angular correlation function for $19 \leq m_R \leq 21.5$. The open circles are the data. 65% uncertainties (500 bootstrap resampling of the data) are shown as vertical lines. The dark solid line is the IP95 $\omega(\theta)$ result with $\delta = -0.8$. The thin solid line is the nonevolutionary model described in the text ($r_0 = 5.1\ h^{-1}$ Mpc, $\epsilon = 0$). The dashed line is a model with clustering evolution ($r_0 = 5.1\ h^{-1}$ Mpc, $\epsilon = 0.8$). The dot-dashed line is a model with either clustering evolution ($r_0 = 5.1\ h^{-1}$ Mpc, $\epsilon = -2.4$) or strong correlation length ($r_0 = 7.3\ h^{-1}$ Mpc, $\epsilon = 0$).

In Figure 2 the fractional excess number of pairs, $(\Delta N/N)_{\rm pairs}$, for $19 \leq m_R \leq 21.5$ are plotted with respect to the random catalog expectation (*thin line*), to IP95 data (*thick line*), and to various models (*dashed lines*) as explained in the next section. At scales $\theta \leq 6''$ our data departs from the canonical $\omega(\theta)$ from IP95 by ≈5 σ. This excess power has not been detected in most previous works; only Carlberg et al. (1994) report an excess in the number of pairs at separations less than 6″ and $V < 22.5$.

4. DISCUSSION

Are there any effects in the data or data reduction techniques that might, in principle, cause an excess in $\omega(\theta)$ at small separations? First, we consider the possibility that rich clusters of galaxies at $z \approx 0.3$ in our fields might significantly enhance $\omega(\theta)$ at $2'' < \theta \leq 6''$. From Table 1 the contribution of groups with more than five members is 52 pairs corresponding to a negligible $(\Delta N/N)_{\rm pairs} = 0.032$. Next, we consider multiple detections of several faint spurious sources for each physically distinct galaxy by our finding algorithm. For this purpose, all images were inspected by eye, eliminating all possible sources of contamination, namely, bright galaxies, scratches, bad pixels, and cosmetic defects on the chip. There is also the possibility of contaminating light. Galaxies that normally would have been below the magnitude limit may be raised above it by the light of the second object. Our photometry accounts for this effect. We do an excision of disturbing objects for crowded field photometry. Our algorithm takes the median in rings and replaces deviant values with the median. And finally, we checked for systematic effects on magnitude determination. Extensive simulations were performed in order to test the detection and photometry of faint images as a function of magnitude. No systematic effects were detected. See Paper I for details regarding the simulations.

TABLE 1

EXCESS NUMBER OF PAIRS

CATALOG	θ_1–θ_2 (arcsec)	$\omega(\theta)$	$N_{\rm total}$	$N^{\rm obs}_{\rm pairs}$	$N^{\rm ran}_{\rm pairs}$	GROUPS 2	3	4	5	6	$(\Delta N/N)_{\rm pairs}$ [a]
Real	2–6	1.753	16749	1317	488	841	114	15	4	3	0.361
Random	2–6	−0.010	16749	477	497	438	14	0	0	0	···
Real	6–24	0.250	16749	9962	7921	1318	314	58	13	2	−0.011
Random	6–24	0.004	16749	7970	7943	1587	255	30	5	1	···

[a] Fractional excess number of pairs over what would be expected from IP95.

4.1. *Comparison with Other Observations*

Several studies have investigated $\omega(\theta)$ of faint galaxies in a number of passbands (IP95 and references therein; Neuschaefer et al. 1995; Shepherd et al. 1996). The principal result from these surveys is that $\omega(\theta)$ follows a power law, $\omega = A\theta^{-\delta}$, where $0.7 < \delta < 0.9$ ($\delta = 0.8$ is the standard value), and A is the amplitude scaling with magnitude. In this work we have taken IP95 as the canonical $\omega(\theta)$ in the red; the solid line in Figure 1 represents this power law, $\omega = 2.3\theta^{-0.8}$. After transforming IP95 F band to m_R of this work [$F = m_R + 0.094(B-R)$; $(B-R) = 1.68$; Metcalfe et al. 1991] we find that the agreement for $6'' < \theta < 68''$ is remarkable. However, at small angular scales ($\theta < 6''$), except for the work by Carlberg et al. (1994), no previous work shows a significant excess in $\omega(\theta)$ by more than 1 σ. The quality and amount of data that we have used in this work are sufficient to make us believe that the excess at small scales is a real effect.

