X-ray Surveys of Distant Galaxy Clusters

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Abstract. I review recent observational progress in the search for and study of distant galaxy clusters in the X-ray band, with particular emphasis on the evolution of the abundance of X-ray clusters out to $z \sim 1$. Several on-going deep X-ray surveys have led to the discovery of a sizeable population of clusters at $z > 0.5$ and have the sensitivity to detect clusters beyond redshift one. These surveys have significantly improved our understanding of cluster evolution by showing that the bulk of the population of galaxy clusters is not evolving significantly since at least $z \simeq 0.8$, with some evolution limited to only the most luminous, presumably most massive systems. Thus far, a well defined sample of very high redshift ($z \gtrsim 1$) clusters has been difficult to assemble and represents one of the most challenging observational tasks for the years to come.

1 Introduction

The redshift evolution of the abundance of galaxy clusters has long served as a valuable tool with which to test models of structure formation and set constraints on fundamental cosmological parameters (e.g. [15], [1]). Being recognizable out to large redshifts, clusters are also ideal laboratories to study the evolutionary history of old stellar systems, such as E/S0s, back to early cosmic look-back times (e.g. [31], [33]). It is therefore not surprising that a considerable observational effort has been devoted over the last decade to the construction of homogeneous samples of clusters over a large redshift baseline. Until a few years ago, however, the difficulty of finding high redshift clusters in deep optical images and the limited sensitivity of early X-ray surveys had resulted in only a handful of spectroscopically confirmed clusters at $z > 0.5$. As a result, the evolution of the space densities of clusters, even at moderate look-back times, has been the subject of a long-standing debate (e.g. [10], [18]).

2 Searches for X-ray clusters

With the advent of X-ray imaging in the 80’s, it was soon recognized that X-ray searches for galaxy clusters have the advantage of revealing physically-bound systems out to cosmologically interesting redshifts and thus offer the unique opportunity to construct flux-limited samples with well-understood selection functions. Pioneering work in this field was carried out by Gioia et al.
(1990) and Henry et al. (1992) based on the Einstein Medium Sensitivity Survey (EMSS). By extending significantly the redshift range probed by previous samples [14] (based on non-imaging X-ray data), the EMSS survey has been for years the basis for several intensive follow-up studies (e.g. CNOC survey [1]).

The ROSAT-PSPC detector, with its unprecedented sensitivity and spatial resolution, made clusters high contrast, extended objects in the X-ray sky and has thus allowed for a significant leap forward. ROSAT data have provided the means to carry out large contiguous area surveys of nearby clusters with the ROSAT All-Sky Survey (RASS) ([13]; Böhringer, this volume), as well as much deeper serendipitous searches based on single pointings. On-going X-ray surveys of distant galaxy clusters which utilize PSPC archival data include the ROSAT Deep Cluster Survey (RDCS [24], [25]), the Serendipitous High-Redshift Archival Rosat Cluster survey (SHARC [9], [4]), the Wide Angle Rosat Pointed X-ray Survey of clusters (WARPS [28], [20]), the CfA large area survey ([34], [35]), and the RIXOS survey ([7]). An additional survey is being carried out in the North Ecliptic Pole (NEP, [19]; Gioia, this volume), using the deepest area scanned by the RASS.

2.1 Strategies and Selection Functions

Most studies have adopted a similar methodology but somewhat different strategies. Cluster candidates are selected from a serendipitous search for extended X-ray sources above a given flux limit in deep ROSAT-PSPC pointed observations. Particular emphasis is given in these searches to detection algorithms which are designed to probe a broad range of cluster parameters (X-ray flux, surface brightness, morphology) and to deal with the confusion effect at faint flux levels. A popular and well-suited approach is that of multi-scale analysis based on wavelet techniques (e.g. [24], [34]).

By covering different solid angles at varying fluxes these surveys probe different regions in the X-ray luminosity–redshift plane (i.e. the \( N(L_X, z) \) distribution peaks at slightly different positions). Fig. illustrates the effective sky coverage of the EMSS, compared to that of two ROSAT surveys ([23], [34]). The EMSS has the greatest sensitivity to the most luminous, yet most rare, systems but only a few clusters at high redshift lie above its bright flux limit. On the other hand, deep ROSAT surveys probe instead the intermediate-to-faint end of the X-ray Luminosity Function (XLF). As a result, they have lead to the discovery of many new clusters at \( z \gtrsim 0.4 \). The RDCS, has pushed this search to the faintest fluxes yet, providing sensitivity to the highest redshift systems (including \( z \gtrsim 1 \)) with \( L_X \approx L_X^* \), whereas the CfA survey has covered a significantly larger area at high fluxes thus probing the interesting bright end of the XLF at \( z \lesssim 0.6 \).

