X-ray spectroscopy of the Virgo Cluster out to the virial radius

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ABSTRACT

We present results from the analysis of a mosaic of 13 XMM–Newton pointings covering the Virgo Cluster from its centre northwards out to a radius \( r \sim 1.2 \) Mpc (\( \sim 4.5 \) ), reaching the virial radius and beyond. This is the first time that the properties of a modestly sized (\( M_{\text{vir}} \sim 1.4 \times 10^{14} M_\odot, kT \sim 2.3 \) keV), dynamically young cluster have been studied out to the virial radius. The density profile of the cluster can be described by a surprisingly shallow power-law \( n_e \propto r^{-\beta} \) with index \( \beta = 1.21 \pm 0.12 \). In the radial range of \( 0.3 r_{\text{vir}} < r < r_{\text{vir}} \), the best-fitting temperature drops by roughly 60 percent. Within a radius \( r < 450 \) kpc, the entropy profile has an approximate power law form \( K \propto r^{1.1} \), as expected for gravitationally collapsed gas in hydrostatic equilibrium. Beyond \( r > 450 \) kpc, however, the temperature and metallicity drop abruptly, and the entropy profile becomes flatter, staying consistently below the expected value by a factor of 2–2.5. The most likely explanation for the unusually shallow density profile and the flattening of entropy at large radius is clumping in the ICM. Our data provide direct observational evidence that the ICM is enriched by metals all the way to \( r_{200} \) to at least \( Z = 0.1 Z_\odot \).

Key words: X-rays: galaxies: clusters – X-rays: individual: Virgo.

1 INTRODUCTION

Sitting at the top of the mass spectrum of the virialized objects in the Universe, galaxy clusters serve as unique probes of cosmological parameters (e.g. Schuecker et al. 2003; Allen et al. 2008; Vikhlinin et al. 2009; Mantz et al. 2010) and provide an approximately fair sample of the matter content of the Universe (White et al. 1993; Carlberg et al. 1996).

Over the past 20 yr, progress in understanding the astrophysics of galaxy clusters and their use as probes for cosmology was driven by X-ray observations. However, those observations only targeted the inner part of their volumes extending at most out to \( r_{500} \), where the X-ray emission is brightest; extrapolations were used to infer their properties further out. Until very recently, the thermodynamic properties of the cluster outskirts were not directly observable.

Early work on the outskirts of clusters focused on determining the surface brightness profiles, using ROSAT data in particular (Vikhlinin, Forman & Jones 1999; Neumann 2005). This provided density estimates, but essentially no temperature information. Reliable information regarding the temperature of the intracluster medium (ICM) at the virial radius (which approximately corresponds to \( r_{200} \)) has become available only recently. Properties of the ICM in the outskirts of a handful of clusters, including PKS 0745–191 (George et al. 2009), Abell 2204 (Reiprich et al. 2009), Abell 1795 (Bautz et al. 2009), Abell 1413 (Hoshino et al. 2010) and Abell 1689 (Kawaharada et al. 2010), could be studied thanks to the low instrumental background of the Suzaku satellite. The most detailed radial profiles of thermodynamic quantities measured all the way out to \( r_{200} \) were recently obtained for the Perseus Cluster (Simionescu et al. 2011). Among other results, these observations provide evidence that the ICM at large radii is highly clumped.

However, all of these clusters studied with Suzaku at large radii to date are hot, massive, relatively relaxed systems. In order to have a complete picture of how galaxy clusters evolve within the context of hierarchical structure formation, we also need to understand less massive, less relaxed systems. Such systems are also critical to understand for cosmological studies: a large fraction of the integrated Sunyaev–Zel’dovich (SZ) power spectrum is expected to come from modestly sized clusters and groups, which are much more common than their more massive counterparts.

The nearest, brightest, modestly sized, dynamically young cluster and therefore the ideal object to study for these purposes is the Virgo Cluster. The cluster is at a distance of 16 Mpc and...
has an average temperature of $\sim 2\,\text{keV}$. The bulk of the X-ray emission from this relatively cool system arises in the soft X-ray band, where the effective area of current X-ray mirrors is large and the signal-to-detector background contrast is optimal. Therefore, using a careful background treatment, we can study the thermodynamic properties and the chemical abundances of the low surface brightness regions of Virgo out to $r_{200}$, even with the XMM–Newton satellite.

Böhringer et al. (1994) used ROSAT Position Sensitive Proportional Counter (PSPC) observations from the ROSAT All-Sky Survey (RASS) to study the structure of the Virgo Cluster. They discovered that the X-ray emission in general traces the galaxy distribution and confirmed three subclumps, centred on the galaxies M87, M49 and M86, respectively (reported earlier by Binggeli, Tammann & Sandage 1987; Binggeli, Popescu & Tammann 1993). Shibata et al. (2001) derived an extensive temperature map using hardness ratio values from ASCA observations covering an area of $19\,\text{deg}^2$. For a mean temperature of $kT = 2.3\,\text{keV}$, the scaling relations by Arnaud, Pointecouteau & Pratt (2005) predict $M_{200} = 1.4 \times 10^{14}\,\text{M}_\odot$ and $r_{200} = 1.08\,\text{Mpc}$, which is a projected radius of $\sim 3.9$ in the sky.

