Giant cavities, cooling and metallicity substructure in Abell 2204

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Abstract
We present results from deep Chandra and XMM–Newton observations of the relaxed X-ray luminous galaxy cluster Abell 2204. We detect metallicity inhomogeneities in the intracluster medium on a variety of distance scales, from a ∼12 kpc enhancement containing a few times 10^7 M⊙ of iron in the centre to a region at 400 kpc radius with an excess of a few times 10^9 M⊙. Subtracting an average surface brightness profile from the X-ray image yields two surface brightness depressions to the north and south of the cluster. Their morphology is similar to the cavities observed in the cluster cores, but they have radii of 240 and 160 kpc and a total enthalpy of 2 × 10^62 erg. If they are fossil radio bubbles, their buoyancy time-scales imply a total mechanical heating power of 5 × 10^46 erg s⁻¹, the largest such bubble heating power known. More likely, they result from the accumulation of many past bubbles. Energetically this is more feasible, as the enthalpy of these regions could combat X-ray cooling in this cluster to 500 kpc radius for around 2 Gyr. The core of the cluster also contains five to seven ∼4 kpc radius surface brightness depressions that are not associated with the observed radio emission. If they are bubbles generated by the nucleus, they are too small to balance cooling in the core by an order of magnitude. However, if the radio axis is close to the line of sight, projection effects may mask more normal bubbles. Using reflection grating spectrometer (RGS) spectra, we detect a Fe XVII line. Spectral fitting reveals temperatures down to ∼0.7 keV; the cluster, therefore, shows a range in X-ray temperature of at least a factor of 15. The quantity of low temperature gas is consistent with a mass deposition rate of 65 M⊙ yr⁻¹.

Key words: galaxies: clusters: individual: Abell 2204 – cooling flows – intergalactic medium – X-rays: galaxies.

1 INTRODUCTION

Abell 2204 is a luminous galaxy cluster at a redshift of 0.1523 (Lx = 2 × 10^45 h₅₀⁻² erg s⁻¹ in the 2–10 keV band; Edge et al. 1990). On large scales, the cluster has a regular morphology (Buote & Tsai 1996; Schuecker et al. 2001; Hashimoto et al. 2007), appearing relaxed. Reiprich et al. (2008) recently used a Suzaku observation of this cluster to measure its temperature near to the virial radius, finding it close to the predictions from hydrodynamic simulations.

We previously analysed a short snapshot observation of the cluster by Chandra (Sanders, Fabian & Taylor 2005). The core of the cluster has a fairly complex structure, containing a flat plateau and plume-like feature. One of the most peculiar features was a high-metallicity ring found around the core of the cluster, which, we hypothesised, may have been due to a merger in the past.

Here, we present results from a deep 77 ks Chandra observations of this cluster, in addition to the new Very Large Array (VLA) radio observations. We assume H₀ = 70 km s⁻¹ Mpc⁻¹ and ΩΛ = 0.7, translating to a scale of 2.6 kpc per arcsec. Metallicity measurements assume the relative solar abundances of Anders & Grevesse (1989). Abell 2204 has a weighted Galactic hydrogen column density of 5.7 × 10^20 cm⁻² determined by HI surveys (Kalberla et al. 2005).

2 DATA PROCESSING

The data analysed in this paper come from three different observations of the cluster by Chandra (Table 1). Two of the observations were taken in the ACIS-I detector mode, which uses lower detector background front-illuminated CCDs. The other observation was made with the ACIS-S detector mode, which has a higher background but larger effective area, smaller field of view and better energy resolution.

For the part of the analysis concentrated in the bright central region, we use all the three data sets in combination. In the outer region, we concentrate on the 7940 and 6104 data sets, or just the 7940 data set, as they have a lower non-X-ray background.

Each of the observations was made with the ACIS VFAINT mode. We applied this VFAINT filtering to reduce the detector...
Table 1. Chandra observations analysed in this paper.

| Observation ID | Detector | Observation date | Exposure (ks) |
|----------------|----------|------------------|---------------|
| 499            | ACIS-S   | 2000-07-29       | 10.1          |
| 6104           | ACIS-I   | 2004-09-20       | 9.6           |
| 7940           | ACIS-I   | 2007-06-06       | 77.1          |

background, after ensuring that the observations used the latest gain files.

2.1 Background modelling

Comparison of the spectra extracted from the edge of the ACIS-I observations with the standard blank-sky observations showed excess soft emission. This soft emission appears to be spatially flat, not declining with radius from the cluster centre, indicating that it is not a cluster emission and is likely Galactic in origin. The emission is very similar between the 6104 and 7940 observations, showing it is not a time-variable background.

Rather than using the standard blank-sky observations, we decided to construct our own backgrounds to account for this soft emission. First, we took stowed background observations (where the detector is not observing the sky). These observations, after normalizing to the observations in the 9–12 keV band and removing VFAINT-filtered events, closely match the particle and the detector backgrounds.

