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CORRELATION LENGTH OF X-RAY–BRIGHTEST ABELL CLUSTERS

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ABSTRACT

We compute the cluster autocorrelation function $\xi_{cc}(r)$ of an X-ray flux-limited sample of Abell clusters (XBACs). For the total XBACs sample we find a power-law fit $\xi_{cc} = (r/r_0)^{\gamma}$ with $r_0 = 21.1$ Mpc h^{-1} and $\gamma = -1.9$, consistent with the results of $R \geq 1$ Abell clusters. We also analyze $\xi_{cc}(r)$ for subsamples defined by different X-ray luminosity thresholds where we find a weak tendency of larger values of r_0 with increasing X-ray luminosity, although with a low statistical significance. In the different subsamples analyzed we find 21 Mpc $h^{-1} < r_0 <$ 35 Mpc h^{-1} and $-1.9 < \gamma < -1.6$. Our analysis suggests that cluster X-ray luminosities may be used for a reliable confrontation of cluster spatial distribution properties in models and observations.

Subject headings: galaxies: clusters: general — X-rays: galaxies

1. INTRODUCTION

Different authors have analyzed the cluster-cluster spatial two-point correlation function finding power-law fits of the form $\xi_{cc}(r) = (r/r_0)^{\gamma}$ with $\gamma \simeq -1.8$ (Bahcall & Soneira 1983; Peacock & West 1992). The value of the cluster-cluster correlation length r_0 is controversial, as is its dependence on cluster mass. This has been achieved by studying samples selected by cluster richness and the associated mean inter-cluster separation $d_c = n_c^{-1/3}$, where n_c is the mean number density of clusters. Bahcall & West (1992) and Bahcall & Cen (1992) argue for a universal scaling relation for the two-point correlation function of rich clusters where the cluster correlation length satisfies $r_0 = 0.4 d_c$. At low values of $d_c \simeq$ 30–50 h^{-1} Mpc the Automatic Plate Measuring Facility (APM) Cluster Survey (Dalton et al. 1994), the Edinburgh/Durham Cluster Catalog (EDCC) (Lumsden et al. 1992), and the Abell (1958) and Abell, Corwin, & Olowin (1989) cluster samples give similar results consistent with r_0 = 15–20 h^{-1} Mpc. At larger d_c, however, the analyses rely only on the Abell catalog and on a cluster sample selected from the APM Galaxy Survey (Croft, Dalton, & Efsthatiou 1997). The results of this high-richness APM cluster sample are not consistent with the universal scaling relation derived from Abell clusters by Bahcall & West (1992) since only a weak dependence of r_0 on d_c is found in the rich APM cluster sample. A partial explanation for the different results between rich Abell and APM clusters could rely on the fact that the Abell catalog is subject to visual artificial inhomogeneities in contrast with the automated and well-controlled APM cluster catalog (Croft et al. 1997). It should be noted, however, that given the steeper correlations for richer clusters these results are not inconsistent with the universal relation in terms of correlation amplitude.

The problems of projection effects in cluster selection (see van Haarlem, Frenk, & White 1997) may be strongly overcome by selecting clusters in the X-ray rather than the optical. Moreover, given the good correlation between X-ray luminosity and cluster mass ($L_x \propto M^{4/3}$) found in both analytical solutions (Bertschinger 1985) and in numerical simulations (Navarro, Frenk, & White 1995), an X-ray–selected sample is suitable to study the dependence of cluster spatial correlations on mass. In this work we explore the values of r_0 in subsamples taken from the X-ray brightest Abell-type clusters of galaxies (XBACs) (Ebeling et al. 1996). This sample of clusters is complete in X-ray flux, and we have selected subsets with different cuts in X-ray luminosity L_x.

