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# A scientific case for future X-ray astronomy: galaxy clusters at high redshifts

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**Abstract.** Clusters of galaxies at high redshift ($z > 1$) are vitally important to understand the evolution of the large scale structure of the Universe, the processes shaping galaxy populations and the cycle of the cosmic baryons, and to constrain cosmological parameters. After 13 years of operation of the Chandra and XMM-Newton satellites, the discovery and characterization of distant X–ray clusters is proceeding at a slow pace, due to the low solid angle covered so far, and the time-expensive observations needed to physically characterize their intracluster medium (ICM). At present, we know that at $z > 1$ many massive clusters are fully virialized, their ICM is already enriched with metals, strong cool cores are already in place, and significant star formation is ongoing in their most massive galaxies, at least at $z > 1.4$. Clearly, the assembly of a large and well characterized sample of high-z X-ray clusters is a major goal for the future. We argue that the only means to achieve this is a survey-optimized X-ray mission capable of offering large solid angle, high sensitivity, good spectral coverage, low background and angular resolution as good as 5 arcsec.

**Key words.** Galaxies: clusters: general – galaxies: high-redshift – cosmology: observations – X-ray: galaxies: clusters – surveys

## 1. Introduction

X-ray observations of clusters of galaxies over a significant range of redshifts have been used to investigate the chemical and thermodynamical evolution of the X-ray emitting intracluster medium (ICM) and to constrain the cosmological parameters and the spectrum of the primordial density fluctuations. In this respect, X-ray surveys of clusters of galaxies represent a key tool for cosmology and the physics of large scale structure. The compilation of more and larger X-ray selected samples with well-defined completeness criteria is one of the critical requirements of present-day cosmology.

There is a remarkable lack of recent wide-area X-ray surveys suitable to this scope. Most of the existing cluster samples are still based on ROSAT data. The most recent constraints on cosmological parameters from X-ray clusters are based on the Chandra follow-up of 400 deg$^2$ ROSAT serendipitous survey and of the All-Sky Survey (Vikhlinin et al. 2009; Mantz et al. 2010). At present, there are no cosmological constraints based on the mass function of clusters selected from Chandra or XMM-Newton data. There is, however, a significant effort devoted to new X-ray surveys based on data from currently operating X-ray satellites,

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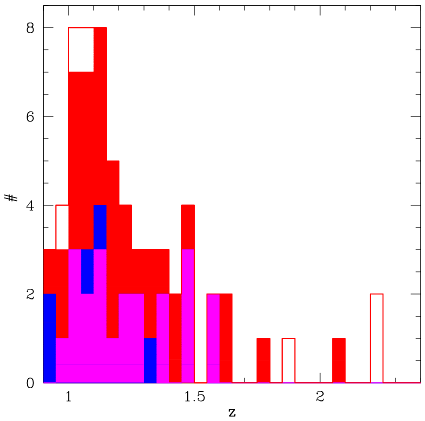


**Fig. 1.** Redshift histrogram distribution of clusters at $z > 1$ reported in the literature as of September 2012. Colors corresponds to different selection methods: red=IR; magenta=X-ray; blue=SZ; white=other.

realized thanks to compilations of serendipitous medium and deep extragalactic fields not associated with previously known X-ray clusters, plus a few dedicated, contiguous observations. A table summarizing the properties of post-ROSAT cluster surveys is presented in Tundo et al. (2012).

One of the most important goals of these surveys is to find massive clusters at high $z$. If we focus on the most distant clusters reported in the literature, irrespective of the selection band, we find that only nine have been spectroscopically confirmed at $z \geq 1.5$ to date, and only a few of them have estimated masses in excess of $10^{14}$ $M_{\odot}$. The redshift histogram distribution of clusters and cluster candidates at $z > 1$ (less than 70 overall) is shown in Figure 1. While the redshift limit for X-ray selected clusters is $z \sim 1.57$ (Fassbender et al. 2011), extended X-ray emission has been detected in optical and IR selected clusters out to $z = 1.75$ (Stanford et al. 2012), $z = 2.07$ (Gobat et al. 2011), and $z \sim 2.2$ for an extreme candidate (Andreon et al. 2012). However, many other cluster candidates identified in the IR are undetected, suggesting uncomplete virialization.

