A CHANDRA ARCHIVAL STUDY OF THE TEMPERATURE AND METAL ABUNDANCE PROFILES IN HOT GALAXY CLUSTERS AT 0.1 ≤ z ≤ 0.3

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ABSTRACT

We present an analysis of the temperature and metallicity profiles of 12 galaxy clusters in the redshift range 0.1–0.3 selected from the Chandra archive with at least ~20,000 net ACIS counts and kT > 6 keV. We divide the sample between seven cooling-core (CC) and five non-cooling-core (NCC) clusters according to their central cooling time. We find that single power laws can properly describe both the temperature and metallicity profiles at radii larger than 0.1r180 in both CC and NCC systems, with NCC objects showing steeper profiles outward. A significant deviation is present only in the inner 0.1r180. We perform a comparison of our sample with the De Grandi & Molendi BeppoSAX sample of local CC and NCC clusters, finding a complete agreement in the CC cluster profile and a marginally higher value (at ~1σ) in the inner regions of the NCC clusters. The slope of the power law describing kT(r) within 0.1r180 correlates strongly with the ratio between the cooling time and the age of the universe at the cluster redshift, with a slope >0 and τC/τage ≤ 0.6 in CC systems.

Subject headings: galaxies: clusters: general — intergalactic medium — X-rays: galaxies: clusters

Online material: color figures

1. INTRODUCTION

Clusters of galaxies represent unique signposts in the universe, in which the physical properties of the cosmic diffuse baryons can be studied in great detail and used to trace the past history of cosmic structure formation (see, e.g., Rosati et al. [2002] and Voit [2005] for reviews). As a result of adiabatic compression and shocks generated by supersonic motion during shell crossing and virialization, a hot thin gas permeating the cluster gravitational potential well is formed. Typically, this gas, which is enriched with metals ejected from supernovae (SNe) explosions through subsequent episodes of star formation (e.g., Matteucci & Vettolani 1988; Renzini 1997), reaches temperatures of several 107 K and therefore emits most of the elements are either fully ionized or in a high ionization state.

Particularly evident in X-ray spectra of galaxy clusters are the strong transitions to the n = 1 level (K shell) of the H-like and He-like ions of iron in the energy range 6.7–6.9 keV. Below 2 keV, the n = 2 level (L shell) transition of iron and α-elements can be detected, especially in the low-temperature region in the centers of the so-called CC clusters, which are characterized by a strong peak in the surface brightness distribution and therefore short cooling times. Spatially resolved CC clusters show a peak in the metal distribution associated with the low-temperature core region (e.g., De Grandi & Molendi 2001, 2002, hereafter DM01, DM02). Although the amount of energy supplied to the intracluster medium (ICM) by SNe explosions depends on several factors (e.g., the physical condition of the ICM at the epoch of the enrichment) and cannot be obtained directly from X-ray observations, the radial distribution of metals, as well as their abundance as a function of time, is crucial information to shed light on the cosmic star formation history and to trace the effect of SN feedback on the ICM.

Several analyses have been presented in the literature, with the aim being to study the radial distribution of metals in clusters of galaxies. Finoguenov et al. (2000) performed a spatially resolved X-ray spectroscopic analysis of 11 relaxed clusters observed by Röntgensatellit (ROSAT) and the Advanced Satellite for Cosmology and Astrophysics (ASCA), deriving a radial distribution of single heavy elements such as Fe, Si, Ne, and S. They found that the total Fe abundance decreases significantly with radius in all clusters, while the Si, Ne, and S abundances are either flat or decrease less rapidly. DM01 derived radial metallicity profiles (mainly driven by Fe) of 17 nearby clusters observed by BeppoSAX. They found a strong enhancement in the abundance in the central regions of the CC clusters. A flatter metallicity profile was observed instead for the NCC clusters in their sample. Since all the NCC clusters show signs of recent merger activity, they suggested that the merger events may have redistributed

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efficiently the metal content of the ICM. Irwin & Bregman (2001) derived iron-abundance profiles for 12 clusters with $0.03 \leq z \leq 0.2$ observed by BeppoSAX. Although they investigated the differences between CC and NCC clusters in a less systematic way than DM01, they found a negative gradient in the abundance profiles of all the CC clusters and, to a lesser significance, also in the NCC clusters. Similarly to DM01, they found that CC clusters have a higher metallicity than NCC clusters at every radius. It is worth mentioning that the aforementioned papers investigated the metallicity trends only within $r_{500}$. Spatially resolved measures of the metal abundance in galaxy clusters were performed also with XMM-Newton. In particular, Tamura et al. (2004) analyzed a sample of 19 X-ray-bright relaxed clusters, obtaining elemental abundances of Fe, Si, S, and O. They found that while the distribution of Fe, Si, and S is generally peaked toward the center, the O abundances are uniform throughout the cluster, pointing to a different origin among these metals, most likely in SNe Ia and II. More recently, Vikhlinin et al. (2005) have derived temperature and metallicity profiles of a sample of 12 clusters with temperatures larger than 6 keV observed with Chandra at intermediate redshift, $0.11 \leq z \leq 0.32$. We take advantage of the ACIS superior spatial and spectral resolution to investigate in a systematic fashion the differences that may exist between CC and NCC clusters. The spectroscopic measurements of the ICM temperature and metallicity allow us to characterize statistically the radial profiles and to quantify their gradients in this unexplored redshift region.

All the uncertainties are quoted at 1 $\sigma$ (68%) for one interesting parameter. The abundance estimates are relative to the compilation of cosmic values given in Anders & Grevesse (1989, hereafter AG89), unless otherwise stated. Indeed, these values for the solar metallicities have more recently been superseded by the new values of Grevesse & Sauval (1998) and Asplund et al. (2005, hereafter A05), who introduced a 0.676 and 0.60 times lower iron solar abundance, respectively (photospheric value), while the other elements do not change significantly. Our measurements of metallicity are expected to be driven mainly by iron; however, for clarity, we also performed the fits using solar abundances by A05.

