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The Edinburgh–Durham Southern Galaxy Catalogue – V. The cluster correlation function*

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SUMMARY

The spatial cluster correlation function for a 90 per cent complete sample of 79 clusters from the Edinburgh–Durham Southern Galaxy Catalogue is presented. These clusters are selected in an objective manner using an automated cluster-finding algorithm and correspond to a richness mid-way between the Abell richness classes $RC=0$ and 1. Projection effects in this sample have been reduced by using a small cluster radius and deblending overlapping clusters. For 80 per cent of the sample we have observed $\simeq 10$ galaxies in the direction of each cluster core. For these reasons this work supersedes previous determinations of the cluster correlation function. We derive a correlation length for the sample of $r_0 = 16.4 \pm 4.0$ h^{-1} Mpc, a value systematically smaller than that calculated from Abell cluster samples. On scales $\simeq r_0$, the anisotropy in the correlation function between the redshift and transverse components is the lowest of any ξ_{cc} yet published. It is therefore unlikely that the strong anisotropy seen in previous correlation determinations is the result of real line-of-sight clustering or large cluster peculiar velocities.

Key words: galaxies: clustering – large-scale structure of Universe.

1 INTRODUCTION

One of the most controversial results in cosmology over the last decade has been the amplitude of the two-point spatial cluster–cluster correlation function (ξ_{cc}). The bench-mark for such studies is the work of Bahcall & Soneira (1983), who use a statistical cluster sample of 104 redshifts which constitute all of the high galactic latitude $RC \geq 1$, $D \leq 4$ Abell clusters (Abell 1958). Their correlation function has the form $\xi_{cc}(r) = (r/r_0)^{-1.8}$, with $r_0 = 25$ h^{-1} Mpc. If correct, this result provides a strong indication that clusters are $\simeq 15$ times more clustered than galaxies on the same spatial scale. More recently, Postman, Huchra & Geller (1992; PHG) have analysed a complete magnitude-limited sample of 351 Abell clusters. They find a correlation length of 20.0 ± 4.0 h^{-1} Mpc. Correlation lengths as large as this imply that galaxies and clusters cannot both be tracers of the large-scale matter distribution. One implication of a correlation length $r_0 \simeq 20$ h^{-1} Mpc is that it is inconsistent with a flat universe dominated by cold dark matter (e.g. White *et al.* 1987). Although these results have had a major impact, the cluster samples in each case are based on the Abell (1958) cluster catalogue which has been the focus of substantial criticism. The Bahcall & Soneira (1983) result has been criticized on the grounds that the Abell cluster catalogue contains projection effects. Sutherland (1988) suggests that such effects cause spurious line-of-sight elongations of ξ_{cc}. When corrected for projection effects, the correlation length is much reduced to $r_0 = 14$ h^{-1} Mpc, a value less discordant with the cold dark matter model. However, Dekel *et al.* (1989) conclude that the uncertainties inherent in this decontamination procedure are too large for the resulting ξ_{cc} to constrain the standard theory. In any case the decontamination correction may be overdone, since elongations in the redshift direction may be due to peculiar velocities $\simeq 2000$ km s^{-1} or the real geometry of the clusters in space (Bahcall, Soneira & Burgett 1986; Jing, Plionis & Valdarnini 1992). In addition to the uncertainties introduced by projection effects, it has been recognized for some time that the intrinsically subjective nature of the Abell catalogue gives rise to severe problems in homogeneity and statistical completeness (Postman, Geller & Huchra 1986).

In this paper we report on the ξ_{cc} for a sample of galaxy clusters selected automatically from the Edinburgh–Durham Southern Galaxy Catalogue (EDSGC). This is a digitized

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*Based in part on data collected at the European Southern Observatory, La Silla, Chile.

galaxy survey covering ≃ 1400 square degrees at the South Galactic Cap. The advantage of using a machine-based cluster sample is that it is completely objective. In addition, great care has been taken in the selection procedure to reduce the effects of cluster projection (see Section 2). Both of these factors enable us to avoid the major criticisms which befall cluster samples that have been selected from the Abell catalogue.

2 THE CLUSTER SAMPLE

The details of the EDSGC and statistical results on the galaxy clustering are reported in earlier papers of this series (see Collins, Nichol & Lumsden 1992, Paper III). Lumsden *et al.* (1992) present the complete sample of 737 clusters selected from the EDSGC along with a detailed description of the cluster-finding algorithm.