To account for the Galactic and extragalactic X-ray emission, we modelled a far-off axis region (after accounting for the particle background) with a thermal (fixed at a temperature of 0.25 keV and solar metallicity) plus power-law ($\Gamma = 1.5$) model. This model was a good fit to the data ($\chi^2 = 211/225 = 0.94$). Taking this model, we simulated spectra in a grid over the detector (iterating in $8 \times 8$ detector pixel cells) for each of the observations, taking the change in the effective area into account by using ancillary response files generated at each grid point. By deconstructing the spectra into individual events (randomizing spatially within each grid point), we generated simulated event files for each observation. This X-ray background event file was then merged with the normalized stowed background event file to make a total background event file (we simulated the X-ray background file to have the same exposure time as the stowed background.). This part-synthetic background provides a very good match to the spectra extracted from the edge of the detector and accounts for the particle background in the centre of the observation properly.

The advantage of this procedure over modelling the soft component in each spectral fit is that we can easily account for the detector variation (bad pixels, vignetting, etc.) and that it simplifies the spectral fitting by only having one background data set per observation.

2.2 Radio observations

VLA observations of the radio source, J1632+0534 at the centre of A2204, were performed on 2007 July 3 at 0.329 GHz in the ‘A’ configuration and on 2007 November 25 at 1.4 GHz in the ‘B’ configuration. We also make use of the data from the VLA archive at 1.4, 5 and 8.4 GHz. Details regarding the radio observations are summarized in Table 2. All data were reduced in aips (astronomical image processing system) following the standard procedures. Absolute flux density calibration was tied to the observations of 3C 286.

3 IMAGING

3.1 Central structure

In Fig. 1 (left-hand panel), we show a merged exposure-corrected image of the core of the cluster. As previously described in Sanders et al. (2005), there is a core with flat surface brightness of dimensions of $7 \times 9$ arcsec. This core is embedded within another flat central ‘plateau’ of radius $\sim 10$ arcsec. A plume-like feature extends from the west of the plateau, wrapping around from south to east.

The unsharp-masked images in Fig. 1 (centre and right-hand panels) show that there is considerable structure visible inside the inner 6 arcsec radius and the surrounding plume.

The central radio nucleus (J1632+0534) corresponds with a peak in the X-ray emission offset to the north of the centroid of the cluster (Fig. 2). The X-ray spectrum is compatible with a $\Gamma = 2.0 \pm 0.2$ power law with a luminosity of $(1.4 \pm 0.3) \times 10^{42}$ erg s$^{-1}$. The nuclear spectrum is equally well fitted with a thermal model with a best-fitting temperature suspiciously close to that of the surrounding gas ($kT \sim 3$ keV).

Although noted in a few surveys, the radio source at the centre of the Abell 2204 cluster, TXS1630+056 = 1632+0534, has received little attention. This is understandable given its relatively modest flux and small angular size as compared to most of the radio galaxies in cooling core clusters.

At 8.4 GHz J1632+0534 consists of a compact nucleus with flux density 16.7 mJy, with weaker compact components to the north and south. The total flux density is $\sim 22$ mJy. The nucleus has a flat spectrum. The components on either side of the nucleus are steep spectrum, with some evidence for extended, steep-spectrum emission at 1.4 GHz with a largest angular size of 15 arcsec (39 kpc). A steep-spectrum component, with flux density $\sim 1$ mJy, is present about 10 arcsec north of the nucleus. This component is likely associated with the nearby companion galaxy seen in Fig. 2. At 1.4 GHz, J1632+0534 also extends to the south-west, and there is a hint of diffuse emission 10 arcsec to the east and west that reaches five times the rms noise level of 30 $\mu$Jy beam$^{-1}$ and could possibly be associated with a mini-halo (Fig. 2). The total flux density of J1632+0534 at 1.4 GHz is 58 mJy and the corresponding total radio power at 1.4 GHz is $3.7 \times 10^{23}$ Hz$^{-1}$. Our

Table 2. Radio observational parameters.

| Source            | Date     | Frequency (MHz) | Bandwidth (MHz) | Configuration | Duration (min) |
|-------------------|----------|-----------------|-----------------|---------------|----------------|
| J1632+0534        | July 2007| 322/329         | 6.25            | A             | 171            |
|                   | November 2007 | 1365/1435       | 50              | B             | 83             |
|                   | April 1998 | 1365/1435       | 25              | A             | 240            |
|                   | April 1998 | 4635/4885       | 50              | A             | 61             |
|                   | August 1998 | 8115/8485       | 50              | B             | 134            |

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Figure 1. Left-hand panel: 0.3 to 7 keV images of the core; the cluster with 0.492 arcsec pixels. Centre panel: unsharp-masked image, created by subtracting images smoothed by Gaussians of $\sigma = 0.5$ and 5 pixels (regions with more emission on small scales are shown as lighter here). Right-hand panel: unsharp-masked image, created by subtracting images smoothed with $\sigma = 2$ and 10 arcsec.

Figure 2. Comparison of Hubble Space Telescope (HST) image of the central galaxies, VLA L-band (20 cm) image, VLA C-band (6 cm) image and Chandra unsharp-masked image. The HST image was created by combining data sets U5A44101R and U5A44102R (F606W filter).

