A high coverage view of the thermodynamics and metal abundance in the outskirts of the nearby galaxy cluster Abell 2199

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Accepted 2020 July 22. Received 2020 July 20; in original form 2020 June 22

ABSTRACT

We present a joint Suzaku and XMM–Newton analysis of the outskirts of the nearby galaxy cluster Abell 2199, the only nearby galaxy cluster to be observed with near complete azimuthal coverage with Suzaku. Using the XMM–Newton observations to correct for the effects of gas clumping, we find that the azimuthally averaged entropy profile in the outskirts follows a power law with a slope of 1.20 ± 0.23, statistically consistent with a slope of 1.1 predicted by non-radiative simulations for purely gravitational hierarchical structure formation. However, when divided into 10 sectors, the entropy shows significant azimuthal variation, with some sectors lying below the baseline level. The azimuthally averaged gas mass fraction is found to agree with the cosmic mean baryon fraction. The metal abundance in the outskirts is found to be consistent with being uniform in all directions and it has an average value of 0.29\(^{+0.03}_{-0.03}\)Z\(_\odot\), consistent with the gas accreting on to clusters being pre-enriched with metals.

Key words: galaxies: clusters: intracluster medium – intergalactic medium – X-rays: galaxies: clusters.

1 INTRODUCTION

The low and stable particle background of the Suzaku X-ray observatory allowed the first temperature measurements to be made of the intracluster medium (ICM) near the virial radius\(^1\) (see Walker et al. 2019 for a review). However a complete, detailed view of the outskirts of the ICM was challenging owing to the large point spread function (PSF) of Suzaku (a half-power diameter of around 2 arcmin) and its modest field of view. Suzaku was able to achieve high azimuthal coverage of higher redshift clusters (\(z > 0.07\)) with mosaics of around four observations, however the large PSF meant that these clusters could only be resolved into a small number of annuli, and only around 4 sectors (e.g. A1689, Kawaharada et al. 2010b; A2029, Walker et al. 2012a; PKS0745-171, Walker et al. 2012b). To get around Suzaku’s large PSF, nearby clusters were also observed in strips from the centre to the outskirts, such as the Perseus cluster (Walker et al. 2013), the Coma cluster (Simionescu et al. 2012a; PKS0745-171, Walker et al. 2012b). A2199’s large spatial extent means that it can be divided into many more spatially resolved sectors than the higher redshift clusters Suzaku has studied. This is important because simulations predict that the outskirts of galaxy clusters should become increasingly asymmetric in their outskirts (e.g. Roncarelli et al. 2006; Vazza et al. 2011; Avestruz et al. 2014; Lau et al. 2015). Congruent archival XMM–Newton observations for the majority of the Suzaku observations are available, and allow for an independent measure of the gas density and, importantly, allow the clumping factor of the ICM to be measured. XMM–Newton’s higher spatial resolution allows gas clumping to be measured through the ratio of the mean to median surface brightness, as has been demonstrated by e.g. Eckert et al. (2015), Tchernin et al. (2016), and Ghirardini et al. (2018).

Using Suzaku, we can also measure the spatial variation of the metal abundance of the ICM in the outskirts. Measurements of the metal abundance in the outskirts of galaxy clusters are a powerful probe of feedback physics (Werner et al. 2013; Simionescu et al. 2017; Urban et al. 2017; Biffi et al. 2018; Mernier et al. 2018). This is because the metal distribution in the ICM is strongly dependent on the history of chemical enrichment. Cosmological hydrodynamical simulations (Biffi et al. 2017, 2018) found that active galactic nuclei (AGN) feedback at early times (\(z > 2\)) is effective at removing pre-enriched gas from galaxies, which leads to metals being spread uniformly throughout the cluster outskirts. On the other hand, late-time enrichment leads to inhomogeneous distributions of ICM metals that rapidly decline with cluster radius.

