AGN feedback and iron enrichment in the powerful radio galaxy, 4C+55.16

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ABSTRACT

We present a detailed X-ray analysis of 4C+55.16, an unusual and interesting radio galaxy, located at the centre of a cool core cluster of galaxies. 4C+55.16 is X-ray bright ($L_X^{\text{cluster}} \sim 10^{45}$ erg s$^{-1}$), radio powerful, and shows clear signs of interaction with the surrounding intracluster medium. By combining deep Chandra (100 ks) with 1.4 GHz VLA observations, we find evidence of multiple outbursts from the central AGN, providing enough energy to offset cooling of the ICM ($P_{\text{bubbles}} = 6.7 \times 10^{44}$ erg s$^{-1}$).

Furthermore, 4C+55.16 has an unusual intracluster iron distribution showing a plume-like feature rich in Fe L emission that runs along one of the X-ray cavities. The excess of iron associated with the plume is around $10^7 M_\odot$. The metal abundances are consistent with being Solar-like, indicating that both SNIa and SNII contribute to the enrichment. The plume and southern cavity form a region of cool metal-rich gas, and at the edge of this region, there is a clear discontinuity in temperature (from $kT \sim 2.5$ keV to $kT \sim 5.0$ keV), metallicity (from $\sim 0.4 Z_\odot$ to $\sim 0.8 Z_\odot$), and surface brightness distribution, consistent with it being caused by a cold front. However, we also suggest that this discontinuity could be caused by cool metal-rich gas being uplifted from the central AGN along one of its X-ray cavities.

Key words: Galaxies: clusters: individual: 4C+55.16 - X-rays: galaxies: clusters - cooling flows - galaxies: jets - radio continuum: galaxies

1 INTRODUCTION

AGN feedback plays a major role in quenching star formation, enriching the surrounding medium with metals, and fuelling the supermassive black hole (SMBH) of the host galaxy. Major advancements in understanding the details of how AGN feedback operates have been possible through detailed studies of X-ray cavities (see a review on the topic by McNamara & Nulsen 2007; Peterson & Fabian 2006). The SMBH lying at the centre inflects these cavities, also known as bubbles, through jets of relativistic plasma. Bubbles therefore provide a direct measurement of the energy being injected by the SMBH into the surrounding medium.

In cool core clusters of galaxies, the active galactic nuclei (AGN) lying at the centre can energetically offset cooling of the intracluster medium by inflating these large cavities correlated with radio lobes, inducing weak shocks and propagating energy through sound/pressure waves (Birzan et al. 2004; Rafferty et al. 2006; Dunn & Fabian 2008; McNamara & Nulsen 2002; Fabian et al. 2003, 2004; Forman et al. 2003; Sanders & Fabian 2007).

This paper aims to study the AGN feedback processes arising in 4C+55.16, an unusual and interesting radio galaxy, located at the centre of a cool core cluster of galaxies at a redshift of $z = 0.2412$ (Pearson & Readhead 1981; 1983; Whyborn et al. 1983; Hutchings et al. 1988; Schneider et al. 2002). 4C+55.16 is X-ray bright ($L_X \sim 10^{45}$ erg s$^{-1}$), radio powerful ($L_R = 8 Jy$ beam$^{-1}$ at 1.4GHz), and shows clear signs of interaction between its central galaxy and the intracluster medium (ICM) (see Whyborn et al. 1985; Iwasawa et al. 1999, 2001), providing an interesting case for studying AGN feedback in clusters of galaxies.

Furthermore, 4C+55.16 has an unusual intracluster iron distribution. Using a 10 ks Chandra exposure, Iwasawa et al. (2001) found that there was a large increase in metallicity at a radius of about 10 arcsec ($\sim 40$ kpc), that went from half solar to twice solar. The authors suggested that this increase was due to a plume-like structure located in the south-west side of the cluster, which had a strong Fe L emission feature. The reason as to how so much iron could be accumulated remained unclear. Here, we use significantly deeper Chandra observations of the source (100 ks) to study the abundance, and its distribution. By combining the Chandra observa-
tions with VLA radio data, we make a detailed study of the X-ray cavities of the source.

Section 2 presents the details of the data reduction. In Section 3 and Section 4, the techniques and results concerning the imaging and spectral analysis are respectively shown. Finally, we discuss the results in Section 5 and present the conclusions in Section 6. We adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ throughout this paper, and all error estimates are on the 1$\sigma$ level. The redshift of the source corresponds to a scale of 3.807 kpc arcsec$^{-1}$.

2 DATA REDUCTION

2.1 Chandra - X-ray

4C+55.16 was originally observed with Chandra on 2000 October 10 for 10 ks (ObsID 1645) with the Chandra CCD Imaging Spectrometer (ACIS) in FAINT mode, such that the cluster was centred on the ACIS-S3 back-illuminated chip. It was subsequently observed on 2004 January 3 for 100 ks (ObsID 4940) in VFAINT mode, significantly improving the image quality, and was centred on the ACIS-S3 back-illuminated chip, with the ACIS-S1, ACIS-S2, ACIS-I2 and ACIS-I3 also switched on.