4.2. *Comparison with Models*

How can a high clustering amplitude at small separations be understood? One of the possibilities is to assume that mergers were more frequent at $z \approx 0.35$ and the excess of pairs that we are seeing at that epoch is, in fact, due to mergers in progress. They represent a true density excess. Another scenario that we cannot rule out is the possibility of an excess of strongly clustered dwarf galaxies. Two alternatives are possible in this hypothesis: a new class of dwarf population proposed by Babul & Rees (1992) which would be recently "active" but subsequently fading out of view; or the "subunits" proposed by Broadhurst, Ellis, & Glazebrook (1992) which would slowly merge to form more massive galaxies. It is also possible that this excess in $\omega(\theta)$ is due to brightening of low luminosity companions (Carlberg 1992). A fourth possibility is that, although there is clustering evolution at scales larger than 6″, there is no clustering evolution at scales less than 6″. In this case, $\omega(\theta)$ is well fitted by a model with $\epsilon = 0$ at $2'' < \theta \leq 6''$ and $\epsilon = 0.8$ at $\theta > 6''$. Thus, there is a scale $\theta \approx 6''$ ($\sim$20 h^{-1} kpc, $z \approx 0.35$) at which the clustering evolution slows down.

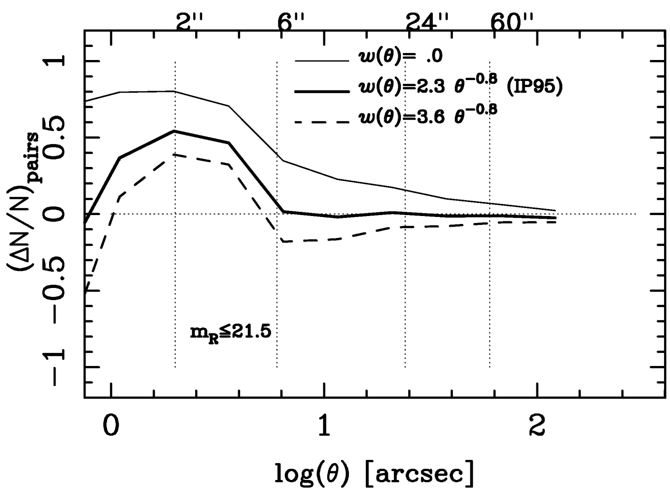

FIG. 2.—Fractional excess number of pairs for $19 \leq m_R \leq 21.5$, as defined in equation (2). The dark solid line is the IP95 $\omega(\theta)$ result with $\delta = -0.8$. The dashed line is the nonevolutionary model described in the text ($r_0 = 5.1\,h^{-1}$ Mpc, $\epsilon = 0$). The thin solid line is the fractional excess with respect to a random distribution of points.

In order to show this latter point we have computed *standard models* for $\omega(\theta)$. If we assume a power-law spatial correlation function,

$$\xi(r, z) = \left(\frac{r}{r_0}\right)^{-\gamma} (1 + z)^{-(3+\epsilon)}, \qquad (3)$$

where r is the proper distance, r_0 is the proper correlation length, and ϵ is the clustering evolution index; $\epsilon = \gamma - 3$ means clustering fixed in comoving coordinates and $\epsilon = 0$ represents stable clustering in physical coordinates. The angular correlation function is obtained through Limber's equation (Peebles 1980 eqs. [56.7] and [56.13]; IP95). The nonevolutionary redshift distribution, dN/dz, is taken from Metcalfe et al. (1991) (see IP95 for discussion and justification of our choice).

In Figure 1 three models are shown: the *standard model* ($\gamma = 1.8$, $\epsilon = 0$, $\Omega = 0.2$ and $r_0 = 5.1\,h^{-1}$ Mpc; *solid line*), a model with clustering evolution ($\gamma = 1.8$, $\epsilon = 0.8$, $\Omega = 0.2$ and $r_0 = 5.1\,h^{-1}$ Mpc; *dashed line*), and a model with either clustering evolution ($\gamma = 1.8$, $\epsilon = -2.4$, $\Omega = 0.2$ and $r_0 = 5.1\,h^{-1}$ Mpc; *dot-dashed line*) or a model with a strong local correlation length ($\gamma = 1.8$, $\epsilon = 0$, $\Omega = 0.2$ and $r_0 = 7.3\,h^{-1}$Mpc; *dot-dashed line*).

The *standard model* with clustering evolution ($\epsilon = 0.8$) fits the observations in the range $6'' \leq \theta < 24''$ very well. The value of ϵ agrees with the results obtained by Shepherd et al. (1996), where the low amplitude of the correlation function might be due to strong clustering evolution since $z \approx 0.35$.

The small scale data ($\theta < 6''$) is better fitted by a model with either a high local clustering length ($r_0 = 7.3\,h^{-1}$ Mpc) or $\epsilon = -2.4$. If we assume a correlation length as observed for present day L^* galaxies ($r_0 = 5.1\,h^{-1}$ Mpc), no clustering evolution ($\epsilon = 0$), and no luminosity evolution, the clustering properties of galaxies at $\langle z \rangle = 0.35$ and spatial separations $\sim$20 h^{-1} kpc (for $z \approx 0.35$), in the m_R passband are similar to present day L^* galaxies. The excess in $\omega(\theta)$ with respect to this model might correspond to the galaxy merger rate discussed in the next section.