There are two aspects to the selection of clusters which are specifically designed to reduce projection effects. First, the sample was corrected by deblending clusters which had overlapping radii. Galaxies in the overlap region were assigned to the appropriate cluster based on a Gaussian fit to the cluster density profiles. Secondly, to select the sample for the correlation function a radius $r_A = 1\ h^{-1}$ Mpc was used in place of the $r_A = 1.5\ h^{-1}$ Mpc value adopted by Abell. This reduced the number of cluster blends, since the galaxies defining each cluster are constrained to lie closer to the cluster core. If the standard Abell radius had been used, ≃ 30 per cent of the clusters would be deblended. This is consistent with the level of contamination in Abell clusters estimated by Lucey (1983). For the smaller Abell radius, 8 per cent of the clusters were deblended.

The cluster sample used in this paper to determine ξ_{cc} corresponds to a subsample of the full 737 clusters selected according to the following criteria: richness $R \geq 22$ inside a radius corresponding to $r_A = 1\ h^{-1}$ Mpc, where R is the number of cluster galaxies between the limits m_3 and $m_3 + 2$ as defined by Abell (1958); clusters having an $m_{10}(b_j) \leq 18.75$; clusters within the area $\alpha = 21^h53^m$ to 03^h35^m and $\delta = -22°53'$ to $-42°12'$. The number of clusters satisfying these criteria is 97.

In total we took redshifts for 96 clusters from the full list of 737, using both the European Southern Observatory 3.6-m telescope and the Anglo-Australian Telescope. On average, for the clusters we observed ourselves, redshifts of 10 galaxies towards each cluster core were taken. These 96 observed clusters constitute the Edinburgh–Milano cluster redshift survey. Results from this sample will appear in other papers (e.g. Guzzo *et al.* 1992). Of these, 71 satisfy the selection criteria described above and we supplement them with 16 from the literature, so we have cluster redshifts for 87 of the 97 selected clusters. However, from the 71 clusters we observed, eight were rejected as spurious clusters using strict objective criteria based entirely on the redshift distributions (Nichol 1992). Therefore, the final statistical sample used to determine ξ_{cc} corresponds to 79 observed clusters out of 89 selected clusters and represents a completeness of 90 per cent.

From a comparison between the clusters in the EDSGC sample ($R \geq 22$, 97 clusters) and the southern Abell catalogue (Abell, Corwin & Olowin 1989), we find that our sample is equivalent to an Abell richness of $R = 40$, i.e. between the Abell richness classes $RC = 1$ and $RC = 0$. This comparison is consistent with the spatial number density of the cluster samples (n_c). For the EDSGC sample, $n_c = 1 \times 10^{-5}\ h^3$ Mpc^{-3} compared to $n_c = 1.2 \times 10^{-5}\ h^3$ Mpc^{-3} for the PHG $RC \geq 0$ sample. On these criteria alone we would expect to see a clustering amplitude close to that reported by PHG.

3 CALCULATION AND RESULTS

The correlation function was calculated by comparing the observed distribution of cluster pairs with that of a random distribution within an identical volume. ξ_{cc} can then be estimated from

$$\xi_{cc}(r) = 2\frac{n_r}{n_d}\frac{N_{dd}}{N_{dr}} - 1, \tag{1}$$

where n_d and n_r are the number density of data and random points respectively ($n_r \gg n_d$). N_{dd} and N_{dr} are the number of data–data pairs and data–random pairs respectively (Davis & Peebles 1983). In order to account for the redshift selection function, the random data set was constructed by selecting angular positions randomly from within the survey area and assigning them redshifts taken from our own observed redshift distribution, smoothed with a Gaussian of width 3000 km s^{-1}. The final result was insensitive to the exact smoothing width used. The calculated correlation function is shown in Fig. 1. Also shown in this figure are the points of the PHG correlation functions recalculated by us for their $RC \geq 0$ statistical sample and $RC \geq 1$ sample using the technique they prescribe. The stability of the EDSGC correlation function was checked using an estimator which depends on

