The Most Distant X-ray Clusters and the Evolution of their Space Density

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Abstract. We briefly review our current knowledge of the space density of distant X-ray clusters as measured by several ROSAT serendipitous surveys. We compare old and new determinations of the cluster X-ray Luminosity Function (XLF) at increasing redshifts, addressing the controversial issue of the evolution of its high end. We use complete subsamples, drawn from the ROSAT Deep Cluster Survey (RDCS), to quantify the statistical significance of the XLF evolution out to $z \sim 1$. A consistent observational picture emerges in which the bulk of the cluster population shows no significant evolution out to $z \sim 1$, whereas the most luminous systems ($L_X \gtrsim L_X^*\left[0.5-2\text{ keV}\right] \approx 5 \times 10^{44} \text{ erg s}^{-1}$) were indeed rarer, at least at $z > 0.5$, in keeping with the original findings of the EMSS. We also report on the recent spectroscopic identification of four clusters in the RDCS lying beyond $z = 1$, the most distant X-ray clusters known to date, which set an interesting lower limit on the space density of clusters at $z > 1$.

1 Introduction

Over the last five years, remarkable observational progress has been made in constructing large samples of local and distant galaxy clusters with the aim of quantifying the evolution of their space density and providing the basis for follow-up studies of their physical properties. The ROSAT satellite is largely responsible for this progress, both with All-Sky Survey data and pointed observations, which have been a gold mine for serendipitous discoveries.

About a thousand clusters have now been selected from the ROSAT All-Sky Survey and several statistical complete subsamples have been used to obtain a firm measurement of the local abundance of clusters \textsuperscript{7,11} and their spatial distribution (cf. Böhringer this volume). Serendipitous searches for distant clusters, selected as extended X-ray sources in deep PSPC pointings \textsuperscript{14,10,18}, have
boosted the number of known clusters at $z > 0.5$ by an order of magnitude, being just a few before the ROSAT era. As we will show below, this recent work has complemented the original Einstein Medium Sensitivity Survey (EMSS) [3, 4], and has corroborated its findings.

In this paper, we provide a brief update on our current knowledge of the redshift dependent cluster X-ray Luminosity Function (XLF) [3] from results published over the last year. The reader is referred to the contributions of H. Ebeling, I. Gioia, L. Jones, A. Vikhlinin in this volume for additional details and recent findings on specific surveys. We also report the most recent results from the ROSAT Deep Cluster Survey (RDCS) which has allowed these studies to be pushed beyond $z = 1$ for the first time.

Unless otherwise stated, we assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$.

Figure 1: Sky coverage as a function of X-ray flux for 3 different cluster surveys [14, 18, 8] (thin lines, right axis). Thick curves are the corresponding volumes (left axis) covered by each survey at $z > 0.7$ for a local $L_X^*$ cluster of $5 \times 10^{14}$ erg s$^{-1}$.

2 The Cluster X-ray Luminosity Function at $z < 1$

ROSAT distant cluster surveys [14, 18, 8], besides employing different X-ray selection methods, have adopted different strategies in terms of survey depth and
Figure 2: Distant and local cluster XLFs from the literature. The number in parenthesis are the median redshift and the number of clusters of various samples in each redshift bin.

In Fig. 1, we show the sky coverage of three surveys which span a wide region of the solid angle–limiting flux plane, from the large, shallow EMSS survey, to the moderately deep 160 deg$^2$ CfA survey, and the deep, small area (50 deg$^2$) RDCS (the other ROSAT surveys generally fill the space in between). This complementary coverage of the Ω – S plane has the advantage of providing a better sampling of the XLF at different redshifts when results from various surveys are combined. As an example, we also show in Fig. 1 the corresponding survey volume which is covered at $z > 0.7$ for an $L_X^*$ cluster. This illustrates the good sensitivity of the RDCS for detecting very distant “common” clusters, whereas a similar plot would show that the EMSS explores a larger volume for the most luminous rare systems ($L > L^*$).

In Fig. 2, we show several measurements of the cluster XLF that have been
published to date. Sample sizes and median redshifts of each sample are also indicated. Based on these data, several groups have argued that no significant evolution is observed in the space density of distant clusters with $L_X [0.5-2 \text{keV}] \lesssim 3 \times 10^{44} \text{erg s}^{-1}$. As demonstrated by the RDCS, this trend persists out to $z \approx 0.8$. Measurements of the distant XLF at $L_X \lesssim L_0 \approx 5 \times 10^{44} \text{erg s}^{-1}$ are difficult with current samples, due to low number statistics. As a result, the evolution of the high end of the XLF has remained a hotly debated issue, ever since it was first reported in the EMSS \cite{9,8}. More recently, Vikhlinin et al. \cite{18} have confirmed the EMSS findings by comparing the observed number of very luminous systems with the no evolution prediction. This result seems to be also in agreement with a preliminary analysis of the Bright SHARC sample \cite{11} (Fig. 2).

