ABUNDANCE GRADIENTS AND THE ROLE OF SUPERNOVAE IN M87

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ABSTRACT

We make a detailed measurement of the metal abundance profiles and metal abundance ratios of the inner core of M87/Virgo observed by XMM-Newton during the performance verification phase. We use multi-temperature models for the inner regions, and we compare the plasma codes APEC and MEKAL. We confirm the strong heavy-element gradient previously found by ASCA and BeppoSAX, but also find a significant increase in light elements, in particular O. This fact, together with the constant O/Fe ratio in the inner 9', indicates an enhancement of contribution in the core of the cluster, not only by Type Ia supernovae but also by Type II supernovae.

Subject headings: galaxies: abundances — galaxies: clusters: general — galaxies: individual (M87) — X-rays: galaxies

1. INTRODUCTION

The X-ray–emitting hot intracluster medium (ICM) of clusters of galaxies is known to contain a large amount of metals; for rich clusters between redshift 0.3 and 0.4 and the present day, the observed metallicity is about one-third the solar value (Mushotzky & Lowenstein 1997; Fukazawa et al. 1998; Allen & Fabian 1998; Della Ceca et al. 2000; Ettori et al. 2001), suggesting that a significant fraction of the ICM has been processed into stars already at intermediate redshifts.

While the origin of the metals observed in the ICM is clear (they are produced by supernovae [SNe]), what is less clear is the transfer mechanism of these metals to the ICM. The main mechanisms that have been proposed for the metal enrichment in clusters are enrichment of gas during the formation of the protocluster (Kauffmann & Charlot 1998), ram-pressure stripping of metal-enriched gas from cluster galaxies (Gunn & Gott 1972; Toniazzi & Schindler 2001), and stellar winds that are active galactic nucleus (AGN)- or SN-induced in early-type galaxies (Matteucci & Vettolani 1988; Renzini 1997).

Spatially resolved abundance measurement in galaxy clusters is of great importance because it can be used to measure the precise amounts of metals in the ICM and to constrain the origin of metals, both spatially and in terms of the different contributions of the two different types of SNe (SN II and SN Ia) as a function of the position in the cluster.

The first two satellites able to perform spatially resolved spectroscopy, ASCA and BeppoSAX, have revealed abundance gradients in cD clusters (Dupke & White 2000b; De Grandi & Molendi 2001), in particular M87/Virgo (Matsumoto et al. 1996; Guainazzi & Molendi 2000), and variations in Si/Fe within a cluster (Finoguenov et al. 2000) and among clusters (Fukazawa et al. 1998). Since the SN Ia products are iron enriched, while the SN II products are rich in α elements, such as O, Ne, Mg, and Si, the variations in Si/Fe suggest that the metals in the ICM have been produced by a mix of the two types of SNe. The exact amount of this mix still remains controversial; Mushotzky et al. (1996) and Mushotzky & Lowenstein (1997) showed a dominance of SN II ejecta, while other works on ASCA data (Ishimaru & Arimoto 1997; Fukazawa et al. 1998; Finoguenov et al. 2000; Dupke & White 2000a), still indicating a predominance of SN II enrichment at large radii in clusters, do not exclude that as much as 50% of the iron in clusters comes from SN Ia ejecta in the inner part of clusters.

M87 is the cD galaxy of the nearest cluster, and its high flux and close location allows, using the unprecedented combination of spectral and spatial resolution and high throughput of the EPIC experiment on board XMM-Newton, a detailed study of the ICM abundance down to the kiloparsec scale. Throughout this paper, we assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $z_0 = 0.5$, and at the distance of M87, 1$'$ corresponds to 5 kpc.

Recently, when we were finishing the writing of this paper, we learned of the Finoguenov et al. (2002) analysis of the same data. Our work is complementary to theirs in the sense that we use 10 annular bins instead of two, fully exploiting the quality of the XMM data and taking into account the multitemperature appearance of spectra in the inner regions with adequate spectral modeling.

The outline of the paper is as follows. In § 2 of this paper, we give information about the XMM observation and the data preparation. In § 3 we suggest the use of a unique set of “standard” abundances. In § 4 we describe our spectral modeling. In § 5 we present spatially resolved measurements of metal abundances and abundance ratios, and in § 6 we discuss our results. A summary of our conclusions is given in § 7.

