X-MAS2: STUDY SYSTEMATICS ON THE ICM METALLICITY MEASUREMENTS

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ABSTRACT

X-ray measurements of the intracluster medium metallicity are becoming more and more frequent due to the availability of powerful X-ray telescopes with excellent spatial and spectral resolutions. The information that can be extracted from measurements of the α-elements, such as oxygen, magnesium, and silicon, with respect to the iron abundance is extremely important to a better understanding of stellar formation and its evolutionary history. In this paper we investigate possible source of bias or systematic effects connected to the plasma physics when recovering metal abundances from X-ray spectra. To do this, we analyze six simulated galaxy clusters processed through the new version of our X-Ray Map Simulator (X-MAS), which allows us to create mock XMM-Newton EPIC MOS1 and MOS2 observations. By comparing the spectroscopic results inferred from the X-ray spectra to the expected values directly obtained from the original simulation, we find that (1) the iron is recovered with high accuracy for both hot (T > 3 keV) and cold (T < 2 keV) systems; at intermediate temperatures, however, we find a systematic overestimate, which depends inversely on the number counts; (2) oxygen is well recovered in cold clusters, while in hot systems the X-ray measurement may overestimate the true value by a up to a factor of 2–3; (3) being a weak line, the measurement of magnesium is always difficult; despite this, for cold systems (i.e., with T < 2 keV) we do not find any systematic behavior, while for very hot systems (i.e., with T > 5 keV) the spectroscopic measurement may strongly overestimate the true value by up to a factor of 4; and (4) silicon is well recovered for all the clusters in our sample. We investigate in detail the nature of the systematic effects and biases found in performing XSPEC simulations. We conclude that they are mainly connected with the multitemperature nature of the projected observed spectra and to the intrinsic limitation of the XMM-Newton EPIC spectral resolution, which does not always allow disentangling the emission lines produced by different elements.

Subject headings: cosmology: miscellaneous — galaxies: clusters: general — hydrodynamics — methods: numerical

Online material: color figures

1. INTRODUCTION

Measuring the metallicity of the intracluster medium (ICM) represents a unique means toward a unified description of the thermodynamical properties of the diffuse gas and of the past history of star formation within the population of cluster galaxies (e.g., Renzini et al. 1993). The total mass in metals is directly related to the number of supernovae (SNe) that exploded in the past. Furthermore, measuring the relative abundance of iron with respect to α-elements provides information on the relative fraction of Type II and Type Ia SNe and, therefore, on the shape of the initial mass function (IMF) for star formation. Finally, the redshift evolution of the metal content of the ICM reflects the rate at which metals are released into the diffuse medium. This in turn is directly related to the star formation history.

From an observational point of view, measurements of the global content of different metal species within the ICM were first made possible with the advent of the Advanced Satellite for Cosmology and Astrophysics (ASCA) satellite (e.g., Fukazawa et al. 1994, 1998, 2000; Mushotzky et al. 1996; Finoguenov et al. 1999, 2000, 2001; Finoguenov & Ponman 1999; Finoguenov & Jones 2000; Matsushita et al. 2000;). Based on a collection of ASCA data for a fairly large number of clusters, Baumgartner et al. (2005) determined the relation between the global ICM content of different metal species and the temperature. At the same time, data from the BeppoSAX satellite allowed us to perform a detailed study of the spatial distribution of iron (De Grandi & Molendi 2001). This study showed that significant negative metallicity gradients are present in cooling flow clusters, with a central metallicity spike associated with the brightest cluster galaxy (De Grandi et al. 2004). More recently, the excellent spatial resolution of Chandra has allowed us to obtain iron metallicity profiles (Ettori et al. 2002; Buote et al. 2003; Dupke & White 2003; Humphrey et al. 2006) and maps (Sanders et al. 2004; Sanders & Fabian 2006) for a significant number of clusters. Furthermore, the large collecting area of XMM-Newton is now allowing us to study in detail the abundances of several elements, thereby providing a test bed for different models of SNe yields (de Plaa et al. 2006, 2007; Böhringer et al. 2005 and references therein), and to significantly improve the description of the metal content associated with cluster cool cores (Molendi & Gastaldello 2001; Tamura et al. 2001, 2004; Böhringer et al. 2002, 2004; Finoguenov et al. 2002; Gastaldello & Molendi 2002; Sakelliou et al. 2002; Matsushita et al. 2003, 2007a; Werner et al. 2006). Chandra and XMM-Newton allowed us to analyze in detail the iron bias already...
noted with ASCA (Buote 2000a). This bias arises when fitting with a single-temperature model a plasma characterized by a temperature gradient or by a multitemperature structure with the colder component below 1 keV (Molendi & Gastaldello 2001; Buote et al. 2003). More recently, the Suzaku telescope is providing accurate detections of oxygen and magnesium lines and has already provided measurements of the distribution of α-elements in the Fornax Cluster (Matsushita et al. 2007b) and in Abell 1060 (Sato et al. 2007) out to fairly large clustercentric distances. Finally, archival studies based on Chandra and XMM-Newton observations are now providing information on the evolution of the global iron metal content out to z ∼ 1.3 and show a decrease of about 50% of the ICM metallicity from the present time to that redshift (Balestra et al. 2007; Maughan et al. 2007).

From the theoretical point of view, a number of methods have been developed to describe the ICM enrichment associated with the cosmological hierarchical buildup of galaxy clusters. De Lucia et al. (2004), Nagashima et al. (2005), and Bertone et al. (2007) studied the ICM enrichment by coupling N-body simulations to semianalytical models (SAMs) of galaxy formation. This approach, although quite flexible for exploring the space of parameters relevant for star formation and galaxy evolution, does not provide detailed information on the spatial distribution of metals within clusters and on the role of gasdynamical processes (e.g., ram pressure stripping, turbulent diffusion, etc.) in distributing metals. In order to overcome these limitations, Cora (2006) developed a hybrid technique, which applies SAMs to nonradiative hydrodynamical simulations. Another approach is to simulate clusters with hydrodynamical codes, which have included a treatment of specific effects, such as galactic winds (Schindler et al. 2005), ram pressure stripping (Domainko et al. 2006), and active galactic nuclei (AGNs; Moll et al. 2007), although coupled with simplified descriptions of star formation. Finally, cosmological hydrodynamical simulations of galaxy clusters have been presented in the last few years in which the production of metals is self-consistently related to the process of gas cooling and star formation by accounting in detail for the contribution from different stellar populations and the corresponding lifetimes (Lia et al. 2002; Valdarnini 2003; Tornatore et al. 2004, 2007; Romeo et al. 2006).

