Mem. S.A.It. Suppl. Vol. 17, 66

Memorie della
Supplementi

Are there cool-core clusters at high-redshift? Chandra results and prospects with WFXT

J.S. Santos[1], P. Tozzi[1] and P. Rosati[2]

[1] INAF–Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34131 Trieste, Italy
e-mail: `jsantos@oats.inaf.it`
[2] European Southern Observatory

Abstract. Cool core clusters are characterized by strong surface brightness peaks in the X-ray emission from the Intra Cluster Medium (ICM). This phenomenon is associated with complex physics in the ICM and has been a subject of intense debate and investigation in recent years. The observational challenge of analyzing high redshift clusters and the small sample statistics have prevented an accurate assessment of the population of cool-cores at z >0.5. In this contribution we trace the evolution of cool-core clusters out to $z \sim 1.3$ using high-resolution *Chandra* data of three representative cluster samples spanning different redshift ranges. Our analysis is based on the measurement of the surface brightness (SB) concentration, c_{SB}, which strongly anti-correlates with the central cooling time and allows us to characterize the cool-core strength in low S/N data. We confirm a negative evolution in the fraction of cool-core clusters with redshift, in particular for very strong cool-cores. Still, we find evidence for a large population of well formed cool-cores at $z \sim 1$. This analysis is potentially very effective in constraining the nature and the evolution of the cool-cores, once large samples of high-z clusters will be available. In this respect, we explore the potential of the proposed mission Wide Field X-ray Telescope (WFXT) to address this science case. We conclude that WFXT provides the best trade-off of angular resolution, sensitivity and covered solid angle in order to discover and fully characterize the cool-core cluster population up to z=1.5.

Key words. Galaxy clusters - cosmology: Galaxy clusters - high redshift: observations - X-rays

1. Introduction

The majority of local X-ray clusters show a prominent central surface brightness peak in the intra cluster medium (ICM). The cluster core is also associated with a short cooling time, implying the presence of a cooling flow (Fabian et al. 1994), although the gas is not observed to cool below a minimum temperature of the order of 1/3 of the average value in the ICM, indicating that some heating mechanism counteracts the cooling process. The properties and the formation mechanism of these cool-cores (CC) are an open problem which forces one to consider complex non-gravitational physical processes able to provide smoothly distributed heating on scales of about 100 kpc. A successful model is expected to include phenomena such as removal of radiatively cooled gas, heating by a central radio source, thermal conduction or other forms of feedback (see Peterson & Fabian 2006).

The impact of cool-cores on the local cluster population has been extensively studied for over a decade (Peres et al. 1998). X-ray observations have established that cool-cores dominate the local clusters, with an abundance of 50 to 70%, depending on the adopted definition of cool-core (e.g. Chen et al. 2007, Dunn & Fabian 2008, Hudson et al. 2009).

The evolution of cool-cores has been measured only up to redshift 0.4. Bauer et al. (2005) reported that the fraction of cool-cores does not significantly evolve up to $z \sim 0.4$, since clusters in this redshift range have the same temperature decrement (about one-third), as the nearby CC's, and their central cooling times are similar. The study of cool-cores at redshift greater than 0.5 is plagued by low statistics, and, so far, is limited to two works. Using the 400 Square Degree Survey (hereafter 400 SD, Burenin et al. 2007) which reaches $z = 0.9$, Vikhlinin et al. (2007) concluded, on the basis of a cuspiness parameter defined as the logarithmic derivative of the density profile, that there is a lack of cool-core clusters, with respect to the local cluster population. In Santos et al. (2008), we adopted a simple diagnostic based on the concentration of the surface brightness (which strongly anti-correlates with the central cooling time), and measured the fraction of cool-cores out to the current redshift limit ($z \sim 1.4$). At variance with previous results, we found a significant fraction of what we term moderate cool-cores.

In this contribution we present our results on the abundance of cool-cores across the entire cluster population, out $z \sim 1.3$, exploiting all the available data in the *Chandra* archive (Santos et al. 2010), and we assess the potential of the next-generation X-ray mission Wide Field X-ray Telescope (WFXT, Giacconi et al. 2009) in measuring the cool-core evolution.

2. Cluster samples

The local cluster sample used in this work is drawn form the catalog of the 400 Square Degree (SD) Survey (Burenin et al. 2007), an X-ray survey which detected 266 confirmed galaxy clusters, groups or individual elliptical galaxies out to $z \sim 1$ using archival ROSAT PSPC observations. The sample is complete down to a flux limit of 1.4×10^{-13} erg s^{-1} cm^{-2}. We extract a subsample of 26 clusters observed with Chandra with $z > 0.05$, in order to be able to sample the surface brightness profiles out to a radius of 400 kpc within the field of view. Hence, our local sample spans the redshift range [0.05 - 0.217].