0.33 GHz (90 cm) image, with noise level 1 mJy beam$^{-1}$, does not reveal any further extension, any old emission from a previous outburst or any sign of a mini-halo or cluster halo.

The X-ray and radio nuclei are coincident with the optical nucleus of one of the central galaxies. The two central galaxies are likely to be associated because of the small velocity difference along the line of sight (Jenner 1974).

The plateau contains a number of X-ray surface brightness depressions. These include ones to the east, west, south-east and north-east. There are also possible depressions to the south and north. Each of the depressions has a radius of around 1.5 arcsec (3.9 kpc), although the western hole could be larger with a radius of around 2 arcsec (5.2 kpc). Also, there is depression at the X-ray centroid of the core and plateau, with a radius of around 1.5 arcsec. This depression lies around 2 arcsec south-east of the nucleus.

Such depressions are seen in the cores of galaxy clusters, where the relativistic gas in radio lobes displaces the thermal X-ray plasma (e.g. Hydra A, McNamara et al. 2000; Perseus, Böhringer et al. 1993, Fabian et al. 2000; Abell 2052, Blanton et al. 2001; Centaurus, Sanders & Fabian 2002). None of these depressions is coincident with sources in our new deep radio data, suggesting that if they are coincident with radio bubbles, the electrons in the bubbles have aged too much to be observable in radio (i.e. they are ‘ghost’ cavities).

3.2 Outer structure

We show in Fig. 3 (left-hand panel), the larger scale surface brightness in the 0.5 to 5 keV band (generated from the lower background ACIS-I observations). In this image, we used the make_readout_bg script (written by M. Markevitch) to generate out-of-time events background images to subtract from the data. Out-of-time events occur while the detector is being read, leading to a streak in the read-out direction (the exposure of these events is effectively 1/78.05 of the normal exposure.). Without subtraction, the streak runs about 12’ north from the west through the centre of the cluster for the 7940 observation (coincidentally running along the plume).

In Fig. 3 (right-hand panel), we show the fractional deviation of each of the pixel in the surface brightness image from the average at that radius (accounting for the effects of background and out-of-time events). Immediately apparent are the enhancements roughly in the east–west direction, and depressions in the north–south direction.

To examine these in more detail, Fig. 4 displays an azimuthal surface brightness profiles at two different radii, chosen to coincide with the inner (southern) and outer (northern) decrements. The decrements are very significant, at around 30 per cent level.

The northern decrement and its surrounding bright rims can easily be seen in an image of the cluster with a large binning factor applied (Fig. 5). In addition, an edge-like feature is apparent 950 kpc to the north-west of the cluster, close to the maximum extent
Figure 3. Left-hand panel: X-ray image of the larger scale cluster emission between 0.5 and 5 keV from the ACIS-I observations, binned into pixels of 2.0 arcsec and smoothed with a Gaussian with $\sigma = 6$ arcsec. Right-hand panel: fractional difference of each pixel from the average at that radius. The image was then smoothed with a $\sigma = 6$ arcsec Gaussian. The colour bar shows the numerical scale of the fractional differences.

Figure 4. Surface brightness profile around in azimuth at two radii, chosen to overlap with the inner decrement to the south and outer decrement to the north. The profiles have been normalized by the average at each radius.

Figure 5. 0.5 to 5.0 keV exposure-corrected and background-subtracted image of the outer region of the cluster, with point sources excluded, binned using 7.87 arcsec pixels and smoothed with a Gaussian of 1 pixel.

The most important question is the physical nature of these decrements in Figs 3 and 4. The first option is that they are an artefact of the analysis procedure. If the cluster has an elliptical surface brightness distribution in the sky, then if we subtract the average surface brightness at each radius, we will obtain a sinusoidal profile. Numerical tests show that we need approximately a 2:1 ratio of major-to-minor axis to achieve the observed 30 per cent surface brightness variation. Fitting elliptical surface brightness models to the data imply that the cluster is fairly close to the circular (see also Hashimoto et al. 2007 who find a low ellipticity), excluding the very inner regions. The profiles (Fig. 4) are also not very sinusoidal, particularly the sharp edges to the depression to the north. Fig. 5 shows that there are real surface brightness enhancements surrounding the northern decrement, indicating that it is not a data analysis issue.

Therefore, the depressions are likely to be real cluster features. Their morphology is similar to the X-ray cavities observed in other galaxy clusters. In this case, the cavities are very large as compared to those typically found: the northern cavity has a radius of around 85 arcsec (225 kpc) and the southern one of 55 arcsec (145 kpc). If they are cavities, then they are significantly larger than the 100 kpc radius cavities in MS 0735$^{+}$7421 (McNamara et al. 2005) and Hydra A (Wise et al. 2007). The cavity interpretation is favoured by the enhancement in surface brightness around the depression, particularly for the northern feature (see Fig. 5). These enhancements would correspond to the bright rims seen around bubbles in other objects.