These numerical descriptions of the ICM enrichment have reached a good enough accuracy, in terms of physical processes included and resolution, to allow a detailed comparison with observational data to be performed. It is, however, clear that for this comparison to be meaningful one has to be sure to understand observational biases, related to the instrumental response of the X-ray detectors on board the different satellites. A typical example of such biases in the study of the ICM is the measure of the X-ray temperature. Mazzotta et al. (2004) showed that the combination of a complex thermal structure of the ICM and of the finite energy band, within which X-ray spectra are measured, can bias the spectroscopic temperature toward low values (see also Vikhlinin 2006). Therefore, it is worth asking whether similar biases also affect the determination of the ICM metallicity when fitting the X-ray spectrum with single-temperature and single-metallicity plasma models.

In this paper we address the issue of the biases in the X-ray measurement of the ICM metallicity by performing mock observations of hydrodynamical simulations of galaxy clusters, which include a detailed description of the process of chemical enrichment and follow the production of different chemical species (Tornatore et al. 2007). For this purpose, we generate XMM-Newton observations of both EPIC MOS1 and EPIC MOS2 cameras, performed with a new version of the X-Ray Map Simulator (X-MAS; Gardini et al. 2004) package, which now also includes the contribution from metal lines in the generation of the X-ray spectra. Taking advantage of this tool, we can carefully check for the presence of systematics in the X-ray measurement of the metallicity, by distinguishing the behavior of iron and of α-elements, when observations are performed at the spectral resolution of XMM-Newton. In particular, we investigated the biases related only to the physics of the plasma. The biases related to the uncertainties in the calibration, the background, and/or the plasma model are beyond the scope of this paper. As such, this paper mainly focuses on quantifying the possible presence of these systematics and understanding their relation to the complex thermal and chemical structure of the ICM. We defer to a forthcoming analysis a comparison between results of hydrodynamical simulations of ICM enrichment and observational data (D. Fabjan et al. 2008, in preparation).

The plan of the paper is as follows. The new version of our X-Ray Map Simulator, X-MAS2, is presented in § 2. The characteristics of the hydrodynamical simulations are described in § 3. The procedure followed for the X-ray analysis is presented in § 4. Our results are described in § 5, where we also provide a critical discussion of the effect of observing X-ray spectra with the typical XMM-Newton energy resolution (§ 5.6). These results are discussed in § 6, while the main conclusions of our analysis are summarized in § 7. All errors quoted are at the 1σ level (68.3% level of confidence for one interesting parameter).

2. X-MAS2

The numerical code X-MAS (Gardini et al. 2004) produces mock Chandra and XMM-Newton observations starting from outputs of hydro−N-body simulations of galaxy clusters. The software is composed of two main parts: the first section computes the emissivity of each gas particle contained in the selected field of view and projects it into the sky plane; the second one convolutes the flux reaching the telescope using the response of a given detector. One of the main characteristics of X-MAS is that it is able to create the event file containing all the spectral information for each incoming simulated photon. Moreover, it properly reproduces the spatial features and the characteristics of the Chandra and XMM-Newton detectors. Furthermore, the header of the final event file stores all the fundamental keywords common to true observed files. In this way, the application of the routines and analysis programs commonly used by observers is straightforward. In previous work, the code was used only in the Chandra ACIS-S3 mode to address several issues, such as the difference between the emission-weighted and spectroscopic temperature definitions (Gardini et al. 2004), the validity of the spectroscopic-like formula proposed by Mazzotta et al. (2004), and the possible sources of bias in the X-ray estimates of cluster masses (Rasia et al. 2005, 2006). To do that, the ICM metallicity has been kept fixed at 0.3 Z⊙ (assuming Anders & Grevesse 1989), and the emissivity has been computed by simply adopting a MEKAL model (Mewe et al. 1985, 1986; Liedahl et al. 1995). For the purpose of this paper, a much more detailed analysis of the metal content of the ICM is required. Therefore, X-MAS has been subject to substantial upgrading, which affected both the first and second parts.

2.1. First Part: Implementing the Metallicity

We refer to Gardini et al. (2004) for a detailed derivation of the incoming photon flux, F⊙. Here we report its final expression as a function of redshift z, luminosity distance dL, emission measure EM = ∫ dV n e n H dV (where the integrals of the electron, n_e, and
hydrogen, \( n_{\text{H}} \), densities are computed over the volume \( V \), and power coefficient \( P^{\gamma}_{\nu(1+z)}(T, Z) \),

\[
F^{\gamma}_{\nu} = \frac{(1 + z)^2}{4\pi d_L^2} \text{EM} P^{\gamma}_{\nu(1+z)}(T, Z).
\]

(1)

Note that the power coefficient is a function of both temperature and metallicity. To take this latter into account, the metal content is split into different elements, and their contributions are computed separately.

Thus, the total power coefficient per particle is given by

\[
P^{\gamma}_{\nu(1+z)}(T, Z_{\text{tot}}) = P^{\gamma}_{\nu(1+z)}(T, H)
+ \sum_i m_i(Z_i)[P^{\gamma}_{\nu(1+z)}(T, Z_i) - P^{\gamma}_{\nu(1+z)}(T, H)],
\]

(2)

where the sum is over each chemical element, \( Z_i \), considered in the simulation (He included). The power coefficients are computed assuming a single-temperature VMEKAL model, where we fix to 1 \( Z_i \), the contribution of each element, namely, He, C, N, O, Mg, Si, and Fe. The spectrum computed by VMEKAL for each element, \( P^{\gamma}_{\nu(1+z)}(T, Z_i) \), will be the sum of the continuum, given by the power coefficient corresponding to hydrogen, \( P^{\gamma}_{\nu(1+z)}(T, H) \), plus the contribution of the different elements. The factor \( m(Z_i) \) represents the weight equal to the \( Z_i \)-element mass in units of its solar values (defined using the abundances reported in Anders & Grevesse 1989). Below we compute the emissivity by using a MEKAL model; however, the code does include a flag to switch to the APEC model (and corresponding VAPEC for multimetal elements treatment; see Smith et al. 2001) whenever desired.

In the new version of the simulator, we have also modified the routine based on the smoothed particle hydrodynamics (SPH) kernel (Monaghan & Lattanzio 1985) to distribute the particle emissivity, and assign the interesting quantities to the projected pixels. The change consists of computing the integration over the area through the products of two integrals along the two directions of the plane, where each integral has been analytically calculated a priori. This trick significantly shortens the computational time.

As in the previous version of X-MAS, we also include the effect of the Galactic H i absorption. After choosing a value of the column density \( N_{\text{H}} \), we multiply the flux in each energy channel by an absorption coefficient computed by adopting the WABS model (Morrison & McCammon 1983).