X-ray images of distant clusters suffer a strong surface brightness dimming ($\propto (1+z)^{-4}$) and have a small angular size, thus the study of their central regions requires the sub-arcsecond resolution provided only by *Chandra*. Beyond redshift 0.5 there are only three X-ray complete cluster samples, all selected from ROSAT PSPC pointed observations. They are: (i) the 400 SD high-z sample which includes all clusters (20) from the 400 SD catalog with $z \geq 0.5$; (ii) the Rosat Deep Cluster Survey (RDCS, Rosati et al. 1998; and (iii) the Wide Angle ROSAT Pointed Survey (WARPS, Jones et al. 1998). While the distant 400 SD sample has been fully observed with Chandra, the RDCS and WARPS samples have been only partially observed with a Chandra follow up. For this reason, we merge them into the RDCS+WARPS sample, containing a total of 15 clusters.

3. Surface brightness concentration

The simplest observational signature of the presence of a cool-core is a central spike in the surface brightness profile. This is also the only possible diagnostic we can apply to high redshift clusters, given the difficulty in performing spectral analysis to detect the temperature decrease in the core region.

In Santos et al. (2008) we defined the phenomenological parameter c_{SB} that quantifies the excess emission in a cluster core by measuring the ratio of the surface brightness within a radius of 40 kpc with respect to the SB within a radius of 400 kpc: $c_{SB} = SB(r < 40kpc)/SB(r < 400kpc)$. This simple parameter has been shown to be robust and particularly useful when dealing with the low S/N data of distant clusters. We validated the redshift independence of c_{SB} (apart from possible K-corrections as described in Santos et al. 2010) by cloning low-z clusters to high redshift. After this detailed investigation, we propose the use of c_{SB} as the best proxy for the cool-core stength in the high-z range.

Before comparing the c_{SB} distribution of local and distant samples (400 SD high-z and RDCS+WARPS), we compare the two distant samples separately in Figure 1, top panel. Quite unexpectedly, the shape and range of the two high-z c_{SB} distributions are statistically different. We perform a K-S test and find a null hypothesis probability of 0.6%, implying that the two distant samples do have different distributions of cool-core strength. The 400 SD high-z reaches $c_{SB} = 0.10$, with median $c_{SB} = 0.043$, whereas the RDCS+WARPS reaches $c_{SB} = 0.15$, with a median c_{SB} value equal to 0.082. The RDCS+WARPS clusters have thus a significantly higher surface brightness concentration with respect to the 400 SD clusters.

Since both the RDCS+WARPS and the 400 SD are samples based on ROSAT data, we argue that this c_{SB} difference is likely due to different selection criteria used in the 400SD survey, resulting in a bias against compact clusters with a relatively high surface brightness. To check for these effects, we need to go through a detailed comparison of the selection criteria in the three surveys, a task that goes beyond the scope of this work. In order to investigate the evolution of the cool-cluster population, we decide to use the RDCS+WARPS only.

The c_{SB} distribution of the local sample (Figure 1, bottom) spans a broad range of values and reaches c_{SB}=0.315, with a significant peak at low c_{SB} and a median c_{SB} equal to 0.079. We performed a K-S test to the local and distant RDCS+WARPS samples and found a null hypothesis probability of 16%, implying that the two samples have a non-negligible probability to be statistically similar. Our findings are compatible with a significant population of cool-core clusters already well established at redshift $z \sim 1.3$ (5 Gyr after the Big Bang), while strong cool-cores ($c_{SB} > 0.150$) must wait for a longer time span before they can develop. To reinforce these results, it is necessary to use larger samples of high-z clusters.

