THE ROSAT BRIGHTEST CLUSTER SAMPLE (BCS): THE CLUSTER X-RAY LUMINOSITY FUNCTION WITHIN $z = 0.3$

H. EBELING, A. C. EDGE, A. C. FABIAN, S. W. ALLEN, AND C. S. CRAWFORD
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

AND

H. BÖHRINGER
MPI für extraterrestrische Physik, Giessenbachstr., D-85740 Garching, Germany

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ABSTRACT

We present and discuss the X-ray luminosity function (XLF) of the ROSAT Brightest Cluster sample (BCS), an X-ray flux limited sample of clusters of galaxies in the northern hemisphere compiled from ROSAT All-Sky Survey data. The BCS allows the local cluster XLF to be determined with unprecedented accuracy over almost three decades in X-ray luminosity and provides an important reference for searches for cluster evolution at higher redshifts.

We find the significance of evolution in both the XLF amplitude and in the characteristic cluster luminosity $L_X$ to be less than 1.8 $\sigma$ within the redshift range covered by our sample thereby disproving previous claims of strong evolution within $z \approx 0.2$.

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

1. INTRODUCTION

The ROSAT Brightest Cluster sample (BCS; Ebeling et al. 1996a, hereafter Paper I) is a 90% complete, flux limited sample of the 199 X-ray brightest clusters of galaxies in the northern hemisphere ($\delta \geq 0^\circ$), at high Galactic latitudes ($|b| \geq 20^\circ$, with redshifts $z \leq 0.3$, fluxes higher than $4.45 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ and luminosities higher than $5 \times 10^{42}$ erg s$^{-1}$ in the 0.1–2.4 keV band. Second in size only to the XBCs sample of Ebeling et al. (1996b), the BCS is one of the largest statistical cluster samples compiled at X-ray wavelengths. It is the only large-scale sample available today that is not only X-ray flux limited but also X-ray selected in the sense that the BCS, unlike the XBACs sample, is not limited to systems initially found in optical surveys but contains clusters selected by their X-ray properties only.

Several previous studies based on much smaller samples of typically 50 clusters found the evolution in the cluster X-ray luminosity function to be “negative” in the sense that X-ray luminous clusters are more numerous now than they were in the past (Edge et al. 1990; Gioia et al. 1990; Henry et al. 1992; David et al. 1993). They were, however, not only in conflict with other studies, which found no evidence for cluster evolution (e.g., Kowalski et al. 1984), but also somewhat inconsistent among themselves. The strong evolution seen by Edge et al. (1990) in their sample of 46 X-ray bright clusters at high Galactic latitude and $z \approx 0.18$ is not present in the first two redshift bins (44 clusters at $0.14 \leq z \leq 0.3$) of the sample of Gioia et al. (1990) and Henry et al. (1992), who find significant evolution only at $z > 0.3$. More recently, two studies found no sign of evolution at all in the XLF of samples of Abell and ACO clusters at $z \leq 0.36$ (Briel & Henry 1993) and $z \leq 0.15$ (Burg et al. 1994), respectively. However, these samples were neither X-ray selected nor X-ray flux limited and may thus not be fair representations of the cluster population in general. At considerably higher redshifts ($z > 0.5$) on the other hand, studies based on yet smaller samples observed in deep X-ray pointings (Bower et al. 1994; Castander et al. 1994; Castander et al. 1995) suggest a significant drop in the cluster space density as compared to the value observed locally.

Although the overall evidence is thus in favor of negative evolution of the cluster XLF at least for X-ray luminous clusters at redshifts well in excess of 0.3, the overall picture is anything but clear. With the completion of the BCS we are now able to provide a definitive answer to the question of whether cluster evolution is significant at low to intermediate redshifts and, in any case, provide an accurate determination of the local cluster XLF as a much-needed reference for ongoing and future evolutionary studies at higher redshifts. The implications of our findings for cosmological models of cluster evolution will be addressed in a forthcoming paper (Ebeling et al., in preparation). We assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ throughout this paper.