2. OBSERVATION AND DATA PREPARATION

M87/Virgo was observed with XMM-Newton (Jansen et al. 2001) during the PV phase with the MOS detector in full frame mode for an effective exposure time of about 39 ks. Details on the observation have been published in Böhringer et al. (2001) and Belsole et al. (2001). We have obtained calibrated event files for the MOS1 and MOS2 cameras with SAS v5.0. Data were manually screened to remove any remaining bright pixels or hot columns. Periods in which the background is increased by soft proton flares have been excluded using an intensity filter; we rejected all events that accumulated when the count rates exceed 15
counts (100 s)\(^{-1}\) in the [10–12] keV band for the two MOS cameras.

We have accumulated spectra in 10 concentric annular regions centered on the emission peak, extending our analysis out to 14′ from the emission peak, thus exploiting the entire \textit{XMM} field of view. We have removed point source contributions and the substructures that are clearly visible from the X-ray image (Belsole et al. 2001), except in the innermost region, where we have kept the nucleus and knot A, because on such small angular scales it is not possible to completely exclude their emission. We prefer to fit the spectrum of this region with a model that includes a power-law component to fit the two pointlike sources. We include only one power-law component because of the similarity of the two sources’ spectra (Böhringer et al. 2001). The bounding radii are 0′–0′5, 0′5–1′, 1′–2′, 2′–3′, 3′–4′, 4′–5′, 5′–7′, 7′–9′, 9′–11′, and 11′–14′. The analysis of the four central regions within 3′ was already discussed in Molendi & Gastaldello (2001).

Spectra have been accumulated for MOS1 and MOS2 independently. The Lockman Hole observations have been used for the background. Background spectra have been accumulated from the same detector regions as the source spectra.

The vignetting correction has been applied to the spectra rather than to the effective area, as is customary in the analysis of EPIC data (Arnaud et al. 2001). Spectral fits were performed in the 0.5–4.0 keV band. Data below 0.5 keV were excluded to avoid residual calibration problems in the MOS response matrices at soft energies. Data above 4 keV were excluded because of substantial contamination of the spectra by hotter gas emitting farther out in the cluster, on the same line of sight.

As discussed in Molendi (2001), there are cross-calibration uncertainties between the spectral response of the two EPIC instruments, MOS and PN. In particular for the soft energy band (0.5–1.0 keV) fitting six extragalactic spectra for which no excess absorption is expected, MOS recovered the \(N_H\) galactic value, while PN gives smaller \(N_H\) by (1–2) \times 10^{20} \text{ cm}^{-2}.\) Thus, we think that at the moment, the MOS results are more reliable than the PN ones in this energy band, which is crucial for the O abundance measure. For this reason and for the better spectral resolutions of MOS, which is again important in deriving the O abundance, we limit our analysis to MOS data.

3. SOLAR ABUNDANCES

The elemental abundances of astrophysical objects are usually expressed by the relative values to the solar abundances. The so-called solar abundances can be either “meteoritic” or “photospheric.”

This distinction between meteoritic and photospheric solar abundances was made in the review by Anders & Grevesse (1989). Significant discrepancies exist between the two sets of abundances quoted in that paper, particularly for iron, and in the past this has caused some controversy in the discussion of the results of cluster abundances (Ishimaru & Arimoto 1997; Gibson et al. 1997). However, recent photospheric models of the Sun indicate that photospheric and meteoritic abundances agree perfectly, and the community has converged toward a “standard solar composition” (Grevesse & Sauval 1998), with suggestions to the astrophysical community to accept this new state-of-the-art (Brighenti & Mathews 1999). For the above reason, in this paper we adopt the Grevesse & Sauval (1998) values. Since the solar abundance table used by default in XSPEC is based on the photospheric values of Anders & Grevesse (1989), we have switched to a table taken from the data by Grevesse & Sauval (1998) by means of the XSPEC command ABUND. In general, a simple scaling allows us to switch from one set of abundances to the other.