2. DATA AND ANALYSIS

The XBACs of galaxies survey (Ebeling et al. 1996) totals 277 objects and makes up a 95% complete flux-limited sample. We have restricted this catalog to galactic latitudes $|b| > 25°$ and X-ray flux $f > f_{cut} = 5 \times 10^{-12}$ ergs cm^{-2} s^{-1} in the 0.1–2.4 keV band, making up a final sample of 248 clusters. This sample, although optically selected, is confirmed by the X-ray emission of the intracluster gas, thus excluding spurious Abell clusters generated by projection effects. Also, as discussed by Ebeling et al. (1996), the XBAC sample is unaffected to first order by the incompleteness in volume of the Abell catalog at large distances since missing Abell clusters of low richness would not be included in XBACs because of their low X-ray luminosity.

In Figure 1 we plot the X-ray luminosity of the clusters' L_x as a function of redshift z taken from Table 3 of Ebeling et al. (1996). The smooth curve corresponds to the luminosity of an object with flux f_{cut} at redshift z in a flat cosmology. Cluster distances d were derived using the standard relation (e.g., Sandage 1961)

$$d = \frac{c\{q_0 z + (q_0 - 1)[(1 + 2q_0 z)^{1/2} - 1]\}}{h_0 q_0 (1 + z)^2}, \qquad (1)$$

where z is the cluster redshift, h_0 is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}, and c is the speed of light. Throughout this paper we have adopted a deceleration parameter $q_0 = 0.5$.

We calculate the cluster-cluster two-point spatial correlation function $\xi_{cc}(r)$ cross-correlating the data with a random catalog constructed by randomizing the angular positions of the clusters with the same redshift distribution. Each random catalog has n_{ran} points homogeneously dis-

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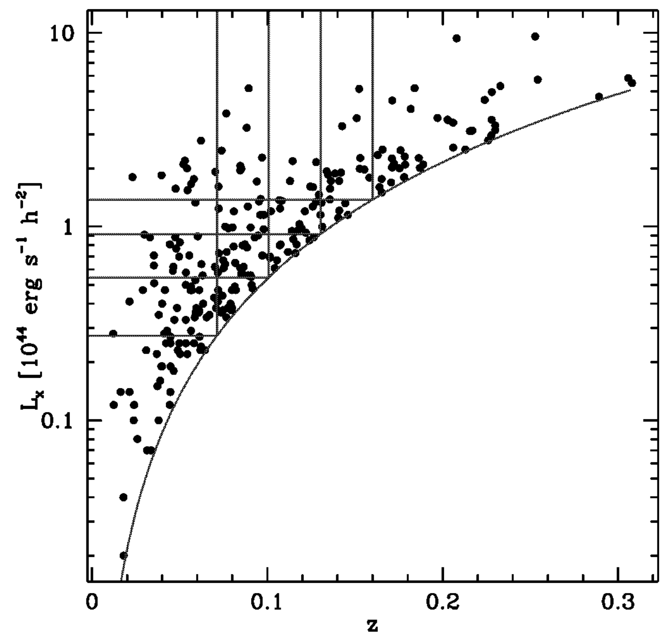

FIG. 1.—X-ray luminosity L_x vs. redshift z for the total sample of 248 clusters analyzed. The smooth curve displays the luminosity corresponding to flux $f_{\rm cut}$ at redshift z in a flat cosmology.

tributed within the same boundary as the subsamples. To compute $\xi_{\rm cc}(r)$ we have used the estimator

$$\xi_{\rm cc}(r) = 2f\,\frac{n(r)}{n_{\rm ran}(r)} - 1 \;, \qquad (2)$$

where $n(r)$ and $n_{\rm ran}(r)$ are the number of cluster-cluster and cluster-random pairs separated by a distance r, respectively, and $f = N_{\rm ran}/(N-1)$, where N and $N_{\rm ran}$ are the total number of clusters in the observed sample and random catalog, respectively.