Throughout this paper, we adopt a lambda cold dark matter cosmology with \(\Omega_m = 0.3\), \(\Omega_{\Lambda} = 0.7\), and \(H_0 = 100h_{100}\) km s\(^{-1}\) Mpc\(^{-1}\) with \(h_{100} = 0.7\). At the redshift of Abell 2199 (\(z = 0.03\)), 1 arcmin corresponds to 36 kpc.

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\(^1\)In this paper, we follow the common practice of refering to \(r_{200}\) (the radius within which the mean density is 200 times the critical density of the Universe) as the virial radius.

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In this work, a joint analysis of Suzaku and XMM–Newton observations were used to analyse the thermodynamic properties of A2199 up to the virial radius. The Suzaku mosaic consists of 22 pointings, whereas the XMM–Newton mosaic consists of 12 pointings. The details regarding the Suzaku and XMM–Newton observations are summarized in Tables A1 and A2, respectively.

2.1 XMM data reduction

The XMM data were reduced using the XMM–Newton Science Analysis System, XMM-SAS v18.0, and the calibration files, following the procedures illustrated in the Extended Source Analysis Software manual (ESAS; Snowden & Kuntz 2014). The data were examined for anomalous CCDs, and any affected CCDs were removed from the analysis. The ESAS tool cheese and also the Chandra tool wavdetect were used to mask point sources and extended substructures that contaminated the field of view. For all three detectors, the spectra and response files were created by running the mos-spectra and pn-spectra tasks. These files were then used to create the quiescent particle background spectra and images using the mos-back and pn-back. The data were also examined for residual soft proton contamination using the ESAS task proton.

The analysis procedures described above created all of the required components for a background-subtracted and exposure-corrected image. After weighting each detector by its relative effective area, these components from all three XMM detectors and 12 pointings were then combined and adaptively smoothed into a single image. Furthermore, we applied a Voronoi tessellation algorithm using the method of Diehl & Statler (2006) to create an adaptively binned image, where each bin contains at least 20 counts. The resulting background-subtracted and exposure-corrected image of A2199 is shown in the right-hand panel of Fig. 1. The X-ray image of A2199 was created in the 0.7–1.2 energy band in order to maximize the signal-to-noise ratio in the outskirts (e.g. Tchernin et al. 2016).

The surface brightness profile for the mosaicked image of A2199 was then extracted in concentric annuli centred at the cluster centre (RA, Dec.) = (16:28:38.21, +39:33:02.31). This corresponds to the location of the peak X-ray flux in the cluster. The radial profile of the surface brightness is shown in the upper panel of Fig. 2. In the lower panel of this figure, we present the radial profile of the azimuthally averaged electron density of A2199. The profile is recovered from the deprojection of the median surface brightness profile using the onion peeling technique (Ettori et al. 2010), and assuming that the ICM plasma is spherical symmetry. To convert from surface brightness to density, we use the following widely used approach (Eckert et al. 2012; Tchernin et al. 2016; Ghirardini et al. 2018; Ghirardini et al. 2019; Walker et al. 2020). Using XSPEC and the response files for XMM–Newton, the conversion factor between APEC normalization and X-ray count rate in the 0.7–1.2 keV band is found. In the 0.7–1.2 keV band, this is largely independent of the temperature of the gas, so this allows a direct conversion from the deprojected X-ray surface brightness profile to a deprojected profile of APEC normalization. The APEC normalization is related to the gas density by the equation:

\[
\text{Norm} = \frac{10^{-14}}{4\pi [d_A/(1+z)]^2} \int n_e n_H dV,
\]

where the electron and ion number densities are \(n_e\) and \(n_H\), respectively (for a fully ionized plasma these are related by \(n_e = 1.17 n_H\), Asplund et al. 2009), the angular diameter distance to the cluster is \(d_A\), and \(z\) is the cluster redshift. The deprojected APEC normalizations are then converted to deprojected density in the usual fashion, assuming spherical symmetry and a constant density in each shell, by calculating the projected volumes, \(V\), of each shell in the 2D annuli. When performing this conversion, we used a column