### TABLE 1

| Name     | $z$ (2) | Instrument (3) | Obs. Date (4) | Obs. ID | $t_{\text{exp}}$ (ks) | $t_{\text{clean}}$ (ks) | $N_{\text{H}}$ ($10^{20}$ cm$^{-2}$) |
|----------|--------|----------------|--------------|--------|----------------------|------------------------|---------------------------|
| A2034....| 0.113  | ACIS-I         | 2001 May 5   | 2204   | 53.9                 | 53.9                   | 1.6                       |
| A1413....| 0.143  | ACIS-I         | 2001 May 16  | 1661   | 9.7                  | 9.7                    | 2.2                       |
| A907..... | 0.153  | ACIS-I         | 2000 Jun 29  | 535    | 11.0                 | 10.9                   | 5.4                       |
| A2104....| 0.155  | ACIS-S        | 2000 May 25  | 895    | 49.8                 | 48.9                   | 8.7                       |
| A1914....| 0.171  | ACIS-I         | 2003 Sep 3   | 3593   | 18.9                 | 18.8                   | 0.9                       |
| A2218....| 0.176  | ACIS-I         | 2001 Aug 30  | 1666   | 49.2                 | 20.2                   | 3.2                       |
| A963..... | 0.206  | ACIS-S        | 2000 Oct 11  | 903    | 35.8                 | 35.8                   | 1.4                       |
| A2261....| 0.224  | ACIS-I         | 2004 Jan 14  | 5007   | 24.6                 | 24.3                   | 3.3                       |
| A2390....| 0.228  | ACIS-S        | 2000 Oct 8   | 500    | 9.8                  | 9.8                    | 6.8                       |
| A1835....| 0.253  | ACIS-S        | 2003 Sep 11  | 4193   | 96.3                 | 91.0                   | 9.1                       |
| Zw Cl3146| 0.291  | ACIS-I        | 2001 May 10  | 909    | 46.6                 | 45.6                   | 5.0                       |
| A1995....| 0.319  | ACIS-S        | 2000 May 8   | 906    | 57.5                 | 53.8                   | 1.4                       |

**Notes.**—Col. (1): Name. Col. (2): Redshift of the clusters. Cols. (3)–(5): Instrument used, observation date, and observation ID, respectively. Cols. (6) and (7): Observing time before ($t_{\text{exp}}$) and after ($t_{\text{clean}}$) the removal of high background intervals. Col. (8): Galactic column density $N_{\text{H}}$ in the line of sight of the observation.

In this paper, we present measurements of the radial temperature and metallicity profiles of a sample of 12 clusters with temperatures larger than 6 keV observed with Chandra at intermediate redshift, $0.11 \leq z \leq 0.32$. We take advantage of the ACIS superior spatial and spectral resolution to investigate in a systematic fashion the differences that may exist between CC and NCC clusters. The spectroscopic measurements of the ICM temperature and metallicity allow us to characterize statistically the radial profiles and to quantify their gradients in this unexplored redshift region.

2. **SAMPLE DEFINITION AND DATA ANALYSIS**

From Chandra archival data we select a sample of 12 intermediate-redshift clusters ($0.11 \leq z \leq 0.32$). We also require the clusters to have at least $\sim 20,000$ ACIS-S or ACIS-I counts in order to study their properties in at least three circular annuli. The sample is presented in Table 1, where the name of the cluster and the Chandra observing logs are listed.

The Chandra data analysis has been performed using the latest version of CIAO (ver. 3.3.0.1). All of our data sets are processed by a version of the standard data processing (SDP) pipeline prior to version DS 7.4.0, which uses the tool acisdetectafterglow to flag possible cosmic-ray events in the level=1 event file; it has been determined that a significant fraction of the X-ray events from a source in imaging mode might be removed using this tool. Therefore,
we reset the correction performed by `acisdetectafterglow` on the level=1 event file so that the hot pixels and the afterglow events may be properly removed by the improved CIAO tool `acisrunhotpix` (introduced after SDP ver. DS 7.4.0). A new level=1 event file is then created (through the CIAO tool `acisprocessesevents`) to apply the latest calibration files to the data (e.g., the newest ACIS gain maps, the time-dependent ACIS gain correction, or the ACIS charge transfer inefficiency correction). Moreover, in the case of observations telemeasured in VFAINT mode, it is possible to reduce the background using the additional screening of the events with significantly positive pixels at the border of the 5×5 event island. Two further filtering steps are then required to obtain the level=2 event files: (1) a filter for bad grades (using ASCA grades) and for a “clean” status column, and (2) applying the good time intervals (GTIs) supplied by the pipeline. The final step is to examine background light curves during each observation in order to detect and remove the periods of high background due to flaring episodes. We perform the flare detection and removal following the recommendations suggested in Markevitch et al. (2003); both the total and the clean exposure times are listed in Table 1. Most of the observations are affected by background flares; thus, we were able to use practically all the exposure time. The only exceptions are ObsIDs 3205, 4193, 906, and especially 1666, where ~29 ks of the exposure were lost due to high background.

2.1. Background Subtraction

An accurate subtraction of the background is crucial to performing a correct study of the spectral properties of the clusters in our sample, especially in their outskirts. Since we are dealing with extended objects, occupying most of the ACIS field of view, we need to use a compilation of the blank-field observations, processed in an identical way to the cluster observation (i.e., as described above) and reprojected onto the sky using the aspect information from the cluster pointing. It is worth noting that the synthetic backgrounds correspond to longer exposure times (~0.5 Ms) than any of our observations, giving us a very good sampling in the estimate of the background to subtract. Moreover, in order to “tailor” the background to our data, we follow the recommendations given in the CIAO Web pages. In particular, we renormalize the blank fields to the background in each observation, considering a region of the ACIS field of view practically free from cluster emission (mainly ACIS-S1 for ACIS-S observations, and ACIS-S2 for ACIS-I observations) and a spectral band (9.5–12 keV) where the Chandra effective area is nearly zero; therefore, all the observed flux is due to the particle background.