Extensive optical follow-up programs associated with these surveys have, to date, lead to the identification of roughly 200 new clusters or groups, and have increased the number of clusters known at \( z > 0.5 \) by about a factor of...
five. As an example, out of more than 100 clusters spectroscopically identified in the RDCS, roughly one-third lie at $z > 0.4$ and a quarter at $z > 0.5$. The fact that very few have been discovered so far at $z > 0.85$ is not due to a lack of sensitivity of X-ray searches at these redshifts, but rather reflects the difficulty of carrying out the spectroscopic confirmation with 4m-class telescope.

Since cluster candidates in such surveys are selected on the basis of their spatial extent, a challenging task is to understand and quantify selection effects at varying fluxes. With the PSPC PSF degrading rapidly at large off-axis angles across the detector, the survey becomes surface brightness limited below a given flux. This important effect can be accounted for by modelling the sky coverage of a given survey as function of flux and intrinsic size of the clusters (fig.1). An overestimate of the solid angle covered at low fluxes and its corresponding search volume can lead to overestimating the amount of evolution of the cluster population ([7]). Furthermore, the surface brightness ($\Sigma$) dimming at high-$z$ can be a serious source of incompleteness in the faintest flux bins and depends critically on the unknown steepness of the $\Sigma$-profile of X-ray clusters at high redshift, as well as its evolution. Again, the task of the observer is to understand the X-ray flux in a given survey below which this effect becomes important. An additional source of incompleteness, which will be difficult to quantify until the next generation of high resolution X-ray imagers become available, may be caused by clusters hosting X-ray bright AGN. A discussion of the methods which are most effective in quantifying the selection function of X-ray surveys goes beyond the purpose of this review.

On pure empirical grounds, the importance of these effects will become apparent when it will be possible to compare the number densities of distant

Figure 1: Comparison between the effective sky solid angle covered by three cluster surveys as a function of the X-ray flux (EMSS [18], CfA Survey [64], RDCS [25]).
clusters selected of the basis of their angular extent with the NEP survey, which set out to identify all the X-ray sources down to a given flux over a 80 deg² area, regardless of their spatial extent.

3 Evolution of the Cluster Abundance out $z \approx 0.8$

One of the primary goals of the aforementioned X-ray surveys is to study the redshift evolution of the cluster abundance at a given X-ray luminosity. This is characterized by the $z$–dependent XLF or its projections along the redshift and flux axis, respectively, i.e. the number counts, $N(S)$, and the redshift distribution, $N(z)$. Such distribution functions of observables can then be directly compared with theories of structure formation.

3.1 The Local XLF

The determination of the local ($z \leq 0.3$) XLF obviously plays a crucial role in assessing the evolution of the cluster abundance at higher redshifts and much progress has recently been made in this direction.

![Figure 2: Local X-ray Luminosity Function of clusters from different surveys.](image)

Fig. 2 shows different determinations of the local cluster abundance. The Brightest Cluster Survey (BCS) [13] covers a large $L_X$ range, similar to an
Figure 3: The observed cluster cumulative number counts from various sources.

independent RASS survey in the southern sky ([12] and Böhringer, this volume). Complementing data are provided by the RDCS and the survey by Burns et al. ([5]) which probes the very faint end. An excellent agreement is apparent between all these independent determinations, all having faint end slopes in the range $1.75 - 1.85$ and consistent normalizations. This is quite remarkable considering that all these surveys used completely different selection techniques (from pure optical to pure X-ray) and independent datasets. This situation contrasts with that existing only two years ago, when different surveys were finding faint end slopes in the range $1.1 - 2.2$. This discrepancy was possibly due to the completeness levels and sky coverages of early samples which were not fully understood. It would thus appear that the local cluster abundance, $N(L_X, z \simeq 0)$, is now well established and can be safely used as a reference for studying the evolution at higher redshifts. Moreover, the BCS analysis at $z < 0.3$ ([13]) shows that the evolution of the bright end found by the EMSS at $z > 0.3$ (fewer high luminosity clusters) does not extend to lower redshifts.
3.2 The Cluster LogN-LogS