In this work, we study the structure of the Virgo Cluster using a mosaic of XMM–Newton pointings, which cover it from the centre northwards out to $r_{200}$. The pointings are shown in Fig. 1 as circles overplotted on the adaptively smoothed ROSAT PSPC image. Section 2 discusses the data reduction and extraction of the data products. In Section 3 we present projected surface brightness, temperature and metallicity profiles and determine the deprojected profiles of temperature and density. Based on these values we calculate the pressure and entropy profiles of the ICM. We also discuss in detail various possible sources of systematic errors and their impact on our results. In Section 4 we discuss the implications of our results and provide a summary and conclusions in Section 5.

All the errors are given at 1σ (68 per cent) confidence level unless otherwise stated. We assumed the distance of Virgo as that of the central galaxy M87 (16.1 Mpc, Tonry et al. 2001). At this distance, 1 arcmin corresponds to 4.65 kpc.

## 2 OBSERVATIONS AND DATA ANALYSIS

### 2.1 Observations

A total of 14 XMM–Newton observations were used, the details of which are listed in Table 1. The observations were carried out in 2002 June and July, with the exception of the southernmost ones. 13 of the pointings are partially overlapping and cover a stripe in the sky with dimensions roughly 30 arcmin (east–west) by 4.5 (north–south). The combined image of these pointings using the MOS detectors is shown in Fig. 2. The northernmost observation located $\sim 5.5$ from the cluster centre (not shown in Figs 1 and 2) lies beyond the virial radius of Virgo, contains no significant ICM emission, and was used to determine the local X-ray background.

### 2.2 Data analysis

The data analysis was carried out using the XMM–Newton Science Analysis System (SAS) version 9.0.0. The filtering and extraction of the MOS data products and the subtraction of their instrumental background was performed using the XMM–Newton Extended Source Analysis Software (XMMSAS) and methods described in Snowden & Kurtz (2008), Snowden et al. (2008), Snowden & Kurtz (2010). The filtering and subtraction of the instrumental background for the pn data was based on that performed by Werner et al. (2008).

In brief, to remove the soft proton flares, we used the MOS-filter procedure in XMMSAS (Snowden & Kurtz 2010). The MOS-detector background was modelled and subtracted using the filter-wheel-closed (FWC) data together with data from the unexposed corners of the CCDs. The total count rates and hardness ratios are determined in the unexposed regions of the CCDs for each source observation and a data base of all archived observations is searched for FWC data with similar count rates and hardness ratios. FWC data with the most similar count rates and hardness ratios are then scaled by the ratio of the source observation spectra from the CCD corners to the FWC spectra from the corners. These scaled FWC data are then used to produce the background files for the appropriate regions. The background modelling is done for each MOS chip individually.

To remove the soft proton flares from the EPIC/pn detectors, we extracted light curves in the hard energy band, 10–14 keV, and created count rate histograms which have a roughly Gaussian peak at the nominal count rate. We excluded the time periods when the count rate exceeded the mean by more than $3\sigma$. We repeated this procedure in the soft energy, 0.3–1 keV, band. The spectral properties of the EPIC/pn detector background are relatively stable and the chip-to-chip variations are not significant. For EPIC/pn, we therefore used a stacked FWC data set which we again scaled by the ratio of the number of the counts in the unexposed corners of the source observation and the FWC data. We also tried to normalize...
extraction regions of radius 12 arcmin, centred on the aim points of tainties), we have only used the data collected from within circular analysis.

as missed by ewavelet. For the central pointing, we used the list of point sources from an earlier analysis by Simionescu et al. The stacked images were visually inspected to correct for false

taskEW A VELETto detect point sources down to 5

stacked the images for all three instruments and used the SAS band indicates residual soft proton contamination. Therefore, it too has not been used in the further analysis.

Images were extracted in the 0.6–3.0 keV energy range. We checked for residual soft proton contamination by comparing the hard energy band where the number of source counts is negligible. Both methods of scaling produced consistent results.

Table 1 shows the observation ID, date, revolution number, exposure times before and after cleaning for each instrument, and the coordinates of each pointing. For both EPIC/MOS and EPIC/pn, we fixed the Galactic absorption column density to the value determined by the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005). The metallicities are reported relative to the solar abundances given by Grevesse & Sauval (1998). We used the extended C-statistic (which allows for background subtraction) in all the spectral modelling.

2.3 Spectral analysis

We extracted spectra from all clean observations north of the central pointing. Previous results from these data for the cluster’s central region are discussed by e.g. Belsole et al. (2001), Molendi (2002), Böhringer et al. (2001), Matsushita et al. (2002), Matsushita, Finoguenov & Böhringer (2003), Werner et al. (2006), Simionescu et al. (2007, 2008, 2010).

The spectra were extracted from a set of annular regions centred on the active nucleus of M87 ($\alpha = 12^{h}30^{m}49.4^{s}$, $\delta = 12^{\circ}23'28''$). The widths of the annuli were varied to maintain a nearly constant number of instrumental background subtracted counts (10000) in each region. The SAS task rmfgen was used to create response matrices (RMF). Auxiliary response files (ARF) were created for each region using the task arfgen.