Both ObsID were processed, cleaned and calibrated using the latest version of the CIAO software (CIAO v4.3, CALDB 4.4.1), and starting from the level 1 event file. We applied both CTI (charge time interval) and time-dependent gain corrections, as well as removed flares using the other back-illuminated chip (ACIS-S1) and the LC_CLEAN script, with a 3$\sigma$ threshold.

For ObsID 4940, some strong background flares were seen towards the end of the exposure, and were removed. This resulted in a final exposure time of 73.6 ks. We then exposure-corrected the image, using an exposure map generated with a monoenergetic distribution of source photons at 1.5 keV (which is almost the peak energy of 4C+55.16). The exposure-corrected 0.5 – 7 keV Chandra image of 4C+55.16, spatially smoothed with a 1″ gaussian function and covering $\sim 500 \times 500$ kpc (or $130 \times 130″$). Shown in this image are the inner cavities, which are filled with 1.4 GHz radio emitting particles, the other possible cavity (with no GHz radio emission), the outer and inner edge as seen in the X-ray, and the plume-like structure associated with the abundance increase. Right - Hubble Legacy Archive image of the cluster (Edge 2000).

Spectra were analysed using XSPEC (v12.6.0df, e.g. Arnaud 1996). The Galactic absorptions throughout this paper were kept frozen at the Kalberla et al. (2005) value, $4.29 \times 10^{20}$ cm$^{-2}$ ($\log(N_H) = 20.63$). Letting the absorption free to vary for the spectrum of the entire cluster did not improve significantly the fit. We also used the abundances of Anders & Grevesse (1989) throughout this paper.

2.2 VLA - Radio

There exists a short exposure ($\sim 6$ mins) of published VLA observations at 1.4 GHz and bandwidth of 50 MHz in configuration A (Xu et al. 1995). This configuration is needed in using the VLA to produce maps with similar spatial resolution to Chandra. We retrieved the data from the NRAO archive and reduced it in AIPS (ASTRONOMICAL IMAGE PROCESSING SYSTEM) using the standard procedures. We used 3C286 as a flux calibrator, and the DIFMAP software to clean and self-calibrate the data (Shepherd et al. 1994).

The VLA observations reveal a strong core and twin lobes. The shorter of the two lobes points to the north-west, while the longer lobe is oriented almost directly to the south. 4C+55.16 has been imaged with VLBI (Polatidis et al. 1995; Xu et al. 1995) and shows a core and one-sided jet pointing to the north-west.
3 IMAGING ANALYSIS

We use the deep Chandra observations (100 ks) to analyse the physical state of the hot ICM, unless otherwise. Combining this data set with the 10 ks observations would not have improved significantly the signal-to-noise.

In Fig. 1 (right), we show the Hubble Legacy Archive image of the cluster (Edge 2000), and in Fig. 2 we show in same-scale images, the optical image taken from the Hubble Legacy Archive, the Chandra X-ray and unsharp-masked images, as well as the 1.4 GHz VLA radio contours of the central regions of the cluster. The Chandra image was obtained after applying the CIAO sub-pixel scripts in order to obtain images with the best resolution possible. The unsharp-masked image was obtained by subtracting a strongly 2D gaussian smoothed image (σ = 10 pixels or σ = 4.9″) from a less smoothed image (σ = 2 pixels), and reveals deviations in the original Chandra image. At least two X-ray cavities are seen: one to the south, and one to the north-west of the central point source. However, there seems to be another cavity to the west of the cluster.

In the optical, we can see the central galaxy surrounded by a diffuse envelope, along with a bright point source that coincides with the X-ray and radio point sources. We also see a small jet in the optical, where the axis of the jet is aligned with the radio filled X-ray cavities. There could be a counterpart of the jet in the X-rays, but the resolution is not good enough to resolve it (even with the CIAO sub-pixel scripts that give the best resolution for Chandra, see middle panel of Fig. 2).

To further enhance the surface brightness fluctuations in the X-ray image, at each point, we subtract from the X-ray image the average value within an ellipse centred on the X-ray point source. We used an ellipse rather than a circle, since the surface brightness contours better follow this shape. Using the surface brightness contours, we determine the average ratio between the major (a) and minor (b) axis of the ellipses, as well as the average rotated angle of the ellipses with respect to the north (θ) counter-clockwise. We find a/b ~ 1.6 and θ ~ 35°. Using these values, at each point, we subtract from the Chandra image the average value within an ellipse centred on the X-ray point source.
point in the X-ray image, we build an ellipse passing through the point and centred on the central X-ray point source, and then subtract the average value within the ellipse and calculate the fractional difference. We then smooth the image with a 2D gaussian function of $\sigma = 2$ pixels. This gives the image shown in Fig. 3. Initially, we remove all point sources, except for the one associated with the central galaxy. To do this, we identify them with the CIAO program WAVDETECT, and replace them with the average value of a surrounding background.