Instead of a single episode, the depressions may be the cumulative result of a set of repeated outbursts along a single axis. These outbursts could accumulate into a large region occupied by non-thermal particles, displacing the thermal plasma. Repeated sets of bubbles along one direction have been seen in Hydra A (Wise et al. 2007), estimated to have lasted over 200–500 Myr. In addition, the Perseus cluster shows a low-thermal-pressure channel and further possible bubbles to the south beyond the outermost southern radio bubble. There is also a possible intact bubble 170 kpc to the north (Sanders & Fabian 2007).

Bubbles should ‘pancake’ at large radius (Churazov et al. 2001), where the bubble density matches the ambient density. It may be that they have not yet done so here, perhaps because of the magnetic fields.
Other possibilities include a merger. However, the cavities with their sharp edges appear unlikely to be the result of a merger. Finally, we could perhaps be observing the accretion of matter on to the cluster along filaments to the east and west of the image. This could be a possibility as the temperature of the gas is enhanced along these directions (see Section 4.2). However, the temperature enhancement can only be measured close to the centre of the cluster, not where the material would be being accreted. Also, the sharp edges of the depressions make this explanation unlikely.

4 SPECTRAL FITTING

4.1 Mapping the cluster core

To investigate the metallicity and temperature structure in the core of the cluster, we applied spatially resolved spectroscopy techniques. We divided the central \( \sim 70 \times 70 \) arcsec into bins using the Contour Binning algorithm (Sanders 2006), which follows the surface brightness variations. We chose regions with a signal-to-noise ratio of 30 (around 900 counts), restricting the length of the bins to be at most twice their width.

We extracted spectra from each of the data sets, generating appropriate responses and ancillary responses. Background spectra were extracted from the part-synthetic backgrounds (Section 2.1). The 6104 and 7940 data sets were added together (as they use the same detector), weighting responses and backgrounds.

We fit each spectrum with an absorbed \texttt{APEC} model (Smith et al. 2001). The absorption was fixed to the Galactic value, but the temperature, metallicity and emission measure were allowed to vary in the fit. The fitting procedure minimized the C-statistic (Cash 1979), and we fitted the data between 0.5 and 7 keV.

Shown in Fig. 6 are the derived temperature and metallicity maps of the core of the cluster, with an image of the cluster at the same scale. Note that the temperature is emission-weighted and projected and that the metallicity measurements are most sensitive to iron. The bright core and plateau correspond to a cool region, where the projected temperature drops below 3 keV in some places. There also appears to be an extension in the cool gas along the plume to the west of the core.

The metallicity structure appears to have a different morphology. The core and plateau contain a number of metallicity inhomogeneities. The most significant is a high-metallicity region around 11 arcsec to the south of the centre (Fig. 7). This is adjacent to a region with low metallicity to the south-east of the core at the same radius. We show the combined spectrum in the three high-metallicity bins compared to the three low-metallicity bins to their east in Fig. 8. The metallicity of the low-metallicity region is \( 0.38^{+0.17}_{-0.14} \) \( \odot \) and the high-metallicity region is \( 1.60^{+0.39}_{-0.32} \) \( \odot \). If both regions are constrained to have the same temperature, this makes very little difference to this result. Markov Chain Monte Carlo (MCMC) tests in \texttt{XSPEC} confirm these uncertainties.

Looking at the spectra (Fig. 8), the significance of the enhancement in the three high-metallicity bins relative to the three low-metallicity bins is around \( 4 \sigma \) (corresponding to a probability of occurrence of \( 6 \times 10^{-5} \) by chance). There are 168 bins in the image, so there are approximately 170 sets of three radial
bins and around 340 unique sets of three radial bins next to the three radial bins. This increases the chance probability to around 2 per cent.

However, the highest, second highest and fifth highest metallicity bins are next to each other. They are statistically independent bins, so the chances of this occurring by chance are of the order of \((2/167) \times (3/164)^2 \approx 4 \times 10^{-4}\). This small probability is still further decreased by the chances of finding three of the lowest metallicity regions in the central part of the cluster immediately adjacent to these high-metallicity regions.

4.2 Mapping the outer regions of cluster

We show in Fig. 9 the temperature and metallicity maps of a \(\sim 870 \times 870\) kpc box around the cluster core. To generate these maps, we binned the image to have regions with a signal-to-noise ratio of 63 (~4000 counts) with the Contour Binning algorithm. We generated combined spectra from the 6104 and 7940 ACIS-I observations, fitting the data with the same APEC model as for the core region.

We investigated the effect of accounting for out-of-time events (events occurring while the CCDs are being read out), but this made little difference to the spectral-fitting results for this region. Minimizing \(\chi^2\) instead of the C-statistic made some difference, but the morphology remained very similar.

The temperature map shows that the temperature of the gas to the east which flattens off to around 8 keV until a radius of around 190 kpc, where it steeply rises to above 12 keV. The temperature rises more steeply to the west. At large radius, there is an apparent decline in the temperature.