We used xspec 12.6.0 (Arnaud 1996) to model the spectra. Fits were carried out in the 0.4–7.0 keV energy range using the combined data from all three detectors. We excluded the 1.2–1.8 keV interval due to the instrumental Al and Si lines. For the diffuse X-ray emission, we used a single-temperature apec model (Smith et al. 2001), which describes an optically thin plasma in collisional ionization equilibrium. The redshift was fixed to that of M87 ($z = 4.36 \times 10^{-3}$). For each pointing, we fixed the Galactic absorption column density to the value determined by the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005). The metallicities are reported relative to the solar abundances given by Grevesse & Sauval (1998). We used the extended C-statistic (which allows for background subtraction) in all the spectral modelling.

2.4 X-ray foreground and background

We extracted the cosmic X-ray foreground/background (CXFB) spectrum from the northermmost pointing using the combined data from all three detectors, after removing the point sources. We assumed a sum of three components in the CXFB model – an absorbed power law from the unresolved point sources (De Luca & Molendi 2004), an $\sim$0.2 keV emission from the Galactic halo (Kuntz & Snowden 2000) and the Local Hot Bubble emission modelled

Table 1. Summary of the observations. Columns give the observation identifier, starting date of the observation, XMM–Newton revolution of the observation, total and cleaned exposure times for MOS1, MOS2 and pn instruments, respectively, and the coordinates of the pointings. The pointings in the table are ordered from the south to the north.

| Obs. ID | Date YY/MM/DD | Rev. | Exp. time (ks) MOS1 | Exp. time (ks) MOS2 | Exp. time (ks) pn | Clean time (ks) MOS1 | Clean time (ks) MOS2 | Clean time (ks) pn | RA (°) | Dec. (°) |
|---------|---------------|------|---------------------|---------------------|-------------------|---------------------|---------------------|---------------------|--------|---------|
| 0200920101 | 05/01/11 | 932 | 95.36 | 95.37 | - (a) | 74.87 | 75.65 | - | 187.71 | 12.36 |
| 0106060101 | 01/07/12 | 291 | 9.29 | 9.28 | 5 | 8.75 | 9.04 | 5 | 187.71 | 12.73 |
| 0106060201 | 02/07/08 | 472 | 8.36 | 8.37 | 5 | 4.65 | 4.51 | 1.7 | 187.71 | 13.06 |
| 0106060301 | 02/07/04 | 470 | 8.89 | 8.89 | 5.52 | 6.87 | 7.3 | 5.1 | 187.71 | 13.39 |
| 0106060401 | 02/02/04 | 470 | 11.33 | 11.35 | 7.64 | 10.54 | 10.68 | 6.77 | 187.71 | 13.73 |
| 0106060501 | 02/07/06 | 471 | 17.38 | 17.42 | 13.87 | 14.3 | 14.7 | 11.58 | 187.71 | 14.06 |
| 0106060601 | 02/07/08 | 472 | 14.37 | 14.37 | 11 | 9.38 | 9.81 | 8.52 | 187.71 | 14.39 |
| 0106060701 | 02/07/05 | 471 | 13.85 | 13.87 | 10.5 | 4.89 | 6.09 | 0 | 187.71 | 14.73 |
| 0106061401 (b) | 02/06/13 | 460 | 8.23 | 8.26 | 4.88 | 7.84 | 7.92 | 4.88 | 187.71 | 15.06 |
| 0106060901 | 02/06/10 | 458 | 15.03 | 15.03 | 11 | 11.28 | 11.38 | 7.8 | 187.71 | 15.39 |
| 0106061001 | 02/06/06 | 456 | 12.39 | 12.18 | 8.89 | 8.58 | 8.45 | 5 | 187.71 | 15.73 |
| 0106061101 | 02/06/09 | 458 | 15.93 | 15.95 | 11.98 | 8.31 | 8.43 | 4.96 | 187.71 | 16.06 |
| 0106061201 | 02/06/09 | 458 | 17.57 | 17.65 | 13.52 | 14.19 | 14.36 | 10.22 | 187.71 | 16.39 |
| 0106061301 (c) | 02/06/10 | 458 | 15.99 | 16.03 | 12 | 14.7 | 14.39 | 11.33 | 187.71 | 17.89 |

(a) Data from pn were not used for the central pointing.
(b) Replacement for flared observation 0106060801.
(c) Background pointing (see text).
Figure 2. Mosaic XMM–Newton image in the 0.6–3.0 keV energy range. The background pointing lies 1:5 to the north of the northernmost pointing shown. Only the central region within the radius of 12 arcmin from the telescope’s aim-point was used for each instrument. The image has been exposure corrected, smoothed with a Gaussian with the width of 3 pixels, and the point sources have been removed. The left-hand panel shows the southern part of the mosaic and the right-hand panel shows the northern part. The white circle marks the overlap in both panels. The central part of the cluster is clearly dominated by the emission of M87, the cold front discussed in Simionescu et al. (2010) is visible at ~20 arcmin to the north of the centre.
by 0.08 keV thermal plasma (LHB, $^2$ Sidher et al. 1996; Kuntz & Snowden 2000). During the CXFB model fitting, the normalizations of the three components, the power-law index, and the temperature of the Galactic halo gas were left to vary independently. The metallicities of the foreground thermal plasmas were fixed to the solar value. The absorption column density was fixed at $N_H = 2.13 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005). The resulting foreground/background parameters are summarized in Table 2. The observed flux of the power-law component is lower than the value reported by De Luca & Molendi (2004), which is to be expected given that the point sources detected and resolved in our analysis were excluded.