2.2. Second Part: Simulating EPIC Observations

Once the projected flux has been obtained by the first unit of X-MAS, the second unit takes care of the simulation of cluster "observations." This second part has been implemented to simulate XMM-Newton observations made with the EPIC camera. This is done by generating a set of photons given the incoming ICM and an exposure time. These are then applied to a ray-tracing procedure designed to mimic the main characteristics of the telescope optical paths and detector responses (see also Bourdin et al. 2004).

The incoming set of photons \( \{ p(k, l, e) \} \), having position on mirrors \( [k, l] \) and individual energy \( e \), is generated from random realizations of the total energy expected assuming a given ICM flux \( F^{\gamma}_{\nu} \), a telescope area \( A \), and an exposure time \( t \). To this end, we project the energies \( tAF^{\gamma}_{\nu} \) along the line of sight, and we store the obtained quantity in a three-dimensional array (where two dimensions represent the position on the mirrors and the third one is for energy). Assuming Poisson statistics, we can finally associate a discrete number of photons with the resulting total energies. Initially, we consider an array having angular and spectral resolutions of \( \Delta r = 3'' \) and \( \Delta e = 20 \text{ eV} \), respectively, which are below the expected performances of the XMM-Newton EPIC instruments.

The ray-tracing procedure emulating the EPIC observations comprises a set of filtering and redistribution functions of the photon energies and positions across the detector planes. Information about the different instrumental effects is coming from ground-based and on-flight calibrations and are essentially provided in the XMM-Newton current calibration files (CCFs) and EPIC redistribution matrix files (RMFs). The main steps of our procedure are as follows:

1. redistribution of the photon coordinates, \( [k, l] \), according to the instrument point-spread functions (PSFs), given as a function of the position on mirrors and the energy of the incident photons;
2. rejection of part of the incoming photons due to the spatially dependent cross section of mirrors (the so-called vignetting);
3. suppression of photons falling outside CCDs or within dead pixels;
4. rejection of part of the incoming photons due to energy-dependent effective area of mirrors, filter absorption, and quantum efficiency of detectors;
5. redistribution of photon energies \( e \) according to the detector response; and
6. addition of particle-induced false detections, with random drawing performed following the relative energy spectrum expected for a given exposure time.

We finally obtain a list of events, \( \{ \text{ev}(k, l, e) \} \), corresponding to photon detections, but also including some false ones due to particles, with registered positions \( [k, l] \) on the detector plane and energies \( e \).

3. THE SIMULATED CLUSTERS

The six simulated clusters analyzed in this paper have been selected from a larger ensemble of simulations of 19 clusters presented by Saro et al. (2006); we refer to that paper for more details. These clusters are extracted from a parent simulation of only dark matter (DM; Yoshida et al. 2001) with a box size of 479 h^{-1} \text{ Mpc} of a flat ΛCDM model with \( \Omega_{\text{m}} = 0.3 \) for the present matter density parameter, \( h = 0.7 \) for the Hubble constant in units of 100 km s^{-1} Mpc^{-1}, \( \sigma_8 = 0.9 \) for the rms fluctuation within a top-hat sphere of 8 h^{-1} \text{ Mpc} radius, and \( \Omega_{\text{b}} = 0.04 \) for the baryon density parameter. Mass resolution is increased inside the interesting regions by using the zoomed initial condition (ZIC) technique proposed by Tormen et al. (1997). Besides the low-frequency modes, which were taken from the initial conditions of the parent simulation, the contribution of the newly sampled high-frequency modes was also added. Once initial conditions are created, we split particles in the high-resolution region into a DM and a gas component whose mass ratio is set to reproduce the assumed cosmic baryon fraction. In the high-resolution region, the masses of the DM and gas particles are set to \( m_{\text{DM}} = 1.13 \times 10^{9} \) and \( m_{\text{gas}} = 1.7 \times 10^{8} h^{-1} \text{ M}_{\odot} \), respectively. The Plummer equivalent softening length for the gravitational force is set to \( \epsilon_{\text{Pl}} = 5 h^{-1} \text{ kpc} \), kept fixed in physical units from \( z = 5 \) to 0, while \( \epsilon_{\text{Pl}} = 30 h^{-1} \text{ kpc} \) in comoving units at higher redshifts.

The simulations have been carried out with a version of the GADGET-2 code^9 (Springel 2005), which includes a detailed treatment of chemical enrichment from stellar evolution (Tornatore et al. 2004, 2007). GADGET-2 is a parallel tree + SPH code with fully adaptive time stepping, which includes an integration scheme
that explicitly conserves energy and entropy (Springel & Hernquist 2002), the effect of a uniform and evolving UV background (Haardt & Madau 1996), star formation from a multiphase interstellar medium, a prescription for galactic winds triggered by SN explosions (see Springel & Hernquist 2003 for a detailed description), and a numerical scheme to suppress artificial viscosity far from the shock regions (see Dolag et al. 2005). In the original version of the code, energy feedback and global metallicity were produced only by SNe II under the instantaneous recycling approximation (IRA). We have suitably modified the simulation code to correctly account for the lifetimes of different stellar populations and follow metal production from both SNe Ia and SNe II, as well as from low- and intermediate-mass stars, while self-consistently introducing the dependence of the cooling function on metallicity (Sutherland & Dopita 1993). A detailed description of the implementation of these algorithms is presented in detail by Tornatore et al. (2007). The simulations analyzed here assume the power-law shape for the initial stellar mass function, as proposed by Salpeter (1955), and galactic ejecta with a speed of 500 km s⁻¹.

The main global properties of the simulated clusters are reported in Table 1. In the sample there are two big objects with mass (computed inside the radius R200, which comprises an overdensity of 200 over the universe critical density) larger than 10¹⁵ M☉, a medium-mass cluster (M₂₀₀ = 3.5 × 10¹⁴ M☉), and three smaller systems, namely, G676, G914, and G1542. Since these last three objects have very similar characteristics and behaviors, we chose to report our results only for the first one, as an example. In Figures 1 and 2 we show the projected maps for the spectroscopic-like temperature and for the metallicity, respectively. The map size is equal to the field of view of XMM-Newton; i.e., 30′, since we put our clusters at redshift z = 0.06, this corresponds to 2088 kpc, using the cosmological model here assumed. The different metal maps refer to iron and oxygen (representative of the α-elements). From these maps, it appears that the largest clusters, G1.a and G51, have a rather complex structure, while the smaller cluster G676 appears more relaxed, with G1.b representing an intermediate case.

