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 \( \xi_{cc} \sim (r/r_0)^\gamma \) with \( r_0 = 21.1 \text{ Mpc} h^{-1} \) 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 \( 21 \text{ Mpc} h^{-1} < r_0 < 35 \text{ Mpc} h^{-1} \) 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 \( \xi_{cc}(r) \sim (r/r_0)\gamma \) with \( \gamma \sim -1.8 \) (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 \( d_c = n^{-1/3}, \) 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 \( r_0 = 0.4d_c \). At low values of \( d_c \approx 30-50 \text{ h}^{-1} \) 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 \( r_0 = 15-20 \text{ h}^{-1} \) 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, & Efstathiou 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 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 \( (L_x \propto M^{0.5}) \) 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 \(|b| > 25\degree\) and X-ray flux \( f_{\text{cut}} > 5 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}\) in the 0.1–2.4 keV band, making up a final sample of 428 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 \( f_{\text{cut}} \) at redshift \( z \) in a flat cosmology. Cluster distances \( d \) were derived using the standard relation (e.g., Sandage 1961)

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

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 \( n_{\text{ran}} \) points homogeneously dis-
shift in order to build volume-complete subsamples (subsamples 1i to 4i). We have also defined four other subsamples that define volume-incomplete subsamples of clusters from the 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 ($z_{\text{cut}}$) in order to build volume-complete subsamples.

\[ \xi_{cc}(r) = 2f \frac{n(r)}{n_{\text{ran}}(r)} - 1, \]

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

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### TABLE 1

| Subsample | $L_x$ ($10^{44} \text{ ergs s}^{-1}$) | $N$ | $\gamma$ | $r_0$ (Mpc) |
|-----------|-----------------|----|------|-------------|
| All ........ | ≥ 0.02 | 248 | -1.92 | 21.1$_{\pm 0.6}^{+2.3}$ |
| 1i ........ | ≥ 0.27 | 214 | -1.89 | 22.1$_{\pm 0.7}^{+2.9}$ |
| 2i ........ | ≥ 0.54 | 168 | -1.80 | 23.5$_{\pm 0.5}^{+3.5}$ |
| 3i ........ | ≥ 0.91 | 117 | -1.59 | 30.1$_{\pm 0.8}^{+10.9}$ |
| 4i ........ | ≥ 1.38 | 85 | -1.75 | 27.0$_{\pm 1.2}^{+16.0}$ |

### TABLE 2

| Subsample | $L_x$ ($10^{44} \text{ ergs s}^{-1}$) | $z$ | $N$ | $\gamma$ | $r_0$ (Mpc) |
|-----------|-----------------|----|----|------|-------------|
| 1c ........ | ≥ 0.27 | ≤ 0.0713 | 59 | -1.76 | 26.4$_{\pm 0.8}^{+9.0}$ |
| 2c ........ | ≥ 0.54 | ≤ 0.1009 | 72 | -1.80 | 24.6$_{\pm 0.3}^{+8.5}$ |
| 3c ........ | ≥ 0.91 | ≤ 0.1305 | 54 | -1.59 | 30.1$_{\pm 0.8}^{+10.9}$ |
| 4c ........ | ≥ 1.38 | ≤ 0.1600 | 43 | -1.77 | 34.7$_{\pm 1.5}^{+18.9}$ |

### 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 $f_{\text{sun}}$ at redshift $z$ in a flat cosmology.

### FIG. 2

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

We have fitted the correlation functions obtained with power laws of the form $\xi_{cc}(r) = (r/r_0)\gamma$. We have estimated the best-fitting parameters $\gamma$ and $r_0$ and their associated errors using a maximum likelihood estimator using a $\chi^2$ minimization procedure developed by Levemerg & 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 $\equiv [n(r)]^{1/2}$ in each bin to estimate the uncertainty in the correlation function (see Croft et al. 1997 and references therein).

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

Estimates of the uncertainties in the power-law best-fitting parameters $r_0$ and $\gamma$ of the correlation functions may be visualized as plots of error contours $\chi^2 - \chi^2_{\text{ML}}$ in the ($r_0, \gamma$)-plane. In Figures 4, 5a, and 5b we show the corresponding error contours of confidence (1, 2, and 3 $\sigma$ 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 XBAVc sample we find a power-law fit of the form $\xi_{cc}(r) = (r/r_0)^\gamma$ 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).
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 $L_x > 1.38 \times 10^{44} \, h^{-2} \, \text{ergs}^{-1}$ we obtain the highest value of correlation length, $r_0 \approx 34.7^{+12.9}_{-10.3} \, \text{Mpc} \, h^{-1}$. Nevertheless, this value does not differ significantly from $r_0 \approx 26.4^{+6.9}_{-7.7} \, \text{Mpc} \, h^{-1}$ corresponding to subsample 1c with $L_x > 0.271 \times 10^{44} \, h^{-2} \, \text{ergs}^{-1}$.

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.
$d_e$ 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 $d_e$ is found to be either very weak (Croft & Efthathiou 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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