2 DATA

Figure 1. Left: Suzaku mosaic of A2199 with sectors overplotted. Green circles show the brightest point sources which were excluded from the analysis. Right: Voronoi tesselated, background subtracted, and exposure corrected XMM–Newton mosaic of A2199. The magenta circles show the regions in which the local background counts were extracted.
A2199 outskirts

Figure 2. Top: Azimuthal median of the background-subtracted surface brightness profile for the A2199 cluster in the 0.7–1.2 keV energy band. Bottom: Density profile obtained from the deprojection of the surface brightness radial profile using the onion peeling technique. The error bars are the 1σ percentiles computed using a Monte Carlo technique. The vertical dotted and dashed lines represent the \( r_{500} \) and \( r_{200} \) radii, respectively.

Figure 3. Density profiles in the 10 angular sectors recovered from the deprojection of the X-ray surface brightness using the onion peeling technique. The error bars are the 1σ percentiles computed using a Monte Carlo technique. The thick black line shows the azimuthally averaged density profile. The vertical dotted and dashed lines mark the \( r_{500} \) and \( r_{200} \) radii, respectively. We introduce small offsets between data points at the same radius to aid readability.

Figure 4. Profiles of the clumping factor for the azimuthally averaged profile (blue) and azimuthal sectors (red). The vertical dotted and dashed lines mark, respectively, the \( r_{500} \) and \( r_{200} \) radii.

The density profile is also derived in each of the 10 azimuthal sectors shown in Fig. 1, taking advantage of the high signal-to-noise ratio of our data. In this azimuthal sector analysis, any small gaps found in the XMM–Newton mosaic are linearly interpolated over. For sector 8, where there is no XMM–Newton coverage, we used the Suzaku data to derive the gas density. Fig. 3 shows the density profiles in the azimuthal sectors of the A2199 cluster.

The derived gas density profiles, however, could be biased by presence of gas clumping, which become increasingly important near the virial radius (Walker et al. 2019). We estimated the level of this possible bias directly from the mosaicked images by dividing the mean surface brightness by the median surface brightness in each annulus region, following Eckert et al. (2015). The inferred clumping factor, \( \sqrt{C} \), is plotted in Fig. 4. The estimated values of the clumping factor are less than 1.1 over the entire cluster-radial range, implying that the clumping bias is very mild in A2199.

Typically, the radial profile of the X-ray surface brightness is subject to various sources of systematic uncertainties. The choice of the local background region is the major source of systematic uncertainty in the imaging-data analysis. To address this issue, we chose two local background regions in two different positions outside the virial radius of A2199, as shown in the magenta regions in Fig. 1. Furthermore, we take into account uncertainty due to background fluctuations by considering a ±5 per cent uncertainty of the background level as an additional uncertainty in the radial surface brightness profile. Measurements presented in this work take account of the systematic uncertainties.

2.2 Suzaku data reduction

Suzaku observed Abell 2199 with 22 observations covering the whole cluster with high azimuthal coverage in the outskirts, and these observations are tabulated in Table A1, and a background subtracted, exposure corrected mosaic of the observations is shown in the left-hand hand panel of Fig. 1. The reduction of the Suzaku data follows the methods described in Walker et al. (2012a, b, 2013). Each observation was reprocessed using the tool AEPipeline, performing the standard cleaning described in the Suzaku ABC guide.2 The calibration regions at the edges of the detectors were removed, and the small strip of the XI0 detector that is defective (from a micrometeorite hit) was excluded from the analysis.

2https://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/
allows us to calculate the expected level of the unresolved cosmic X-ray background below a threshold flux of $1 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$.

For a given spectral extraction region, we can then calculate the expected variance of the unresolved CXB level following Walker et al. (2013) and include this uncertainty in our systematic error budget. Because Abell 2199 is very nearby ($z = 0.03$), we can use large spectral extraction areas, which reduces the variance in the unresolved CXB level.