In the following, we briefly describe the dynamical state of our simulated clusters. This is fundamental to explaining the sample characteristics that could influence the presence of any bias. The two massive clusters, G1.a and G51, both have an active dynamical state and strong inhomogeneities in the temperature maps (Fig. 1, top). They show a monotonically increasing mass history, especially lately. This means that there is a significant amount of material that continuously infalls inside the cluster virial region. All these small structures can be recognized both in the temperature maps (Fig. 1) and in the metallicity maps (Fig. 2) of these objects (see also the photon images reported in Fig. 3). Those are cold blobs that have not had enough time to thermalize in the hot ICM. Their presence does not affect the results of our analysis, since they have been identified and excluded from the X-ray analysis (the masked regions are shown as gray circles in Fig. 1; see § 4). The metal maps show rather elongated structures, which trace the direction of the most recent merger events.

The cluster G1.b is close to G1.a, lying in the same resimulated Lagrangian region. It has experienced two consecutive important major merger events, and it has not had enough time to relax. This clearly appears from the complex features in the temperature map (see also the presence on the photon image of a bright extended source on the west side of the center). The core of the merged halo is detectable by eye from the metal maps. Quite interestingly, the oxygen distribution can be used to reconstruct the merging dynamics.

The cluster G676 is an isolated system, which presented a relevant merging event at z ≈ 0.7, but after then it has had time to relax. The object can be considered to be in dynamical equilibrium at the present time, in the sense that its global velocity dispersion and its mass are almost constant in time after the merging event. Its homogeneous temperature map, round flux contours, and spherical metallicity distribution confirm this picture. Similar considerations can apply to the other two small objects, G914 and G1542 (not shown in the figures).

### 4. THE X-RAY ANALYSIS

The simulated clusters have been processed through X-MAS2 in order to produce mock observations with the EPIC MOS1 and EPIC MOS2 cameras with an exposure time of 200 ks. As mentioned before, the field of view is 30′, corresponding to 2088 kpc in physical units. The images have been created by integrating along the line of sight a box of 10 Mpc centered on the clusters. In our analysis we assume that XMM-Newton is perfectly calibrated.

#### 4.1. Spatial Analysis

We create the photon images in the 0.7–2.0 keV band and use them to detect the presence of compact X-ray–bright gas regions. These correspond to cool and very dense gas clumps present in the simulation and likely produced by overcooling effects. These clumps are generally not observed in real clusters, so to avoid contamination, we remove these regions from our analysis. For this purpose, we used the wavelet decomposition algorithm proposed by Vikhlinin et al. (1998). Parameters are settled to localize sources with a peak above 4.5 σ and to identify the surrounding region above the 2.5 σ level. The selected areas are shown as circles in the temperature maps (Fig. 1). In Figure 3 we show the photon images, extracted in the 0.7–2 keV energy band, corrected by
vignetting, out-of-time events, point-spread function, background, and out-field-of-view component, binned to 3.2".

4.2. Spectral Analysis

The spectral analysis has been performed by extracting the spectra from the event file in concentric annuli, centered on the brightest X-ray peak of the cluster. The first annulus has an internal radius of 50 kpc (the central region is excluded from the analysis) and an external radius 1.25 times larger. All the remaining annuli are logarithmically equally spaced, with the same step of 1.25. During the spectrum extraction, we also subtracted all photons coming from the masked regions, already mentioned in §4.1, and from box regions containing the CCD gaps (clearly detectable as horizontal and vertical lines in the photon images displayed in Fig. 3). The spectra have been fitted using the C-statistic in the XSPEC version 11.3.2 package (Arnaud 1996) and following two procedures widely used by observers:

Method 1.—We fit the data with an absorbed VMEKAL model in the 0.4–8 keV energy band, leaving all the parameters of interest free at the same time: temperature, iron, silicon, magnesium, oxygen, and normalization. This approach is faster and more automatic, but can lead to artificially biased results because of the degeneracy of the parameters.

Method 2.—This is a four-step procedure. (1) We fit the data with an absorbed MEKAL model in the 0.4–8 keV band to obtain the temperature (metallicity and normalization are considered free parameters); (2) we fix the temperature and use a VMEKAL model in the same energy band to recover the iron abundance (the other three metals are left free); (3) we keep temperature and iron fixed to measure the oxygen in the 0.4–1.5 keV band; and (4) finally we fix the values of temperature, iron, and oxygen to estimate the magnesium and silicon abundances in the 1.2–3.2 keV band.

In both fitting methods, we fixed the Galactic absorption $N_H$ and the redshift to the input values used to simulate the observations with X-MAS2 (i.e., $N_H = 5 \times 10^{20}$ cm$^{-2}$ and $z = 0.06$).

5. RESULTS

From the spectral analysis, we recovered the projected profiles for temperature, iron, silicon, magnesium and oxygen, and
we compared them to the values directly extracted from the hydrodynamical simulations. The simulation profiles are computed by projecting the quantities along the line of sight, within the same radial bins used in X-ray analysis and masking out the same regions described in § 4. The temperature is computed using the spectroscopic-like definition, $T_{\text{sl}}$ (Mazzotta et al. 2004), summing over all particles with temperature higher than 0.5 keV. For the metal profiles we use instead the emission-weighted formula,

$$Z_{\text{ew}} = \frac{\sum Z_i W_i}{\sum W_i},$$  \hspace{1cm} (3)$$

where $W_i$ is the emissivity of the $i$th particle computed in the 0.4–8 keV energy band, considering the contribution of each particle metal.

The results for G1.a, G51, G1.b, and G676 are presented in Figure 4. The black lines refer to the simulated input values, while spectroscopic values determined from the full-band fitting (method 1), and the ones recovered in the narrow band are shown by the crosses. The vertical error bars are at the 1σ level, while the horizontal bars represent the width of the radial bin.

5.1. Temperature

The recovered spectroscopic temperature matches well the input temperature, leading to a maximum relative error of 5% for hot systems. This difference is expected for objects with a complex temperature structure (see Fig. 1) and steep temperature gradients (see Fig. 4), as already delineated in Mazzotta et al. (2004). It is worth noting that this excellent agreement is also valid for the three cooler systems, for which the temperature falls

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Fig. 2.—Iron and oxygen distribution map for the same clusters as shown in Fig. 1: G1.a (top right), G51 (top left), G1.b (bottom right), and G676 (bottom left). The linear color scale (in solar units; Anders & Grevesse) is reported in each panel. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 3.—Photon images in the 0.7–2 keV energy band of the clusters in Fig 1: G1.a (top right), G51 (top left), G1.b (bottom right), and G676 (bottom left). The images are binned to 3.2″, background subtracted, and corrected for vignetting and out-of-time events. [See the electronic edition of the Journal for a color version of this figure.]
from 2 keV at $2^{\prime}$ (~150 kpc) down to 1 keV at $6^{\prime}$ (~450 kpc). Indeed, this result is expected, since these objects show a regular and homogenous temperature map, and any weighting (i.e., mass-weighted, emission-weighted, and spectroscopic-like) gives the same consistent result in the limit of isothermal systems (Mazzotta et al. 2004).