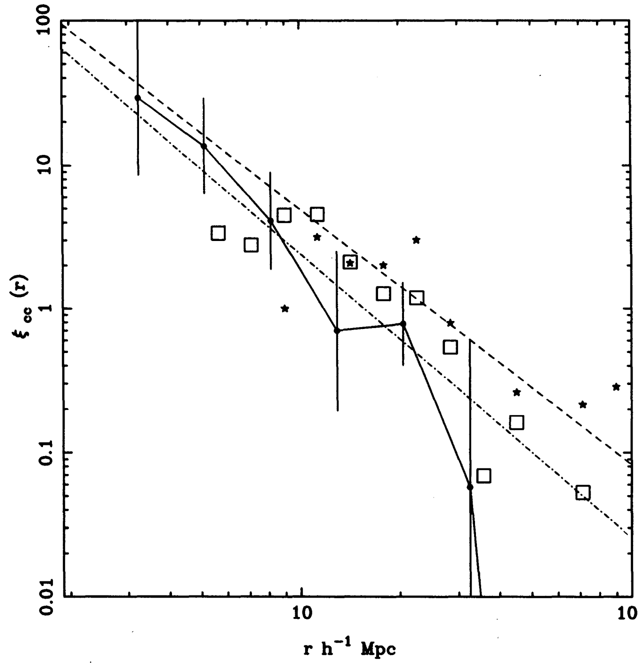

Figure 1. The $\xi_{cc}(r)$ for the 79 EDSGC clusters (●), the $RC \geq 0$ statistical sample (□) and the $RC \geq 1$ sample of PHG (★). The dot–dashed line represents our best fit to $\xi_{cc}(r)$ (see text) and the single-dashed line corresponds to the Bahcall & Soneira $r_0 = 25\ h^{-1}$ Mpc correlation function. The bootstrap error bars are shown.

the number of random–random pairs and an identical result to that in Fig. 1 was found.

One possible systematic effect of using the observed redshift distribution to generate the random catalogue is that the large structures in the redshift direction of our survey (Guzzo *et al.* 1992) cause ξ_{cc} to be underestimated. To check this, a random catalogue was constructed, based on the assumption that our cluster sample is volume-limited to a redshift $z=0.13$. Excellent agreement was obtained between the resulting correlation function and the points in Fig. 1.

The error bars shown are estimated by the bootstrap method described by Ling, Frenk & Barrow (1987). These estimates are more conservative than simple Poissonian errors, but are more realistic given that we have a partially incomplete sample. On the assumption that $\xi_{cc}(r)=(r/r_0)^{-\gamma}$, a least-squares fit to our correlation function over the range 3–35 h^{-1} Mpc gives $r_0=16.4\pm4.0$ h^{-1} Mpc and $\gamma=2.1\pm0.3$. If the error bars are Poissonian, $r_0=16.2\pm2.3$ h^{-1} Mpc and $\gamma=2.0\pm0.2$. This compares with the PHG correlation length of 20.0 ± 4.0 h^{-1} Mpc for their complete $RC\geq0$ statistical sample and 23.7 ± 8.0 h^{-1} Mpc for their $RC\geq1$ sample.

In order to characterize the line-of-sight elongations in the correlation functions, we followed the procedure described by Sutherland (1988) and computed ξ_{cc} as a function of both radial (r_z) and transverse (r_p) separations. Contour values of $\xi_{cc}(r_z, r_p)$ for the EDSGC data and the PHG $RC\geq1$ sample are shown in Fig. 2.

4 DISCUSSION

The correlation function of the EDSGC clusters is systematically below the Bahcall & Soneira (1983) result and both of the PHG $RC\geq0$ and $RC\geq1$ cluster samples, although the difference between our correlation length of $r_0=16.4\pm4.0$ h^{-1} Mpc and the values given by PHG is not statistically significant. Fig. 2(a) demonstrates there is little anisotropy detected for our sample on scales ≤30 h^{-1} Mpc. The contours are virtually spherical on these scales. In comparison, the PHG sample (Fig. 2b) shows considerable anisotropy and the $\xi_{cc}(r_z, r_p)$ contours are extended by a ratio of 3 to 1 in the redshift direction compared to the transverse direction on scales ≤30 h^{-1} Mpc. A similar result for the $RC\geq0$ statistical sample of PHG was found recently by Efstathiou *et al.* (1992).

The lack of anisotropy in Fig. 2(a) compared to Fig. 2(b) should not be surprising as our data represent a substantial advance over existing samples used for cluster correlation studies. There are three main differences to note. First, our clusters are selected in a completely objective manner from the EDSGC and are not subject to unquantifiable systematics introduced by 'Abell's eye'. Secondly, precautions have been taken to avoid including clusters which would otherwise be spuriously selected due to projection effects (Section 2). Thirdly, for 71 clusters in our sample we have taken redshifts for $\simeq10$ galaxies in the direction of each cluster core. This significantly reduces the possibility of introducing spurious peculiar velocities to the clusters. For the PHG data, 43 per cent of the cluster redshifts are based on one or two galaxies. These effects point towards a natural explanation of the anisotropy in Fig. 2(b) in terms of projection effects. It is unnecessary to invoke either line-of-sight clustering or large cluster peculiar velocities as the explanation for the anisotropy evident in the cluster samples selected from the Abell catalogue (Section 1).