2. THE BCS XLF AND ITS PARAMETERIZATION

The BCS as published in Paper I is only 90% complete, and corrections for incompleteness need to be applied to account for clusters missing from the sample. In doing this we use a selection function based on the $z$, $L_X$ distribution of our sample (see § 7.1 of Paper I). We use the usual definition of the unbinned, differential XLF for a sample with flux limit $f_{X,\text{lim}}$:

$$\text{XLF}(L_X, z, f_{X,\text{lim}}) = \frac{dn(L_X, z, f_{X,\text{lim}})}{dL_X},$$

where $dn(L_X, z, f_{X,\text{lim}})$ is the space density of clusters with X-ray fluxes above the flux limit and X-ray luminosities within an interval $dL_X$ around $L_X$. Since we use an unbinned representation, $dn$ is given for each cluster by $1/V(L_X, z, f_{X,\text{lim}})$, i.e., the inverse search volume defined by the luminosity distance at which the X-ray flux from a cluster with intrinsic luminosity $L_X$...
represented by the dotted line.

The luminosity range covered by the B50 in the 0.1–2.4 keV band is indicated by the shaded region marking the luminosity range not covered by the BCS. Overlaid is the best Schechter function fit. The dashed line shows the best Schechter function fit. The systems’ X-ray pseudo-bolometric band from 0.01 to 100 keV. We discuss the robustness of the fit by comparing it to the XLF obtained using the X-ray temperatures and Galactic column densities determined by BLL. The dot-dashed line, finally, shows the XLF determined by De Grandi (1996) for a sample of 111 clusters selected from ROSAT data in the southern hemisphere. The luminosity range of this sample is indicated by the solid vertical lines (De Grandi 1996, private communication).

We use a Schechter function (Schechter 1976) of the form

$$\frac{dn}{dL_X} = A \exp \left( -L_X/L_X^* \right) L_X^{-\alpha}$$

to model the XLF and determine $A$, $L_X^*$, and $\alpha$ in a maximum-likelihood fit to the unbinned data.

Table 1 gives an overview of the fit results obtained in all five standard energy bands currently in use within the scientific community: 0.1–2.4, 0.5–2.0, 0.3–3.5, and 2–10 keV, as well as the pseudo-bolometric band from 0.01 to 100 keV. We discuss the results in detail in the following paragraphs.

Figure 1 shows the differential XLF for the BCS in the generic 0.1–2.4 keV band of the ROSAT observatory. We test the robustness of the fit by comparing it to the XLF obtained for the larger, 80% complete BCS (unpublished, see Paper I) and find excellent agreement. Also shown in Figure 1 are the XLF data points for the high Galactic latitude sample of Edge et al. (1990, hereafter B50) (open diamonds), which is X-ray flux limited in the 2–10 keV band. Since all 46 B50 clusters have measured X-ray temperatures, the conversion of their luminosities to the 0.1–2.4 keV band of the BCS is less inaccurate than the opposite operation, i.e., the conversion of the BCS luminosities into the 2–10 keV band, which relies heavily on temperature estimates rather than measured values. To assess the impact of band conversion effects we make the comparison between the XLFs of the B50 and the BCS in either band. In the 0.1–2.4 keV band we find the XLF for the B50 to be, in general, in good agreement with the BCS XLF. At low X-ray luminosities, however, the best Schechter function fit for the B50 (the dotted line in Fig. 1 and obtained with the same ML algorithm used throughout for the fitting of the BCS XLFs) severely underpredicts the observed volume density of clusters, indicating incompleteness of the B50 at $L_X \approx 1 \times 10^{44}$ erg s$^{-1}$ (0.1–2.4 keV). This is, however, not surprising given that the B50 is, by design, only flux-limited in the 2–10 keV band.