A summary of the observed cumulative cluster number counts is given in fig. 3. This compilation includes both shallow and deep surveys (CfA, RDCS, WARPS) so as to cover more than three decades in flux. Once again, we note an encouraging agreement at the 2σ level among independent determinations. The slight difference between the RDCS and the Vikhlinin et al. survey at low fluxes may be due to different prescriptions used in these samples to evaluate the “total flux” of the clusters, a measurement which inherently depends on the assumed Σ-profile of a cluster in background limited regime. Although the LogN–LogS is not a very robust diagnostic tool to investigate the evolution of the cluster population, particularly for the most luminous, rare systems, we note that the observed counts are consistent with no-evolution predictions based on a fit of the local XLF in fig. 3.

3.3 The Cluster XLF at higher redshifts

Moving to higher redshifts, several measurements of the XLF can now be compared with the original determination of the XLF in the range $z = [0.3 - 0.6]$.
Figure 5: The latest determination of cluster X-ray Luminosity Function from the RDCS (81 clusters with $F_X > 3.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$).

from the EMSS. Fig. shows that the number densities from different samples are in general in very good agreement in regions of overlapping luminosities. Further inspection of the XLF in bins of increasing redshift fails to show any significant evolution out to $z \simeq 0.8$ (25). By combining independent analyses based either on the XLF (1, 25) or the LogN–LogS (20, 25, 35), it emerges that the volume density of clusters per unit luminosity has remained constant within the present uncertainties, over a wide range in luminosities ($2 \times 10^{42} \leq L_X (\text{erg s}^{-1}) \leq 3 \times 10^{44}$). This $L_X$ range encompasses the bulk of the cluster population, from poor groups to moderately rich clusters with $L_X \approx L_X^* \approx 4 \times 10^{44}$ erg s$^{-1}$ (roughly the Coma cluster). These results are not in conflict with the EMSS findings of a steepening of the XLF at luminosities in excess of the local $L_X^*$, a result which is consistent with the more recent analysis of the CfA survey in the highest luminosity bin (33).

The latest cluster XLF derived from a flux-limited sample ($F_X [0.5-2.0 \text{ keV}] > 3.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) of 81 clusters spectroscopically identified in the RCCS survey is shown fig. The picture described above is further confirmed. It also appears that in order to make a significant step forward in understanding the evolution of the most luminous systems at high redshifts ($z > 0.7$), a new survey covering at least 10 deg$^2$ at $F_X \simeq 1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ is needed. This is within reach with several years of serendipitous pointings to be accumulated with XMM and AXAF.
Figure 6: Cartoon summarizing the observational status of X-ray cluster evolution. Very little is presently known about the cluster population at $z > 0.8$, although bona-fide X-ray clusters have been detected out to $z = 1.27$ \cite{32} and diffuse X-ray emission detected around radio sources to even higher redshifts \cite{11}.

4 Cluster searches at $z \gtrsim 1$

Fig. 6 summarizes our current understanding of cluster evolution in the $(L_X, z)$ plane at the end of the ROSAT era. A major unknown concerns the cluster abundance beyond redshift of one. If one assumes that the evolutionary trend in the cluster population continues past $z = 1$, the observed $N(L_X, z)$ can be extrapolated (taking also into account the estimated incompleteness at the faintest flux levels) to predict that ROSAT-PSPC searches must be still sensitive to the feeble X-ray emission from $L_X^*$ clusters at $z > 1$. For example, in the RDCS one would expect up to a dozen X-ray luminous clusters at $z \gtrsim 1$. However, in order to identify these clusters, near-IR deep imaging and spectroscopy with 8m-class are required.

The efficacy of near-IR searches for high-$z$ cluster searches has recently been proven by Stanford et al. \cite{32} who have identified a cluster at $z = 1.27$ in a near-IR field galaxy survey. A corresponding extended X-ray source was found by the same authors in a deep ROSAT pointing, as well as serendipitously in
the RDCS candidate sample. More recently, another RDCS faint candidate has been confirmed at $z = 1.26$ using IR imaging and Keck spectroscopy [26]. The X-ray luminosities of both these systems are around $10^{44} \text{ erg s}^{-1}$ in the [0.5-2.0 keV] band. These findings show that the combination of deep X-ray observations and near-IR imaging is an efficient method by which to identify massive clusters at $z \gtrsim 1$ in a serendipitous fashion, thus allowing statistical estimates of the cluster abundance to be made. The much improved sensitivities of XMM and AXAF will make this method particularly attractive.