All spectra used this same CXFB model, with the normalizations scaled to account for the areas of the extraction regions.

The north-polar spur region, with its elevated soft foreground emission, is relatively strong throughout the eastern parts of the Virgo Cluster. However, our pointings are in a direction that avoids this emission.

### 3 RESULTS

#### 3.1 X-ray surface brightness

In Fig. 3 we present the background-subtracted surface brightness profile of the Virgo Cluster obtained from the combined, exposure-corrected MOS images in the 0.6–3.0 keV band. It was extracted from 199 annular regions stretching from the centre out to $\sim 255$ arcmin (projected distance $\sim 1.2$ Mpc). In the cluster centre, out to $\sim 8.5$ arcmin = 40 kpc, the regions are 0.1 arcmin wide; at larger intermediate radii their width is $\sim 1.35$ arcmin, and beyond 700 kpc the binsize increases to 2.7 arcmin. The gaps in the profile indicate missing data due to flared observations. The background was assumed constant over the whole cluster, with a value equal to the average surface brightness of the outer background pointing.

The profile shows a prominent discontinuity associated with a cold front at 90 kpc. This feature has previously been discussed by Simionescu et al. (2010). Outside the cold front, the surface brightness distribution can be described by a power-law model $S_X \propto r^{-\alpha}$ with index $\alpha = 1.34 \pm 0.01$. We verified that there is no significant difference between the slopes of surface brightness profiles obtained for different low-energy bands.

In the faint outskirts, beyond $r \sim 700$ kpc, the surface brightness starts to fluctuate significantly and the profile becomes more uneven. We note that the individual surface brightness bins in these outer regions contain at least $\sim 500$ counts. The fluctuations are therefore formally highly statistically significant.

#### 3.2 Spectral results

The results of our spectral fits are shown in Table 3 and in Fig. 4. Because we fitted the data using C-statistics, we do not have a goodness-of-fit indicator similar to the reduced $\chi^2$. In order to confirm that the fits are acceptable, we rebinned the data to a minimum of 50 counts per bin and evaluated our best-fitting model using $\chi^2$ statistics. All the reduced $\chi^2$ values for our best-fitting models are in the range of 0.86–1.38. These values show that, given the present systematics, our fits are acceptable. The goodness-of-fit estimated from the $\chi^2$ statistics does not show a systematic trend with radius: the fits at large radii are, on average, as good as the fits at small radii.

Both the temperature and metallicity profiles show discontinuities at the cold front ($r \sim 90$ kpc), previously studied by Simionescu et al. (2010) and modelled by Roediger et al. (2011). This feature can be explained by the sloshing of the dense gas associated with the cooling core in the gravitational potential of the cluster.

Beyond a radius $r \sim 450$ kpc, the temperature and metallicity both drop abruptly. At the virial radius, the measured temperature reaches $kT = 1.08^{+0.06}_{-0.05}$ keV and the metallicity is $Z = 0.11 \pm 0.02 Z_{\odot}$. This is the first time that the metallicity at $r_{200}$ has been measured with high ($5.5\sigma$) statistical significance. This is possible in Virgo due to its proximity and the low ICM temperature, for which the Fe L line emission is strong. At $\sim 1$ keV, where the Fe L emission peaks, the effective area of the XMM–Newton mirrors is large and the signal-to-detector background contrast is optimal.

The strength of the Fe L signal can be seen in Fig. 5, where we show the spectra from the radius 522–580 kpc or $r \sim 0.5 r_{200}$ and for our outermost source extraction region at 1029–1198 kpc, or $r \sim r_{200}$. The solid lines on the left show the background models for the given spectra; the bottom panels show the ratio of the measured
n observed within law shape, but further out it becomes flatter, staying consistently the detected signal from near the cluster’s virial radius arises in Table 3.

Based on the deprojected values of the temperature and density, Deprojected profiles of the temperature and density were derived = ∝r^{0.12}. The last data point in the deprojected electron density profile is shown in the top panel of Fig. 6. The measured electron density approximately follows a power-law model n_e ∝ r^{-\beta} with index β = 1.21 ± 0.12.

Based on the deprojected values of the temperature and density, we also calculated the entropy (K = kT/n_e^{2/3}) and pressure (p = n_eqT) profiles. These are also shown in Fig. 6. On the entropy profile we overplot K ∝ r^{1.1}, which is expected for gravitationally collapsed gas in hydrostatic equilibrium (Tozzi & Norman 2001; Voit 2005). Out to r ~ 450 kpc, the entropy profile follows the expected power-law shape, but further out it becomes flatter, staying consistently below the expected value by a factor of 2–5. On the pressure profile, we over-plot the average profile for a sample of clusters observed within ~0.5r_200 (Arnaud et al. 2010) extrapolated to larger radii. Our measured profile shows clear departures from this average shape: a deficit is observed at ∼200 kpc, and enhancements are seen at ∼400 and ∼600 kpc. Because the Virgo Cluster is relatively relaxed, the results of the deprojection analysis, which assumes spherical symmetry, should be treated with caution. The systematic uncertainties due to the departures from spherical symmetry are significantly larger than the measurement errors.