Fig. 3 shows interesting structures, including bright rims surrounding the southern cavity, and a tail of enhanced material starting out from the southern cavity and plume-like feature, and making its way from east to north.

As shown in the unsharp-masked image of Fig. 1 (right), there are at least two X-ray cavities (one to the south, and one to the north-west). However, if the potential cavity to the west is real, we should see a disturbance in the surface brightness distribution. In the top panel of Fig. 4 we show different regions we selected along each of the cavities. For each region, we determined the average count-rate pixel$^{-2}$, and then plotted its distribution for each cavity as a function of radius in the lower panel of Fig. 4. This figure shows decrements in X-ray emission for each of the cavities, although it is quite difficult to tell for the north-western cavity. This cavity is however filled with radio emission, and we therefore still consider it as a cavity.

4 SPECTRAL ANALYSIS

4.1 Central AGN

Using the deep Chandra observations, we first examine the nucleus of 4C+55.16. Fig. 2 shows a bright X-ray point source located at the centre of the cluster, which coincides with the radio point source and optical point source of the central galaxy. Although the X-ray point source is bright and point-like, we estimate that there is no significant pileup. Pileup occurs when two or more photons are detected as one event (see for more details Davis 2001; Russell et al. 2010). The significance of pileup can be examined by comparing the amount of good grades (grades 0,2,3,4,6) to the bad grades (grades 1,5,7) for our point-like nucleus. We find the ratio of bad/good to be $\sim 0.03$. Typically, pileup starts becoming problematic when the fraction of bad grades exceeds 10 per cent of the good grades.

To estimate the nuclear luminosity, we analyse the 0.5 – 7 keV spectrum of the inner $r = 1''$ region, centred on the central point source. We use a surrounding annulus ($r = 2 - 3''$) as a background, and bin the spectra with a minimum of 30 counts per bin. We fit an absorbed power-law model to the background-subtracted spectrum, and include ISM absorption to account for Galactic absorption. Initially, we only consider Galactic absorption and keep it frozen to the Kalberla et al. (2005) value. We use $\chi^2$-statistics to find the best fitting model, and let the photon index and normalisation free to vary. We find a photon index of $\Gamma = 1.55 \pm 0.17$, and a reduced $\chi^2$ of 1.3. Using the XSPEC model in XSPEC, we obtain a flux estimate for the nucleus corrected for absorption, and then convert it into a luminosity using the luminosity distance. We find a 2 – 10 keV unabsorbed luminosity for the nucleus of $(1.1 \pm 0.2) \times 10^{43}$ erg s$^{-1}$, and that the value does not depend significantly on the photon index to within $\pm 0.3$. There is also no evidence suggesting that the nuclear luminosity has changed within the 3 year difference separating the observing dates of the 100ks and 10ks data.

If the Galactic absorption is also free to vary, we find that the model is no longer well constrained, and the estimated value for the absorption is not consistent with the values predicted by Kalberla et al. (2005). Adding an additional absorption at the redshift of the source does not improve the fit, and converges towards a null value for the additional absorption. We also fit a single-temperature MEKAL (Mewe et al. 1993) model to the nuclear spectrum, and find a reduced $\chi^2$ of 1.5. The parameters are not well constrained and the estimated temperature ($kT = 10^{0.70}$ keV) is quite large compared to the surrounding gas.

If the X-ray surface brightness profile of the cluster scaled with radius as a power-law, then it would predict...
The cluster around 4C+55.16

4.2 Temperature and abundance maps

To study the temperature and abundance distribution across the cluster, we bin different regions together using a Contour Binning algorithm which follows the surface brightness variations (see Sanders 2006). This technique is better suited to analyse the temperature and abundance variations along radial structures, as opposed to azimuthal structures.

We begin by analysing the large scale structures within 900×900 kpc. We bin the regions so that they have a signal-to-noise ratio of 50 (2500 counts), and restrict the lengths to be at most twice the widths. We extract a 0.5 – 7 keV spectrum for each region, and use a region further away, but still within the chip, as a background. We then fit an absorbed MEKAL model to the data, and use C-statistics. We let the temperature, absorption and normalisation parameters free to vary. The resulting temperature and metallicity maps are shown in Fig. 5. For the temperature, the errors on each value vary from ~ 6 per cent in the inner regions to ~ 30 per cent in the outer regions, and for the abundance they vary from ~ 20 per cent (inner) to ~ 40 per cent (outer).

The large-scale temperature map shows some structure, especially a temperature jump between the cluster core (inner ~ 50 kpc) and surrounding gas on the southern side. The metallicity map also shows some structure. To the north-east, we see a first metal rich region (1Z⊙) located at about 100 kpc, and then a second (0.6Z⊙) at about 160 kpc. Further away (r > 200 kpc), it seems that the north-east side is more metal poor than the south-western side.