Figure 2 shows the BCS XLF in the ROSAT hard band covering the energy range from 0.5 to 2.0 keV. Note that, like for all other energy bands discussed in the following, the conversion from the original BCS band (0.1–2.4 keV) to the ROSAT hard band was performed for each cluster individually using the X-ray temperatures and Galactic column densities given in Table 2 of Paper I and assuming a metallicity of 0.3 of the solar value. Also shown in Figure 2 are the data of the XLF of groups and poor clusters of galaxies as presented by Burns et al. (1996, hereafter BLL) and their best power-law XLF.

We have tested the compatibility of the two samples by comparing the luminosities of the four clusters contained in both the BCS and the BLL sample. We find agreement to within 5% between the respective luminosities for all but one cluster (MKW 8) for which the BLL luminosity falls short of the BCS value by 40%.

### Table 1

| Energy Band (keV) | $A^a$ | $L_X^b$ | $\alpha$ |
|------------------|-------|---------|---------|
| 0.1–2.4          | $5.06^{+0.50}_{-0.46}$ | $9.10^{+1.19}_{-1.24}$ | $1.85^{+0.09}_{-0.09}$ |
| 0.5–2.0          | $3.32^{+0.36}_{-0.33}$ | $5.70^{+1.25}_{-1.93}$ | $1.85^{+0.09}_{-0.09}$ |
| 0.3–3.5          | $4.95^{+0.24}_{-0.22}$ | $10.7^{+1.4}_{-1.8}$ | $1.82^{+0.08}_{-0.08}$ |
| 2–10             | $2.35^{+0.22}_{-0.23}$ | $12.6^{+1.2}_{-1.3}$ | $1.54^{+0.08}_{-0.08}$ |
| Bolometric       | $6.41^{+0.70}_{-0.61}$ | $37.2^{+3.6}_{-3.6}$ | $1.84^{+0.06}_{-0.06}$ |

**Note:** Errors given correspond to 68% confidence for one interesting parameter (2 = 1).

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a Units of $10^{-8}$ Mpc$^{-3}$ (10$^{44}$ erg s$^{-1}$)$^{-1}$.

b Units of $10^{-8}$ ergs s$^{-1}$.
Schechter function XLF determined by De Grandi (1996) for the 111 clusters of the BSGC-KP sample, a subset of a larger ROSAT cluster sample under compilation in the southern hemisphere (Guzzo et al. 1995). For luminosities in excess of $\sim 2 \times 10^{43}$ erg s$^{-1}$ De Grandi’s XLF is in very good agreement with the best-fitting BCS Schechter function. Below this value the BSGC-KP XLF falls increasingly below both the BLL and the BCS fits, reaching a deviation of a factor of 2 and 3, respectively, at the lower end of the BSGC-KP luminosity range.

The reference in the 0.3–3.5 keV band is the EMSS cluster sample of Henry et al. (1992). Figure 3 shows the BCS XLF in the 0.3–3.5 keV band with the EMSS data points from the first two redshift shells (0.14 $\leq z < 0.2$ and 0.2 $\leq z < 0.3$) overlaid as shaded diamonds. (We remind the reader that the power-law descriptions of the EMSS XLF found by Henry and coworkers in these shells are consistent with one another within the errors, so that the comparison with the whole of the BCS made in Fig. 3 is legitimate.) Note the very good agreement between the EMSS and BCS luminosity functions, but also the much higher accuracy provided by the BCS. Also shown in Figure 3 is the XLF from the third EMSS redshift shell (0.3 $\leq z < 0.6$). Contrary to our findings for the EMSS XLF for clusters at 0.14 $\leq z < 0.3$, the EMSS XLF of these high-redshift systems differs noticeably from the BCS XLF as the local reference. A detailed reassessment of the significance of the evolution implied by this discrepancy is presented by Ebeling et al. (in preparation).

Although, in Table 1, we do list the results of a Schechter function fit to the BCS data in the 2–10 keV band, the BCS XLF in this hard energy band should be regarded with caution. The 2–10 keV band has hardly any overlap with the 0.1–2.4 keV BCS detection band, which renders a flux conversion that is largely based on estimated temperatures a dangerous enterprise. Keeping this caveat in mind we nonetheless find the power-law description from Piccinotti et al. (1982) to be in good agreement with the BCS XLF irrespective of whether the Virgo cluster is included or not (Fig. 4).