In addition to the particle-induced background, we check also whether the diffuse soft X-ray background could be an important factor in our observations and whether appropriate adjustments are needed. For each observation, we follow the procedure of Vikhlinin et al. (2005): extracting a spectra in the source-free regions of the detector, subtracting the renormalized blank-field background, and fitting the residuals in XSPEC version 11.3.2p (in the 0.4–1 keV band) with an unabsorbed MEKAL model, whose normalization was allowed to be negative. The best-fit model obtained is therefore included as an additional component in the spectral fits (with its normalization scaled by the area). However, in every observation the adjustments required are minimal and do not affect significantly the determination of \( kT \) and \( Z \), even at large radii. This is also due to the properties of the clusters in our sample, whose high \( kT \) values (>4 keV) even in the resolved outer regions are not affected significantly from the method applied for the subtraction of the diffuse soft background.

2.2. Cash Statistics versus \( \chi^2 \) Statistics

The \( \chi^2 \) statistics require grouping of the spectra, having at least 20 counts per bin, in order to be able to approximate the Poissonian distribution of counts with a Gaussian. On the contrary, Cash statistics do not require any grouping and represent a more reliable (and less biased) approach to fit the data. Indeed, it is well known from the literature (see, e.g., Nousek & Shue 1989; Balestra et al. 2007) that the \( \chi^2 \) statistics systematically “see” the observed spectra softer than the real ones. This usually leads to an overestimate of the slope of the observed spectra in the case of a simple power-law fit, while in the case where a thermal model is fitted to the data, the temperature measured is usually underestimated. As a test to see whether this systematics is present also in our data, we have decided to apply both of these fit statistics. We find that for all the clusters of the sample, a systematically lower temperature is measured with the \( \chi^2 \) (on average 7%–17% lower, depending on the cluster). On the other hand, no obvious systematic trend is observed in the determination of \( Z \), being the variation in the best-fitting value of the metallicity in each cluster ranging between \( \Delta Z \sim 0.01 \) and \( \sim 0.07 \) with no preferential direction. To avoid the dependence on the grouping method, and the bias in the best-fit temperature, we decided to use the modified Cash statistics, as implemented in XSPEC version 11.3.2p, to determine the best-fit parameters and their uncertainties.

2.3. Spectral Analysis

In order to study the radial properties of the cluster emission, we subdivide each cluster in annuli (circular or elliptical, depending on the morphology of the cluster) centered on the X-ray emission peak. In the more disturbed clusters, where an emission peak is not clearly identifiable, we assume the center of the cluster to correspond with the X-ray centroid at 0.5\( r_{200} \). We require each region to have at least ~7,000 net counts so that it would be possible to estimate the temperature and the metallicity of the annulus with sufficient accuracy. For each cluster, the outermost annulus corresponds to an area where the intensity of the source in the 0.8–8 keV band is roughly equal to that of the background. We extract a spectra from each annulus after excluding the 3\( \sigma \) point sources detected by the CIAO tool `wavdetect`. The source list produced is also inspected by eye in order to remove possible additional sources not detected by `wavdetect` (especially in the regions where the diffuse emission from the cluster is brighter). The CIAO script used to perform the spectral extraction is `apecextract`, which generates source and background spectra and builds the appropriate RMF and ARF files. The background is taken from the renormalized blank-field observations using the same region of the source.

The spectra are analyzed with XSPEC version 11.3.2p (Arnaud 1996) and fitted by a single-temperature MEKAL model (Kaastra 1992; Liedahl et al. 1995) in which the ratio between the elements is fixed to the solar value as in AG89. However, as explained in §1, these values for the solar metallicities have more recently been superseded by the new values of Grevesse & Sauval (1998) and Asplund. For clarity and completeness, we also performed the fits using solar abundances by Asplund. The free parameters in the model are the temperature \( kT \), the metallicity \( Z \) of the gas, and the normalization. The spectral band considered in the fit is 0.6–8 keV. We choose not to consider the data below 0.6 keV because of uncertainties in the ACIS calibration below that energy. The \( N_{HI} \) derived from the X-rays is found to be consistent (within 1\( \sigma \)) with the Galactic value in the line of sight of each observation, as

See http://cxc.harvard.edu/cal/Acis/Cal_prods/bkgmd/acisbg/COOKBOOK.
TABLE 2
GLOBAL CLUSTER PROPERTIES OF THE CHANDRA SAMPLE

| Name                  | Net Counts (0.6–8 keV) | \(\langle kT \rangle\) (keV) | \(\langle Z \rangle\) | \(r_{180}\) (kpc) | Aperture (arcsec) | \(\tau_c\) (Gyr) | \(\tau_c/\tau_{age}\) |
|-----------------------|------------------------|------------------------------|----------------------|-----------------|------------------|----------------|-------------------|
| A2034…………………   | 78,900                 | 6.36 ± 0.15                  | 0.30 ± 0.04          | 2222            | 76–433           | 21.2 ± 3.2     | 1.77 ± 0.27       |
| A1413…………………   | 181,500                | 7.52 ± 1.02 ±0.12           | 0.23 ± 0.03          | 2416            | 67–385           | 4.2 ± 0.3      | 0.36 ± 0.03       |
| A907…………………    | 87,500                 | 5.82 ± 0.12                  | 0.34 ± 0.04          | 2125            | 56–320           | 2.0 ± 0.1      | 0.17 ± 0.01       |
| A2104…………………   | 63,100                 | 6.76 ± 0.19                  | 0.24 ± 0.05          | 2290            | 60–341           | 18.1 ± 2.1     | 1.58 ± 0.16       |
| A1914…………………   | 39,100                 | 9.26 ± 0.39                  | 0.27 ± 0.07          | 2672            | 64–367           | 12.2 ± 1.0     | 1.07 ± 0.09       |
| A2218…………………   | 18,300                 | 6.25 ± 0.31                  | 0.24 ± 0.07          | 2202            | 52–295           | 21.3 ± 1.8     | 1.89 ± 0.16       |
| A963…………………    | 41,800                 | 6.03 ± 0.28                  | 0.18 ± 0.06          | 2161            | 45–256           | 6.5 ± 0.4      | 0.59 ± 0.04       |
| A2261…………………   | 21,500                 | 7.43 ± 0.25                  | 0.30 ± 0.07          | 2400            | 47–267           | 7.0 ± 0.4      | 0.65 ± 0.03       |
| A2390…………………   | 202,600                | 9.35 ± 0.15                  | 0.30 ± 0.03          | 2693            | 52–295           | 1.3 ± 0.2      | 0.12 ± 0.02       |
| A1835…………………   | 23,100                 | 8.06 ± 0.53                  | 0.31 ± 0.09          | 2500            | 44–254           | 0.9 ± 0.1      | 0.08 ± 0.01       |
| Zw C13146…………… | 40,500                 | 8.59 ± 0.39                  | 0.24 ± 0.06          | 2582            | 41–237           | 1.0 ± 0.1      | 0.10 ± 0.01       |
| A1995…………………   | 30,200                 | 7.59 ± 0.57 ±0.44           | 0.50±0.12 ±0.11     | 2427            | 37–209           | 12.7 ± 1.3     | 1.28 ± 0.14       |