As expected, we do not find any difference between the spectroscopic temperatures recovered using methods 1 and 2, i.e., between MEKAL and VMEKAL fitting. In fact, we find that for the most massive clusters, the two estimates almost perfectly coincide; in the other cases, the differences are always smaller than 2%.

### 5.2. Iron

Thanks to the powerful emission of both Fe L and Fe K lines, the spectroscopic determination of the iron abundance is recovered with great accuracy and presents relatively small error bars. The strength of Fe K lines for objects having a temperature higher than 3 keV and that of Fe L lines for systems with temperature lower than 2 keV (see Fig. 5) ensures an appreciable agreement for both cold and hot clusters. In each radial bin the iron abundance derived spectroscopically matches the emission-weighted value from the original hydrodynamical simulation at the $3\,\sigma$ level. Moreover, the relative difference, $|\frac{\text{Fe}_{\text{spec}} - \text{Fe}_{\text{sim}}}{\text{Fe}_{\text{sim}}}|$, is less than 5%. The only exception is for G1.b, the 2–3 keV cluster (see Fig. 4). For this object we detect a systematic overestimate with respect to the input profile, which can be as high as 20%. The reason for this discrepancy, which is related to the complex temperature structure of this cluster (already evident in the corresponding panel of Fig. 1) and to its particular temperature range, is extensively discussed in §6.2. Some spatial bins of G676 show an underestimate of iron between 10% and 30%. This feature is
caused by the iron bias described in Buote (2000a). Among our cold clusters, G676 is the only one presenting this characteristic; we investigate this aspect further in §6.3.

It is worth noting that the iron spectroscopic abundances obtained from method 1 and method 2 are not significantly different. In fact, the two procedures differ just by keeping the temperature fixed in the second case, but the possible degeneracy between iron and temperature is weak because of the large number of counts we had (larger than $10^4$). The maximum discrepancy between the two methods is smaller than 10%, and it is present only for some radial bins of the coolest objects.

### 5.3. Oxygen

The spectroscopic measurements of oxygen, as well as magnesium and silicon, are more uncertain in the inner regions of the clusters. The effect is larger for the hottest systems, G1.a and G51, and decreases for objects with smaller masses. The explanation resides in projection effects. In fact, the spectrum of the central region is obtained by integrating along the whole line of sight; thus, it includes contributions from plasma at temperatures that can differ significantly in the case of most massive clusters, because of their steeper radial profile. For the systems with temperature lower than 3 keV, the spectroscopic determination of the oxygen abundance always agrees with the input values inside $1\sigma$ (see Table 2). On the other hand, for the largest clusters, G1.a and G51, the oxygen detection is systematically overestimated, even if the large error bars reduce the statistical significance in most radial bins. Increasing the exposure time, i.e., the photon number, reduces the error, and the systematic effect becomes more evident.

To confirm this result, in Figure 6 we report the spectroscopic result for G1.a, our hottest cluster, for which we simulated a 1 Ms exposure. From this plot, we note how the spectroscopic values significantly overestimate the input value by a factor of 3.

As a general behavior, we note that oxygen values obtained by fitting the spectra with methods 1 and 2 are similar for the smallest objects and with discrepancies always lie inside the error bars. Nevertheless, there is a tendency to obtain abundances larger than the input one when oxygen is measured using the broad band (method 1 is shown as dashed points in Fig. 4), with the difference increasing with the temperature.

### 5.4. Magnesium

Generally speaking, the measurement of magnesium is very difficult because, at the spectral resolution of XMM-Newton, its line energy is well within the energy range of the Fe L line complex (see §5.6; Fig. 5). In a few cases, it is really impossible to detect any magnesium content, and when a detection is obtained, we get always very large errors. Things improve slightly if we use method 2, but not much.

Magnesium lines are stronger for cool systems; in fact, in the cases of G1.b and G676 (see cols. [3] and [4] of Fig. 4), we are able to trace the overall profile, even if no strong constraint can

| TABLE 2 |
|-----------------|-------|-------|-------|-------|
| Oxygen Abundance | $N = 2.000$ | $N = 1.995$ | $N = 1.990$ | $N = 1.985$ |
| $O_{\text{min}}$ | 0.126 | 0.148 | 0.175 (15%) | 0.192 (29%) |
| $O_{\text{mean}}$ | 0.141 | 0.162 (9%) | 0.184 (23%) | 0.198 (38%) |
| $O_{\text{max}}$ | 0.155 | 0.176 (18%) | 0.198 (33%) | 0.220 (48%) |
| $\chi^2_{\text{red}}$ (70 dof) | 1.08 | 1.08 | 1.12 | 1.20 |

**Notes.**—These values of oxygen abundances (with their $1\sigma$ error bars) are derived by fitting a spectrum that is the combination of two plasmas at 6 and 8 keV (more details in the text). In the $\chi^2$ fitting procedure, we fix the temperature at the spectroscopic-like value, and then we also fix the normalization, considering its theoretical value (2) and smaller values (1.995, 1.990, and 1.985). The percentages (within parentheses) represent the difference between the values recovered from the spectral analysis and the expected emission-weighted one: $O = 0.149$. 

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Fig. 5.—Spectra (gray lines) obtained from XSPEC reshifted at $z = 0$ assuming a VMEKAL model with all the metals equal to zero but O, Si, Mg, and Fe, which are fixed to the solar values: the temperature varies from 1, 2, and 3 (top, starting from the left) to 5, 8, and 10 keV (bottom). The separated contributions of the different elements are also plotted; oxygen, magnesium, silicon, and iron are shown by the lines. All spectra are convolved with the response of EPIC MOS1 camera; very similar results can be obtained by considering the EPIC MOS2 camera. [See the electronic edition of the Journal for a color version of this figure.]
Ms. The meaning of the lines is the same as in Fig. 4. 

5.6. toward the softer region. The detector is very difficult to calibrate. However, this problem will not be obtained. In any case, for these cold clusters we do not find any systematic bias. On the contrary, the 6 keV cluster, G51, shows large discrepancies in the external bins where the spectroscopic estimates are between 200% and 400% higher than the input values (see Fig. 4). Finally, for G1.a, no conclusion can be reached, since its high temperature (all radial bins that value above 8 keV) makes the magnesium extremely difficult to detect (see also Fig. 5).

5.5. Silicon

The difference between the results obtained using methods 1 and 2 is also significant in the measurements of the silicon abundance. Shrinking the energy band improves the estimates, mainly for temperatures higher than 2–3 keV. For the cluster G1.b, the choice of a narrow energy band (Fig. 4, gray lines) helps prevent the underestimate of this metal by 40%–50%. G51 and G1.a show a similar tendency, even if this result is less significant because of the larger error bars. The colder clusters, instead, do not show any particular difference between the two spectral methods: in both cases, the input abundance of silicon is well recovered from the X-ray analysis at the 1–1.5 σ level.