The metallicity map shows structure, as we have found previously (Sanders et al. 2005). We find that the metallicity drops outside of the core, but rises again to form a ring or spiral around the core at a radius of around 150 kpc. It is unclear whether this metallicity structure is connected to the spiral-like feature in the very central regions (Fig. 6, centre panel).

One particularly interesting metallicity feature is the region of high metallicity around 300 kpc to the north. There is no high-metallicity material at this radius to the south. This can be demonstrated by directly examining the spectra of two diametrically opposite bins (Fig. 10; the bins examined are marked in Fig. 9). There is no evidence for Fe–K line emission for the southern spectrum, but it is strongly seen for the northern region.

The best-fitting metallicities are zero for the southern region (the 2\(\sigma\) upper limit is 0.28\(Z_\odot\)). The metallicity of the northern region is 0.77 ± 0.21. We have confirmed with the MCMC functionality in xspec that the difference in metallicity between the two regions is significant to 3\(\sigma\).
Figure 10. Comparison of the spectra from regions around 350 kpc to the north (circles) and south (no circles). The solid lines in the top panel are the best-fitting spectral models. In the bottom panel, the ratio of the data to the best-fitting spectral model is shown. The data have been rebinned.

4.3 Profiles of cluster properties

To examine the cluster properties as a function of radius, we extracted projected spectra from circular annuli chosen to give a reasonable quality spectrum. We only used the 7940 data set here, as it simplified much of the analysis without much change in the signal-to-noise ratio. Using the Direct Spectral Deprojection method of Sanders & Fabian (2007) (tested in Russell, Sanders & Fabian 2008), we generated deprojected spectra from the projected spectra. We then fitted single temperature APEC models to the projected and deprojected spectra to create the temperature, metallicity and emission measure profiles. We included the effects of background and out-of-time events in this analysis, assumed Galactic absorption, grouped the spectra to have at least 25 counts per spectral bin, fitted the data between 0.5 and 7 keV and minimized the $\chi^2$ to find the best-fitting model.

Fig. 11 shows the projected and deprojected temperature and projected metallicity profiles out to a radius of $\sim$1200 kpc. Beyond this radius, there is a little cluster emission in the spectra. The plot also shows the electron density, calculated from the emission measure of the fit to the deprojected spectra. By multiplying the deprojected electron density and temperature, we calculated the pressure. We also computed the entropy using $S = kTn_e^{2/3}$. To calculate the errors on the pressure and entropy, we assumed that the errors on temperature and density were independent. Most of the uncertainty is in the temperature, so this assumption could be made.

We are able to measure a density variation of a factor of $\sim$600, pressure $\sim$300 and entropy $\sim$150. We observe the temperature of the intracluster medium (ICM) to decline with radius beyond 400 kpc (in the projected spectra, which have smaller error bars). The temperature profile in the outskirts agrees reasonably well with the Suzaku, Chandra and XMM–Newton profiles published by Reiprich et al. (2008). In the centre, we find values similar to their Chandra results from a shorter observation. The peak Chandra temperatures are higher than Suzaku or XMM, and the central temperature drops more steeply. This is probably due to the point spread function (PSF) effects, though there are claims that the Chandra effective area calibrations contribute to the higher peak temperatures. Interestingly, our results show that the entropy profile remains flat beyond 550 kpc, similar to what was found in PKS 0745 – 191 (George et al. 2008). The entropy profile appears to break at 72, 240 and 650 kpc.

The maps suggest that there is structure in the properties of the cluster as a function of angle. We split up each annulus into four 90° sectors, pointing towards the north, east, south and west. Fig. 12 shows the projected and deprojected temperature profiles for each of these sectors. Much of the structure in the temperature maps is seen in the profiles. For instance, 120 kpc to the west is a higher temperature region. At larger radius to the west, where there is a brighter cluster emission than to the north or south (Fig. 5), the gas is cooler than in the other sectors.
Figure 12. Projected and deprojected temperature profiles in four sectors.

Figure 13. Projected metallicity profiles in four sectors.

The projected metallicity profiles in the quadrants (Fig. 13) show interesting variation. We see the high-metallicity ring strongly to the south at a radius of around 240 kpc. We also see the large metallicities to the north, 650 kpc from the nucleus.

In Fig. 14 (top panel), the deprojected densities in the four sectors are plotted. In the bottom panel, we display the fractional difference of each density from the average at that radius. The plot shows the lower density regions to the north (beyond 300 kpc) and south (around 250 kpc) corresponding to the depressions in the surface brightness image.

4.4 Cool gas in the core

To examine the amount of cool gas which could be present in the core of the cluster, we extracted the spectrum from the inner 100 arcsec radius. We fit a cooling flow model, made up of APEC+MKCFLOW components, to account for the cluster and cooling emission. The MKCFLOW cooling flow model was computed with APEC spectra. Galactic absorption was assumed in the spectral fitting. The upper temperature and metallicity of the cooling flow model were tied to the APEC component and the lower temperature was fixed to 0.0808 keV (the lowest possible). The Chandra spectra were consistent with a $65 \pm 21 \, M_\odot \, yr^{-1}$ mass deposition rate.