Notes.—Col. (1): Name. Col. (2): Total net counts from the inner to the outer annulus considered in the spectral analysis. Cols. (3)–(5): Global temperature \(\langle kT \rangle\), global metallicity \(\langle Z \rangle\), and virial radius \(r_{180}\), computed within 0.07\(r_{180}\)–0.8\(r_{180}\), respectively. Col. (6): Aperture used to measure \(\langle kT \rangle\) and \(\langle Z \rangle\). Cols. (7) and (8): Central cooling times and the ratio, with respect to the age of the universe at the cluster redshift.

-derived from radio data (Stark et al. 1992), except in the cases of A2104 and A2390 (see Table 1 and §2.4). In these clusters the \(N_H\) value measured from X-ray data is significantly different (at more than 2 \(\sigma\) confidence level) from the radio value; therefore, we adopt the X-ray value. The \(N_H\) value is fixed to the Galactic value obtained from the radio data (and listed in Table 1) in the rest of the sample. We have measured \(N_H\) from the X-ray data in each annulus, finding no evidence of radial variation. Therefore, \(N_H\) is fixed to the same value in all the radial annuli.

We have thus divided our sample in CC and NCC clusters according to their central cooling time. The gas temperature and density profiles are recovered from the single-phase spectral fit done in annular rings by correcting the emissivity in each shell by the contribution of the outer shells moving inward. A detailed description of the procedure is presented in Ettori et al. (2002). In brief, the normalization of the thermal component, being proportional to the emission integral, provides the gas density, whereas the deprojected temperature is provided by weighting for the corrected emissivity of the spectral measurement. The deprojected values in the innermost bin are then used to estimate the central cooling times \(\tau_c = 5/2(\mu_e/\mu)T_e(n_e/\epsilon)\), where \(\mu = 0.613\) and \(\mu_e = 1.174\) are appropriate for a plasma with a metallicity of 0.3 times the solar values in AG89, and \(T_e\), \(n_e\), and \(\epsilon\) are the gas temperature, electron density, and emissivity in the innermost bin, respectively.

The central cooling times are reported in Table 2, as well as the age \(\tau_{age}\) of each cluster, and the ratio between the two quantities. The age of the universe at the \(z\) of observation is used as an upper limit to the age of the cluster. Bauer et al. (2005) computed the cooling times for six of the clusters in our sample (A1835, A1914, A2218, A2261, A2390, and Zw C13146), finding a \(\tau_c\) in the center of the cluster, or at 50 kpc, consistent with the values computed for the central bin in our spectral analysis (which might extend farther out than 50 kpc from the center in some cases). Following their criterion, a clear separation between the CC and the NCC in our sample can be located at \(\tau_c \sim 10\) Gyr (Fig. 1; corresponding to \(\tau_c/\tau_{age} \sim 1\)). We have four clusters presenting signs of strong cooling \((\tau_c < 2\) Gyr) and three clusters exhibiting signs of mild cooling \((\tau_c < 10\) Gyr). The remaining five clusters can be classified as NCCs, presenting longer cooling times in the center. The projected temperature and metal abundance profiles for both CC and NCC objects are shown in Figures 2 and 3.

2.4. Notes on Individual Clusters

A2034.—A2034 (\(z = 0.113\)) has been observed with Chandra in one ACIS-I pointing (ObsID 2204). The temperature profile we derived is quite flat in the central regions of the cluster, where the temperature is \(kT \sim 8\) keV. It shows, however, a negative gradient after 400 kpc from the center. A similar trend is observed in the metallicity, where the average value of \(Z = 0.4\) within 400 kpc from the center decreases to \(Z < 0.2\) at larger radii.

A1413.—A1413 (\(z = 0.143\)) has been observed four times with ACIS-I. We discard one observation (ObsID 537) that is affected almost entirely by a persisting flare. In one of the observations used in our analysis (ObsID 5003), the source is placed in a position of the ACIS-I array very close to the S2 chip; therefore,
S2 is still contaminated by source emission, and we cannot use it to renormalize the blank field to the background in the observation. We use instead part of the I1 chip (which is front-illuminated as S2) to renormalize, since it is more distant from the cluster center than S2 and therefore less contaminated by cluster emission. The resulting temperature profile shows a slight decrease in temperature toward the center ($\Delta kT = 1.2^{+0.4}_{-0.4}$ keV within the inner 150 kpc). A1413 has been also observed by XMM-Newton (Pratt & Arnaud 2002), representing one of the clusters with the most accurate temperature profile observed by this satellite. This cluster is also part of the sample of Chandra clusters analyzed by Vikhlinin et al. (2005). The XMM-Newton observation does not find any evidence of a cool core, in contrast with the temperature profiles obtained with Chandra both in our analysis and even more definitively in Vikhlinin et al. (2005). This might be due to the poorer angular resolution of XMM-Newton with respect to Chandra. The metallicity profile is decreasing toward larger radii and consistent within 1 $\sigma$ with the measures of Vikhlinin et al. (2005).

A907.—A907 ($z = 0.153$) has been observed with Chandra in three separate ACIS-I pointings (ObsID 535, 3185, and 3205),
all of them used in our analysis. The temperature profile shows evidence of a cool core in the center of the cluster ($\Delta kT = 1.4^{+0.2}_{-0.3}$ keV in the central 100 kpc). The metallicity profile presents a decreasing trend toward larger radii. A907 is also part of the cluster sample analyzed by Vikhlinin et al. (2005). Their results, for both the temperature and the metallicity, are fully consistent with ours within the 1 $\sigma$ statistical uncertainties.