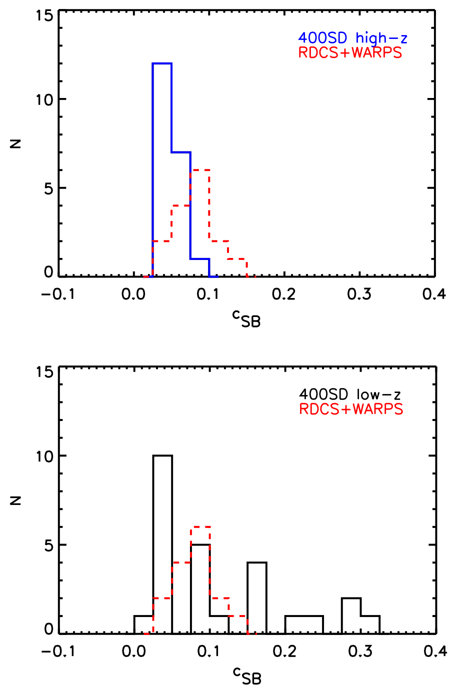

Fig. 1. Comparison of the distribution of c_{SB} of the distant samples (top) and of the local and RDCS+WARPS samples (bottom).

4. Central cooling time

The central cooling time is the measure most often used to quantify cool-cores, as it provides a time-frame for the evolutionary state of the gas. Adopting an isobaric cooling model for the central gas, t_{cool} can be computed as:

$$t_{cool} = \frac{2.5 n_g T}{n_e^2 \Lambda(T)}, \qquad (1)$$

where $\Lambda(T)$, n_g, n_e and T are the cooling function, number density of ions and electrons, electron number density and temperature, respectively (Peterson & Fabian 2006). Using the global cluster temperature we obtained the central cooling time measured at a radius of 20 kpc. The local clusters span a

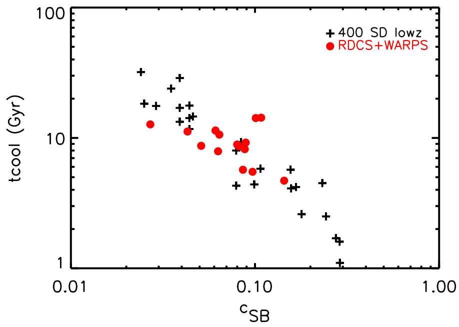

Fig. 2. Correlation between central cooling time and the phenomenological parameter c_{SB} for the local (crosses) and the high-z (filled cirles) samples.

wide range of ages [0.7 - 32.6] Gyr, whereas the RDCS+WARPS sample is limited to [4.7 - 14.3] Gyr.

The local clusters span the wide range of ages [0.7 - 32.6] Gyr, whereas the RDCS+WARPS sample is limited to [4.7 - 14.3] Gyr. The fraction of clusters with a central cooling time lower than the age of the Universe at the cluster redshift is: 58% in the local sample; 27% in the RDCS+WARPS, and 10% in the 400 SD high-z. However, a more meaningful quantity would be the cooling time normalized to the age of the cluster, defined as the time elapsed since the last major merger event. Considering the age of the Universe at z_{obs} is misleading, as this is a loose upper bound on the age of the cluster.

We confirm a strong anti-correlation between t_{cool} and c_{SB} (see Fig. 2), quantified by a Spearman rank test with coefficient ρ=-0.84.

5. The potential of WFXT to measure the evolution of cool-cores

With the present work we show that we can explore the population of cool-core clusters up to the highest redshift where X-ray clusters are selected, by exploiting the archive of *Chandra*. This is possible thanks to the exquisite angular resolution of *Chandra*, which allows us to sample the cool core region at any redshift with about 10 resolution elements. The only way to improve the present work is to add serendipitously discovered high-z clusters followed-up with deep *Chandra* observations. The number of $z > 1$ X-ray clusters is slowly increasing as a result of the ongoing surveys with *Chandra* and XMM-Newton. However, sample statistics is not expected to increase significantly without a dedicated wide area, deep X-ray survey. Hence, it is instructive to look into the future X-ray missions to investigate the capability of characterizing the cool-core strength of high-redshift clusters. Unfortunately, no proposed or planned future X-ray facility foresees an angular resolution comparable to that of *Chandra*. However, two future X-ray missions propose a PSF with a 5 arcsec half energy width (HEW) at 1 keV, the International X–ray Observatory and the Wide Field X–ray Telescope.

The International X-ray Observatory (IXO) (see e.g., Bookbinder 2010) is designed to have a great collecting power and high spectral resolution, therefore it will provide very detailed analysis of known or serendipitously discovered clusters, up to high-redshift. However, IXO will not be used in survey mode, but for a limited solid angle, and therefore it would not increase significantly the statistics of high-z cluster samples.

The Wide Field X-ray Telescope (WFXT) is one of the most promising proposed X-ray missions. The expected number of high-z clusters detected in WFXT surveys with signal to noise comparable to that of the cluster sample used in this work (conservatively expressed as a lower bound of 1500 net counts), is shown in Table 1. Simulations of realistic WFXT fields have been produced in order to investigate the accuracy of WFXT in characterizing cool core clusters. We used the cloning tech-

Table 1. Expected number of clusters sources with temperature >3 keV and minimum net counts 1500 in each of the three planned WFXT surveys in two redshift bins.