If the mean redshift of our sample is 0.35 then our data show a clear detection of the scale, $\approx$19 h^{-1} kpc, at which the clustering evolution approaches a highly nonlinear regime where $\epsilon \leq 0$ is expected.

4.3. *The Galaxy Merger Rate*

The merger rate is expected to have a strong redshift dependence varying as roughly as $(1 + z)^m$, where $m \simeq 4.5\Omega^{0.4}$. However, the difficulty of identifying objects even at moderate redshift is a limiting factor in studies of faint galaxy pairs. Another factor is imposed by the significant amount of large telescope time required in order to obtain redshifts and good quality images for a statistically significant sample of faint galaxies. So far, only a few previous works have redshift information for faint galaxies in pairs (see Koo & Kron 1992 and Ellis 1995 for reviews on redshift surveys and imaging of the faint galaxy population).

There are two ways (not independent, though) to calculate the galaxy merger rate from our data. First, we count the number of isolated pairs of galaxies in the magnitude range $19 \leq m_R \leq 21.5$, corresponding to $\langle z \rangle \approx 0.35$, at scales $2'' \leq \theta \leq 6''$ ($6.4\,h^{-1}$ kpc to $19.3\,h^{-1}$ kpc, for $z \approx 0.35$ and $q_0 = 0.1$) and compare it with numbers of pairs from local galaxy surveys selected in the same way. The fraction of galaxies in pairs in our catalog is $10.04\% \pm 0.17\%$ ($n^{1/2}$ uncertainty). The expected fraction of physical pairs is 0.636 ± 0.007, if $\omega(2''\text{–}6'') = 1.75 \pm 0.05$. Following Carlberg et al. (1994), the fraction of galaxies that will merge is 0.7. Thus, the fraction of galaxies in physical pairs that will eventually merge is $10.04\% \times 0.636 \times 0.7 = 4.47\% \pm 0.01\%$. At low redshifts this value is $2.3\% \pm 0.2\%$ (Carlberg et al. 1994). If the rate at which galaxies merge is proportional to $(1 + z)^m$, then $m = 2.2 \pm 0.5$. (The uncertainty in the merger rate is dominated by the uncertainty in the fraction of galaxies that will merge. We assume 0.1.)

Second, the galaxy merger rate can be calculated using the excess correlation of our faint galaxies over what would be expected from the *standard model*. The fractional excess $(\Delta N/N)_{\rm pairs}$ over what would be expected from the *standard model* is 0.332 ($\langle\theta\rangle = 4''$ corresponding to $15.1\,h^{-1}$ kpc at $\langle z \rangle = 0.35$). Given that $(1 + z)^m = (1 + \omega_{\rm observed})/(1 + \omega_{\rm standard})$, then $m = 1.34$. Note that no corrections for the fraction of physical pairs that will merge has been made in this case.

5. CONCLUSIONS

We have estimated $\omega(\theta)$ from a well-defined sample of galaxies at $19 \leq m_R \leq 21.5$ and at small angular separation, $2'' \leq \theta \leq 6''$. We have performed simulations in order to test detection efficiency of galaxy pairs and the limiting magnitude in our galaxy sample. We find that our algorithms can detect, at a 99% confidence level, the two components of a pair separated by greater than 2″ and with $m_R < 22.5$ in our CTIO 4 m prime focus CCD images.

At $6'' < \theta \leq 68''$ the agreement between the present data and IP95 is remarkable. The amplitude of $\omega(\theta)$ at these separations is 1.6 times smaller than the nonevolutionary standard models.

Our analysis indicates that there is an excess of power in $\omega(\theta)$ at $2'' \leq \theta \leq 6''$ over what would be expected from an extrapolation of the canonical power law $\omega(\theta)$ at larger θ. The significance of this excess is $\approx 5\,\sigma$. These results place limits on the galaxy merger rate of $(1 + z)^{1.3-2.3}$.

At large angular scales ($6'' < \theta \leq 24''$) the data is best described by a model where clustering evolution in $\xi(r, z)$ has taken place. Strong luminosity evolution cannot be ruled out with the present data. At smaller scales, $2'' \leq \theta \leq 6''$, our data are formally fitted by models where $\epsilon = -2.4(\Omega = 0.2)$ or the clustering length $r_0 = 7.3\,h^{-1}$ Mpc. If the mean redshift of our sample is 0.35, then our data show a clear detection of the scale ($\approx 19\,h^{-1}$ kpc) where the clustering evolution approaches a highly nonlinear regime, i.e., $\epsilon \leq 0$.

We are grateful to the High-z Supernovae Search Group for making their images available. D. F. M. thanks CNPq for the fellowship, and L. I. thanks Fondecyt Chile for support through Proyecto 1960414.

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