A2104.---A2104 (z = 0.155) has been observed with Chandra in one ACIS-S pointing (ObsID 895). As described in § 2.3, the value of the $N_{\text{HI}}$ measured from the X-ray data alone is significantly different from the radio value; thus, we have decided to fix the $N_{\text{HI}}$ to the best-fit value obtained from the fit ($1.55 \times 10^{21}$ cm$^{-2}$). The cluster does not show any evidence of a cool core in its center, having a temperature profile decreasing toward the outskirts. The metallicity profile is consistent with being flat, with a value $Z \sim 0.3$--0.4 $Z_{\odot}$, within the 1 $\sigma$ uncertainties.

A1914.---Two ACIS-I pointings of A1914 (z = 0.171) are available in the Chandra archive. However, the oldest (and shortest) observation (ObsID 542) has been performed in 1999. For observations performed in that year, an accurate modeling of the ACIS background is not currently available. Thus, to avoid problems in background subtraction, we have decided to discard it.

**Fig. 3.**---(a) Abundance profiles for the CC clusters in the sample: the different symbols correspond to the clusters listed in Fig. 2a. (b) Normalized abundance profiles for the CC clusters, plotted against the radii in units of $r_{180}$. The symbols have the same meaning as in panel a. (c) Abundance profiles for the NCC clusters in the sample: the different symbols correspond to the clusters listed in Fig. 2c. (d) Normalized abundance profiles for the NCC clusters, plotted against the radii in units of $r_{180}$. The symbols have the same meaning as in panel c. [See the electronic edition of the Journal for a color version of this figure.]
and keep only the longest observation (ObsID 3593). A negative gradient in $kT$ is quite clear: the temperature drops from $kT = 12.0^{+0.9}_{-0.6}$ keV in the center down to $kT = 8.5 \pm 0.6$ keV in the outer radial bin. A similar trend is observed also in the abundance profile, where $Z = 0.5 \pm 0.1 Z_\odot$ in the center, then decreasing to $0.2 \pm 0.1 Z_\odot$ in the two outer radial bins. This is one of the few examples of a metallicity peak without a corresponding cool core (or temperature drop) toward the center.

$A2218$.—$A2218 (z = 0.176)$ has been observed three times with ACIS-S. Unfortunately, two of these observations (ObsIDs 553 and 1454) were performed in 1999, and for the reason described in the case of A1914 we have decided to discard them. Moreover, the remaining observation (ObsID 1666) has been strongly affected by a flare that reduces the good exposure time to only $\sim 20$ ks. With these data we are able to observe the presence of a centrally peaked temperature profile (a hot, instead of a cool, core) and a constant metallicity profile. A temperature profile peaked toward the center has also been seen by Machacek et al. (2002), analyzing the two Chandra observations performed in 1999. This is consistent with the picture of A2218 being involved in a line-of-sight merger, as suggested by a considerable disturbance of the intracluster gas in the X-rays and by the observed substructure in the optical (e.g., Pratt et al. 2005).

$A963$.—$A963 (z = 0.206)$ has been observed with Chandra in one ACIS-S pointing (ObsID 903). We found a decreasing trend of $Z$ with the radius, with only a very weak hint of the presence of a lower temperature in the center.

$A2261$.—Two pointings of A2261 ($z = 0.224$) are available in the Chandra archive. One of the observations (ObsID 550) was performed in 1999 and therefore we discard it for the reason described above in the case of A1914. The temperature profile does show only a hint (more than $2 \sigma$ however) of a decrease in the center, where the temperature drops down from $9.0 \pm 0.4$ to $7.7 \pm 0.4$ keV. The metallicity profile shows a constant behavior for the first two bins and a decrease (significant at more than $1 \sigma$) in the outer radial bin.

$A2390$.—$A2390 (z = 0.228)$ has been observed three times with ACIS-S. One of the observations (ObsID 501) was performed in 1999 and therefore we discard it. We concentrate our analysis on the remaining two observations (ObsIDs 500 and 4193), yielding a total of $\sim 100$ ks of good observing time. The value of the $N_H$ derived from the X-rays ($N_H = 1.1 \times 10^{21}$ cm$^{-2}$) is significantly different than the radio value; therefore, we adopted the X-ray value in the spectral fits. A2390 is also part of the sample analyzed in Vikhlinin et al. (2005). Similarly to them, we find a cool core ($kT = 5.8 \pm 0.2$ keV) in the center of the cluster, with a $kT$ profile getting flatter going toward the outskirts, which is fully consistent with their measured temperatures at every radius. On the other hand, the metallicity profile shows just a hint of a peak in the central part of the cluster. It is, however, consistent at $1 \sigma$ with the profile of Vikhlinin et al. (2005) and not sensitive to the choice of the $N_H$.

$A1835$.—Two different ACIS-S observations of A1835 ($z = 0.253$) are present in the Chandra archive. We discard the older (and longer) observation (ObsID 495), performed in 1999, because of the reason described in the case of A1914, keeping only the $\sim 10$ ks observation performed in 2000 (ObsID 496). The temperature profile of A1835 shows clear evidence of a cool core in its center, where $kT$ drops down by a factor of $\sim 2$. Moreover, the temperature shows a decline after 300 kpc, going toward larger radii. Piffaretti et al. (2005) analyzed XMM-Newton observations of A1835 and detected a temperature decrease at large radii, as in our data. Majerowicz et al. (2002) also analyzed XMM-Newton data and found a decrease in the temperature profile at large radii (at $\sim 400$ kpc from the center); however, their temperature profile becomes constant after such a decrease. The decrease at large radii has not been observed in the analysis of Chandra data by Voigt & Fabian (2006), who found a constant temperature outside the central 100 kpc. However, it is worth noting that in their work they analyzed the 1999 observation (instead of the 2000 observation, as in our analysis), which might have background subtraction problems, especially at large radii. This may explain the difference between the two profiles. The metallicity profile shows a decreasing gradient in the first two bins, becoming constant afterward. The only comparison with the literature comes from an XMM-Newton observation analyzed by Majerowicz et al. (2002), where an almost constant metallicity profile at every radius has been observed.