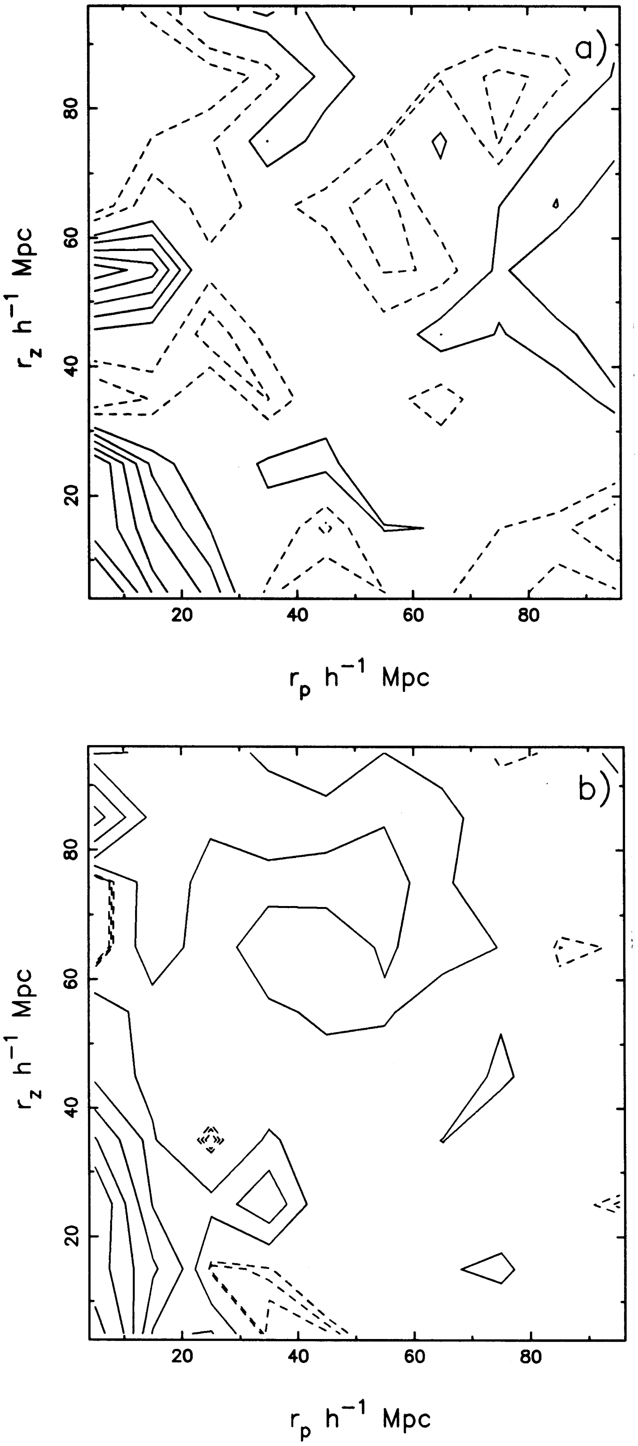

Figure 2. (a) A contour diagram of $\xi(r_z, r_p)$ for the 79 EDSGC clusters. No projection effect correction has been applied. The contour levels are 3.0, 2.0, 1.0, 0.8, 0.6, 0.4, 0.2, −0.2, −0.4. (b) Similar to (a), for the PHG $RC\geq1$ Abell cluster sample. The contour levels are 12.0, 8.0, 6.0, 4.0, 2.0, 1.0, −0.1, −0.2, −0.3. Negative contours are dashed.

The isotropy seen in Fig. 2(a) enables a direct constraint to be placed on the cluster peculiar velocities. We fitted

$\xi_{cc}(r_z, r_p)$ to a model in which $\xi_{cc}(r)=(r/16\ h^{-1}\ \mathrm{Mpc})^{-2}$, convolved with a Gaussian peculiar velocity field (Nichol 1992). From this analysis, peculiar velocities between clusters as large as 1000 km s^{-1} are ruled out at about the 2σ level, although our data are consistent with zero peculiar velocities. Similar values for r_0, γ, and the rms cluster peculiar velocity were obtained when a simultaneous fit was made to all three parameters.

5 CONCLUSIONS

A nearly complete cluster sample selected from the EDSGC has been used to calculate ξ_{cc}. The resulting correlation length has a value $r_0 = 16\ h^{-1}$ Mpc. The anisotropy of ξ_{cc} between the radial and transverse directions is significantly smaller than that found in Abell cluster samples of comparable richness on scales $\leq 30\ h^{-1}$ Mpc. This is a consequence of minimizing the projection effects in the cluster search algorithm and measuring multiple redshifts for most clusters. This result suggests that such effects are not due to real structure or large peculiar velocities as suggested by some authors. We derive an upper limit to the rms peculiar velocities for clusters of $\simeq 1000$ km s^{-1}. We are aware of similar work underway using clusters selected from the APM cluster catalogue (Dalton *et al.* 1992).

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