In general, the agreement between the X-ray results and the input values from the hydrodynamical simulations is remarkably good at all temperatures. It is important to state, however, that the silicon line energy is located in a region where, due to a combination of CCDs and mirrors, the effective area decreases rapidly, and after 2 keV it shows a strong edge due to Au and Ir. For real observations, this may be a problem, as this spectral region of the detector is very difficult to calibrate. However, this problem will not affect high-redshift clusters, for which the silicon line is redshifted toward the softer region.

5.6. Thermal Bremsstrahlung Spectra as Seen by XMM-Newton

Our main goal is to investigate how well we can measure the metal abundances with the newly available XMM-Newton EPIC camera spectra. In order to better understand the results of our analysis, we illustrate here some general features of thermal bremsstrahlung spectra observed with the same spectral resolution of XMM-Newton detectors. We generate with XSPEC six spectra at different values of temperature, 1, 2, 3, 5, 8, and 10 keV. These are convolved with the instrumental response of the MOS1 camera (almost identical results can be obtained considering MOS2). The adopted plasma model is VMEKAL, for which we set to zero the abundances of all metals except O, Mg, Si, and Fe, which are fixed to their solar values. The resulting spectra are shown as gray lines in Figure 5. In the same plot, different lines refer to the separate contribution of each metal: oxygen, magnesium, silicon, and iron. Decreasing the plasma temperature, we can note that the emission lines become more evident and that the ratio between Fe L (the iron lines around 1 keV) and Fe K (the iron lines around 6 keV) rapidly increases. The oxygen lines O vi and O vii show two bumps around 0.6–0.8 keV, which are more evident for systems with temperatures lower than 3 keV. The oxygen lines are located very close to the Fe L complex, whose tail in the soft-energy region, given the spectral resolution of XMM-Newton, can interfere with determining oxygen for systems with temperatures around 1–2 keV. At temperatures higher than 3 keV, the oxygen and Fe L features are well separated. The magnesium lines are quite strong only for very cold systems with temperatures around 1–3 keV. Nevertheless, also in this case the spectral resolution of the XMM-Newton EPIC MOS cameras is not good enough to distinguish this line from the Fe L complex, which has an extremely powerful emission in this temperature range. The importance of the magnesium lines is rapidly decreasing. Silicon instead is present in a more isolated region of the spectrum (close to 2 keV); therefore this guarantees a good measurement of its abundance for systems with temperatures up to approximately 8 keV. Another important property of the energy region around 2 keV is that different temperature spectra with the same normalization have the same flux there. This means that the silicon measurement is not significantly influenced by the presence of a multitemperature plasma or, in other words, by the uncertainties related to the continuum determination. It is important to stress that the possibility of accurately determining the emission lines is subject not only to the mutual interaction of different elements, but also to the capability of accurately measuring the iron lines (which can strongly influence oxygen and magnesium) and the continuum.

6. DISCUSSION

6.1. Differences between the Methods Used in the Spectral Analysis

Considering the results presented in § 5 (see also Fig. 4), we can conclude that the two strategies followed in the X-ray analysis give almost identical estimates in the cases of temperature and iron. The only relevant difference is that in method 2 we fix the temperature to compute the iron abundance. The effect is to eliminate one free parameter, reducing the degeneracy, which, however, is extremely weak in our case, because of the large number of counts per radial bin. The most evident differences between the two procedures are for the abundance measurements of the O-metals (oxygen, silicon, and magnesium). In all cases, we obtain a better result when we fix the continuum and the iron contribution and fit the spectrum in a narrow band centered on the corresponding set of lines. We made several tests to individuate the optimal energy band to adopt. At the assumed redshift, i.e., z = 0.06, the best choices are 0.4–1.5 keV for oxygen and 1.2–3.2 keV for both magnesium and silicon. Note that the bands need to be large enough to include part of the continuum to better estimate the line emission and to evaluate the effects of each single element on the continuum. In particular, this shrewdness is very important for oxygen, for which the continuum contribution is...
relevant on a wide energy range (see the first panel in Fig. 5). Using method 2 instead of method 1 avoids an overestimated result for oxygen. Moreover, it permits detecting magnesium, which would not be recovered without fixing the iron abundance. Finally, it increases the spectroscopic determination of silicon, avoiding a possible underestimate.

6.2. Iron Overestimate for Systems at 2–3 keV

The iron content of the ICM is perfectly recovered for the hot systems, G1.a and G51, because their Fe K lines are extremely well determined (see Figs. 4 and 5). Iron is also accurately estimated for cold systems (the only exceptions are some bins of G676 in Fig. 4; see § 6.3), since their Fe L lines are extremely strong (Fig. 5). The only system for which we obtain a systematic overestimate in all radial bins is G1.b, the 2–3 keV object. Note that this discrepancy is significant, as evident from the error bars in the corresponding panel of Figure 4. The problem is due to the fact that the G1.b temperature is very close to the one at which there is a transition between the relative importance of the lines (Fe L or Fe K) used in determining the global iron content. Moreover, its temperature structure is quite complex; consequently, inside the same radial bin we are averaging different temperatures, which sometimes are characterized by a large Fe K contribution, while other times show strong Fe L. Summing over spectra with both high Fe L and high Fe K has the net effect of increasing the final amount of iron. This effect can be explained by looking at Figure 7. In the top panel we combine a plasma at 1 keV with a plasma at 4 keV. It is evident that the first plasma contributes to bump the Fe L lines, while the second one has the role of bursting the Fe K lines in the resulting global spectrum, which is then characterized by an iron content that is larger than expected, considering its temperature.

In order to quantify this effect, we perform a test with a likely composition of the gas (see Fig. 7, bottom). The input data consists of the spectrum resulting from the combination of two plasmas, the first one with temperature \( T_1 = 2 \text{ keV} \), metallicity \( Z_1 = 0.2 \), and normalization \( K_1 = 1 \) and the second one with \( T_2 = 3 \text{ keV} \), \( Z_2 = 0.1 \), and \( K_2 = 1 \). We produce a few spectra with different number counts and fit them with a C-statistic. The results are reported in Table 3. They show a perfect consistency for the temperature, but a significant overestimate of the iron spectral value with respect to the emission-weighted one. The discrepancy is highly significant and depends on the number counts: for 4,500 counts the disagreement is almost 40%. Increasing the statistic number mitigates the difference, but does not resolve it. Even after observing the cluster for \( 2 \times 10^6 \text{ s} \) and thus having \( 9 \times 10^5 \text{ counts} \) (which is 1 or 2 orders of magnitude above the typical observed counts rate; see, e.g., Balestra et al. 2007), the discrepancy is still present and on the order of 15%. The spectrum corresponding to the best-fit of the \( 4.5 \times 10^5 \text{ counts} \) spectrum is compared to the input data in the same panel of Figure 7, while in the lower part of the bottom panel we show the corresponding residuals. Note that the residual behavior does not have evident features that can make us suspect that the fit is not good or that it can be affected by some bias in the iron lines.