$Zw Cl13146$.—$Zw Cl13146 (z = 0.291)$ has been observed with ACIS-I in one pointing (ObsID 909). Also, this cluster clearly shows the presence of a cool core ($kT$ dropping down by a factor of almost 2). A decreasing trend in metallicity from $Z = 0.50 \pm 0.05$ in the center, down to $Z = 0.17 \pm 0.12$ in the outer bin, is also observed.

$A1995$.—One ACIS-S observation of A1995, the farthest cluster in our sample ($z = 0.319$), is present in the Chandra archive (ObsID 906). Although this observation is quite long ($\sim 50$ ks of good exposure time), the number of counts available allowed us to divide this cluster into only three radial bins. The temperature profile of A1995 is consistent to be flat within the errors, with a temperature around 9 keV. The abundance profile seems to have a positive gradient in the outer bin; however, the errors are large, and this increase in $Z$ is not very significant.

### 3. SELF-SIMILARITY OF RADIAL PROFILES

One of the main goals of this paper is to look for a (purely phenomenological) self-similarity in the radial profiles of temperature and metallicity, after they are scaled to the cluster virial radius $r_{180}$. A measure of $r_{180}$ is thus crucial to test for such self-similarity in our cluster sample. This quantity can be approximated by the following relation,

$$r_{180} = 1.95 \, h^{-1} \, \text{Mpc} \left(\frac{kT}{10 \, \text{keV}}\right)^{1/2}, \quad (1)$$

as calibrated from the nonradiative hydrodynamical simulations of clusters by Evrard et al. (1996). It is worth noting that this relation is in agreement with the scaling relations observed (e.g., Ettori et al. 2004) in the X-rays, where the dependency on $kT$ is consistent with equation (1) and only the absolute normalization may experience some variations. To compute the global temperature ($kT$) necessary to estimate $r_{180}$, we extract spectra with emission ranging from $0.07r_{180}$ to $0.4r_{180}$ in each cluster. The central regions of each cluster are therefore excluded from the spectra in order to avoid contamination from a possible cool core. The values of $kT$ and $r_{180}$ have been evaluated iteratively until a convergence to a stable value of the temperature is obtained ($\Delta kT \leq 0.01$ keV between two different iterations). From the fits, we are able to determine also a global metallicity ($Z$) in each cluster. In Table 2 we list the best-fit values for ($kT$) and ($Z$), and the value of $r_{180}$ computed using the formula above. The minimum and maximum apertures used to extract the total spectrum are listed as well.

#### 3.1. The Temperature Profiles

Figure 2 shows the normalized temperature profiles for all the CC clusters (Fig. 2b) compared with the NCC clusters (Fig. 2d).
This figure has been obtained by normalizing the temperatures in each cluster to its average temperature \( \langle kT \rangle \) computed from the total cluster spectrum excluding the central \( 0.07r_{180} \). The error-weighted mean and the best-fit results after fitting with single power laws \( Y \propto r^{-\mu} \) are presented in Table 3.

Within \( 0.1r_{180} \), the temperature profiles in CC objects increase with a slope \( \mu = 0.25 \). Moving outward, between \( 0.1r_{180} \) and the outer radial limit of our spectral analysis at \( \approx 0.5r_{180} \), these profiles behave as \( r^{-0.1} \). NCC systems have, on average, a profile that is almost flat at \( r < 0.1r_{180} \) and then decreases rapidly as \( r^{-0.3} \). In the outskirts, the temperature profiles of CC and NCC clusters show a significant discrepancy between their slopes, with NCCs being more deviant than the isothermal case.

Our best-fit functional for the CC sample is fully consistent with the best-fit functional form found by Vikhlinin et al. (2005) in their sample of CC clusters, at \( r \lesssim 0.3r_{180} \). The two functionals diverge significantly only above \( 0.3r_{180} \), where our profile is flatter (and therefore the value of \( kT/\langle kT \rangle \) is higher) than the Vikhlinin et al. (2005) profile. However, only a few of our data points are located beyond that radius, preventing us from any statistically significant comparison between the two samples at \( r \gtrsim 0.3r_{180} \).

Adopting the A05 abundances has not changed the best-fit values of \( kT \) at every radius (always fully consistent within the 1 \( \sigma \) errors) in the individual clusters. Therefore, the best-fit functionals representing both the CC and the NCC sample have not varied.

A clearer picture can be seen also if we compute an error-weighted average of the \( kT \) profiles in several bins of width 0.05 in \( r/r_{180} \). The contribution to the single bin is provided from the measurements (and relative error) that fall into that bin, weighted in proportion to the percentage of the spatial coverage of the bin. The error-weighted mean \( kT/\langle kT \rangle \) profile is plotted in Figure 4 and compared with the local estimates from DM02. CC and NCC objects show a well-defined opposite gradient in the inner radial and more similar behavior moving outward. A good agreement is also observed with the local profiles, apart from two significant

### Table 3

Error-weighted means and best-fit parameters of the single power laws \( Y = Y_0 (x/0.1)^\mu \), with \( x = r/r_{180} \) (\( kT \)) and \( \langle Z \rangle \) are measured in the radial range \( 0.07r_{180} \)–0.4\( r_{180} \).

| Sample | \( kT/\langle kT \rangle \) | \( \mu \) | \( \chi^2/dof \) |
|--------|-------------------------|----------|-----------------|
| All    | 0.84 ± 0.04(0.28)       | 1.00     | 1223.4/78       |
| CC     | 0.80 ± 0.04(0.24)       | 1.00     | 744.3/52        |
| NCC    | 1.13 ± 0.07(0.20)       | 1.12     | 76.6/24         |

Note.—Error-weighted means, with errors on the mean and rms quoted within round brackets, and best-fit parameters of the single power laws \( Y = Y_0 (x/0.1)^\mu \), with \( x = r/r_{180} \) (\( kT \)) and \( \langle Z \rangle \) are measured in the radial range \( 0.07r_{180} \)–0.4\( r_{180} \).