Next, we analyse the inner regions of the cluster, within 190×190 kpc. We bin the regions so that they have a signal-to-noise ratio of 30 (900 counts), and also use C-statistics. The resulting temperature and abundance maps are shown in Fig. 6. Here, the errors on each value vary from ~ 9 per cent in the inner regions to ~ 20 per cent in the outer regions for the temperature, and from ~ 30 per cent (inner) to ~ 60 per cent (outer) for the abundance.

The temperature map now reveals more clearly the temperature jump seen between the core and surrounding region just below the southern cavity and plume-like feature. The temperature jumps by a factor of two, from colder to warmer, and is similar to those seen in cold fronts. In the temperature map, we see a second jump in temperature to the west of the cluster at about r ~ 120 kpc. This time, the temperature jumps from a colder (kT ~ 4 keV) to warmer region (kT ~ 8 keV) (see also Section 4.3.2). The metallicity map also clearly reveals that the plume-like feature (located to the south-west at r ~ 1 – 10′′) is metal rich when compared to a region within the same radius but excluding the plume (see also Section 4.3.4).

4.3 Spectral profiles

4.3.1 Previous Chandra observations (10ks)

Using the 10 ks Chandra observations, [Iwasawa et al. 2001] found that there was a large increase in metallicity at a radius of about 10 arcsec (~ 40 kpc), that went from half solar to twice solar, which they associated with the plume-like feature.

In order to confirm this increase in metallicity, we reduce the 10ks observations using the latest Chandra reduc-
sorption (4 value derived by Kalberla et al. (2005) for the Galactic ab-

tion scripts. We then proceed to analyse the data in the same way as in Iwasawa et al. (2001), but choose to use the value derived by Kalberla et al. (2003) for the Galactic absorption (4.29 × 10^{20} cm^{-2}) instead of the one derived by Dickey & Lockman (1990, 4.20 × 10^{20} cm^{-2}). Since these values are almost the same, we do not expect our results to vary significantly based on this choice of parameter.

Iwasawa et al. (2001) argued that the redshift inferred from optical spectroscopy was not consistent with the one inferred by the Fe K line. From their analysis of the Fe K line, they derived a redshift of $z = 0.254_{-0.009}^{+0.010}$. However, our spectra indicates otherwise. Using the deep 100 ks data, we extract a 0.5 – 7 keV spectrum within a radius of $r = 1 – 9''$, since this region is known to contain a strong Fe K line (see also Fig. 8). We then fit an absorbed MEKAL model to the spectrum, and let the redshift, temperature, abundance and normalisation parameter free to vary. We use $\chi^2$ statistics, and find a redshift of $z = 0.235 \pm 0.007$, consistent with the value inferred by optical spectroscopy, and therefore choose to use the optically derived redshift ($z = 0.2412$) throughout this paper.

We now proceed to take spectra from seven annuli, following the spectral profiles extracted in Iwasawa et al. (2001) ($r = 1 – 2.5, 2.5 – 5, 5 – 9, 9 – 15, 15 – 25, 25 – 40, 40 – 60''$). These annuli exclude the nucleus. We then fit an absorbed MEKAL model to each spectrum, and derive the temperature, abundance and normalisation parameter using $\chi^2$ statistics. The results are shown in the left panels of Fig. 7. We do the same using the deep Chandra 100 ks observations. We fit an absorbed MEKAL model to each spectrum, and derive a best fitting value of $kT = 2.93 \pm 0.11$ keV and $Z = 0.74 \pm 0.12$ solar. When analysing this region, Iwasawa et al. (2001) found using the 10 ks observations that $kT = 3.34 \pm 0.35$ keV and $Z = 1.93_{-0.62}^{+0.87}$ solar. In Fig. 8, we plot our spectrum, as derived from the 100 ks observations. Overlaid on top, we plot our best fitting model (black curve), and a model where we kept $kT$ and $Z$ frozen to the values derived by Iwasawa et al. (2001), and only allowed the normalisation parameter free to vary. As shown in the figure, the parameters derived by Iwasawa et al. (2001) seem to overestimate the strength of the Fe K line, and also underestimate the soft energy part of the spectrum. We suspect the latter may be caused by the new calibration for the absorption model of the detector (see for more details Marshall et al. 2004), which now better corrects for the ACIS Chandra contaminant at soft energies. Hence, it is possible that the earlier reduction scripts over corrected the spectrum at soft X-rays, and allowed the fit to converge toward higher abundances.

As shown in Fig. 7, the 100 ks observations give much tighter constraints on the temperature and abundance profiles, and most importantly they do not show the abundance increase seen in the 10 ks observations. The abundance increase we derive from the 10 ks observations is also not the same as in Iwasawa et al. (2001), who found an increase that went from half solar to twice solar. We only find an increase form half solar to one solar. However, when analysing in more detail the 10 ks observations, we first notice that the model is not very sensitive to the abundance. Even if we freeze the abundance to four times solar, it only increases the $\chi^2$ from 40.15 to 42.19. The abundance increase we see from the 10 ks observations should therefore be taken lightly.