The implications of these results are extremely important. Iron is in fact the basis of reference for all the other α-elements; thus,

![Image](https://example.com/image.png)

**Fig. 7.**—Top: Spectra of a plasma at \( T_1 = 1 \text{ keV} \) (light gray line), \( T_2 = 4 \text{ keV} \) (black line), and their combination (dark gray line). Upper part of bottom panel: Fake spectrum with 450,000 counts obtained by combining a plasma with \( T_1 = 2 \text{ keV} \) and \( Z_1 = 0.2 \) and a plasma with \( T_2 = 3 \text{ keV} \) and \( Z_2 = 0.1 \). The dark gray line shows the resulting best-fitting model (see text for more details). Lower part of bottom panel: Corresponding residuals. [See the electronic edition of the Journal for a color version of this figure.]

| PARAMETER | \( 4.5 \times 10^1 \) | \( 4.5 \times 10^4 \) | \( 9 \times 10^4 \) | \( 4.5 \times 10^5 \) | \( 9 \times 10^5 \) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( T_{\text{min}} \) | 2.361 | 2.484 | 2.426 | 2.459 | 2.448 |
| \( T \) | 2.439 | 2.510 | 2.444 | 2.470 | 2.454 |
| \( T_{\text{max}} \) | 2.520 | 2.536 | 2.462 | 2.476 | 2.460 |
| \( \text{Fe}_{\text{min}} \) | 0.158 (10%) | 0.172 (19%) | 0.174 (21%) | 0.170 (18%) | 0.162 (12%) |
| \( \text{Fe} \) | 0.199 (38%) | 0.185 (28%) | 0.183 (27%) | 0.174 (21%) | 0.165 (16%) |
| \( \text{Fe}_{\text{max}} \) | 0.243 (69%) | 0.198 (37%) | 0.192 (33%) | 0.178 (24%) | 0.168 (17%) |

**TABLE 3**

**VALUES OF TEMPERATURE AND IRON ABUNDANCES**

**NOTES.**—Values of temperature and iron abundances (with their 1σ error bars), derived by fitting a spectra of \( T = 2 \text{ keV} \) and \( Z = 0.2 \) plasma combined with another plasma of \( T = 3 \text{ keV} \) and \( Z = 0.1 \). The percentages (within parentheses) represent the difference between the values recovered from the spectral analysis and the expected emission-weighted one: \( \text{Fe} = 0.144 \). The expected spectroscopic-like value of the temperature is equal to 2.45.
overestimating its content can lead to wrong conclusions about the past stellar population. This effect may also explain, at least partially, the recent results obtained by Baumgartner et al. (2005). After stacking in temperature bins 273 clusters observed with ASCA, they studied the global metal abundances as a function of the mean temperature. They found that in all temperature bins (from 0.5 to 12 keV) the emission-weighted iron abundance within the cluster region selected to contain as much flux as possible is around 0.2–0.25 (in solar units), with the only exception being the two bins between 2 and 4 keV, for which a global iron value of 0.43–0.47 Z⊙ is measured.

6.3. Fe Bias for Cold Systems

Another bias affecting the estimate of the iron content is present in some bins of the cold system G676 (see Fig. 4). This systematic underestimate is known in the literature as iron bias (Buote 2000a, 2000b). However, this bias gives at maximum an underestimate of order of 20%, and it is present only in G676, but it does not influence the other two cold systems. The poor evidence of this bias in our sample can be explained as follows.

The iron bias introduced by Buote (2000a) is caused by pretending to fit with a single-temperature model a plasma that is, instead, characterized either by a combination of different temperatures (multitemperature plasma) or by a strong temperature gradient. Observationally, this bias is seen to affect the central cooling core regions, where typically there is a positive temperature gradient (dT/dr > 0), as well as both a negative metallicity gradient (dZ/dr < 0) and a negative emission gradient (dEM/dr < 0). The combination of these factors enlarges the bump of the Fe L shell (the colder plasma with higher metallicity and emission excites the lines on the soft part of the Fe L shell). In our work, we are not in this regime. On the contrary, both the temperature and metallicity gradients are shallow inside the spatial bins we considered. Moreover, the temperature gradient in our external regions is opposite to the direction (dT/dr < 0) of its behavior in the cooling regions.

Another reason we do not detect a strong Fe bias in our system is that it decreases if the spectral fitting is made in an energy band sufficiently large to determine the continuum or, in other words, the temperature profile (Buote 2000b) with accuracy. Buote et al. (2003) suggested extending the minimum of the fitting energy band below 0.6 keV in order to limit the effect of this bias. With our analysis we respect this demand, since the minimum energy considered is 0.4 keV. In addition, a robust determination of the continuum is guaranteed by the high signal-to-noise ratio that we have up to 4 keV. The fact that a good iron measurement depends on a correct temperature measurement is made clear by comparing in Figure 4 the G676 temperature and iron panels.

6.4. Oxygen and Magnesium for Hot Clusters

In § 5 we showed that the abundance estimates for both oxygen and magnesium do not show any problem with systematics for systems colder than 2 keV. On the other hand, for the hot clusters, such as G1.a and G51, we found a clear bias producing a significant overestimate. Note that these elements are the best α-element indicators; thus they are a fundamental tool for studying the stellar evolution and formation history through the ratio between SNe Ia and SNe II. It is therefore necessary to understand in detail the origin of the discrepancy. To this end, we investigate a number of possible reasons that depend on the ICM physics implemented in the original hydrodynamic simulation, on the complexity of the plasma temperature, and on the features of the X-ray spectra.