4. SPECTRAL MODELING AND PLASMA CODES

All spectral fitting has been performed using Version 11.0.1 of the XSPEC package. All models discussed below include a multiplicative component to account for the galactic absorption on the line of sight of M87. The column density is always fixed at a value of 1.8 \times 10^{20} \text{ cm}^{-2}, which is derived from 21 cm measurements (Lieu et al. 1996). Leaving \(N_H\) to freely vary does not improve the fit and does not affect the measure of the oxygen abundance, which could have been more sensitive to the presence of excess absorption. The \(N_H\) value obtained is consistent within the errors with the 21 cm value.

The temperature profile for M87 (Böhringer et al. 2001) shows a small gradient for radii larger than \(\sim 2′\) and a rapid decrease for smaller radii. Moreover, as pointed out in Molendi & Pizzolato (2001), all spectra at radii larger than \(2′\) are characterized as being substantially isothermal (although the spectra of the regions between \(2′\) and \(7′\) are multitemperature spectra with a narrow temperature range, rather than single-temperature [1T] spectra), while at radii smaller than \(2′\), we need models that can reproduce the broad temperature distribution of the inner regions.

We therefore apply to the central regions (inside \(3′\)) three different spectral models:

1. A two-temperature model (2T; vmekal+vmekal in XSPEC and model II in Molendi & Gastaldello 2001) using the plasma code MEKAL (Mewe-Kaastra-Liedahl; Mewe et al. 1985; Liedahl et al. 1995). This model has 15 free parameters: the temperature and the normalization of the two components and the abundance of O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, and Ni, all expressed in solar units. The metal abundance of each element of the second thermal component is bound to be equal to the same parameter of the first thermal component. This model is used (e.g., Makishima et al. 2001 and references therein) as an alternative to cooling-flow models in fitting the central regions of galaxy clusters.

2. A “fake multiphase” model (vmekal+vmcflow in XSPEC and model III in Molendi & Gastaldello 2001). This model has 15 free parameters, as does the 2T model, because the maximum temperature \(T_{\text{max}}\) is tied to the vmekal component temperature. As indicated in recent papers (Molendi & Pizzolato 2001; Molendi & Gastaldello 2001), this model is used to describe a scenario that is different from a multiphase gas, which it was written for; the gas is all at one temperature, and the multiphase appearance of the spectrum comes from the projection of emission from many different physical radii. A more correct description will be given by a real deprojection of the spectrum (F. Pizzolato et al. 2002, in preparation).

3. The third model is the analog of the vmekal 2T model using the plasma code APEC (Smith et al. 2001). This model has 14 free parameters, one less than the corresponding
model using vmekal, because APEC misses the Na parameter.

We cannot adopt an APEC analog of the fake multiphase model because the cooling-flow model that is to calculate its emission using APEC is still under development. Given the substantial agreement between the 2T and fake multiphase models (Molendi & Gastaldello 2001), we can regard the 2T APEC results as also indicative for a fake multiphase model.

For the spectrum accumulated in the innermost region, we also included a power-law component to model the emission of the nucleus and of knot A. For the outer regions (from 3′ outward), we apply 1T models—vmekal using the MEKAL code, with 13 free parameters, and vapec using the APEC code, with 12 free parameters.

As pointed out by the authors of the new code, cross-checking is very important, since each plasma emission code requires choosing from a large, overlapping but incomplete set of atomic data, and the results obtained by using independent models allow critical comparison and evaluation of errors in the code and in the atomic database.

5. RESULTS

5.1. Abundance Measurements and Modeling Concerns

The X-ray emission in the cluster of galaxies originates from the hot gas permeating the cluster potential well. The continuum emission is dominated by thermal bremsstrahlung, which is proportional to the square of the gas density times the cooling function. From the shape and normalization of the spectrum, we derive the gas temperature and density. In addition, the X-ray spectra of clusters of galaxies are rich in emission lines because of K-shell transitions from O, Ne, Mg, Si, S, Ar, and Ca and K- and L-shell transitions from Fe and Ni, from which we can measure the relative abundance of a given element.