Survey	0.5<z<1.0	1.0<z<1.5
Shallow	200	0
Medium	2190	300
Deep	188	94

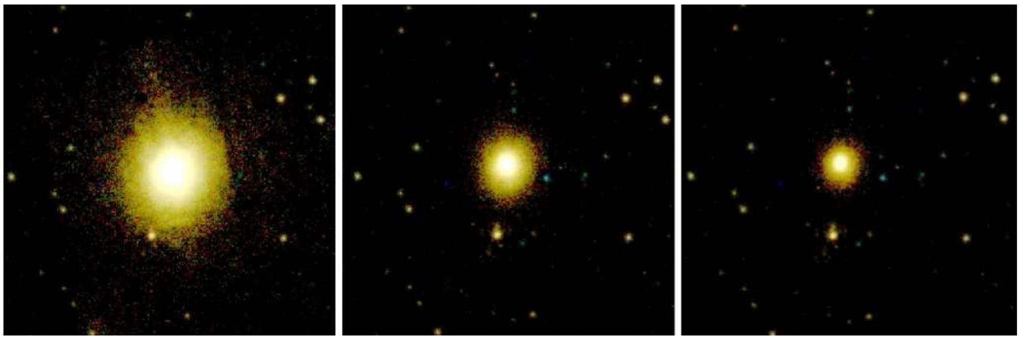

Fig. 3. Simulated WFXT images of the strong cool-core cluster A1835 in the medium survey (13.2 ksec), at redshifts 0.5 (left), 1.0 (middle) and 1.5 (right). The images are 10 arcmin across and are displayed in logarithmic scale.

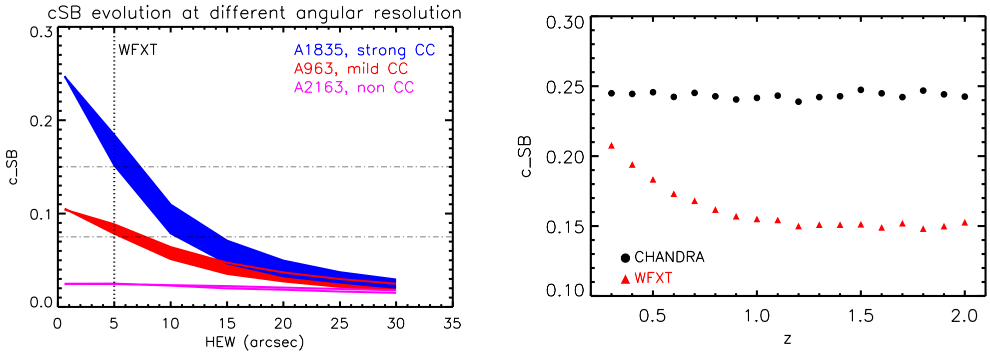

Fig. 4. (Left) Variation of the measured c_{SB} as a function of the telescope HEW for the three typical cases (strong-, moderate- and non-cool core). For each cluster the coloured area is bounded by the c_{SB} value at redshift 0.5 (higher bound) and 1.5 (lower bound). The two horizontal dash-dot lines represent the boundaries between strong CC and moderate CC (upper line, c_{SB}=0.15) and moderate-CC and non-CC (lower line, c_{SB}=0.075). (Right) Comparison between Chandra and WFXT measures of c_{SB} as a function of redshift, for a strong cool-core cluster.

nique (Santos et al. 2008) to simulate WFXT images of three canonical cluster types, corresponding to a typical strong-CC ($c_{SB} > 0.150$, A1835), a moderate-CC ($c_{SB} > 0.075$, A963) and a non-CC ($c_{SB} < 0.075$, A2163) (see Santos et al. 2008 for more details on these clusters), at redshifts 0.5, 1.0 and 1.5. To obtain a quantitative assessment of the cool-core properties of the simulated clusters, we measured c_{SB} in the simulated images.