For the soft background, we use an annular region from the ROSAT All Sky Survey (RASS) reaching from 60–120 arcmin, which we divide into 4 quadrants to assess the annular variation of the soft background. We model an unabsorbed component at 0.16 keV corresponding to the Local Hot Bubble, and an absorbed component at 0.35 keV corresponding to the galactic halo emission. This model provides a good fit for all 4 quadrants, and we use the variation in the best-fitting parameters in each of the 4 quadrants as an estimate of the systematic uncertainty on the measurement of the soft background components when performing our spectral fits.

For each spectral extraction region, our complete background model is therefore an absorbed power law for the unresolved CXB, to which we add the contribution in each region from the resolved point sources that are seen in the XMM observations, added to the soft components measured from the RASS data.

2.2.2 Suzaku spectral fitting

As shown in Fig. 1, we divide the cluster into 10 sectors and extract spectra in these sectors. For each region, we fit the XIS0, XIS1, and XIS3 spectra simultaneously in XSPEC using the extended C-statistic. For each spectrum, the non-X-ray background spectrum is obtained using XISNXBGEN and is subtracted. We then model the background using the background model described in Section 2.2.1. We fit for the cluster emission with an absorbed APEC model, with a hydrogen column of $0.08 \times 10^{22}$ cm$^{-2}$ (Kalberla et al. 2005). Following Urban et al. (2017), we use the abundance tables of Asplund et al. (2009).

Deprojected temperatures and densities were obtained by following a method similar to the XSPEC model PTOC and described in Walker et al. (2013), in which each annulus is modelled as the superposition of the ICM from that annulus and those outside it, weighting by appropriate volume scaling factors.

Any gaps in the mosaics are linearly interpolated over, and are taken into account when performing spectral analysis. The coverage of the Suzaku mosaic is very high, and over 80 per cent of the cluster within $r_{200}$ is covered. To fully appreciate how high this coverage is, the results need to be considered in the context of the other Suzaku studies of nearby galaxy clusters, which were limited to narrow strips from the core to the outskirts. In the Perseus cluster (Urban et al. 2014) the coverage is only 30 per cent of the cluster within $r_{200}$, in the Coma cluster (Simionescu et al. 2013) it is 15 per cent, in the Virgo cluster (Simionescu et al. 2017) it is only around 5 per cent, and in the Centaurus cluster (Walker et al. 2013) it is 10 per cent.

The azimuthally averaged deprojected temperature profile is shown in Fig. 5, while the deprojected temperature profiles in all 10 sectors are shown in Fig. 6. All of the profiles we plot in this work have a linear radial axis to emphasize the outskirts. In Fig. 5, we also show the parametrized temperature profile (the red solid line) obtained from Ghirardini et al. (2019) by fitting the temperature measurements of a sample of 12 higher redshift clusters (the X-COP clusters) with the functional form of the temperature introduced by Vikhlinin et al. (2006). Our temperature measurements agree well

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3https://wind.nasa.gov/
with the best-fitting model of the temperature found by Ghirardini et al. (2019) over most of the radial range.

The metal abundance is also fit for, but we use larger azimuthal binning (we combine together adjacent sectors, thus dividing the cluster abundance measurements into 5 sectors rather than 10). When fitting for the metal abundance, we follow the methods described in Urban et al. (2017). Namely, we only obtain metal measurements at radii greater than 0.25\( r_{200} \) to avoid contamination from the central core. We also used as a threshold for measuring the outskirts metal abundance that the ICM signal to background ratio around the FeK line must be greater than 10 percent. We find that the outermost region we can study that satisfies this criterion is the 0.5–0.7\( r_{200} \) annulus. The azimuthal variation of the metal abundance in this 0.5–0.7\( r_{200} \) annulus is shown in Fig. 12. We find that the metal abundance is relatively uniform with azimuth, and it has an average value of 0.7\( Z_\odot \). This is consistent with the results from studies of other Suzaku clusters (Werner et al. 2013; Urban et al. 2017), which have found the metal abundance to be relatively uniform and consistent with a value of 0.3\( Z_\odot \).