In Figure 1 we show the data of the 3′–4′ bin together with the best-fitting model calculated using the MEKAL code. The model has been plotted nine times; each time, all element abundances except one are set to zero. In this way the contribution of the various elements to the observed lines and line blends becomes apparent. In the energy band (0.5–4 keV) we have adopted for the spectral fitting, the abundance measurements are based on K-lines for all the ele-
ments except Fe and Ni, for which the measure is based on L-lines. The K-lines of O, Si, S, Ar, and Ca are well isolated from other emission features and clearly separated from the continuum emission, which are the requirements for a robust measure of the equivalent width of the lines and consequently, of the abundances of these elements. The Fe-L lines are known to be problematic, because the atomic physics involved is more complicated than K-shell transitions (Liedahl et al. 1995), but from the very good signal of XMM spectra and from the experience of ASCA data (Mushotzky et al. 1996; Hwang et al. 1997; Fukazawa et al. 1998), we can conclude that the Fe-L determination is reliable. Some of the stronger Fe-L lines due to Fe xxii and Fe xxiv are close to the K-lines of Ne and Mg, respectively, and blending can lead to errors in the Ne abundance and, to a smaller extent, the Mg abundance (Liedahl et al. 1995; Mushotzky et al. 1996). In addition, the Ni measure is difficult because of the possible confusion of its L-lines with the continuum and Fe-L blend.

5.2. Abundance Profiles

In Figure 2 we report the MOS radial abundance profiles for O (top panel), Si (middle panel), and Fe (bottom panel), in Figure 3 those for Mg (top panel), Ar (middle panel), and S (bottom panel), and in Figure 4 those for Ne (top panel), Ca (middle panel), and Ni (bottom panel). We note that the measurements obtained using the two different plasma codes agree for Fe, Ar, and Ca; they are somewhat different for O, S, and Ni and are in complete disagreement for Mg and Ne.

The temperature profile obtained with the two codes is shown in Figure 5; there are some differences in the inner regions, while in the outer isothermal bins there is substantial agreement.

The models using the APEC code give a systematically worse description than the ones using MEKAL code. For the multitemperature models with APEC, the $\chi^2$ ranges from 403 to 498 for $\nu = 218$ (216 in the central bin due to the two additional degrees of freedom [dof] of the power-law component), while for MEKAL models (2T and fake multiphase give the same results), the $\chi^2$ ranges from 323 to 382 for $\nu = 217$ (215 in the central bin due to the two additional dof of the power-law component); for 1T models with APEC, the $\chi^2$ ranges from 546 to 731 for $\nu = 221$, while for MEKAL models, the $\chi^2$ ranges from 326 to 731 for $\nu = 221$. In Figure 6 we compare the residuals in the form of $\Delta \chi^2$ between a 2T model using the MEKAL code and the APEC code for the inner bin $1' - 2'$; as well as a 1T model using the MEKAL code and the APEC code for the “isothermal” bins $3' - 4'$ and $11' - 14'$. It is evident that in the external bins, the differences in the fit between the two codes are due to APEC overprediction of the flux of Fe-L lines from high-ionization states, considering the fact that the temperatures obtained by the two codes are nearly coinci-
dent. For the inner regions, the differences between the two codes are further complicated by the different temperature range they find for the best fit. In general, where the temperature structure is very similar, as in the innermost bin, the difference is as in the outer bins in the high-energy part of the Fe-L blend, while where the temperature structure is different, as in the $10-20$ shown in Figure 6, the differences between the two codes are primarily due to different estimates of the flux of the He-like Si-K line.

We therefore choose as our best abundance profiles those obtained with a 2T $\text{vmekal}$ fit for the central regions and with a 1T $\text{vmekal}$ fit for the outer regions. In Table 1 we report the abundance profiles for O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, and Ni obtained in this way. Abundance gradients are clearly evident for Fe, Si, S, Ar, and Ca; O, Mg, and Ni show evidence for an enhancement in the central regions, while only Ne is substantially flat.