We first investigated the effect of the angular resolution in the evaluation of the cool-core strength. The result clearly shows that the ability of an instrument to resolve the core and discriminate between a cool-core and non cool-core is compromised for HEW greater than 10″(see Figure 4, left panel). In more detail, the c_{SB} values for the strong cool-core cluster A1835 (Fig. 3) as measured by WFXT are shown in the right panel of Figure 4, in comparison with the values measured by *Chandra*. We notice an apparent evolution in c_{SB} due to the larger angular resolution of WFXT relative to *Chandra*, but we also confirm that the measure of c_{SB} at face-value allows us to assign the different clusters to their own cool-core class (i.e. strong, moderate or non cool-core) at any redshift, as already shown in Figure 4. In this

Fig. 5. The Bullet cluster as observed by WFXT in the deep (400 ksec) survey, at redshifts 0.5 (left), 1.0 (middle), 1.5 (right). Images sizes are 10x10 arcmin.

regime (i.e. HEW=5″), the degradation of the c_{SB} measurement due to the angular resolution is moderate and can be accounted for, while for angular resolution approaching 10″, this effect rapidly increases and make it impossible to measure the cool-core strength (see Fig. 4).

Besides detecting and characterizing distant cool cores, WFXT's angular resolution will also allow sharp features (such as cold front and shocks) to be detected at high-z. This is illustrated with simulations of the well-known Bullet cluster as it would appear in the WFXT deep survey, at redshifts 0.5, 1.0 and 1.5 (see Figure 5).

6. Conclusions

In this contribution we investigated the evolution of cool-core clusters across the entire redshift range currently available, i.e., out to z=1.3. Our analysis is based on the archival *Chandra* data of three cluster samples, and our results are derived mainly from the cluster X-ray surface brightness properties. The distributions of the surface brightness concentration c_{SB} (Fig. 1) show us that: (i) the 400SD and the RDCS+WARPS high-z samples are statistically different: the 400 SD high-z sample appears to miss concentrated clusters; (ii) the distribution of cool-core strength in the local and the RDCS+WARPS samples is rather similar, even though the distant sample lacks very peaked (or strong cool-core with c_{SB} >0.15) clusters.

The distribution of the central cooling time (Fig. 2) in the local sample spans a broad range, 0.7< t_{cool} <32.6 Gyr, where two-thirds of the sample have $t_{cool} < t_{Hubble}$. The RDCS+WARPS sample shows a somewhat different behaviour, displaying a narrower range of cooling times, ([4.7-14.3] Gyr), and a median t_{cool} ~ of 8.9 Gyr. We confirm a strong anti-correlation between c_{SB} and t_{cool}, quantified by a Spearman rank coefficient of ρ=−0.84.

Our results extend the current knowledge of the cool-core population to the most distant X-ray clusters known to date, and show that even at such large lookback times, we detect a significant population of well developed cool cores. A significant advancement in this research can only be achieved when large samples will be available. This will be possible only with the next generation X-ray survey missions. In particular, we showed that WFXT will have the capacity to resolve the central regions of strong cool-cores up to redshifts $z \sim 1.5$. Since WFXT is expected to yield hundreds of new cluster detections at $z \sim 1$, it will add significant constraints to the formation and evolution of cool-cores in galaxy clusters.

References

Bauer, et al. 2005, MNRAS, 359, 1481

Böhringer, H., et al. 2005, ESO Messenger, 120, 33

Bookbinder, J. 2010, arXiv:1003.2847, submitted in response to Astro2010 Decadal Program Prioritization Panel

Burenin, R.A., et al. 2007, ApJS, 172, 561
Cavagnolo, K.W., et al. 2009, ApJS, 182, 12
Chen, Y., et al. 2007, A&A, 466, 805
Dunn, R.J.H. Dunn, & Fabian, A.C. 2008, MNRAS, 385, 757
Fabian, A.C., et al., 1994, MNRAS, 267, 779
Giacconi, R., et al. 2009, astro2010: The Astronomy and Astrophysics Decadal Survey, 2010, 90
Hudson, D.S., et al 2010, A&A 513, A37
Jones, L.R., et al. 1998, ApJ, 495, 100
Peres, C.B., et al. 1998, MNRAS, 298, 416
Peterson, J. R., & Fabian, A. C. 2006, Phys. Rep., 427, 1
Reiprich, T.H., & Boheringer, H. 2002, ApJ, 567, 716
Rosati, P., et al., 1998, ApJ, 492, 21
Santos, J.S., et al., 2008, A&A, 483, 35
Santos, J.S., Tozzi, P., Rosati, P., Böhringer, H., 2010, A&Ain press, arXiv1008.0754
Vikhlinin, A., et al., 2007, Heating versus Cooling in Galaxies and Clusters of Galaxies, 48
Vikhlinin, A., et al. 2009, ApJ, 692, 1033