The last data point in the deprojected electron density profile is most likely overestimated due to unaccounted emission from outside of this radius, biasing the pressure in the last radial bin high and the entropy low. A small ringing effect from this artefact will also be projected on to the next bin inwards. Such artifacts do not affect our main results on the density and entropy profiles. The observed pressure enhancement at 400 kpc coincides with a region of increased X-ray surface brightness, a possible subgroup surrounding the massive elliptical galaxy NGC4477, lying just outside of our XMM–Newton extraction region (indicated in Fig. 1). The pressure increase at 600 kpc coincides with an X-ray bright region surrounding the massive spiral galaxy M88 (see Fig. 1). Projection effects associated with the gas of these subgroups could be responsible for the observed features in the pressure profile.

The flattening of the entropy profile is robustly measured and particularly interesting. The observed entropy beyond the radius of ∼450 kpc is consistently a factor of 2–5 lower than the expected value, implying that the observed density is higher and/or the observed temperature is lower than expected.

### 3.3 Systematic errors

In order to test the robustness of our results, we fitted the data obtained by the three XMM–Newton EPIC detectors separately. The temperature results are shown in the left-hand panel of Fig. 7. While the results obtained by the MOS1 and MOS2 detectors agree remarkably well at almost all radii, the temperature values

### Table 3. Projected temperatures, metallicities, and normalizations obtained from spectral fitting. The first and the second columns give the inner and outer radii of the annular extraction regions.

| Radius (arcmin) | Temperature (keV) | Metallicity (Solar) | Normalization (1 x 10^{-3} arcmin^{-2}) |
|-----------------|------------------|---------------------|----------------------------------------|
| Inner           | Outer            |                     |                                        |
| 8.2             | 10               | 2.224±0.005         | 0.40±0.04                              | 121.39±2.2 |
| 10              | 12               | 2.326±0.045         | 0.43±0.03                              | 91.63±1.54 |
| 12              | 14               | 2.293±0.042         | 0.39±0.03                              | 74.46±1.114 |
| 14              | 16               | 2.227±0.040         | 0.37±0.03                              | 60.48±0.89 |
| 16              | 18               | 2.232±0.041         | 0.37±0.03                              | 47.68±0.72 |
| 18              | 20               | 2.314±0.047         | 0.36±0.03                              | 35.22±0.59 |
| 20              | 22               | 2.663±0.061         | 0.40±0.05                              | 22.25±0.53 |
| 22              | 25               | 2.697±0.086         | 0.29±0.04                              | 16.53±0.32 |
| 25              | 30               | 2.542±0.069         | 0.31±0.05                              | 13.43±0.3 |
| 30              | 40               | 2.105±0.083         | 0.20±0.05                              | 10.10±0.33 |
| 40              | 52               | 2.328±0.111         | 0.31±0.06                              | 7.01±0.23 |
| 52              | 61               | 2.491±0.081         | 0.35±0.05                              | 5.64±0.15 |
| 61              | 71               | 2.030±0.070         | 0.21±0.04                              | 4.46±0.13 |
| 71              | 79               | 2.413±0.093         | 0.36±0.06                              | 3.95±0.13 |
| 79              | 88               | 2.298±0.101         | 0.49±0.07                              | 3.00±0.11 |
| 88              | 96               | 1.902±0.077         | 0.30±0.04                              | 2.99±0.10 |
| 96              | 102              | 1.708±0.039         | 0.44±0.04                              | 2.46±0.09 |
| 102             | 111              | 1.585±0.055         | 0.22±0.04                              | 2.36±0.09 |
| 111             | 123              | 1.569±0.062         | 0.44±0.04                              | 2.16±0.07 |
| 123             | 156              | 1.549±0.098         | 0.14±0.02                              | 1.64±0.07 |
| 156             | 177              | 1.292±0.074         | 0.08±0.02                              | 1.47±0.07 |
| 177             | 197              | 1.081±0.020         | 0.08±0.02                              | 0.87±0.06 |
| 197             | 219              | 1.213±0.129         | 0.11±0.02                              | 1.07±0.09 |
| 219             | 255              | 1.080±0.022         | 0.11±0.02                              | 0.64±0.05 |

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Figure 4. Projected temperature and metallicity profiles. The virial radius, which we define as r200, lies at about 1.08 Mpc.
Figure 5. Examples of the analysed spectra from $\sim 0.5$ and $\sim r_{200}$. Data from all three EPIC instruments – MOS 1 (black), MOS 2 (red) and pn (green) – were fitted simultaneously. Left: data with overplotted CXFB model. Bottom part of each plot shows the ratio of the total to CXFB flux, thus indicating the amount of cluster emission. Right: spectra with overplotted best-fitting model, which includes the cluster emission.

obtained by EPIC/pn are systematically higher. The largest inconsistency between the MOS and pn detectors is in the one but last annulus (shown with dashed lines in Fig. 7). We can find no reason for this inconsistency – it appears not to be due to residual soft proton contamination or technical issues. On the grounds of their gross inconsistency with the two independent MOS detectors (which are fully consistent with each other), at this radius we have excluded the EPIC/pn data from the analysis. With the EPIC/pn data included, the best-fitting temperature in this region is $1.46 \pm 0.17$ keV.