5.3. Comparison with Results of Finoguenov et al. (2002)

We made a direct comparison of our results with the abundances and abundance ratios derived by Finoguenov et al. (2002). Their values are consistent with ours within the errors, except for the oxygen abundance, which is roughly two times higher in Finoguenov’s analysis. To better understand the origin of this discrepancy, we have extracted spectra from the same radial bins, $1'-3'$ and $8'-14'$; and fitted a 1T model ($\text{vmekal}$) in the 0.5–10 keV band, excising the 0.7–1.6 keV energy range, in order to avoid the dependence from the Fe L-shell peak, as done by Finoguenov et al. (2002). Our results for the O abundance, given in units of the solar values from Anders & Grevesse (1989) in order to make a direct comparison with the results of Table 1 of Finoguenov et al. (2002), are $0.32 \pm 0.03$ for the $1'-3'$ bin and $0.20 \pm 0.02$ for the $8'-14'$ bin, to be compared with $0.535^{+0.019}_{-0.021}$ and $0.386^{+0.025}_{-0.021}$. Also interesting are the results for the Ni abundance: $2.55 \pm 0.33$ for the $1'-3'$ bin and $2.34 \pm 0.26$ for the $8'-14'$ bin, to be compared with $2.573^{+0.924}_{-0.918}$ and $0.800^{+1.732}_{-0.800}$.
We also note that a 2T modeling of the inner bin 1'–3' gives a statistically better fit over a 1T model ($\chi^2$/df of 919/440 with respect to 1083/442, using the 0.5–10 keV band), breaking down the assumption of near isothermality.

We also cross-compare the K- and L-shell results for Ni and Fe in our analysis, performing the spectral fits for all the radial bins in the 0.5–10 keV band, but exciting the 0.7–1.6 keV energy range. The derived abundances for the two elements are consistent within 1σ, although the K-shell Ni abundance is 20% higher than the L-shell abundance in the bins fitted with a 1T model. It should be kept in mind that particularly for the outer bins, the K-shell Ni abundance measure is very sensitive to the background estimate.

5.4. Abundance Ratios and SN Ia Fe Mass Fraction

From the abundance measurements we obtain the abundance ratios between all the elements relative to Fe, normalized to the solar value. They are shown in Figures 7, 8, and 9 and in Table 2, together with the abundance ratios obtained by models of supernovae taken by Nomoto et al. (1997) and rescaled to the solar abundances reported in Grevesse & Sauval (1998). We use these abundance ratios to estimate the relative contributions of SNe Ia and SNe II to the metal enrichment of the intracluster gas. Such estimates are complicated by uncertainties both in the observations and in the theoretical yields. Our approach is to use the complete set of ratios, trying to find the best fit of the function

$$\frac{X/Fe}{X_{Fe}/Fe_{Fe}} = f \left( \frac{X_{Fe}/Fe_{Fe}}{X/Fe} \right)_{SN Ia} + (1 - f) \left( \frac{X_{Fe}/Fe_{Fe}}{X/Fe} \right)_{SN II},$$

(1)

### Table 1

| Bin (arcmin) | O | Ne | Mg | Si | S | Ar | Ca | Ni |
|--------------|---|----|----|----|---|----|----|----|
| 0–0.5........ | 0.31±0.05 | 0.30±0.14 | 0.64±0.08 | 1.05±0.08 | 0.85±0.07 | 1.41±0.19 | 1.16±0.22 | 1.03±0.08 |
| 0.5–1........ | 0.48±0.04 | 0.44±0.12 | 0.69±0.05 | 1.34±0.04 | 0.79±0.03 | 0.91±0.04 | 1.60±0.31 | 1.67±0.28 |
| 1–2........... | 0.36±0.04 | 0.48±0.10 | 0.64±0.04 | 1.20±0.03 | 0.78±0.03 | 1.58±0.13 | 1.71±0.14 | 1.07±0.05 |
| 2–3........... | 0.36±0.03 | 0.37±0.06 | 0.57±0.04 | 0.90±0.03 | 0.66±0.02 | 1.42±0.11 | 2.62±0.11 | 0.92±0.02 |
| 3–4........... | 0.24±0.03 | 0.34±0.05 | 0.49±0.03 | 0.87±0.02 | 0.57±0.02 | 1.23±0.11 | 1.30±0.11 | 0.77±0.01 |
| 4–5........... | 0.27±0.03 | 0.47±0.06 | 0.50±0.03 | 0.72±0.02 | 0.42±0.01 | 1.15±0.11 | 1.24±0.11 | 0.68±0.01 |
| 5–7........... | 0.23±0.02 | 0.44±0.04 | 0.53±0.03 | 0.61±0.02 | 0.38±0.01 | 0.93±0.07 | 1.00±0.08 | 0.60±0.01 |
| 7–9........... | 0.22±0.02 | 0.30±0.03 | 0.48±0.03 | 0.53±0.02 | 0.27±0.01 | 0.57±0.08 | 0.68±0.08 | 0.53±0.02 |
| 9–11 .......... | 0.21±0.03 | 0.28±0.03 | 0.25±0.03 | 0.49±0.02 | 0.20±0.02 | 0.60±0.10 | 0.70±0.09 | 0.46±0.01 |
| 11–14......... | 0.20±0.02 | 0.21±0.03 | 0.20±0.03 | 0.46±0.02 | 0.13±0.02 | 0.59±0.08 | 0.57±0.09 | 0.38±0.01 |