The best-fit parameters from the Schechter function fit to the B50 data published by Edge et al. (1990), on the other hand, provide an unacceptable fit to the BCS XLF at luminosities in excess of about $1 \times 10^{45}$ ergs s$^{-1}$, where the fit given by Edge et al. falls significantly below the BCS data. This failure of the original B50 Schechter function fit to describe the BCS XLF is due to an error in the volume calculation in the work of Edge and coworkers. Fitting the B50 data with our maximum likelihood algorithm we find $A = 1.59_{-0.20}^{+0.15} \times 10^{-7}$ Mpc$^{-3}(10^{44}$ erg s$^{-1})^{-1}$, $L_X = 8.46_{-2.83}^{+1.09} \times 10^{44}$ ergs s$^{-1}$, and $\alpha = 1.25_{-0.20}^{+0.15}$ in good agreement with the results for the BCS (see Fig. 4 and Table 1).

3. EVIDENCE OF EVOLUTION IN THE BCS XLF

We search for evidence of evolution by splitting the BCS at a redshift $z_{sep}$ and independently fitting Schechter functions to the data in the two redshift shells thus created. Care has to be taken not to naively misinterpret every statistically significant difference between the best-fit parameters in the two shells as signature of evolution. In order to avoid effects due to large scale structure, we vary $z_{sep}$ from 0.05 to 0.2 and look for trends that are robust over a range of $z_{sep}$ values. Since, due to the flux-limited nature of our sample, the low-luminosity end of the XLF, and thus $\alpha$, is ill-constrained for the high-redshift subsample once $z_{sep}$ exceeds $z \sim 0.1$, we fix the power-law slope $\alpha$ at its overall best-fit value of 1.85 in the maximum-likelihood fits to the data of either subsample. With $\alpha$ frozen we are thus left with two free parameters, the normalization $A$ and the characteristic luminosity $L_X$.

Figure 5 shows the contours of the C statistic (which is $\chi^2$ distributed) of $A$ and $L_X$ for some of these low-redshift and high-redshift subsamples of the BCS as a function of $z_{sep}$. While differences found at $z_{sep} \lesssim 0.1$ can be attributed entirely to large-scale structure, a significant decrease in $A$ or $L_X$ at higher values of $z_{sep}$ would be indicative of negative evolution. As, for 0.05 $\leq z_{sep} \leq 0.2$, the 68% confidence contours of the low-redshift and high-redshift subsamples overlap, we conclude that there is no significant evolution in either the amplitude $A$ of the cluster XLF or the characteristic luminosity $L_X$ for values of $z_{sep}$ up to 0.2. Since, in the high-redshift subsamples with $z_{sep} \gtrsim 0.16$, $A$ becomes ill-constrained and increasingly
strongly correlated with $L_X$, we also tested for evolution only in $L_X$ by holding $A$ constant at its overall best-fit value of $5.06 \times 10^{47}$ erg s$^{-1}$, a value well within the 68% confidence contours of all fits shown in Figure 5. We find the variations in $L_X$ to be smaller than $30(37)$% for $0.1 < z_{sep} \leq 0.20(0.22)$, which is less than 1.6(1.8) $\sigma$ significant, confirming the no-evolution result of Figure 5.

As an independent check, we also looked for variations in $V/V_{max}$ as a function of both $z$ and $L_X$—and found none. A Kolmogorov-Smirnov test finds the distribution of $V/V_{max}$ values (whose median is 0.47) to be consistent with uniformity at the greater than 74% confidence level, suggesting again that the cluster space density of the BCS is homogeneous out to the limiting redshift of $z = 0.3$.