**Fig. 4.**—Left: Error-weighted mean temperature profile of the CC (circles) and NCC (diamonds) clusters in our sample at intermediate redshift. Right: Comparison between our results and the local measurements in DM02 (shaded regions). The 1 \( \sigma \) errors on the means are plotted as solid lines (dark gray region for the local estimates) while the scatter (rms) in each data bin is shown as a dotted line (light gray region for local estimates).
deviations: (1) our CC mean profile appears flatter at \( r > 0.2r_{180} \), with an error-weighted value of 0.97 ± 0.06 (rms 0.07), to be compared with the local value of 0.85 ± 0.11 (rms 0.16); and (2) our NCC profile is steeper within 0.1r_{180}, with a mean value of 1.27 ± 0.08 (rms 0.14) with respect to the local value of 1.04 ± 0.05 (rms 0.07).

3.2. The Metal Abundance Profiles

The metallicity profiles are plotted against the radius normalized to \( r_{180} \) for the CC and NCC sample in Figures 3b and 3d, respectively. A different behavior in the very central regions between the two samples is quite clear. To characterize this behavior, we have fitted the normalized profiles \( Z/Z_i \) with respect to \( r/r_{180} \) with single power laws \( Y \propto r^p \) over different radial ranges. While the NCC clusters present a flat profile within \( \sim 0.1r_{180} \), a sharper negative gradient is observed in the CC cluster sample (\( \mu = -0.24 \); see Table 3). Also at \( r > 0.1r_{180} \), where a model with a single power law will reproduce the data (reduced \( \chi^2 \) less than 1), the CC clusters show hints of a steeper profile (\( \mu = -0.52 \pm 0.18 \) in the CC sample; \( \mu = -0.29 \pm 0.27 \) in the NCC sample).

We compute an error-weighted average \( Z \) profile, as done for the temperature profile, and compare it with the local measurements in DM01, after scaling the radii to \( r_{180} \) (see Fig. 5). The two profiles are in agreement at \( r > 0.1r_{180} \), with both subsamples showing evidence for a negative gradient in metallicity, significant at least at 2 \( \sigma \). A different behavior between the two subsamples is observable in the central bin, where the value in the CC sample is \( \sim 20\% \)–30\% higher than in the NCC sample. It is worth noting that all the clusters in our sample have \( kT > 6 \) keV, and this trend may be different in lower temperature clusters. DM01 in their analysis observed a clear gradient in the metallicity profiles of their CC clusters, while the profiles of their NCC clusters were almost constant. Moreover, the average metallicity observed in the CC clusters was systematically higher than in the NCC sample, at least within \( \sim 0.3r/r_{180} \) from the center. In our analysis, we do not find a clear difference between the CC and NCC abundance profiles, as in DM01. Except for the inner radial bin where the metallicity in CC objects can be higher by 50\% than in NCC ones, the CC and NCC profiles are very similar and consistent within the errors.

To compare our mean values at intermediate redshift with the results obtained locally from DM01, we estimate an error-weighted average \( Z \) profile for both CC and NCC objects in local and intermediate \( z \) samples (Fig. 5). While the slope of the profiles is generally in agreement with DM01 for both the CC and NCC clusters, the value of \( Z/Z_i \) is systematically higher in our sample with respect to the DM01 sample, with differences up to 50\% within 0.1r_{180} of CC systems. This might be due to the different method used to compute \( Z \) in DM01, estimated as the best fit with a constant to the radial metallicity profile. However, apart from the inner radial region, the discrepancy between the local profiles and the ones at intermediate redshifts is within 1 \( \sigma \). Using the same method to determine \( Z \) on our data, we find that the values of \( Z/Z_i \) are fully consistent with DM01.

3.3. Comparison with the New Compilations of Solar Values

All the analysis described in the current section has been performed adopting the AG89 compilation of photospheric abundances. This choice has been due mainly to the necessity of having a direct comparison with previous works in the literature (e.g., DM01). However, as explained in \S 1, the abundance values listed in AG89 have been recently superseded by the new photospheric values by Grevesse \\& Sauval (1998) and A05, who introduced a 0.676 and 0.60 times lower iron solar abundance, respectively. Therefore, we have also performed the fits using solar abundances by A05 to check whether adopting the “old” AG89 values might have introduced any bias into our analysis.

The shape of the \( Z \) profile for both the CC sample and the NCC sample resembles very closely that observed in Figure 5 for the AG89 values of \( Z \). However, to better quantify this comparison,
we also fitted these new values with a power-law functional. We measure

\[
\frac{Z_{\text{CC}}}{\langle Z \rangle} = (0.67 \pm 0.06)x^{-0.25 \pm 0.03},
\]

\[
\frac{Z_{\text{NCC}}}{\langle Z \rangle} = (1.06^{+0.20}_{-0.18})x^{-0.02 \pm 0.07},
\]

(2)

with \( x \equiv r/r_{180} \). If we compare the result of the fit with the last two rows in the first column of Table 3, it is quite clear that the slope of the power law in both the CC and NCC sample is consistent with what we obtained using the AG89 values (well within the 1σ uncertainties), and the difference is only in the normalization. As expected, this result might indicate that our metallicities are mostly driven by iron and that the contribution of the \( \alpha \)-elements to the determination of the abundances is negligible. Indeed, all our clusters have a temperature larger than \( \sim 6 \) keV; therefore, the abundance measures are dominated by the Fe-Kα line. As a further test to this hypothesis, we tried to fit the Fe abundance independently from the \( \alpha \)-element abundances. To this aim we used a VMEKAL model where the abundances of O, Mg, Si, and S were tied up to the same value and fitted as a single free parameter (in order to reduce the number of free parameters), while the other elements (apart from Fe) were frozen at solar. While the Fe abundance remained always consistent with the value of \( Z \) measured considering the metallicity as a single parameter, in almost all the spectra we could not find any statistically significant detection of a contribution from \( \alpha \)-elements. Their abundances have been measured as upper limits in most cases (generally \( Z_\alpha < 0.3 \)) and as very low values in the rest of the spectra (generally \( Z_\alpha \sim 0.1 \sim 0.2 \), often consistent with \( Z_\alpha \sim 0 \) at 1σ). This is true even in the inner part of the clusters in the sample, where the signal-to-noise ratio of the spectra is higher, and in principle it may be easier to detect the presence of elements other than iron.