### Table 2

| Bin (arcmin) | O | Ne | Mg | Si | S | Ar | Ca | Ni |
|--------------|---|----|----|----|---|----|----|----|
| 0–0.5........ | 0.30±0.06 | 0.29±0.13 | 0.63±0.09 | 1.00±0.12 | 0.83±0.10 | 1.36±0.21 | 1.13±0.24 | 1.41±0.25 |
| 0.5–1........ | 0.39±0.04 | 0.35±0.10 | 0.56±0.09 | 1.06±0.05 | 0.76±0.04 | 1.51±0.15 | 1.29±0.17 | 1.61±0.12 |
| 1–2........... | 0.34±0.03 | 0.45±0.09 | 0.60±0.04 | 1.12±0.04 | 0.73±0.03 | 1.46±0.12 | 1.60±0.14 | 1.48±0.11 |
| 2–3........... | 0.39±0.04 | 0.40±0.10 | 0.62±0.04 | 1.04±0.04 | 0.75±0.03 | 1.58±0.12 | 1.37±0.13 | 1.60±0.12 |
| 3–4........... | 0.31±0.04 | 0.45±0.07 | 0.64±0.06 | 1.13±0.04 | 0.74±0.03 | 1.59±0.14 | 1.69±0.16 | 1.51±0.11 |
| 4–5........... | 0.40±0.04 | 0.69±0.08 | 0.74±0.05 | 1.10±0.04 | 0.65±0.03 | 1.69±0.15 | 1.82±0.16 | 1.69±0.14 |
| 5–7........... | 0.38±0.04 | 0.76±0.08 | 0.85±0.05 | 1.06±0.03 | 0.63±0.03 | 1.52±0.13 | 1.68±0.13 | 1.74±0.11 |
| 7–9........... | 0.41±0.04 | 0.57±0.06 | 0.89±0.07 | 1.00±0.04 | 0.50±0.04 | 1.07±0.15 | 1.27±0.17 | 2.17±0.17 |
| 9–11 .......... | 0.45±0.04 | 0.61±0.07 | 0.50±0.08 | 1.08±0.04 | 0.45±0.04 | 1.31±0.19 | 1.54±0.20 | 2.41±0.21 |
| 11–14......... | 0.52±0.06 | 0.55±0.08 | 0.52±0.07 | 1.26±0.04 | 0.33±0.05 | 1.54±0.24 | 1.50±0.25 | 2.78±0.18 |

### Note.
- The abundances relative to Fe normalized to the solar value, (X/Fe)/(X_{Fe}/Fe_{Fe}), where X and Fe are number density of the element and Fe, are shown. The errors associated with the observed abundance ratios are the propagated 1 σ errors.
- Different models of SNe Ia taken by Nomoto et al. 1997.
- Yields of SNe II taken by Nomoto et al. 1997.
- Gibson et al. 1997, who chose a representative sample of SNe II yields in the literature.
where

\[
\frac{X/Fe}{X_0/Fe_0}\text{_{observed}}
\]