Secondly, we analyse the region between $r = 1 – 9''$, as did Iwasawa et al. (2001), but using the deep 100 ks observations. We fit an absorbed MEKAL model to the spectrum, and derive a best fitting value of $kT = 3.08 \pm 0.11$ keV and $Z = 0.73 \pm 0.12$ solar. When analysing this region, Iwasawa et al. (2001) found using the 10 ks observations that $kT = 3.34 \pm 0.35$ keV and $Z = 1.93_{-0.62}^{+0.87}$ solar. In Fig. 8, we plot our spectrum, as derived from the 100 ks observations. Overlaid on top, we plot our best fitting model (black curve), and a model where we kept $kT$ and $Z$ frozen to the values derived by Iwasawa et al. (2001), and only allowed the normalisation parameter free to vary. As shown in the figure, the parameters derived by Iwasawa et al. (2001) seem to overestimate the strength of the Fe K line, and also underestimate the soft energy part of the spectrum. We suspect the latter may be caused by the new calibration for the absorption model of the detector (see for more details Marshall et al. 2004), which now better corrects for the ACIS Chandra contaminant at soft energies. Hence, it is possible that the earlier reduction scripts over corrected the spectrum at soft X-rays, and allowed the fit to converge toward higher abundances.

4.3.2 Deep Chandra observations (100ks)

We now proceed to do a more in depth analysis of the 100 ks observations. The regions selected by Iwasawa et al. (2001) each had a different number of counts, ranging from ~ 2000 to ~ 8000. As the number of counts is not very large, we use a bigger number of counts in order to get a better signal-to-noise ratio. As shown in Fig. 4, the 100 ks observations give much tighter constraints on the temperature and abundance profiles, and most importantly they do not show the abundance increase seen in the 10 ks observations. The abundance increase we derive from the 10 ks observations is also not the same as in Iwasawa et al. (2001), who found an increase that went from half solar to twice solar. We only find an increase form half solar to one solar. However, when analysing in more detail the 10 ks observations, we first notice that the model is not very sensitive to the abundance. Even if we freeze the abundance to four times solar, it only increases the $\chi^2$ from 40.15 to 42.19. The abundance increase we see from the 10 ks observations should therefore be taken lightly.

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Figure 7. Temperature (top) and metallicity (bottom) profiles for the regions as selected in Iwasawa et al. (2001) (r = 1 − 2.5, 2.5 − 5.5 − 9.9 − 15, 15 − 25, 25 − 40, 40 − 60′′). The left panels show the results for the 10 ks observations, reduced using the latest Chandra calibrations, and those on the right show the results derived from the 100 ks observations (projected and deprojected). The deeper data do not show the increase in metallicity seen in the 10 ks observations and reported in Iwasawa et al. (2001).

Figure 8. Spectrum of the central r = 1 − 9′′ region (excluding the nucleus). The black curve shows the best-fitting model obtained for an absorbed (Galactic) MEKAL model (kT = 2.93 ± 0.11 keV, Z = 0.74 ± 0.12 solar). The red curve shows the best-fitting model while keeping the temperature and abundance frozen to the values found by Iwasawa et al. (2001) for the same region (kT = 3.34 ± 0.35 keV, Z = 1.93 ± 0.62 solar).

Figure 9. Projected (filled symbols) and deprojected (non-filled symbols) temperature and metallicity profiles, as well as deprojected electron density, electron pressure and entropy profiles of the cluster, as derived by selecting annuli with a minimal signal-to-noise ratio of 63 (∼ 4000 counts).

Counts to ∼ 10000 counts. Instead, we choose to select regions containing roughly the same signal-to-noise (S/N ∼ 63 or ∼ 4000 counts), and push the analysis to larger radii. We selected a background region within the same chip (ACIS-S3) but far from the cluster. The net count rate per pixel of the selected background region is also the same as the count rate per pixel of the ACIS-S1 chip (which is also back-illuminated), and should therefore not contain much cluster emission.

The projected and deprojected temperature and metal-
Figure 10. Projected temperature profiles along the southern cavity (red) and plume-like feature (black), derived using a single MEKAL model, as well as electron density, electron pressure and entropy profiles ($S = kT n_e^{2/3}$) as a function of radius are shown in Fig. 10. For each spectrum, we fitted an absorbed MEKAL model, and used $\chi^2$ statistics. Although we include in Fig. 10 the deprojected results, we found that they were consistent with the projected ones to within 1$\sigma$ error estimates. Two-temperature models were also not needed, as they did not improve the fit.

Fig. 9 shows interesting features at $r > 100$ kpc. The temperature structure remains constant at large radii, at least within the error measurements, while the metallicity structure on average decreases with radius (from $Z \sim 0.75$ solar to $Z \sim 0.2$ solar).