Present-day X-ray facilities offer a limited discovery space mostly because of the small solid angle covered so far. Although the exploitation of the Chandra and XMM archives is still far from being concluded, we can predict, on the basis of what has been obtained to date, that in the future the number of clusters firmly detected in X-ray at $z > 1$ will grow up to $\sim 100$ in the most optimistic case. Note that this number applies only to the detection of the cluster X-ray emission. In fact, the number of high-z X-ray cluster with a robust physical characterization will be at best a factor of 3 lower. The reason is that the only means to determine the virialization status of distant clusters, to measure their mass and characterize the thermodynamical and chemical properties of their ICM, is to perform time-expensive observations with Chandra (of the order of few $\times 100$ ks) to collect more than 1000 net photons in the 0.5-7 keV band in high resolution images to remove the effect of contaminating AGN emission and of central cool cores.

This situation is not expected to improve on the basis of currently planned missions. Looking at the near future, the upcoming mission eROSITA will not be efficient in finding extended sources at fluxes below few $\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, where most of the distant clusters are. Finally, although X-ray observations still dominate this field, Sunyev-Zeldovich (SZ) cluster surveys are rapidly gaining momentum, thanks to the South Pole Telescope Survey (Reichardt et al. 2012) and the Atacama Cosmology Project (Sehgal et al. 2011), which will be soon complemented by a shallower, but all-sky survey by the Planck satellite. At present, the most distant confirmed SZ selected cluster is reported at $z \sim 1.32$ (Stalder et al. 2012). The X-ray data, however, are strongly complementary to SZ, and a complete characterization of a galaxy cluster, particularly a distant one, must rely on both X-ray and SZ data. In order to keep the crucial role of X-ray astronomy in this field, a wide and deep coverage of the X-ray sky is needed. This can be achieved only with a dedicated mission optimized for surveys, as we argue in the following sections.

## 2. The Swift X-ray cluster survey

A constant angular resolution across the field of view (FOV) and a low background are two key properties that a future X-ray survey must retain in order to efficiently detect and characterize faint extended sources, such as distant X-ray clusters. The Swift X-ray Cluster Survey (SXCS), built upon the rich set of archival data of the X-ray Telescope (XRT) onboard the Swift satellite (Burrows et al. 2005), is an excellent example of what can be done thanks to these two key properties. The point spread function (PSF) of XRT is characterized by a half energy width (HEW) of $\sim$ 18 arcsec at 1.5 keV, with negligible degradation with the off-axis angle on the entire FOV of 24 arcmin (Moretti et al. 2007). The SXCS catalog presented in Tundo et al. (2012) is based on the 336 GRB fields with galactic latitude $|b| > 20°$ present in the XRT archive as of April 2010. The extended source candidates are identified thanks to a simple growth-curve analysis applied to the soft band (0.5-2 keV) images (see Figure 2). The algorithm is validated via extensive simulations. One of the most relevant aspects is the low level and the high reproducibility of the background not associated with astronomical sources. Due to the low orbit and short focal length, this background component per solid angle, normalized by the effective area, is a factor $\sim$ 7 lower than in Chandra in the 0.5-7.0 keV energy band (Moretti et al. 2012).

The final catalog consists of 72 X-ray group and cluster candidates (mostly at moderate redshifts) with a negligible contamination, a well defined selection function and a robustly estimated completeness, spanning two orders of magnitude in flux down to the limit of $\sim 10^{-14}$ erg s$^{-1}$ cm$^{-2}$. The corresponding logN-logS is in very good agreement with previous deep surveys. Thanks to a cross correlation with the NED database, we are able to associate 24 optical redshifts (spectroscopic or photometric) published in the literature with our cluster candidates. Overall, 46 sources in our catalog are new detections, both as X-ray sources and as clusters of galaxies. We also measured the redshift for about half of the sources thanks to the identification of the red-

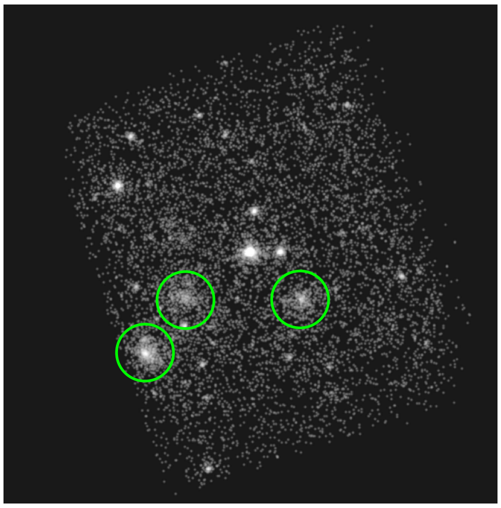

**Fig. 2.** XRT smoothed image of the GRB050505 field in the soft (0.5 – 2.0 keV) band; the exposure time is ~170 ks, and the image size is ~24×24 arcmin. The three clusters in the field are highlighted by the circles. The bright source at the center is the GRB (from Tundo et al. (2012).