is the measured abundance ratio of the X element to Fe, given in solar units,

\[
\frac{X/Fe}{X_0/Fe_0}\text{_{SN Ia}}
\]

and

\[
\frac{X/Fe}{X_0/Fe_0}\text{_{SN II}}
\]

is the theoretical abundance ratio by the two types of supernovae, also given in solar units, and \(f\) is directly the SN Ia Fe mass fraction. The result of the simultaneous fit of the eight ratios is presented as circles in Figure 10, using the SN II model by Nomoto et al. (1997) and W7, WDD1, and WDD2 models for SNe Ia, respectively, for the three panels. Because of the large uncertainties in the yields for the SN II model, the results are strongly SN II model dependent. For comparison, we use the range of SN II yields calculated by Gibson et al. (1997), also listed in Table 2, which involve only ratios for O, Ne, Mg, Si, and S, and as before, we find the best fit for equation (1). The results are shown as squares for the lower end of the range and triangles for the upper part of the range.
The best fits are obtained in the inner bins with a combination of the WDD2 model for SNe Ia and the Nomoto model for SNe II, with reduced $\chi^2$, which ranges from 2 in the inner bin up to 10 in the 4'-5' bin. In the outer bins, the fit is slightly better (reduced $\chi^2$ of 8–10 instead of 12–13), with a combination of the W7 model for SNe Ia and the Nomoto model for SNe II. This is shown in Figure 11, where the fits with the three SN Ia models together with the Nomoto SN II model are reported for the 0.5–1' bin and for the 11'–14' bin. It is clear from the inspection of the residuals in terms of $\Delta\chi^2$ that the combination of the W7 model and Nomoto SN II model fails in the inner bins because it predicts a higher Ni/Fe and O/Fe ratio compared to the delayed detonation models. The situation is the opposite for the outer bins, where a higher Ni/Fe and a lower S/Fe favors the W7 model. However, the preference for the W7 model in combination with the Nomoto SN II model in the outer bins is strongly dependent on the Ni/Fe ratio; if we exclude it from the fit, the WDD2 model provides the better fit to the data.

6. DISCUSSION

The model emerging from the ASCA and BeppoSAX data for the explanation of abundance gradients in galaxy clusters was that of a homogeneous enrichment by SNe II, the main source of $\alpha$ elements, perhaps in the form of strong galactic winds in the protocluster phase and the central increase in the heavy-element distribution due to an enhanced contribution by SNe Ia, strongly related to the presence of a cD galaxy (Fukazawa et al. 1998; Dupke & White 2000b; Finoguenov et al. 2000; De Grandi & Molendi 2001; Makishima et al. 2001). As a textbook example, we can consider the case of A496 observed by XMM-Newton (Tamura et al. 2001). The O-Ne-Mg abundance is radially constant over the cluster, while the excess of heavy elements such as Fe, Ar, Ca, and Ni in the core is consistent with the assumption that the metal excess is solely produced by SNe Ia in the cD galaxy. The crucial ratio for the discrimination of the enrichment by the two types of supernovae, O/Fe, is then decreasing toward the center.

The XMM results for M87/Virgo question this picture. They confirm and improve the accuracy of the measure of heavy-element gradients previously found by ASCA and BeppoSAX, but they also show a statistically significant enhancement of $\alpha$ elements O and Mg in the core. If we consider the inner 9', the ratio O/Fe is constant with $\chi^2 = 6.9$ for 7 dof, and adding a linear component does not improve the fit ($\chi^2 = 5.4$ for 6 dof). These facts also point toward an increase in contribution of SN II, since O is basically only produced by this kind of supernovae. Although there is little or no evidence of current star formation in the core of M87, the O excess could be related to a recent past episode of star formation triggered by the passage of the radio jet, as we see in cD galaxies with a radio source (A1795 cD: van Breugel et al. 1984; A2597 cD: Koekemoer et al. 1999) and nearby (Cen A: Graham 1998) and distant radio galaxies (van Breugel et al. 1985; van Breugel & Dey 1993; Bicknell et al. 2000; for a comprehensive discussion see McNamara 1999).