We have considered four lower limits in X-ray luminosity that define volume-incomplete subsamples of clusters (subsamples 1i to 4i). We have also defined four other subsamples by further imposing the restriction of a cut in redshift ($z_{\rm cut}$) in order to build volume-complete subsamples

TABLE 1

INCOMPLETE SUBSAMPLES

Subsample	L_x ($10^{44}\ h^{-2}$ ergs s^{-1})	N	γ	r_0 (Mpc h^{-1})
All.........	≥ 0.02	248	-1.92	$21.1^{+1.6}_{-2.3}$
1i..........	≥ 0.27	214	-1.89	$22.1^{+2.7}_{-2.9}$
2i..........	≥ 0.54	168	-1.80	$23.5^{+4.5}_{-4.7}$
3i..........	≥ 0.91	117	-1.59	$30.1^{+8.8}_{-10.9}$
4i..........	≥ 1.38	85	-1.75	$27.0^{+11.2}_{-16.0}$

TABLE 2

COMPLETE SUBSAMPLES

Subsample	L_x ($10^{44}\ h^{-2}$ ergs s^{-1})	z	N	γ	r_0 (Mpc h^{-1})
1c	≥ 0.27	≤ 0.0713	59	-1.76	$26.4^{+6.9}_{-7.9}$
2c	≥ 0.54	≤ 0.1009	72	-1.80	$24.6^{+6.5}_{-8.3}$
3c	≥ 0.91	≤ 0.1305	54	-1.59	$30.1^{+8.8}_{-10.9}$
4c	≥ 1.38	≤ 0.1600	43	-1.77	$34.7^{+12.3}_{-16.9}$

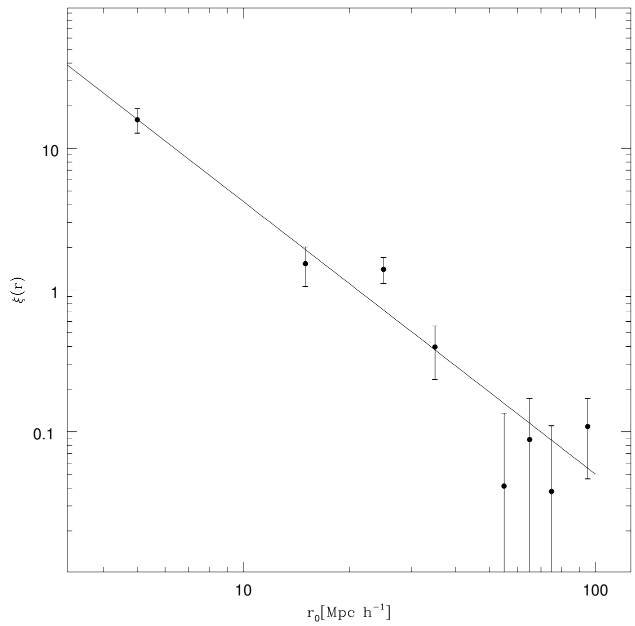

FIG. 2.—Cluster-cluster two-point correlation functions $\xi_{\rm cc}(r)$ corresponding to the total sample.

(subsamples 1c to 4c) (see Tables 1 and 2). In Figure 1 the horizontal lines define the lower limits of the four incomplete subsamples. The regions above the horizontal lines and with limiting redshift at the vertical lines define the four complete subsamples. The resulting number N of clusters is between 85 and 214 in the incomplete subsamples and between 43 and 72 in the complete subsamples.

We have fitted the correlation functions obtained with power laws of the form $\xi_{\rm cc}(r) = (r/r_0)^{\gamma}$. We have estimated the best-fitting parameters γ and r_0 and their associated errors using a maximum likelihood estimator using a χ^2 minimization procedure developed by Levemberg & Marquard (see Press et al. 1987). This method deals with the errors in each distance bin providing a reliable set of fitting parameters to the correlation function. In our calculations we assume Poisson errors $\simeq [n(r)]^{1/2}$ in each bin to estimate the uncertainty in the correlation function (see Croft et al. 1997 and references therein).

In Figures 2, 3*a*, and 3*b* are shown $\xi_{\rm cc}(r)$ corresponding to the total sample, the incomplete subsamples 1i–4i, and the complete subsamples 1c–4c, respectively. Error bars in $\xi_{\rm cc}(r)$ correspond to Poisson estimates of the uncertainties in the number statistics $\simeq [n(r)]^{1/2}$.