There seems to be a slight increase in metallicity at $r \sim 160$ kpc. This could be due to the same feature noticed earlier while analysing the large-scale metallicity map (see bottom panel of Fig. 5), which showed a slight increase at a similar radius on the north-eastern side of the cluster. However, the increase in metallicity is well within the 1$\sigma$ uncertainties, and therefore does not appear to be statistically significant. If we compare the spectra of the different radial intervals with one another, we find no significant change in the iron line complexes.

However, there appears to be an increase in temperature at $r \sim 130$ kpc (Fig. 9), accompanied by a break in electron density, electron pressure and entropy, to more than a 1$\sigma$ level. This could be associated with the warmer region noticed earlier in the temperature map of the inner regions (Fig. 6), where we could see a jump in temperature from colder ($kT \sim 4$ keV) to warmer ($kT \sim 8$ keV).

4.3.3 southern X-ray cavity

We now concentrate on the spectral analysis along the southern cavity. Clear bright rims can be seen surrounding this cavity, and could indicate the presence of a shock front (see Fig. 3). Using regions along the southern cavity, we extract a spectrum, and fit an absorbed MEKAL model to each region. The absorption is again taken as the purely Galactic. The resulting temperature profile is shown in Fig. 10. This figure shows that there is a temperature jump associated with the edge of the cavity at $r \sim 40$ kpc, but it does not indicate a shock front. Instead it shows a temperature jump going from a cooler to warmer region (from $kT \sim 2.8$ keV to $kT \sim 5.0$ keV), i.e. it could be a cold front. In Section 5.2, we discuss in greater detail this front.

4.3.4 Plume-like feature

According to the middle panel of Fig. 6, there is an increase in metallicity associated with the plume-like feature. We can also see from the left panel of Fig. 6 that there is an increase of temperature associated with the edge of the plume-like feature. To be more precise, in Fig. 10 we plot the temperature profile, electron density and pressure, as well as the count rate per pixel$^2$ (equivalent to the surface brightness distribution) as derived by selecting regions along the plume-like feature. However, we derive a count rate per pixel$^2$ for every arcsec in order to better trace the potential disturbances in the surface brightness profile. This figure shows a temperature jump at a radius similar to the one associated with the southern cavity ($r \sim 40$ kpc). We associate
If we test the vmekal model using the enrichment pattern by SNII, following the abundance ratios given by Dupke & Arnaud (2001), we find $kT = 2.99 \pm 0.11$ keV, $Z_{Fe} = 0.47 \pm 0.07$ solar and a reduced $\chi^2$ statistic of 1.37 (same number of degrees of freedom). On the other hand, using the enrichment pattern by SNII, also following the abundance ratios given by Dupke & Arnaud (2001), we find $kT = 2.90 \pm 0.14$ keV, $Z_{Fe} = 0.25 \pm 0.06$ solar and a reduced $\chi^2$ statistic of 2.02. Hence, the enrichment pattern by SNII provides a much better fit, but not quite as much as the Solar photosphere enrichment pattern. We discuss these results in Section 5.3.

5 DISCUSSION

5.1 X-ray cavities

There are at least two, and possibly three, X-ray cavities associated with the central AGN. The energy stored within each of the cavities can be estimated using Eq. (1) (e.g. Birzan et al. 2004; Dunn et al. 2008; Rafferty et al. 2004; Dunn & Fabian 2006, 2008). Here, $P$ is the thermal pressure of the ICM at the radius of the bubble and estimated from the X-ray data, $V$ is the volume of the cavity and for a relativistic fluid $\gamma_1 = 4/3$, therefore $E_{bubble} = 4PV$ (this is also supported observationally, see Graham et al. 2008).

$$E_{bubble} = \frac{\gamma_1}{\gamma_1 - 1} PV$$

We assume that the cavities are of ellipsoidal shape. The volume is then given by $V = 4\pi R_w^2 R_l / 3$, where $R_l$ is the semi-major axis along the direction of the jet, and $R_w$ is the semi-major axis perpendicular to the direction of the jet.

The power injected into the medium is determined by dividing the energy of the bubble with its age. The latter is given by the buoyant rise time, the refill time or the sound crossing time. See respectively Eq. (2) (Churazov et al. 2001), Eq. (3) (McNamara et al. 2008) and Eq. (4) (McNamara & Nulsen 2007). Here, $R$ is the distance from the radio point source to the middle of the cavity (projected), $S$ is the cross-sectional area of the bubble ($S = \pi R_w^2$), $C_D = 0.75$ is the drag coefficient (Churazov et al. 2001), $g$ is the local gravitational acceleration ($g = GM(< R)/R^2$), $r$ is the bubble radius ($r = (R_l R_w)^{1/2}$ for an ellipsoidal bubble), and $c_s$ is the sound crossing time ($c_s = \sqrt{kT/(\mu m_p)}$, where $kT$ is the plasma temperature at the radius of the bubble, $\gamma_2 = 5/3$ and $\mu = 0.62$).