4. CONCLUSIONS

Using the ROSAT Brightest Cluster Sample (BCS) as presented by Ebeling et al. (1996a) we have established the local X-ray luminosity function (XLF) of clusters of galaxies within $z = 0.3$ with unprecedented accuracy. We find the XLF to be well described by a Schechter function whose free parameters $A$, $L_X$, and $\alpha$ we determine in a maximum-likelihood fit for all X-ray energy bands currently used within the community. Comparing our results with previous measurements of the cluster XLF we find very good agreement with the work of Piccinotti et al. (1982), Henry et al. (1992), and Burns et al. (1996), as well as with the XLF for the B50 sample of Edge et al. (1990) when the same maximum likelihood algorithm is used to determine the best Schechter function fit.

We find no significant variations in the amplitude or the characteristic luminosity of the best-fitting Schechter function as a function of redshift. Also, the distribution of $V/V_{max}$ values is consistent at the 74% confidence level with a non-evolving space density of clusters out to $z = 0.3$. Our findings do thus not confirm the claim of strong evolution at $z \approx 0.2$ made by Edge and coworkers but support the notion of Ebeling et al. (1995) that the apparent signature of evolution in the B50 sample is due to a combination of its high X-ray flux limit in the 2–10 keV band and a pronounced, if statistically insignificant, dearth of very X-ray luminous clusters around a redshift of about 0.15.

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REFERENCES

Bower, R. G., Böhringer, H., Briel, U. G., Ellis, R. S., Castander, F. J., & Couch, W. J. 1994, MNRAS, 268, 345
Briel, U. G., & Henry, J. P. 1993, A&A, 278, 379
Burg, R., Giaconi, R., Forman, W., & Jones, C. 1994, ApJ, 422, 57
Burns, J. O., Ledlow, M. J., Loken, C., Klypin, A., Voges, W., Bryan, G. L., Norman, M. L., & White, R. A. 1996, ApJ, 467, L49 (BLI)
Castander, F. J., et al. 1995, Nature, 377, 39
Castander, F. J., Ellis, R. S., Frenk, C. S., Dressler, A., & Gunn, J. E. 1994, ApJ, 424, 179
David, L. P., Sltz, A., Jones, C., Forman, W., Vrtilek, S. D., & Arnaud, K. A. 1993, ApJ, 412, 479
De Grandi, S. 1996, in MPE Rep. 263. Proc. Röntgenstrahlung from the Universe, ed. H. U. Zimmermann, J. Trümper, & H. Yorke (Munich: MPE), 57
Ebeling, H., Böhringer, H., Briel, U. G., Voges, W., Edge, A. C., Fabian, A. C., & Allen, S. W. 1995, in Wide Field Spectroscopy and the Distant Universe, ed. S. J. Maddox & A. Aragón-Salamanca (Singapore: World Scientific), 221
Ebeling, H., Edge, A. C., Böhringer, H., Allen, S. W., Crawford, C. S., Fabian, A. C., Voges, W., & Huchra, J. P. 1996a, MNRAS, submitted (Paper I)
Ebeling, H., Voges, W., Böhringer, H., Edge, A. C., Huchra, J. P., & Briel, U. G. 1996b, MNRAS, 281, 799
Edge, A. C., Stewart, G. C., Fabian, A. C., & Arnaud, K. A. 1990, MNRAS, 245, 559
Gioia, I. M., Henry, J. P., Maccacaro, T., Morris, S. L., Stocke, J. T., & Wolter, A. 1990, ApJ, 356, L35
Guzzo, L., et al. 1995, in Wide Field Spectroscopy and the Distant Universe, ed. S. J. Maddox & A. Aragón-Salamanca (Singapore: World Scientific), 205
Henry, J. P., Gioia, I. M., Maccacaro, T., Morris, S. L., Stocke, J. T., & Wolter, A. 1992, ApJ, 390, 498
Kowalski, M. P., Ulmer, M. P., Crudace, R. G., & Wood, K. S. 1984, ApJS, 56, 103
Piccinotti, G., Mushotzky, R. F., Boldt, E. A., Holt, S. S., Marshall, F. E., Serlemitsos, P. J., & Shaffer, R. A. 1982, ApJ, 253, 485
Schechter, P. 1976, ApJ, 203, 297