Much better determinations of the amount of cool gas can be made with high spectral resolution XMM–Newton RGS data (see Peterson & Fabian 2006 and references therein). We processed each of the RGS observations of Abell 2204 (Table 3) with sas version 8.0.0. We used a PSF extraction region of 90 per cent and a pulse-height distribution region of 95 per cent. We created combined first-order RGS1 and combined RGS2 spectra and responses using the rgscombine task. The data were grouped to have at least 25 counts per spectral bin. Background model spectra were created with rgsbkgmodel.

We fit the first-order data between 7 and 26 Å with a multitemperature model. The temperature components were APEC models with fixed temperatures of 0.25, 0.5, 1, 2, 4 and 8 keV but free normalizations. The components shared the same metallicities, with O, Ne, Mg, Si, Fe and Ni free in the fits, and with S, Ar and Ca tied to Fe. The components were absorbed with fixed Galactic absorption. We did not account for the spatial distribution of the source in the modelling as the bright region is small compared to the XMM PSF.

We fit the model to minimize the $\chi^2$ statistic. The reduced $\chi^2$ of the best-fitting model was $0.994 = 1273.56/1281$.

In Fig. 15, we show the best-fitting emission measures for each of the temperature components (these are the normalizations produced by xspec). Also plotted are the emission measures found by fitting a simulated spectrum of a cooling flow with a mass deposition rate of $200 \, M_\odot \, yr^{-1}$ cooling from 8 to 0.0808 keV. We also plot the normalizations for a $65 \, M_\odot \, yr^{-1}$ cooling flow, as found from the Chandra spectra.
We show in Fig. 16 the fluxed version of the spectrum. There are hints of the two strongest Fe XVII emission lines. Fitting zero-width Gaussian Fe XVII lines to the raw spectrum, and using an F-test to test for the significance of the line components, gives a chance probability of $1.5 \times 10^{-3}$ (3.2σ) for the redshifted 17.06 Å line, but only a chance probability of 0.33 (1σ) for the redshifted 15.01 Å line. The 17.06 Å line has a luminosity of $(7.6 \pm 2.6) \times 10^{41}$ erg s$^{-1}$ (which is compatible with a 120 M$_\odot$ yr$^{-1}$ cooling flow).

Fitting the RGS data with a model made up of a thermal VAPSEC component and a VMCFLOW component cooling to 0.0808 keV gives a mass deposition rate of $124 \pm 25$ M$_\odot$ yr$^{-1}$ (fixing the upper temperature of the cooling flow to the VAPSEC and using the same free metallicities as above).

5 DISCUSSION

5.1 Inner surface brightness depressions

The core of the cluster contains at least five or seven X-ray surface brightness depressions. If these are interpreted as X-ray cavities caused by the bubbles of relativistic plasma, then their $PV$ energies are of the order of $8 \times 10^{57}$ erg (or a few times more for the larger depression), where $P$ is the pressure of the surrounding ICM and $V$ is the bubble volume. These are fairly typical values for the cavities in clusters (Dunn & Fabian 2004). At a moderate distance of this cluster, the depressions are hard to spatially resolve. We observe no radio emission associated with the depressions, so we cannot confirm them as radio bubbles. If they are radio cavities, they are ghost bubbles where the electrons have aged out of the observed band.

Their morphology is rather unusual for radio bubbles, however. There are five strong depressions, plus another two possible ones. They all lie roughly around 20 kpc distance from the X-ray centroid. However, if you measure the distance from the X-ray nucleus (Fig. 17), the north-east and west depressions are at similar radius ($\sim 12$ kpc), so are the north and east features ($\sim 16$ kpc), and the south and south-east regions ($\sim 25$ kpc), leaving the central depression at 6 kpc distance. This may be coincidental, but it fits with the picture of the bubbles being created in pairs (except for the central depression). We do not know the component of distance from the nucleus along the line of sight, however. It could be that these are like the series of ‘frothy’ bubbles in M87 (Forman et al. 2007).

Using a radius of 25 kpc (the maximum) and the sound speed implies a time-scale of $2.7 \times 10^7$ yr. Using 4$PV$ enthalpy (if the gas in the bubbles is relativistic; Birzan et al. 2004; Dunn & Fabian 2004), this would translate into a mechanical heating rate of $4 \times 10^{43}$ erg s$^{-1}$ per bubble.

The bolometric luminosity from the inner 100 kpc is $1.6 \times 10^{45}$ erg s$^{-1}$. Five bubbles would fall short of providing the required heating rate to compensate cooling by an order of magnitude.
From the cavity heating power correlation of Birzan et al. (2008),
the 1.4-GHz radio luminosity implies a cavity heating power of
around $10^{44}$ erg s$^{-1}$. This power is similar to the calculated heating
power of the cavities. It still falls short of the required heating power
to prevent cooling by an order of magnitude. However, there are a
couple of orders of magnitude scatter in the correlation between
radio and heating power, so this is not conclusive at all.