shifted $K_\alpha$ Fe line in the spectral analysis, following the procedure described in Yu et al. (2011). At present, the largest measured redshift in the SXCS sample is $z = 1$, while many redshift measurements are still lacking for the faintest part of the sample. This shows that despite its low collecting area (about one fifth of Chandra at 1 keV) XRT is unexpectedly providing a well characterized X-ray survey reaching the realm of distant galaxy clusters. To summarize, although XRT is not able to offer the large solid angle and the sensitivity needed to find and characterize a consistent number of high-z clusters, we argue that flat PSF across the FOV and low background are two fundamental properties for future missions aiming at bringing the X-ray sky to the same depth and richness of the optical and IR sky in the next decade.

## 3. The WARPJ1415 field

To obtain a robust characterization of distant X-ray clusters, including the measure of the ICM temperature, its iron abundance, and hence the redshift from the detection of the Fe emission line complex at 6.7-6.9 keV, a relatively high effective area in the energy range 2-7 keV is also required. In addition, as opposed to the mere identification of an extended source, which requires about 20 counts, a meaningful, single-temperature spectral analysis requires a 1000-1500 net counts (in the 0.5-7 keV band). On the other hand, about $\sim$ 10000 net counts are required if we aim at a spatially resolved spectral analysis, which allows a much better mass determination, a study of the iron distribution, and a detailed characterization of the central regions (within $r_{500}$). These science goals can be achieved at any redshift only if the angular resolution is equal or better than 5 arcsec HEW (see Santos et al. 2011).

A remarkable case to illustrate both regimes is the WARPJ1415 field which has been observed with Chandra ACIS-S for 280 ks (plus 90 ks with ACIS-I) with the aim of studying the properties of the cool core of WARPJ1415 at $z = 1.03$ (see Santos et al. 2012). The sharp and deep Chandra data allowed us to measure a very low central cooling time $t_{cool} \leq 0.23$ Gyr in the inner 20 kpc, with a surprisingly pronounced metallicity peak, $Z_{Fe} = 3.60^{+1.50}_{-0.85} Z_{\odot}$. The cluster total X-ray mass, under the assumption of hydrostatic equilibrium, is accurately measured as $M_{200}$=$3.0^{+0.6}_{-0.4}$$\times$$10^{14}$M$_{\odot}$. Using VLA data we detected a radio source coincident with the brightest central galaxy (BCG) with a faint, one-sided structure extended for 80 kpc in the north-west direction, where a significant lack of X-ray emission was found. Thanks to this study, we are able to confirm that a feedback mechanism powered by AGN in the radio mode, as observed in local clusters, is at work also in the core of WARPJ1415. In addition, the prominent iron peak indicates that the metal enrichment mechanisms by type Ia supernovae and star formation in the BCG happened on a short timescale (given the large lookback time of 7.8 Gyr), and that the transport processes that drive away the metals to the outskirts were not efficient to smear out the iron excess. Overall, these observations enabled the most detailed analysis of the ICM of a $z \sim 1$ cluster to date and highlight the importance of deep, high-resolution data to adequately characterize distant clusters. With current X-ray facilities, we expect that only few cases can be studied with an accuracy comparable to that of WARPJ1415.

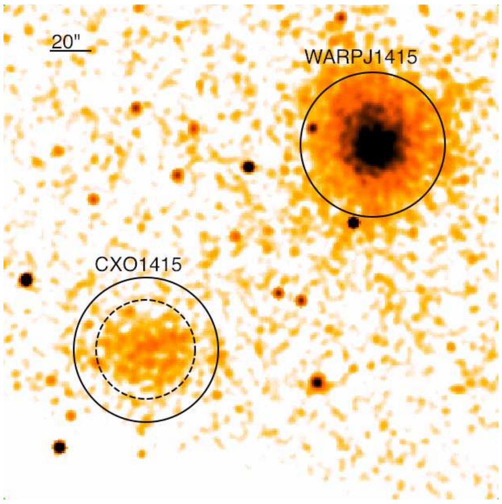

**Fig. 3.** ACIS-S+I image of the WARPJ1415 field. The bright cluster WARPJ1415 at $z = 1$ is visible in the upper right, whereas CXO1415 at $z \sim 1.5$ lies at $\sim 2'$ in the south-west direction. The solid circles have a radius of 35″ (corresponding to 300 kpc at $z = 1.46$), whereas the dashed circle with $r = 24''$ refers to the aperture of maximum S/N. The image has a size of $4' \times 4'$ (see Santos et al. 2012).