Estimates of the uncertainties in the power-law best-fitting parameters r_0 and γ of the correlation functions may be visualized as plots of error contours $\chi^2 - \chi^2_{\rm ML}$ in the (r_0, γ)-plane. In Figures 4, 5*a*, and 5*b* we show the corresponding error contours of confidence (1, 2, and 3 σ level) of the total sample: incomplete subsamples 1i–4i and complete subsamples 1c–4c.

3. CONCLUSIONS

We have analyzed the two-point spatial correlation function of clusters of galaxies selected from a sample of X-ray brightest Abell-type clusters of Ebeling et al. (1996). For the total XBACs sample we find a power-law fit of the form $\xi_{\rm cc}(r) = (r/r_0)^{\gamma}$ with $r_0 = 21.1^{+1.6}_{-2.3}$ Mpc h^{-1} and $\gamma = -1.92$, values consistent with those derived for $R \geq 1$ Abell clusters (see Bahcall & West 1992 and references therein).

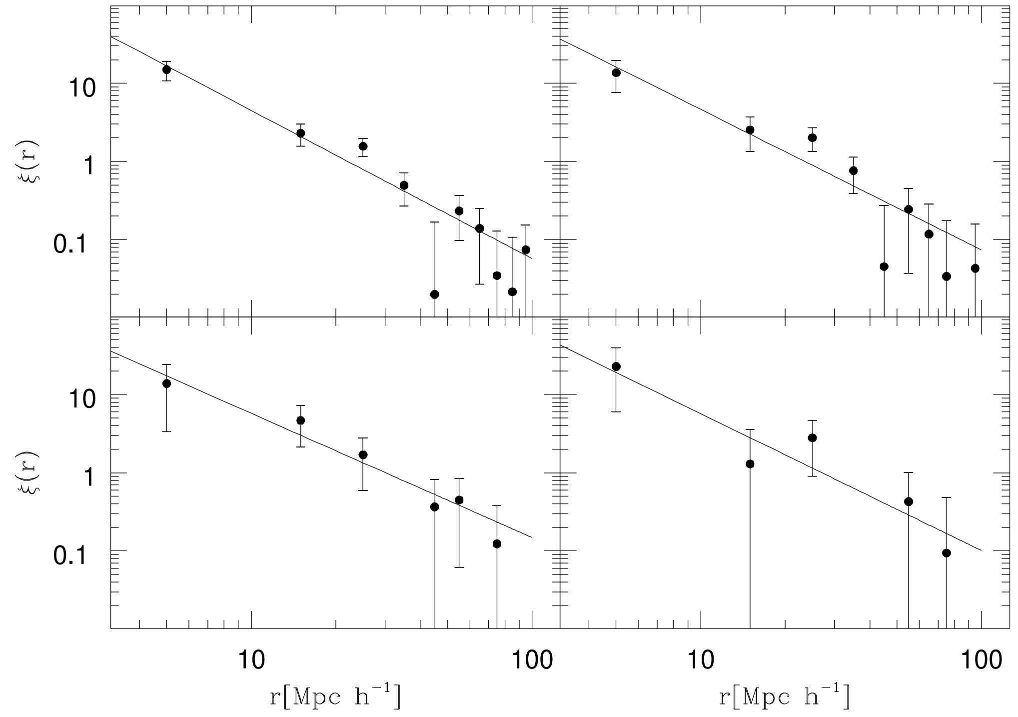

FIG. 3*a*

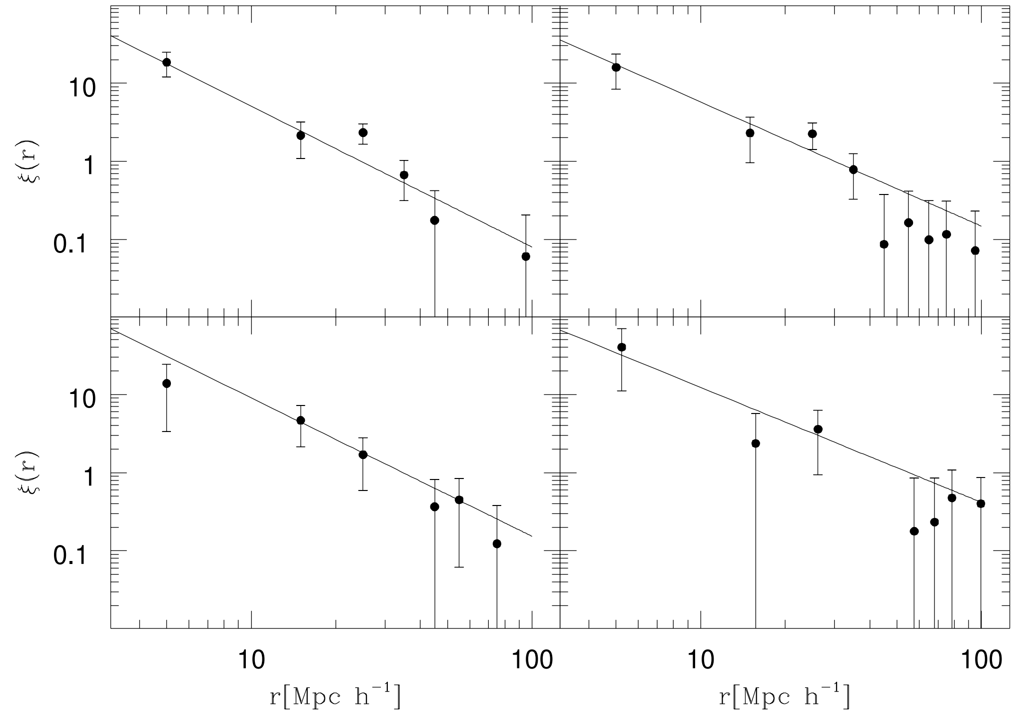

FIG. 3*b*

FIG. 3.—Cluster-cluster two-point correlation functions $\xi_{cc}(r)$ corresponding to the different subsamples analyzed. (*a*) Incomplete samples. (*b*) Complete samples.