However, we emphasize that the results are in a relatively good agreement at most radii and the general trend with the temperature decreasing at large radii is robust.

3.3.1 Cosmic X-ray fore- and background

The right-hand panel of Fig. 7 shows the radial dependence of the ratio of the ICM/CXFB fluxes in the 0.4–3.0 keV range. The ratio drops below unity beyond $\sim 800$ kpc. However, as we show in the left-hand side of Fig. 5, the signal at $\sim 1$ keV is relatively strong even in the outermost annulus.

We determine the variation of the soft foreground components within the area covered by our pointings using the images obtained in the RASS in the soft 0.1–0.3 keV (R1 + R2) band. Most of the LHB and GH foreground is emitted in this energy band. Studying the point-to-point variation in these ROSAT all-sky maps we determined a conservative upper limit of 30 per cent for the variation of the LHB and Galactic halo fluxes along our investigated region. The Galactic halo temperature was found using the ROSAT hardness ratio maps to vary by up to 20 per cent of its value. Due to the exclusion of point sources down to a faint level, the root mean square variation of the normalization of the power-law component is expected to be smaller than the statistical uncertainty with which its value has been determined in the background pointing. Thus we varied this parameter by its $3\sigma$ statistical error.

These uncertainties were used to determine the bracketing values for the temperature and normalization profiles shown in Fig. 8. The background parameters were upscaled and downscaled one at a time, leaving the others with their original values, and the model was refitted. Although at radii larger than $\sim 500$ kpc the systematic errors dominate over the statistical uncertainties, the values remain well determined and the trends in the profiles are robust.

3.3.2 Instrumental background

The uncertainty in the normalization of the instrumental background is 3–5 per cent. These uncertainties arise mainly from the Poisson error associated with the scaling factor which is used to account for
the variation of the instrumental background level with time. The scaling factors of all three detectors were simultaneously raised or lowered by $1\sigma$ to achieve a conservative estimate. The bracketing values for the temperature and normalization profiles obtained in this fashion are shown in Fig. 9. Again, the trends suggest that the results are robust.

4 DISCUSSION

We have presented the first well-constrained measurements of the ICM properties for a modestly sized, dynamically young galaxy cluster out to large radii. Here we compare our findings with the results obtained for hotter, more massive clusters, and with predictions based on numerical simulations. Finally, we discuss the implications.
4.1 The unrelaxed outskirts of a forming cluster

The surface brightness profile along the northern direction of the Virgo Cluster is unusually shallow. For $100 < r < 1200$ kpc it follows a power-law shape $S_r \propto r^{-\alpha}$ with index $\alpha = 1.34 \pm 0.01$, which is significantly smaller than $\alpha \sim 3$ for Abell 1795 (Bautz et al. 2009) or $\alpha = 3.6$ for a sample of massive luminous clusters observed with Chandra between 0.4 and 0.7$r_{200}$, (Ettori & Balestra 2009). Simulations of low-mass clusters (M_{vir} < 10^{15} M_\odot) by Roncarelli et al. (2006) predict the ratio between the surface brightnesses at $r_{200}$ and $0.3r_{200}$ to be $\sim 0.8 \times 10^{-3}$, which is more than an order of magnitude smaller than the value of 0.16 measured in Virgo. The emission in the outskirts of this young forming cluster is therefore considerably brighter than expected.

The derived density profile follows a power-law shape $n_e \propto r^{-\beta}$ with index $\beta = 1.21 \pm 0.12$. For comparison, the density profile of the Perseus cluster has $\beta = 1.68 \pm 0.04$ (Simionescu et al. 2011) and that of Abell 1795 is even steeper ($\beta = 2.27 \pm 0.07$). Simulations by Roncarelli et al. (2006) predict that the gas density in the cluster outskirts (out to $\sim 1.2 r_{200}$) can be described by a power-law model with an index $\beta = 2.4$–2.5.

We measure a $\sim 60$ per cent drop in temperature between 0.3 and 1$r_{200}$, which is consistent with previous observations of some more massive relaxed clusters with Suzaku (Reiprich et al. 2009; Bautz et al. 2009; Hoshino et al. 2010; Simionescu et al. 2011). In PKS 0745-191 the temperature drops by a factor of 4 (George et al. 2009). Simulations (Roncarelli et al. 2006) predict a drop of $\sim 40$ per cent, which is also consistent with the analytic result by Ostriker, Bode & Babul (2005).

As we show in the middle panel of Fig. 6 in Section 3.2, outside $r \sim 450$ kpc the measured entropy is consistently lower, by a factor of 2–2.5, than values expected from hydrodynamic simulations of gravitationally collapsed gas in hydrostatic equilibrium, which predict $K \propto r^{1.1}$ (Tozzi & Norman 2001; Voit 2005). Flattening entropy profiles have also been seen in PKS 0745-191 (George et al. 2009) and especially in the Perseus Cluster (Simionescu et al. 2011); however, in these hotter systems the entropy profile starts to deviate from the expected shape at larger scaled radii.