2.1 Quantifying the XLF Evolution

The binned representation of the XLF in Fig. 2 does not provide a full picture of the space density evolution observed in a given sample. For example, it fails to provide the statistical significance of a possible departure from no evolution models \cite{12}. The information contained in the RDCS can be more readily recovered by analyzing the unbinned $(L_X, z)$ distribution with a maximum-likelihood (ML) approach, which compares the observed cluster distribution on the $(L_X, z)$ plane with that expected from a given XLF model.

We characterize the cluster XLF as an evolving Schechter function, $\phi(L) = \phi_0 (1+z)^A L^{-\alpha} \exp(-L/L^*)$, with $L^* = L_0 (1+z)^B$; where $A$ and $B$ are two evolutionary parameters. Different surveys find consistent values for the faint end slope $\alpha$, which is not observed to vary as a function of redshift (Fig. 2). For the local XLF, we use here the measurement of the BCS sample \cite{7}, i.e. $\alpha = 1.85$, $L_0 = 5.7 \times 10^{44} \text{erg s}^{-1}$, $\phi_0 = 3.32 (10^{-7} \text{Mpc}^{-3} L_{44}^{-1})$.

For this analysis, we use a complete flux limited sample ($F_{\text{lim}} = 3.5 \times 10^{-14} \text{erg cm}^{-2} \text{ s}^{-1}$) of 81 spectroscopically confirmed RDCS clusters drawn from 33 deg$^2$ ($z_{\text{max}} = 0.83$). Observed flux errors are included in the likelihood computation. The resulting $1\sigma$, $2\sigma$ and $3\sigma$ c.l. contours in the A-B plane are shown in Fig. 3 for two different cosmologies. Best fit values for the $\Omega_m = 1$ case are $A = 0.4^{+1.5}_{-1.8}$ and $B = -3.0^{+1.8}_{-1.2}$ ($2\sigma$ errors). The no evolution model ($A = B = 0$) is excluded at more than a $3\sigma$ confidence level, even when the uncertainties of the local XLF are taken into account. The departure of our best fit model from the no-evolution scenario is due to the small number of observed clusters in the RDCS at $z > 0.5$ with luminosities $L_X \lesssim L_0$ compared to the no-evolution prediction. Interestingly, this effect is barely significant with a slightly shallower sample ($F_{\text{lim}} = 4 \times 10^{-14} \text{erg cm}^{-2} \text{ s}^{-1}$, 70 clusters). This evolutionary trend is similar to that observed in the EMSS \cite{9,8}.

By excluding the most luminous clusters from our ML analysis, we find that there is no evidence of evolution (with $2\sigma$ confidence level) at luminosities $L_X \lesssim 2 \times 10^{44} \text{erg s}^{-1}$, confirming previous results obtained with smaller samples. A redshift
Figure 3: Left: Confidence regions in the plane of the two evolutionary parameters $A$ and $B$ obtained by fitting the function $\phi(L) = \phi_0(1+z)^A L^{-\alpha} \exp(-L/L^*)$, $L^* = L_0^*(1+z)^B$, to an RDCS subsample. Maximum likelihood contours ($1\sigma$, $2\sigma$ and $3\sigma$ confidence levels) are plotted for two different cosmologies. Right: Loci of the A-B plane for which the corresponding XLF predicts 0.1, 1, 4, 10, 20 clusters at $z > 1$ for the whole RDCS sample ($F_{lim} = 1 \times 10^{-14}$ erg cm$^{-2}$s$^{-1}$, sky coverage as in Fig.1). Four clusters at $z > 1$ have been confirmed in the RDCS to date.

dependent inspection of the likelihood also shows that little can be said on the evolution of the high end of the XLF at $z \lesssim 0.5$ with the current RDCS sample.

These findings lead to a consistent picture in which the comoving space density of the bulk of the cluster population is approximately constant out to $z \sim 0.8$, but the most luminous ($L_x \gtrsim L_0^*$), presumably most massive clusters were indeed rarer at high redshifts. Constraints on cosmological models based on this same RDCS sample are discussed elsewhere (Borgani et al. this volume; [1]).

3 Beyond $z = 1$

An inspection of Fig.1 indicates that the RDCS probes an appreciable volume at high redshifts. The maximum sensitivity for clusters at $z \gtrsim 1$ is reached at fluxes below $3 \times 10^{-14}$ and for luminosities $L_x \approx 2 \times 10^{44}$ erg s$^{-1}$. The discovery
of the first X-ray selected cluster (RXJ0848.9+4452, Fig. 4) at \( z = 1.26 \) in the RDCS \([13]\) has confirmed these expectations. Deep near-IR imagery and optical spectroscopy with Keck/LRIS were required to secure this identification. This system has \( L_X \approx 1.5 \times 10^{44} \text{ erg s}^{-1} \) (in rest frame [0.5-2 keV] band) and is found to lie only 4.2' away (5.0 h\(_{50}^{-1}\) comoving Mpc) from an IR selected cluster previously discovered by Stanford et al. \([16]\) at \( \langle z \rangle = 1.273 \), also known to be X-ray luminous with half the \( L_X \) of RXJ0848.9. This is, most likely, the first example of a high-redshift supercluster consisting of two separate systems in an advanced stage of collapse. Scheduled Chandra and XMM observations of this field should provide important information on the temperature and metal enrichment of their intra-cluster media.