In order to provide an insight into the dependence of the cluster spatial correlation length r_0 on mass, we have estimated autocorrelation functions for subsamples of clusters with different X-ray luminosity thresholds. We find a weak increase of the correlation amplitude with increasing X-ray luminosity, which is not statistically significant and suggests a lack of a strong dependence of r_0 on cluster mass. For instance, in our complete subsample 4i with the highest X-ray luminosity threshold $L_x > 1.38\ 10^{44}\ h^{-2}$ ergs^{-1} we obtain the highest value of correlation length, $r_0 \simeq 34.7^{+12.3}_{-16.9}$ Mpc h^{-1}. Nevertheless, this value does not differ significantly from $r_0 \simeq 26.4^{+6.9}_{-7.9}$ Mpc h^{-1} corresponding to subsample 1c with $L_x > 0.2710^{44}\ h^{-2}$ ergs^{-1}.

There is a well-documented evidence for the dependence of the correlation length on cluster richness as indicated by the relation between r_0 and the mean intercluster separation

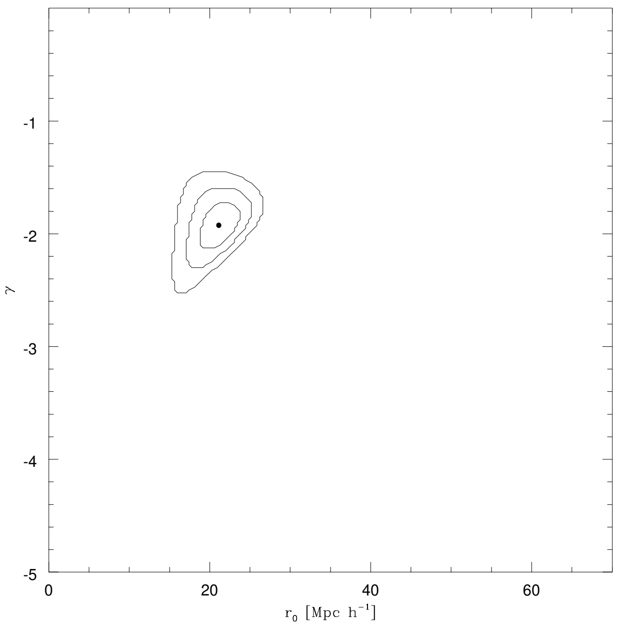

FIG. 4.—Ellipses of confidence (1, 2, and 3 σ level) corresponding to the correlation functions shown in Fig. 2.