In each spectral fit, to determine the effect of systematic uncertainties we followed Walker et al. (2013) and produced 10000 realizations of the background model and the NXB level (which Tawa et al. 2008 has found to have a systematic uncertainty of \( \pm 3 \) per cent), allowing all of these background components (unresolved CXB, Local Hot Bubble, Galactic Halo, and the NXB level) to vary simultaneously within their expected variances. We then performed the spectral fits for each realization of the background. The uncertainty in the background parameters is therefore folded through the deprojection, allowing a complete propagation of the systematic errors. Using the distribution of the 10000 spectral fits, we can that find the 1\( \sigma \) systematic errors, which we show as the solid blue lines in the temperature and entropy plots in Figs 5 and 7, respectively.

### 3 JOINT ANALYSIS

In order to explore the thermodynamic properties of the cluster A2199, we combined our clumping corrected density measurements recovered from the XMM–Newton observations with the deprojected gas temperature recovered from the Suzaku observations. The entropy profile of A2199 is recovered through the gas temperature (7) and density (\( n_e \)) profiles as

\[
K = \frac{kT}{n_e^2},
\]

The gas entropy is of particular interest since it tracks the thermal history of a cluster. In the presence of only non-radiative processes, numerical simulations (Voit, Kay & Bryan 2005) predicted that the gas entropy outside the cluster core follows a power law with a characteristic slope of 1.1,

\[
\frac{K}{K_{500}} = 1.47 \left( \frac{r}{r_{500}} \right)^{1.1},
\]

where the normalization is given by

\[
K_{500} = 106 \text{ keV cm}^2 \left( \frac{M_{500}}{10^{14} \text{ M}_\odot} \right)^{2/3} E(z)^{-2/3} f_b^{-2/3},
\]

\( M_{500} \) is the cluster mass at \( r_{500} \), \( f_b \) is the universal baryon fraction and assumed to be equal to 0.15, and \( E(z) \) describes the redshift evolution of Hubble parameter.

This baseline entropy profile tells us what the entropy of the ICM should be if only gravitational processes are considered. In addition to its shape, it also importantly gives a prediction for the normalization of the entropy. Any observed deviations from the predicted shape and normalization of the baseline entropy profile must be produced by non-gravitational processes, and so provide an insight into the history of heating of the ICM.

On very small scales (much smaller than the scales we consider) in the very central cores of cool core clusters (the inner 10 s of kpc), feedback from the central AGN causes the central entropy to be much flatter than the \( r^{1.1} \) power law, at around \( r^{0.67} \) (e.g. Babyk et al. 2018). Outside the central 10 s of kpc, the effect of the AGN on the entropy shape diminishes, and the entropy profile has been found to have a steeper gradient, typically close to but slightly less steep than an \( r^{1.1} \) power law (e.g. Babyk et al. 2018) find \( K \propto R \) in the 0.1–1\( r_{200} \) region, corresponding to around the 0.03–0.3\( r_{200} \) region). However, the normalization of observed entropy in the region 0.1–0.5\( r_{200} \) has been found to be significantly higher than the baseline.
entirety of the surface brightness within a given region of the cluster. This indicates that the effect of the AGN on the entropy level in clusters can only reach as far out as 0.6r_{200}. The main focus of this paper is on the behaviour of the ICM in the outskirts, in the region between 0.6 and 1.0r_{200}. These regions are so far out that the central AGN cannot affect them, and any deviation of the observed entropy from the baseline entropy profile must be due to some other physical factor.