These results suggest that the measure of \( Z \) in our cluster sample consists mainly of a measure of iron metallicity. Therefore, adopting the AG89 solar abundances instead of those from A05 (which have different \( Z_{\text{Fe}}/Z_{\odot} \) ratios) produces only a difference in the value of the relative \( Z \) measured. This does not introduce any bias in the analysis of the radial profiles, since the absolute value of \( Z \) does not change, and only the reference value assumed for the solar metallicity experiences a variation.

### 3.4. Gradients and Cooling Times

We investigate the correlation of the central slopes of the temperature and metallicity profiles with the central cooling time in each cluster. To this aim, the values of \( kT(r)/\langle kT \rangle, Z(r)/\langle Z \rangle \), and \( r/r_{180} \) (normalized to the average temperature, the average metallicity, and the virial radius measured in each cluster, respectively, as described in § 3) with \( r < 0.1r_{180} \) have been considered to characterize the cooling cores. We find that the most robust correlation is present between the slope \( \mu \) of the temperature profiles,

\[
kT/\langle kT \rangle = A\left(\frac{r}{r_{180}}\right)^{\mu},
\]

and \( \tau_c/\tau_{\text{age}} \), with a Spearman \( \rho \) rank correlation value of \(-0.87 \) that corresponds to a significance of the noncorrelation case of \( P = 2 \times 10^{-4} \). In the \( kT-Z \) and \( Z-r \) relations, the values of the Spearman \( \rho \) are 0.44 and 0.54, corresponding to a significance of 0.15 and 0.07, respectively. The exponent \( \mu \) correlates with \( \tau_c/\tau_{\text{age}} \), being higher at lower values of \( \tau_c/\tau_{\text{age}} \), with all the CC clusters having \( \mu > 0 \) and \( \tau_c/\tau_{\text{age}} \leq 0.6 \) (Fig. 6).

### 4. CONCLUSIONS

In the present work, we analyzed a sample of 12 galaxy clusters present in the Chandra archive with at least \( \sim 20,000 \) net ACIS counts and \( kT > 6 \) keV. These clusters were chosen in the 0.1—0.3 redshift range, regardless of their shape. We computed the cooling time of the clusters, subdividing the sample in seven cool-core clusters and five non-cool-core clusters. This subdivision allowed us to compare the two categories in a systematic fashion, following the approach of DM01. We performed a spectral analysis in radial bins of each cluster in the sample, requiring each bin to have \( \sim 7000-8000 \) counts, fitting the spectra with a thermal model with Galactic absorption. This allowed us to derive temperature and metallicity profiles for each cluster. The virial radius \( r_{180} \) was computed in order to renormalize the radii to physically meaningful quantities and investigate for self-similarities in the radial profiles. To this aim, the global temperature \( \langle kT \rangle \) and metallicity \( \langle Z \rangle \) in each cluster were measured as well. The main results from our work can be summarized as follows.

1. The temperature profiles in the inner \( 0.1r_{180} \) have on average a positive gradient, \( kT(r) \propto r^{h} \), with \( h \approx 0.25 \) in CC systems, whereas it is almost flat in NCC systems. The outer regions are well fitted with a single power law with slopes significantly different, being steeper (\( h = -0.32 \pm 0.05 \)) in NCC objects. The general trend of our CC sample is fully consistent with Vikhlinin et al. (2005) at \( r \leq 0.3r_{180} \). The low-number statistics above \( 0.3r_{180} \) prevent us from any statistically significant comparison between the two samples at \( r \geq 0.3r_{180} \).

2. The metallicity profiles in the inner regions are almost constant in NCC clusters around the value measured, excluding counts from \( r < 0.07r_{180} \). In the CC sample, a steep negative gradient is observed (\( h = -0.27 \pm 0.03 \)) in the central regions. At \( r > 0.1r_{180} \), a power law reproduces well the distribution of the spectral measurements, with a slope that is marginally steeper in CC clusters (\( h = -0.52 \pm 0.18 \)) than in NCC clusters (\( h = -0.29 \pm 0.27 \)).
3. Comparing our averaged metallicity profiles with the ones in DM01, we found that our values of $Z(r)/Z_{\text{age}}$ are systematically higher, with differences up to 50% within 0.1$r_{180}$ of CC systems. This may be explained by the different method adopted in DM01 to estimate ($Z$), as best fit with a constant over the entire metallicity profile, without any exclusion of the central core.

4. Using the solar abundances from A05 gives consistent results with what we obtain using the values by AG89, with a discrepancy only in the normalization (as expected, ~60%–70% higher), but not in the slope of the $Z/\text{age}$ profiles. Together with the fact that, in most cases, we were able to measure the $\alpha$-elements only as upper limits, this indicates that our metallicities are mostly driven by iron and that adopting the AG89 solar abundances instead of those by A05 results in a difference only in the absolute values of the $Z$ measured, but does not introduce any bias in the radial profile analysis.

5. Fitting a power-law shape to the temperature profiles, $kT/(rT_{\text{age}}) = A(rT_{180})^\mu$, we found that $\mu$ correlates strongly with the cluster cooling times, being higher at low values of $r_T/\text{age}$, with all the CC clusters having $\alpha > 0$ and $\tau_c/\text{age} \leq 0.6$. As expected, a strong correlation is also observed between the inner slope of the metallicity profile and the cluster cooling time.

In general, our results further demonstrate the invaluable role played by X-ray archival studies of the chemodynamical and thermodynamical properties of galaxy clusters. Analyses based on the Chandra archive, like that presented here (see also Vikhlinin et al. 2005; Balestra et al. 2007; Maughan et al. 2007), in combination with analogous studies from the XMM-Newton archive, will constitute an important heritage from the present generation of X-ray satellites for years to come. Nowadays, available data on the evolution of the chemical enrichment of the ICM provide important constraints on models aimed at explaining the past history of star formation and the dynamical processes taking place during the cosmological build-up of galaxy clusters. However, the study of the thermodynamical properties of the cooling cores and the evolution of the abundance distributions in clusters with the redshift are just a part of what can be currently done by exploiting in full the existing Chandra and XMM-Newton archives. Archival works like ours have the potential to shed new light on the properties of the stellar populations responsible for the ICM enrichment, and on the mechanisms that lead to the generation of the cool cores and determine the transport and diffusion of heavy elements from star-forming regions.

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