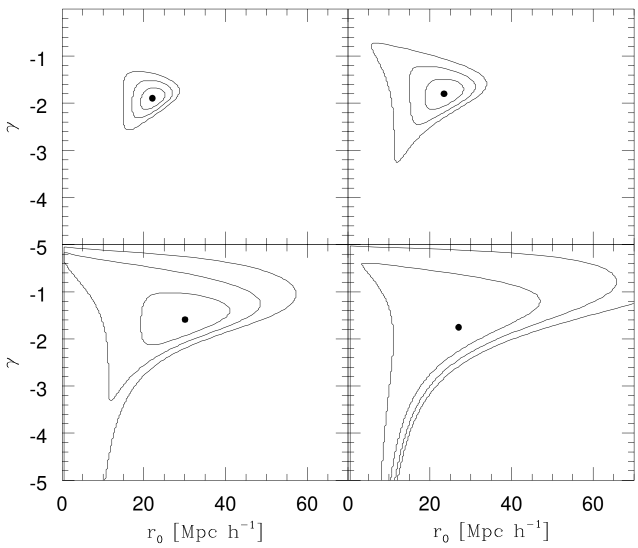

FIG. 5*a*

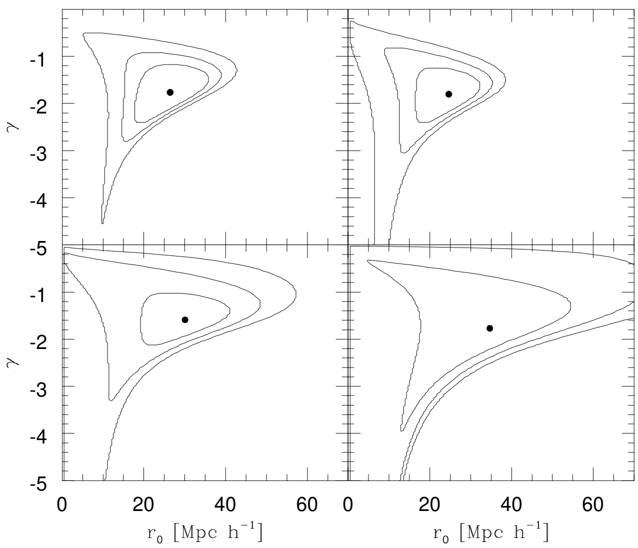

FIG. 5*b*

FIG. 5.—Ellipses of confidence (1, 2, and 3 σ level) corresponding to the correlation functions shown in Figs. 3*a* and 3*b*.

d_c in Abell cluster samples. The weak dependence of r_0 on the X-ray luminosity threshold as derived from our analysis is partially related to the broad relation between L_x and richness (Briel & Henry 1994). The relation between mass, richness, and X-ray luminosity is uncertain and is affected by several observational biases and systematics (contamination by projection, departures from hydrostatic equilibrium, etc.) as well as astrophysical issues (galaxy formation and evolution in clusters, preheating of the intracluster gas, shocks and supernova heating, etc.). These effects are important for a suitable interpretation of the observations, given the different mass dependence of the cluster correlation length expected in the variety of scenarios for structure formation. On the theoretical side the situation is also unclear. In hierarchical models of the CDM type the dependence of r_0 on d_c is found to be either very weak (Croft & Efstathiou 1994) or moderate (Bahcall & Cen 1992), discrepancies that according to Eke, Cole, & Frenk (1996) may rely on the different cluster identification algorithms. These considerations and the results of our analysis suggest that cluster X-ray luminosities may be used for a reliable confrontation of models and observations.

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