$$t_{buoyant} = R \sqrt{\frac{SC_D}{2gP}}$$

$$t_{refill} = 2 \sqrt{\frac{r}{g}}$$

$$t_{cs} = \frac{R}{c_s}$$

The buoyant rise time is the time it takes a bubble to reach its terminal buoyant velocity, which depends on the medium drag forces. This is a good estimate of a bubble’s age that has clearly detached from their AGN and has risen.
such as the cavity to the west in 4C+55.16. The refill time is the time it takes a bubble to rise buoyantly through its own diameter starting from rest (which is probably not the case). The sound crossing time is the time it takes a bubble to travel at the speed of sound. The latter is used under the assumption that the bubbles travel at subsonic speeds. Between the three time estimates, it is still not clear which is the best to use, although they should not vary significantly.

Table I shows the estimates we obtain for the power being injected into the ICM by each of the bubbles. 4C+55.16 has a cooling luminosity in the 0.5–7 keV range of $L_{\text{cool}} = (1.99 \pm 0.02) \times 10^{44}$ erg s$^{-1}$ ($r_{\text{cool}} = 45$ kpc for a cooling time of 3 Gyr). The power being injected into the medium by all three cavities is therefore sufficient to prevent the gas from cooling, at least within a factor of two. The studies by Rafferty et al. (2006) and Dunn et al. (2005) included 4C+55.16 in their sample of clusters with X-ray cavities. Our results are consistent with theirs, on average within a factor of two.

5.2 Cold front

Cold fronts in cool core clusters are contact discontinuities thought to originate from sloshing of low-entropy gas in the cluster core caused by disturbances on the central potential by phenomena such as past subcluster mergers (see a review by Markevitch & Vikhlinin 2007). Simulations support this idea, but require that clusters with cold fronts have steep entropy profiles (e.g. Ascasibar & Markevitch 2004). This is generally the case for cool core clusters. Although cold fronts could harbour significant amounts of kinetic energy, it is not clear that they could dissipate it efficiently (Markevitch et al. 2001). The exact cause of the sloshing is also not well known. Past mergers could cause sloshing of the cluster core (as supported by simulations, see Ascasibar & Markevitch 2003), but another possibility is whether outbursts from the central AGN could cause the core to recoil and slosh.

In Section 4., we showed that 4C+55.16 has a clear temperature jump on the south-western side of the cluster associated with the southern cavity and plume-like feature, and that the plume-like feature is about twice as rich in metals than a region located within the same radius but excluding the plume (see the temperature and abundance map in Fig. 9). A more detailed analysis also showed that there is a discontinuity in the surface brightness profile associated with this front, see bottom panel of Fig. 10 (although the break is at a radius slightly further away from the jump in temperature). These results are all consistent with the discontinuity being a cold front.

In the literature, we find several examples of cold fronts showing a metallicity jump like in 4C+55.16, but without any clear discontinuity in the temperature profile, e.g. A2052 (de Plaa et al. 2010), A2199 and 2A 0335+096 (Sanders & Fabian 2006b). Others do not show any evidence of a metallicity jump, but clearly show a discontinuity in temperature, such as A496 (Dunkle & White 2003) or A2204 (Sanders et al. 2005). Our front also shows a break in entropy and pressure. The pressure remains constant across the front, a typical feature of cold fronts. Another key point that seems to support the idea that the front we observe is a cold front is the spiral (or tail-like) structure we see in Fig. 3. This figure was obtained by subtracting at every pixel, the average value of an ellipse passing through the point, centred on the X-ray point source. The figure shows an excess of emission (~30 per cent from the mean) in the shape of a large one-armed spiral structure extending from the metal-rich plume feature to the outskirts of the cluster. The mass within this structure is roughly $6 \times 10^{13} M_\odot$, if we assume a cylindrical shape.

Similar spiral-like structures have been seen in other clusters, such as in A2029 (Clarke et al. 2004), in 2A 0335+096 (Sanders et al. 2006) and even in Perseus (e.g. Churazov et al. 2003; Fabian et al. 2000). Simulations in the context of cold fronts have shown that gaseous merging clusters with non zero impact parameters are able to reproduce these spiral structures as the central cool gas acquires angular momentum, in addition to the cold front (e.g. Ascasibar & Markevitch 2006). It takes several Gyrs for the cluster to regain a relaxed morphology. We expect 4C+55.16 to be relaxed, since the cluster shows no obvious signs of recent merger activity. The X-ray cavity to the south could therefore still have the time to form, post merger, as bubble time scales are much shorter (~0.1 Gyr).

If the discontinuities we see in temperature, abundance, pressure and entropy are not caused by a merger-induced cold front, they could simply be caused by feedback of the central AGN. As bubbles rise, they are expected to drag behind them, cool, metal-rich gas (Churazov et al. 2001). However, if there is originally cool low-entropy metal-rich gas at the base of the bubble, as its being inflated by the AGN, it could push the cooler metal-rich gas outwards. The gas would eventually slide back down around the bubble and would cause the appearance of a plume-like metal-rich feature running along the cavity, just like in 4C+55.16.