![Fig. 8.—Radial profiles for oxygen in G1.a (top) and magnesium in G51 (bottom), obtained by considering only particles with temperature higher than 5 keV. Symbols and lines are the same as in Fig. 4. [See the electronic edition of the Journal for a color version of this figure.]](image)

Presence of small undetected cold blobs.—Clusters G1.a and G51 show in their photon images (Fig. 3) a large number of compact gas clouds spread in the ICM, which are usually associated with cold blobs in the temperature maps (Fig. 1). Most of them have been detected by the wavelet decomposition algorithm and then excluded from our analysis, but some of them are still present, in particular in the external regions. These structures, which have a very low temperature, could in principle be responsible for overestimating oxygen or magnesium, since their importance is greater for cold systems. To investigate this problem in more detail, we generate new event files for G1.a and G51, but use only the particles having a temperature higher than 5 keV. In this way, we are sure to avoid any contamination from cold (diffuse and clumped) gas. To these event files, we apply the whole procedure described above. As expected, using the wavelength algorithm we do not find any compact cool source, and we just exclude the second brightest blob, located on the east side of the center of G51. The comparison between the spectroscopic results and the simulation profiles of oxygen for G1.a and magnesium for G51 (recomputed excluding the particles with temperature lower than 5 keV) is shown in Figure 8. It is clear that the discrepancies are not resolved.
Dynamical state of the cluster.—Since the bias is evident only for the two largest clusters, which clearly have a complex morphological structure, while it does not affect the coolest systems, which are more symmetric and regular, its relevance could be enhanced by the presence of thermal inhomogeneities in the ICM. However, we note that G1.b does not show this phenomenon, even if it represents a perturbed object. To further investigate this possibility, we generate another series of event files, fixing the temperature of all the particles at a given constant value (8 keV), but letting all the metal abundances equal their original values. In this way, we create an object with a completely flat temperature structure. We repeat the analysis on these new images, finding again the same discrepancy for the oxygen and magnesium abundances.

Fe L/Fe K ratio.—The spectra we have extracted from the images are the sum of contributions coming from the plasma present along the line of sight and having different temperatures and metallicities. The resulting spectra, therefore, could have an Fe L/Fe K ratio different from the typical value reported by the VMEKAL model corresponding to the measured temperature. The iron content of hot systems is estimated basically using the Fe K systems, which are much more powerful than the Fe L lines at those temperatures. Thus, the Fe L group of the spectra can be weaker than we expect from a VMEKAL model in which we estimate the iron content by fitting the Fe K lines. In this situation, one way to fill the gap between the true Fe L of the spectra and the expected one of the model is to increase the emission power by other elements present in the same energy band. We performed a detailed comparison of the spectral Fe L and Fe K measurements and the corresponding model expectations. We conclude that the magnesium estimate can be affected for this reason. In fact, for G51, which is a system showing a large disagreement in Mg lines, the iron determination from the Fe L is always higher than we derive from the Fe K lines. On the other hand, this behavior is not present in G1.a and thus cannot explain the disagreement found for oxygen, which is also displaced by Fe L at temperatures higher than 8 keV (see Fig. 5).

Continuum determination.—Oxygen is a weak line at temperatures higher than 5 keV; thus a wrong determination of the continuum can strongly influence the measurement of this element. In particular, an underestimate of the continuum can result in a systematic overestimate of magnesium in hot clusters. This effect is much larger than the expected one. This simple test shows us how oxygen is very dependent on the goodness of the continuum determination and suggests that the measurements made through XMM-Newton in high-temperature systems can be significantly biased.

7. CONCLUSIONS

The intracluster medium presents a perfect laboratory to study the physics of all the cluster subcomponents, such as its galaxies and the stars in galaxies. In particular, the ICM metallicity is a rich source of information to test the stellar evolution models. In this work we thoroughly investigated all possible systematic biases present in the metallicity measurements from X-ray spectra having the same spectral resolution of XMM-Newton. To this end, we improved the X-Ray Map Simulator in order to correctly consider the metal information that is provided by our simulations. The six clusters analyzed here cover a wide range of temperature and have a different dynamical state. This allows us to determine how the biases we analyzed are effectively influenced by the complexity of the thermal structure and by the value of the temperature itself.

Performing the X-ray analysis, we tested two standard procedures adopted by X-ray observers. First, we fitted the spectra in a large band, at the same time leaving free all the parameters of interest (T, Fe, O, Mg, and Si), and second, we recovered the temperature and the iron content from a fit over a large band, and then we measured the Fe L/Fe K ratio different from the typical value reported by the VMEKAL model. Simulating a simple model that describes this system in XSPEC, we found that the spectroscopic iron is overestimated by up to 15%–40% depending on the number statistic: decreasing the source counts worsens the disagreement. This result has strong implications. In fact, one of the main goals of measuring the ICM metallicity is the derivation of the Fe L/Fe K ratio and [Si/Fe] ratios (see §1). Therefore, the fact that we detect a clear systematic effect in the iron measurements can affect the results that we can derive from them about the stellar formation history.

3. Oxygen is well measured for clusters with temperature lower than 3 keV, while we find evidence of overestimation for the hottest system in our sample, which has a temperature profile ranging from 8 to 12 keV (see Fig. 4). We carefully check some of the possible reasons for this effect. The explanation turns out to be the problematic balancing between the determination of the continuum and the weakness of this line at temperatures higher than 8 keV. A discrepancy smaller than 1% in normalization is sufficient to explain the oxygen overestimate.

4. The measurement of magnesium is difficult at all temperatures: for cold objects (with T < 2 keV) its line is, in fact, lying in the same spectral range of strong Fe L lines, and thus this line is hidden, while at high temperatures it is a very weak line. We found a systematic overestimate of magnesium in hot clusters. This effect can be related to the fact that the Fe L/Fe K ratio is higher in the spectra than in the model used to fit them. Thus, to fill the
Fe L group lines, it is necessary to pump the emission of other elements present in the same energy band, which in our case is magnesium.

5. Finally, from the X-ray analysis of the spectra we can measure silicon with good precision for all the objects in our sample independently of their dynamical state. This is due to the fact that the value of the spectra around 2 keV is only slightly dependent on the temperature.

The method used in this paper to investigate the metallicity distribution gains an enormous advantage by using high-resolution simulations in which the hydrodynamic physics is treated, including many different physical processes relevant for the thermal and chemical evolution of the ICM. Other aspects that can play a significant role, such as AGNs, cosmic rays, and magnetic fields, are not included in these simulations, but could be added in the near future. At the present, our simulations do not fully reproduce the cluster core, where more of the X-ray information comes from, but it is a proper description of the temperature gradient outside 0.1R200 (Pratt et al. 2007). Nevertheless, it is worth stressing that our results and the corresponding explanations do not depend on the kind of simulations used. In fact, when we found some disagreement between the input profiles from our simulation and the X-ray spectroscopic measurements, we investigated the problem by analyzing the spectral properties of fake plasma spectra generated using XSPEC. For this reason, our results can be considered valid for observations of spectra generated by a plasma with a multicomponent temperature. The only restrictions of our results are due to the fact that we focused our effort on a fixed spectral energy resolution, like the XMM-Newton one. The power of the analysis of the ICM metal content could radically change in the near future with an X-ray satellite having a microcalorimeter on board. EDGE (Explorer of Diffuse Emission and Gamma-Ray Burst Explosions)10 and Constellation-X11 are two projects that have been proposed to incorporate such technology and will allow us to resolve the blending of Fe L and oxygen lines.

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