To put this idea quantitatively, waiting for a true deprojection of our data, we use a previous ROSAT estimate of the deprojected electron density in the center of the Virgo cluster (Nulsen & Böhringer 1995) to calculate the excess mass of oxygen. To estimate the excess abundance, we fit the inner bins, where we see the stronger increase in the O abundance, with a constant, obtaining an abundance of 0.32, while for the outer bins, we obtain an abundance of 0.21, so the excess is 0.11. Then we estimate the oxygen mass, $M_O$, to be $M_O = A_O [Z/Z_\odot]_{\text{excess}} M_H$, where $M_H = 0.82 n_\text{H} (4\pi/3) (R_\text{out} - R_\text{in})^3$, $R_\text{in}$ and $R_\text{out}$ being the bounding radii in kpc of the bins, $A_O = 16$, and $[Z/Z_\odot]_{\text{excess}} = 6.76 \times 10^{-5}$ from Grevesse & Sauval (1998). We obtain a rough estimate of $10^7 M_\odot$, which, assuming that about $80 M_\odot$ of star formation is required to generate a SN II (Thomas & Fabian 1990) and Nomoto SN II oxygen yield, requires a cumulative star formation of $(4.5) \times 10^8 M_\odot$. This star formation is in agreement with a burst mode of star formation ($\lesssim 10^7$ yr) at rates of $\approx 10$–40 $M_\odot$ yr$^{-1}$, as it is observed in the cD galaxies of A1795 and A2597 (McNamara 1999).
For heavy-element gradients and the contribution of SNe Ia, M87 data suggest an agreement with delayed detonation models (in particular for the inner bins), as stressed by Finoguenov et al. (2002), in contrast with the preference of the W7 model set by the high Ni/Fe ratios found by Dupke & White (2000a). This is particularly evident if we consider the S/Fe ratio in Figure 7. If we consider the set of theoretical values for SN II and W7 SN Ia models, the behavior of these ratios would indicate an increasing contribution by SNe Ia going outward to the center. We recover the correct behavior if we choose the WDD1 yield and we reduce the SN II yield of Nomoto et al. (1997) by a factor of 2–3, as was already indicated by ASCA data (Dupke & White 2000a). We caution, however, that this is a substantial contribution larger than that allowed by the SN II models chosen by Gibson et al. (1997). The use of a delayed detonation model for SNe Ia could also explain the overabundance of S and also Si (with respect to the W7 model) found by Tamura et al. (2001) for the core of A496.

With increasing radius, the W7 model gives a better fit to the data with respect to delayed detonation models. This fact indicates a SN Ia abundance pattern change with radius and could be taken as an independent X-ray confirmation of the conclusions of Hatano et al. (2000) on the optical spectroscopic diversity of SNe Ia, as suggested by Finoguenov et al. (2002). However, we stress that the preference of W7 over WDD models in the outer bins is entirely due to the Ni/Fe ratio, which could be affected by systematic uncertainties, as discussed in §§ 5.1 and 5.3.

In Figure 10, we show the relative importance of SNe Ia, measured by the Fe mass fraction provided by this kind of supernovae. This is substantially constant through the 14’’ analyzed. This fraction is considerable and ranges between 50% and 80%, and it depends only slightly on the SN Ia model used. Instead, the uncertainties involved in using different SN II models are large, and a definitive answer cannot be reached until further convergence of SN II models is achieved.

7. SUMMARY

We have performed a spatially resolved measurement of the element abundances in M87, the Virgo cluster cD galaxy. The main conclusions of our work are:

1. The APEC code gives a systematically worse description than the MEKAL code in modeling M87 spectra.
2. We confirm the increase of Fe and other heavy elements toward the core, indicating that the SN Ia contribution increases.
3. The increase in O abundance and a constant O/Fe ratio in the inner 9’’ indicates an increase also in SN II ejecta, possibly from starburst in the recent past.
4. Si/Fe and S/Fe profiles favor WDD models over W7, also requiring substantial reduction of the SN II yield of S.
5. The indication of a change in the SN Ia abundance pattern, provided by a preference of the W7 model over delayed detonation models in the outer bins, is entirely due to the Ni/Fe ratio. Since the Ni measurement is difficult and uncertain, this indication should be taken with some caution.

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