At even higher redshifts, a viable method to identify clusters is to target powerful radio sources (e.g. [11]). Deep ROSAT pointings on these sources have revealed the existence of diffuse X-ray emission out to $z \approx 1.8$ which most likely arises from hot intra-cluster gas trapped in deep cluster potential wells at such early epochs [1].

5 Discussion

Remarkable observational progress has been made over the last years in determining the abundance of galaxy clusters out to $z \sim 1$, as is underscored by the convergence of the results from several independent studies. At the beginning of the ROSAT era, only a few years ago, controversy surrounded the usefulness of X-ray surveys of distant galaxy clusters. This prejudice arose from an overinterpretation of the early results of the EMSS survey which, as of today, remain basically correct. Although in the early analysis of Gioia et al. [17] it was clearly stated that the evolution of the XLF was limited only to the very luminous systems, this detail was often overlooked for many following years. Indeed, this evolution was believed to extend through the bulk of the cluster population ($L_X \lesssim L_X^\ast$) not adequately probed by the EMSS at high redshifts. The original controversy concerning cluster evolution inferred from optical and X-ray data finds a possible explanation in this. Optical surveys ([10], [23]) have shown no dramatic decline in the comoving volume density of rich clusters out to $z \approx 0.5$. This was considered to be in contrast with the EMSS findings. However, these optical searches covered limited solid angles (much smaller than the EMSS) and therefore did not probe adequately the seemingly evolving high end of the cluster mass function.

The theoretical interpretation of the new results on the evolution of the cluster abundance is still ambiguous. The implications that these findings have for models of cluster formation have been discussed by several authors (e.g. [21], [22], [8], [2], [3]). By following a phenomenological approach, one can constrain cosmological parameters and evolutionary parameters of the intra-cluster medium by matching models with observed distributions, such as $N(L_X, z)$, $N(z)$, $N(> S)$. This analysis has shown [2] that without additional observational inputs from the temperatures of high-$z$ clusters or a better understanding of the physics governing the evolution of their gaseous component, it is difficult to draw firm conclusions on the value of the density parameter.
Figure 7: Constraints at 90% c.l. on the $\Omega_0 - A$ plane by matching the XLF as a function of redshifts from various X-ray surveys [2]. The parameter $A$ describes the redshift evolution of the X-Luminosity-Temperature relation: $L_X \sim (1 + z)^{\Delta T}$.

$\Omega_0$. As an example, fig. 7 shows the degeneracy between $\Omega_0$ and the evolutionary parameter of the X-Luminosity-Temperature (L-T) relation. Recent measurements of cluster temperatures at moderate redshifts indicate that the L-T relation does not evolve significantly out to $z \simeq 0.5$ ([29], [19]) (i.e. $A \approx 0$), which would favour a low-$\Omega$ universe.

6 Future Prospects

The next decade promises to be particularly exciting for cluster astrophysics. The new ROSAT samples described herein will figure prominently in studies for years to come. The new generation of optical and near-IR mosaic imagers and highly efficient multiplexing spectrographs on 8-meter class telescopes (Keck, VLT, GEMINI) will probe a region of the parameter space of redshift, solid angle and limiting flux which has been completely unexplored with 4m-class telescopes and conventional detectors. The Advanced Camera aboard HST (2000) will add sub-kpc morphological information to this multi-dimensional data set and will permit detailed studies of their lensing patterns. The impact of AXAF, XMM, and Sunyaev-Zeldovich measurements are described elsewhere in this volume (see contributions from K.Romer; M.Pierre; J.Bartlet).

The next generation of X-ray satellites and the already available large optical telescopes should open the possibility of determining masses of distant clusters via X-ray temperature measurements, virial analysis and gravitational lensing studies. Carrying on such observations for an even limited number of clusters, extracted from a well defined statistical sample, will determine both the evolution of the cluster internal dynamics and the value of the cosmological density parameter.

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