The low X-ray surface brightness in these regions means that the gas temperature can only be measured through X-ray spectroscopy using an X-ray telescope with a low and stable X-ray background, and so accurate measurements of the temperature in these regions only became possible thanks to the Suzaku observatory, whose low Earth orbit provided it with the requisite low and stable background level. Early observations of the outskirts of clusters with Suzaku tended to find that the entropy in the 0.6–1.0r_{200} region was below the expected baseline entropy profile, indicating that some additional physical process in the outskirts must be acting to reduce the observed entropy level (see Walker et al. 2019 for a review). One important factor indicated by simulations is the effect of gas clumping: clumps of dense gas are expected to be more prevalent in the outskirts of clusters (Nagai & Lau 2011). Such clumps are too faint to be resolved directly by Suzaku (whose PSF is 2 arcmin half-power diameter), and would act to bias the observations by raising the observed surface brightness and density, causing the density to be overestimated in the outskirts, and hence causing the entropy \( K = kT/n_e^{2/3} \) to be underestimated.

Subsequent work using XMM–Newton observations of the outskirts of clusters (which has a much better PSF than Suzaku of around 15 arcsec half-power diameter) has found that it is possible to measure the level of gas clumping in the outskirts by binning the XMM image into a Voronoi tessellation, and examining the distribution of the surface brightness within a given region of the cluster (Eckert et al. 2015; Tchernin et al. 2016; Ghirardini et al. 2018). The gas clumping causes certain areas of the tessellation to have a higher than expected surface brightness, and this effect can be quantified by comparing the mean surface brightness in a region to the median surface brightness. The median is far less susceptible to outliers, and therefore provides a more realistic measure of the surface brightness, which is not affected by gas clumping. This allows the clumping factor to be found, as discussed in Section 2.1, and allowing the densities we measure to be corrected for any clumping bias.

Fig. 7 shows our measurements of the azimuthally averaged entropy profile of the A2199 cluster, which has been corrected for the effect of gas clumping. In the same figure, we also show the power-law entropy profile predicted by non-radiative simulations whose range is shown by the shaded pink region. Within r_{500}, our clumping corrected entropy measurements are in excess of the baseline entropy profile predicted by Voit et al. (2005), as typically found for low-mass clusters (Pratt et al. 2010).

Beyond r_{500}, however, our clumping corrected measurements agree well with the baseline entropy profile predicted by non-radiative simulations (the pink shaded region in Fig. 7). This shows that, when the whole cluster is considered and corrected for gas clumping, the entropy level agrees with the level expected from purely gravitational structure formation.

To quantify the slope of our azimuthally averaged entropy measurements, we fitted the entropy profile with piecewise power laws in several radial ranges, as described in Ghirardini et al. (2019). At radii between 2 and 26 arcmin, we find that the best fit yields a slope of 0.81 ± 0.19. Between 26 and 34 arcmin, the slope computed from the piecewise power-law fits is 0.14 ± 0.09. Beyond 34 arcmin, however, the estimated slope is 1.20 ± 0.23, which is consistent with a slope of 1.1 predicted by non-radiative simulations.

In Fig. 8, we present our clumping corrected entropy profiles in angular sectors. Beyond r_{500}, the entropy measurements in sectors show a significant azimuthal variation, with some of them lying significantly below the baseline entropy profile. These deviations from the baseline entropy profile suggest that, for a given sector considered by itself, some other physical process is affecting the entropy level. In particular, we see that the entropy in the outermost annulus of sector 3 lies well below the baseline entropy profile range. One candidate for causing such a low entropy in just one sector is the effect of filamentary gas streams, which are streams of low entropy gas seen in simulations (Zinger et al. 2016), flowing into the cluster along the direction of the cosmic web filaments which connect the cluster to the cosmic web.

We also calculated the gas and total masses of A2199 from the recovered density and temperature measurements using non-parametric methods, i.e. no modelling is adopted for the ICM properties. For the gas mass, the density measurements are integrated over a given volume and multiplied by the mean mass per electron, \( \mu_e m_p \). The gas mass takes the form:

\[
M_{gas} = 4\pi \mu_e m_p \int n_e(r) r^2 dr,
\]  

where the integration is computed using a four-point spline interpolation and the limit is taken out to some cut-off radius.