Simionescu et al. (2011) show that the break in the measured entropy profile, and a simultaneous increase in the apparent gas mass fraction above the cosmic mean in the outskirts of the Perseus Cluster, are most likely caused by clumping in the ICM. The quantity that we infer from the observed deprojected emission measure is the average of the square of the electron density ($n_e^2$), not the average of the electron density squared ($n_e$). Therefore, if the gas is clumpy, its non-uniform density will lead to an overestimate of the average electron density calculated from the emission measure. If the dense clumps are in pressure equilibrium with the surrounding gas, then they will be cooler than the ambient medium. However, it is more likely that they will be falling into the cluster, moving through the ICM and therefore partly confined by ram-pressure. Depending on the ratio of ram-pressure to thermal pressure support of the clumps, the average temperature in the multiphase regions will be underestimated because denser and cooler blobs have larger volume emissivity. Therefore, increasing clumping as a function of radius will result in a flattening of the observed surface brightness and density profiles and a steepening of the observed temperature profile. The over-estimated density and underestimated temperature at large radii will then combine into a flattening of the entropy profile, as observed.

In order to test further whether clumping can be responsible for the observed features in our profiles, we simulated an XMM–Newton spectrum of a two phase ICM, where both phases have a metallicity of $Z = 0.3 Z_\odot$. A hotter 2 keV component is used to represent the ambient ICM and a 1 keV phase represents the clumps of cooler plasma. The emission measures were adjusted so that, assuming thermal pressure equilibrium, the cooler clumps will have a volume filling fraction of $f = 0.2$ (additional ram-pressure support will make the volume filling fraction of the clumps smaller). The simulated spectrum contains all the observed background components in the Virgo Cluster and has a similar statistical quality to our observed spectra from large radii. When fitting this spectrum with a single temperature thermal model we obtain a good fit, with a temperature of $kT = 1.24$ keV and a metallicity of $Z = 0.16 Z_\odot$, underestimating the true metallicity by about a factor of 2. We also overestimate the density of the ICM by a factor of 1.6. The entropy inferred from this fit is about 2.2 times lower than the true entropy of the ICM, indicating that such multiphase medium could indeed be responsible for the flattening entropy profile. The presence of cooler, denser blobs also explains the abrupt decrease of the temperature and observed metallicity beyond 450 kpc, where the entropy starts to deviate from the expected power-law shape.

Clumping therefore appears to provide a natural explanation for the properties of the observed density, temperature, entropy, pressure and metallicity profiles in the Virgo Cluster. We note that the real ICM is, however, probably multiphase with different clumps having slightly different temperatures and the clumps being partly ram-pressure confined.

While X-ray observations provide the measurement of $\langle n_e^2 \rangle$, SZ observations depend linearly on $n$. Therefore, in regions with clumped ICM, we expect to see a discrepancy between the X-ray and the SZ signals. If there is no bias in measuring the temperature (e.g. the clumps are completely ram-pressure supported and have the same temperature as the ambient plasma) then this difference will provide an independent measurement of the clumping factor. Temperature biases arising from the multiphase structure of the ICM may complicate the interpretation.
4.2 Metals at large radii

We present a metallicity profile spanning from the cool core region all the way out to \( r_{200} \). Our metallicity measurement is dominated by the line emission of the Fe L complex and therefore primarily represents the Fe abundance. Our data provide direct observational evidence that the ICM is enriched by metals all the way to \( r_{200} \). In the range of \( \sim 0.5 - 1 \, r_{200} \), the observed metallicity profile is consistent with being flat at a value of \( Z = 0.1 \, Z_\odot \). Previously, the ICM metallicity at large radii has been obtained by Fujita et al. (2008) from a large region spanning \( 0.5 - 1 \, r_{200} \) in the compressed area between the clusters Abell 399/401 at the onset of a merger. They found that the ICM at large radii has been enriched to \( Z \sim 0.3 \, Z_\odot \) (with respect to the solar abundances of Grevesse & Sauval 1998). More recently, Simionescu et al. (2011) showed that the outskirts of the Perseus Cluster have also been enriched to a similar metallicity of \( Z \sim 0.3 \, Z_\odot \).

The gas within our analysed region is, however, most probably multiphase, consisting of multiple temperature components. It has been shown that the metallicity is often sensitive to the modelling of the underlying temperature structure and, if multitemperature plasma is modelled with a single-temperature spectral model, the metallicity of gas can be significantly underestimated (e.g. Buote 2000, see also our simulation in Section 4.1). This is especially true around the temperature of 1 keV, where the Fe L complex is very sensitive to the underlying temperature structure. Our measured metallicity could thus be an underestimate of the true metallicity and should be considered a lower limit.

Nevertheless, using the best-fitting metallicity values and assuming that both the gas density and the metal distribution are homogeneous, we calculate the cumulative Fe mass of the Virgo cluster. The total Fe mass obtained this way is \( \sim 4 \times 10^9 \, M_\odot \) within \( 0.1 - 1 \, r_{200} \), approximately half of which resides outside of \( 0.5 \, r_{200} \). Because the metallicity is likely biased low and neither the gas density nor the distribution of metals is likely to be homogeneous, this metal mass is almost certainly an underestimate. We conclude that the total mass of Fe beyond \( 0.5 \, r_{200} \) is at least \( 2 \times 10^9 \, M_\odot \).