We note that the projection of cool gas in front of bubbles could
create the observed complex morphology. The bright emission to the
east of the bubbles in Perseus (Fabian et al. 2000) is much stronger
than the deficit in the bubbles. If the bubbles were observed along a
different line of sight, they may be completely obscured or difficult
to interpret. Therefore, there may be much larger bubbles present
in Abell 2204 than we infer. We would require a bubble around the
same size as the bright central core to completely prevent cooling.

5.2 Outer surface brightness depressions

The cluster contains a surface brightness depression to the north,
between radii of 135 and 295 arcsec (355 to 780 kpc). To the south,
there is a depression between radii of 65 and 185 arcsec (170 to
490 kpc). Given their morphology, they are either old radio bubbles
or the cumulative result of many generations of radio bubble.

We can estimate how much energy each cavity could inject me-
chanically into its surroundings as the enthalpy $4PV$. The average
electron pressure (Fig. 11) can be fitted outside 200 kpc radius by a
model with the form $P_e = 0.156 [1 + (r/149.5 \text{ kpc})^2]^{1.13}$ keV cm$^{-3}$.
If the total thermal pressure at each radius is integrated over the vol-
ume of each bubble (assuming that they are spherical), this leads
to enthalpies for the northern and southern cavities, respectively, of
$9.9 \times 10^{51}$ and $1.3 \times 10^{52}$ erg (simply using $4PV$ with the pressure
at the midpoint gives a very similar result). The total enthalpy is
therefore around $2 \times 10^{52}$ erg.

If they are a single set of bubbles, to estimate their mechanical
heating power, we need an appropriate time-scale for the heating.
If the bubble is rising at a terminal velocity (Churazov et al. 2001),
then the time-scale for it to rise to its current radius is $t_{\text{buoy}} \sim R/\sqrt{SC/2gV}$ (Birzan et al. 2004; Dunn & Fabian 2004),
where $S$ is the cross-sectional area of the bubble, $V$ is its volume, $R$ is the
distance of the bubble from the cluster nucleus, $g$ is gravitational
acceleration there and $C$ is a drag coefficient, 0.75.

For the northern bubble, at a radius of 220 arcsec could in the cluster,
the mass enclosed is around $4.5 \times 10^{14} M_\odot$ (Clowe & Schneider
2002), which, with our assumed value of $H_0$, implies $g \sim 1.9 \times
10^{-8}$ cm s$^{-2}$. This leads to a buoyancy time-scale of $2.7 \times 10^7$ yr.
The enclosed mass at the radius of the southern bubble is $2.6 \times 10^{14}$,
implying that the buoyancy time-scale is $1.2 \times 10^8$ yr. The total
mechanical power of the two bubbles is around $5 \times 10^{46}$ erg s$^{-1}$.
This value is still larger than the most powerful outburst known,
MS 0735+7421.

If these cavities are produced by a single episode, then it must
have avoided heating the core of the cluster. We measure a minimum
central mean radiative cooling time of $2.5 \times 10^8$ yr.

If, however, the features are caused by the cumulative effect of
many generations of radio bubbles then we can estimate how long
the enthapy would combat cooling in the cluster. The bolometric
X-ray luminosity within 500 kpc is calculated from our spectral
fitting results (Fig. 11) to be $3.5 \times 10^{48}$ erg s$^{-1}$. This means that
the two features contain enough energy to stop cooling for around
2 Gyr.

5.3 Metallicity substructure

Abell 2204 presents metallicity substructure from the innermost re-
gions (Fig. 6, left-hand panel) to several hundred kpc radius (Fig. 9,
bottom panel).

The metallicity substructure in the centre does not have any obvious
correlation with the observed X-ray cavities. Bubbles are
expected to drag cool, metal-rich gas behind them (Churazov et al.
2001). However, when looking at the best data the picture is com-
plex (Sanders et al. 2004; Sanders & Fabian 2007), with some high-
metallicity regions correlated with some bubbles. The metallicity
structure on small scales points towards the intracluster medium
not being well mixed (Sanders & Fabian 2002; Sanders et al. 2004;
Durret, Lima Neto & Forman 2005; Fabian et al. 2005; O’Sullivan,
Vrtilek & Kemper 2005; Sanders, Fabian & Dunn 2005;
Finoguenov et al. 2006; Sanders & Fabian 2007; Simionescu et al.
2008).

The high-metallicity blob in the central region (Fig. 6, centre
panel; Fig. 8) has a metallicity $1.2 Z_\odot$ greater than the neighbouring
low-metallicity region (or four times its value). Using a volume of
$24 \times 12 \times 12$ kpc and an electron density of 0.1 cm$^{-3}$, this represents
an enhancement of iron of $2 \times 10^7 M_\odot$.

To examine the outer northern metal enhancement, we calculated
cumulative mass profiles in the four different quadrants, shown in
Fig. 18 (also shown is the iron mass profile above a metallicity value
of 0.15$Z_\odot$). The uncertainties were calculated using a Monte Carlo technique.