5.3 Metal enrichment

We now focus on analysing the metal enrichment associated with the plume-like structure. This structure is rich in the Fe emission feature (see Fig. 11). It is about 0.4$Z_\odot$ more metal rich than a region located within the same radius, but excluding the plume (which has a metallicity of ~0.45$Z_\odot$). If we assume that the plume has a cylindrical shape with a length of 30 kpc and width of 14 kpc, and that the density is ~0.065 cm$^{-3}$ (based are the deprojected value along the plume), then the excess of iron mass is around $8.9 \times 10^6 M_\odot$. It is worth mentioning that our results are based on the fits we have obtained using the abundance ratios of Anders & Grevesse (1998), whereas the more recent tables of Asplund et al. (2005) or Lodders (2003) predict an iron abundance about 1.5 times lower. Refitting the data with these tables instead, we find that the plume has an iron excess of ~0.6$Z_\odot$ instead of ~0.4$Z_\odot$. However, the excess of iron in terms of mass does not change, as this quantity also depends on the relative abundance ratios, and the net effect cancels out.

We can estimate the age of this structure in several ways. First, by using a measure of the diffusion coefficient, such as the one derived for Perseus in Rebusco et al. (2003) $2 \times 10^{20} \text{cm}^2 \text{s}^{-1}$, and an average size of the plume (30 × 14 kpc$^2$), we find that time-scale associated with the plume should be on the order of ~6 × 10$^8$ yr. Second, we can estimate the age of the plume if we consider that it has to

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be younger than the local cooling time. The temperature and density of the plume then correspond to a cooling time of \( \sim 5 \times 10^8 \) yr. We are ignoring heating here, which may be plausible since turbulence has not yet had the time to destroy it according to the long diffusion time. An age of about \( 5 - 6 \times 10^8 \) yr implies that if the iron enrichment of the plume was caused by SNIa, then it would require around \( 2.5 \) SNIa per century, if we assume that \( 0.7M_\odot \) are produced for every SNIa. This is at least an order of magnitude higher than the predicted rate of SNIa in an elliptical galaxy of similar \( L_\odot \) (see e.g. Campellaro et al. 1997).

The ages we derive for the plume are in agreement with those of the X-ray cavities (\( t_{\text{bubble}} \sim 10^7 - 10^8 \) yr, see Table 1), and are consistent with the idea that the plume could be created by the uprising of the southern bubble. Other examples of clusters have also shown evidence of significant quantities of metal-rich gas (\( 10^8 - 10^9 M_\odot \)) being uplifted by buoyantly rising bubbles. These include Sérpic 159-03 (Werner et al. 2011), MS7 (Werner et al. 2010) and Hydra A (Simionescu et al. 2009). In order for the plume-like structure to be long lived, magnetic fields could contribute to stabilizing it such as in the case of the emission-line filaments in Centaurus (Taylor et al. 2007) and in Perseus (Fabian et al. 2003).

In Section 4, we analysed the enrichment pattern of the plume using either SNIa or SNII enrichments. Past studies, including the previous one on 4C+55.16 by Iwasawa et al. (2001), suggested that the central iron excess seen in clusters was only caused by SNIa (see also Matsushita et al. 2003). However, our results led us to conclude that although the spectrum is more consistent with it being enriched by SNIa compared to SNII, the solar enrichment pattern still provides a better fit. Sanders & Fabian (2006a) also find that the enrichment pattern of the core of the Centaurus cluster is more consistent with Solar values, suggesting that both SNIa (~70 per cent) and SNII (~30 per cent) contribute to the enrichment (see also de Plaa et al. 2007, Lovisari et al. 2011). Our results agree with this picture.

### 6 CONCLUDING REMARKS

4C+55.16 is X-ray bright (\( L_X \sim 10^{45} \) erg s\(^{-1}\)), radio powerful, and shows clear signs of interaction between its central galaxy and the ICM. 4C+55.16 has at least two, and possibly three X-ray cavities, two of which are filled with radio emitting particles. The power stored within them is around \( 6.7 \times 10^{43} \) erg s\(^{-1}\), and is sufficient to prevent the ICM from cooling. Our study confirms earlier results suggesting that there is a plume-like feature, running along one of the cavities, rich in the Fe L emission feature. However, we also find that the plume and cavity form a region of cool metal-rich gas that has a temperature and metallicity jump (by a factor of 2), and density jump. It could therefore be a cold front, or this could also be an example of metal enrichment by the central AGN, which has the potential to uplift cool metal-rich gas from the central galaxy. Finally, we find that the plume has an excess of iron (\( M_{Fe} = 8.9 \times 10^6 M_\odot \)), and that its enrichment is more consistent with being Solar-like, and therefore suggesting that both SNIa and SNII contribute. This is in disagreement with the more general view that only SNIa enrich in the central regions of clusters.

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