The two dominant mechanisms by which metals pollute the ICM are galactic winds and ram-pressure stripping. Galactic winds, driven by the thermal energy of a large number of supernova explosions (e.g. Heckman 2003), are expected to dominate the enrichment of the intergalactic medium at redshifts of \( z = 2 - 3 \), when the bulk of the star formation happened. Part of this pre-enriched intergalactic medium subsequently fell into the gravitational potential of clusters where it got shock heated and today constitutes the ICM.

Fujita et al. (2008) interpret the high metallicity in the outskirts of Abell 399/401 as evidence for early enrichment by galactic superwinds. They argue that in order to exceed the pressure of \( \sim 2 \times 10^{-12} \, \text{Pa} \) necessary to start stripping the galaxies (Fujita & Nagashima 1999) their velocities would have to exceed \( \sim 2000 \, \text{km s}^{-1} \). Following this argument, the relative velocities between the galaxies of the Virgo Cluster and the ICM would have to exceed the unrealistically high value of \( \sim 3000 \, \text{km s}^{-1} \). However, H\,\alpha imaging surveys have revealed several galaxies falling into the Virgo Cluster that display long H\,\alpha tails at projected radii of 0.6–1.2 Mpc from the centre of the cluster (e.g. Kenney, van Gorkom & Vollmer 2004; Chung et al. 2007; Kantharia, Rao & Sirothia 2008). There are furthermore several examples which suggest that stripping also operates in lower density, lower velocity dispersion environments of poor clusters and groups of galaxies (Kantharia et al. 2005; Levy et al. 2007). Recent simulations (e.g. Roediger & Brüggen 2007, 2008) show that galaxies can get stripped already at large radii with low ICM densities due to continuous or turbulent/viscous stripping (see Nulsen 1982). In principle, all the metals outside \( 0.5 \, r_{200} \) could be supplied by the complete stripping of \( \sim 150 \) galaxies, assuming \( 10^{10} \, M_\odot \) of stripped gas, enriched to the solar metallicity, per average galaxy. Stripping would, however, produce a radially decreasing metallicity profile at the large radii, while the observed profiles in both Virgo and Perseus are consistent with being flat.

The outskirts of Virgo have three times lower apparent metallicity than the outskirts of the Perseus Cluster and the compressed region between the clusters Abell 399 and Abell 401. A similar ultralow metallicity of \( Z = 0.15 \, Z_\odot \) has only been measured in the group of galaxies NGC 5044 at radii 0.2–0.4 \( r_{vir} \) (Buote & Lewis 2004). Given that the stellar over ICM baryon fraction of clusters is decreasing with the increasing cluster mass (e.g. Gonzalez, Zaritsky & Zabludoff 2007) explaining the higher metal content of the more massive clusters would be challenging. However, this difference may be primarily due to the multiphase gas biasing the Fe abundance low in cooler systems more strongly than in hotter systems.

While the metallicity of Virgo at large radii has been determined based on the Fe L lines, the metallicities of hotter clusters, \( kT > 3.5 \, \text{keV} \), are determined based on their Fe K lines. The metallicity of the hotter ICM could be biased both towards higher and lower values, depending on the temperature structure. The bias is however much smaller than in the cooler systems, only of the order of up to \( \sim 30 \) per cent (e.g. Rasia et al. 2008; Simionescu et al. 2009; Gastaldello et al. 2010).

5 CONCLUSIONS

We present the results of the analysis of a mosaic of XMM–Newton observations of the modestly sized, dynamically young Virgo Cluster from the centre to the north out to \( \sim 1.2 \, \text{Mpc} \). We detect X-ray emission all the way out to this radius, which allows us to study the ICM properties in unprecedented detail. The surface brightness and density profiles are significantly shallower than predicted by simulations and measured in other more massive systems. The temperature is measured to drop by \( \sim 60 \) per cent between 0.3and1 \( r_{vir} \). Beyond the radius of \( \sim 450 \, \text{kpc} \) the temperature and metallicity drop abruptly and the entropy profile deviates from the power-law shape \( k \propto r^{-1.1} \) expected for gravitationally collapsed gas in hydrostatic equilibrium (Tozzi & Norman 2001; Voit 2005). At these radii, the entropy is consistently lower than expected by a factor of 2–2.5.

The most likely explanation for the unusually shallow density profile, the flattening of the entropy profile, and sharp drops in temperature and metallicity at \( r > 450 \, \text{kpc} \) is the onset of significant gas clumping, which then increases as a function of radius. The clumping in the Virgo Cluster becomes significant at smaller scaled radii than has been detected in the more massive Perseus Cluster (Simionescu et al. 2011).

Our data provide direct observational evidence that the ICM is significantly enriched with metals all the way to \( r_{200} \). The measured metallicity profile flattens out in the cluster outskirts and reaches \( Z = 0.11 \pm 0.02 \, Z_\odot \) at \( r_{200} \). The metallicity at large radii is, however, likely underestimated significantly because of the clumping and therefore this measured value should be considered a lower limit.

The Virgo Cluster, being the closest galaxy cluster to us, provides a unique opportunity to study large-scale structure formation in detail as it happens. The similarities and differences between the results for the Virgo Cluster presented here and for the Perseus Cluster discussed by Simionescu et al. (2011) point to a wealth of interesting physics at large radii of clusters that is just beginning.
to be probed. Understanding this physics presents an exciting challenge for numerical simulations.

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