Recently, two additional faint RDCS candidates have been spectroscopically confirmed, using Keck/LRIS and VLT/FORS, as clusters at \( z = 1.10 \) and \( z = 1.23 \). It should be stressed that these clusters, with \( F_X \approx 2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \), are low surface brightness “fluctuations” in PSPC images, and therefore the fraction of spurious candidates can be significant at these low fluxes. Moreover, the spectroscopic follow-up work of such distant clusters is particularly time consuming, even with 8-10 meter class telescopes. Although the optical identification is not yet complete at these faint flux levels, the high-\( z \) tail of the RDCS can be used to
Figure 5: The best determination to date of the cluster XLF out to $z \approx 1.2$. Data points at $z < 0.85$ are derived from a complete RDCS sample of 103 clusters over 47 deg$^2$, with $F_{lim} = 3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. The triangles represent a lower limit (due to incomplete optical identification) to the cluster space density obtained from a sample of 4 clusters with $\langle z \rangle = 1.1$ and with $F_{lim} = 1.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. Long dash curves are Schechter best fit XLFs for $z = 0.4$ and $z = 0.6$, according to the model of fig. 3.

set an interesting lower limit to the space density of clusters at $\langle z \rangle = 1.1$. This is shown in Fig. 3, where an extended RDCS sample has been used to obtain the best estimate of the XLF of distant clusters out to $z \approx 1.2$. Such a sample contains 107 clusters drawn from a 47 deg$^2$ area, with 8 clusters at $z > 0.8$. We also plot in Fig. 3 the best fit XLF model described above, at $z = 0.4$ and $z = 0.6$.

To better understand the constraints that these newly-identified high redshift clusters set on the XLF evolution, we have plotted in Fig. 3 (right) the loci of the A-B plane for which the corresponding XLF, $\phi_{A,B}(L,z)$, predicts 0.1, 1, 4, 10, 20 clusters at $z > 1$, for the entire RDCS sample. About 20 clusters would have to be identified in the no-evolution scenario. This seems very unlikely, unless the sample is severely incomplete at faint fluxes. Given that 4 clusters have already
been discovered, the portion of the A-B plane which is allowed by this preliminary analysis suggests that the evolution is still rather mild at $z \gtrsim 1$, at luminosities just above $10^{44} \text{erg s}^{-1}$.

The next obvious step in the effort to understand cluster formation and evolution is to push the cluster (or proto-cluster) search out to even higher redshifts, namely out to $z \sim 3$ where the signature of large scale structure has already been unveiled [7]. Finding clusters around high-$z$ AGN is a viable method (e.g.[4, 6, 3]), although not suitable for assessing the cluster abundance. Serendipitous searches with Chandra and XMM will of course be actively pursued, but it will take several years to build large enough survey areas, and furthermore, the spectroscopic follow-up of cluster candidates at $z > 1.3$ may turn out to be too difficult with existing telescopes. While the short-term prospects for exploring the era at $1.5 \lesssim z \lesssim 2.5$ may appear somewhat bleak, it should be kept in mind that earlier this decade many theorists and observers were convinced that clusters at $z > 1$ were either out of reach, or did not exist.

References

[1] Borgani, S., Rosati, P., Tozzi, P., & Norman, C. 1999, ApJ, 517, 40
[2] Burke, D.J. et al. 1997, ApJ, 488, L83
[3] Carilli, C.L. et al. 1998, ApJ, 494, L143
[4] Crawford, C.S. & Fabian, A.C. 1996, MNRAS, 282, 1483
[5] De Grandi et al. 1999, ApJ, 514, 148
[6] Dickinson M. et al. 1999, ApJ, submitted
[7] Ebeling, H. et al. 1997, ApJ, 479, L101
[8] Henry, J.P. et al. 1992, ApJ, 386, 408
[9] Gioia, I.M. et al. 1990, ApJ, 356, L35
[10] Jones, L.R. et al. 1998, ApJ, 495, 100
[11] Nichol, R.C. et al. 1999, ApJ, 521, L21
[12] Page, M.J., Carrera, F.J. 1999, MNRAS, in press
[13] Rosati, P. 1998, in Wide Field Surveys in Cosmology, 14th IAP Meeting (Paris, Publ.: Editions Frontieres) p.219
[14] Rosati, P., et al. 1998, ApJ, 492, L21
[15] Rosati, P. et al. 1999, AJ, 118, 76
[16] Stanford, S.A. et al. 1997, AJ, 114, 2232
[17] Steidel C.C. et al. 1999, ApJ, 519, 1
[18] Vikhlinin A. et al. 1998, ApJ, 498, L21