![Figure 18. Cumulative iron mass profiles in the four different quadrants. Top panel shows the total Fe mass. The second shows the mass above a metallicity value of 0.15$Z_\odot$. The uncertainties were calculated using a Monte Carlo technique.](https://academic.oup.com/mnras/article-abstract/393/1/71/1081453)
Cumulative mass profiles were calculated from each simulated metallicity profile. The median, 16th and 84th percentiles were calculated to obtain the final cumulative mass and uncertainties. The plot shows that there is an excess of a few times $10^7 M_\odot$ of iron towards the north and east compared to the south (the east is enhanced in mass as compared to the north, as the density is higher there as is no surface brightness depression). We note that metal masses can depend on the inhomogeneity of the metallicity distribution (Kapferer et al. 2007).

The northern outer metal enhancement may be associated with the cavity to the north, as the high-metallicity region is roughly at the base of the northern cavity (Fig. 9). The data quality is not good enough to map this exactly. An outburst, a merger or the cumulative effect of many radio bubbles may be required to lift the few times $10^7 M_\odot$ of iron from the cluster core to the outskirts. The metals could have been pulled out of the cluster core in the wake of a rising bubble or many bubbles. In addition, the progress of the bubble(s) may have disturbed the cluster core enough to make the inner metallicity spiral, though smaller outbursts may have been responsible for this.

We note that the injection of metals into the intracluster medium should be a smooth process. The Type Ia supernovae in the central galaxy should be mainly responsible for the enrichment, and these will be uniformly distributed over the galaxy. Some other process must be responsible for making the metallicity clumpy.

5.4 Diffusion coefficient

Given that we have a high-metallicity feature of the order of 6 kpc in size and if we assume it lasts for $\sim 10^6$ yr, this gives a diffusion coefficient of $< 10^{23}$ cm$^2$ s$^{-1}$. This is similar to the value obtained for Centaurus (Graham et al. 2006) and an order of magnitude smaller than Perseus (Rebusco et al. 2005). Multiplying the sound speed and the 6 kpc scale gives a diffusion coefficient around $10^{20}$ cm$^2$ s$^{-1}$. Unless these metallicity features are very short lived, then diffusion must be heavily suppressed, implying that turbulent motions are damped on these scales.

5.5 Cool gas

The mass deposition rate calculated assuming that the X-ray luminosity comes from cooling alone and is in steady state is around $850 M_\odot$ yr$^{-1}$ (Peres et al. 1998). The RGS spectra from the cluster show evidence for cool gas down to around 0.5 keV from spectral fitting, and directly from the presence of the Fe xvi line. The quantity of cool gas is consistent with a cooling flow of $65 M_\odot$ yr$^{-1}$ down to the lowest detectable temperature. There is a wide range of temperature of the X-ray emitting material in cluster from around 12 keV all the way down to 0.5 keV. The gas below this temperature is consistent to $2\sigma$ with $65 M_\odot$ yr$^{-1}$.

This level of cooling is also consistent with the star formation rate of $14.7 M_\odot$ yr$^{-1}$ measured from infrared emission (O’Dea et al. 2008). We note that the optical spectra of Crawford et al. (1999) indicate only a rate of $1.29 M_\odot$ yr$^{-1}$. Feedback must be affecting the gas below 0.5 keV to prevent at least 80 per cent of it cooling.

6 CONCLUSIONS

We observe large and significant surface brightness depressions 570 and 330 kpc from the core of the cluster of galaxies Abell 2204. Morphologically they look like much larger versions of the X-ray cavities seen in the cores of galaxy clusters, but energetically they would be extremely powerful sources of mechanical heating if that were the case ($5 \times 10^{46}$ erg s$^{-1}$). They could, instead, be the accumulation of multiple episodes of radio bubble formation in the cluster core. The bubbles could rise in the same direction, forming a bubble repository at large radius. If this is the case then they would have had to avoid pancaking. The energy in this case could have offset cooling in the cluster over 2 Gyr. The core of the cluster contains several cavities, showing evidence for continued active galactic nucleus feedback.

We see a high degree of metallicity substructure in the intracluster medium, from a 12 kpc feature containing $10^7 M_\odot$ of iron in the core to a massive feature with $10^9 M_\odot$ of iron at 400 kpc radius to the north. These results, with other observations of the intracluster medium, indicate that metals in the intracluster medium are not efficiently mixed. The northern metallicity feature could have been lifted by the giant outburst in the past, or the continuous action of smaller outbursts.

In the core of the cluster are small depressions which may be cavities generated by the nucleus. They could not provide enough heating to prevent cooling in the central region, however. There is evidence for cool X-ray emitting gas a factor of more than 10 lower in temperature than the outer parts of the cluster. A cooling flow of around $65 M_\odot$ yr$^{-1}$ could be operating, in the absence of heating.

In the future, upcoming bolometers and other high-energy resolution detectors will allow us to gain a much better understanding of the dynamical state of the ICM. We will be able to see the direct effect of bubbles on the motion of the intracluster medium (although filaments allow us to observe this indirectly; see Fabian et al. 2003) and examine the turbulence on different scales.

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