As an unexpected bonus, CXO J1415 was serendipitously detected in the same observation (see Tozzi et al. 2012). The new system, located at a distance of $\sim$ 2 arcmin in the south-west direction of WARPJ1415, was immediately detected by visual inspection as an extended X-ray source in the ACIS-S image (see Figure 3) with a $S/N \sim 11$ within a radius of 24 arcsec. The soft-band flux within $r = 24''$ is equal to $S_{0.5-2.0keV} = (6.5 \pm 0.3) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. We measure a redshift of $z = 1.46 \pm 0.025$ by identifying the Fe $K_{\alpha}$ complex line at a $\sim 2.8\sigma$ confidence level. This shows that the measure of redshift through X-ray spectral analysis is possible up to the highest redshift where X-ray clusters are currently detected. This makes CXO1415 the highest-z cluster discovered with Chandra so far. The spectral fit with a `mekal` model gives $kT = 5.8^{+1.2}_{-1.0}$ keV, for a total mass of $M(r < 300\mathrm{kpc}) = 1.38^{+0.33}_{-0.28} \times 10^{14} M_{\odot}$, while the ICM mass is $M_{ICM}(r < 300\mathrm{kpc}) = 1.09^{+0.30}_{-0.20} \times 10^{13} M_{\odot}$, resulting in a ICM mass fraction of $\sim 13\%$. The color-magnitude diagram of cluster member candidates shows both a red sequence and a significant fraction of blue, irregular-morphology galaxies. Finally, when compared with the expectations for a ΛCDM universe, CXO1415 appears to be a typical cluster at $z \sim 1.5$ for a WMAP cosmology (Komatsu et al. 2011); however, the redshift and the total mass of CX01415 place it among the sample of massive, distant galaxy clusters which may be used to accurately test the standard ΛCDM model once a sizeable sample of high-z clusters will be assembled.

## 4. Conclusions

After 13 years of operations of the Chandra and XMM-satellites, we have a robust vision of cluster properties at $1 < z < 1.5$, and a glimpse of it at $z > 1.5$. Now we know that not only massive X-ray clusters are abundant at $z > 1$, but also that at $z > 1.5$ we keep finding clusters whose ICM is already virialized, strongly enriched with metals, and whose color-magnitude relation is already partially established. Without any doubt, high-z, X-ray clusters represent a scientific case which can provide critical insights into the physics of cosmic structure formation, galaxy evolution, the life cycle of the cosmic baryons, and provide constraints on cosmological parameters.

At present, the investigation of distant X-ray clusters is proceeding slowly. High-z clusters are rare, faint objects with a small extension ($\leq 1$ arcmin), and require deep and wide-angle observations, with a good angular resolutions, in order to be found. Moreover, a good spectral coverage up to 7 keV and a large collecting area are needed to physically characterize them. In this perspective, the future looks grim. The planned eROSITA satellite (Predehl et al. 2010) will be confusion limited in the flux regime where the majority of the high-$z$ clusters are expected. In addition, its low hard-band sensitivity hampers a robust measure of the temperature for hot clusters, limiting cosmological studies. The only means to address this scientific case is a survey-optimized mission such as the proposed Wide Field X-ray Telescope (WFXT Murray et al. 2010). The WFXT, thanks to its good angular resolution and a constant image quality across a 1 deg$^2$ FOV, coupled with a large effective area, will provide a direct measurement of temperatures, density profiles and redshifts for about 1000 X-ray clusters at $z > 1$, without the need of time-prohibitive spectroscopic follow-up programs. This will improve by almost two orders of magnitude any well-characterized cluster sample that we can possibly assemble using the entire wealth of data from present and planned X-ray facilities. We conclude that a mission such as WFXT is able to fully address the scientific case of high-z clusters, among many others, as well as to match in depth, survey volume and angular resolution surveys at other wavelengths which are planned for the next decade.

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