The total mass, which is mainly made up of the dark matter, is calculated assuming that the ICM gas is in the hydrostatic equilibrium in the cluster’s gravitational potential. The total mass can be expressed as

\[
M_{tot} = \frac{r^2}{G \mu_e m_p n_e(r)} \frac{dP_g(r)}{dr},
\]
where \( G \) is the Newtonian gravitational constant, and the gas pressure, \( P_g = 1.83n_e kT \), satisfies the ideal gas law. The derivative in equation (6) is computed using a three-point quadratic interpolation.

From these mass measurements, the gas mass fraction is then recovered as \( f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\text{tot}}} \). In Fig. 9, we show the gas and total masses of A2199 out to the virial radius. We find that our total mass measurement within \( r_{500} \) is \( (2.41 \pm 0.15) \times 10^{14} M_\odot \), consistent with the total mass of \( (2.08 \pm 0.28) \times 10^{14} M_\odot \) derived from the \( M-T \) scaling relation (Lovisari, Reiprich & Schellenberger 2015). Within \( r_{200} \) \((\approx 1.60 \text{ Mpc})\), the derived value of the total mass is \( (3.10 \pm 0.25) \times 10^{14} M_\odot \). This value consistent with the total mass of \( (3.16 \pm 0.48) \times 10^{14} M_\odot \) measured within 1.65 Mpc using the Wide-field Infrared Survey Explorer data (Lee et al. 2015). Our computed gas mass fraction at \( r_{200} \) is \( 0.160 \pm 0.008 \), and agrees well with the universal baryon fraction of \( 0.156 \pm 0.003 \) derived by Planck Collaboration XIII (2016).

4 DISCUSSION

4.1 Azimuthal variation in sectors

Fig. 11 illustrates the azimuthal variation of the entropy in the last bin for all of the sectors. Sectors 3, 5, and 9 show a significant deviation from the azimuthally averaged entropy and with the theoretical expectations from purely gravitational collapse. Fig. 12 shows the metal abundance in the radial range 0.5–0.7 \( r_{200} \). There is no sign of significant deviation of the metal abundance from the azimuthally averaged profile in the outskirts.

We also investigated the level of asymmetry of the thermodynamic properties of the ICM in the entire cluster’s radial range by computing the azimuthal scatter (Vazza et al. 2011; Ghirardini et al. 2018). The azimuthal scatter at radius \( r \) is defined as

\[
\sigma_q(r) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{q_i(r) - \bar{q}(r)}{\bar{q}(r)} \right)^2},
\]

where \( q_i(r) = \{C, n_e, T, M_{\text{gas}}, M_{\text{tot}}, f_{\text{gas}} \} \) in sector \( i \), \( N \) is the number of sectors, and \( \bar{q}(r) \) is the azimuthally averaged profile taken over the entire cluster volume.

In Fig. 13, we plot the azimuthal scatter in the radial profiles of the recovered thermodynamic quantities of the A2199 cluster. A large value of \( \sigma_q(r) \) seen in the cluster’s core and outskirts for some thermodynamic quantities implies the presence of an asymmetric gas. Also, there is a location near a radial range of 20–30 arcmin where we see a jump in the azimuthal scatter of the gas density, temperature, and entropy of the ICM.
values found in the simulations of Vazza et al. (2011), which find an apparent entropy deficit near the virial radius relative to the power-law entropy predicted from purely gravitational collapse, as shown in Figs 8 and 11. In those directions, A2199 is connected kinematically to the cluster A2197 (Rines et al. 2001) through a filamentary gas. These authors also found that two X-ray groups, positioning outside the virial radius of A2199, are connected to the A2199 cluster from the south direction. However, we find no sign of entropy decrement in this direction.

Such low-entropy gas in the north and north-east directions is consistent with what is expected for a filamentary gas stream (Zinger et al. 2016) with low entropy penetrating deep into the inner region of a cluster. However, we did not find a clear entropy deficit along those directions below \( r_{500} \). Zinger et al. (2016) argued that the penetration of a filamentary gas stream into the inner region of a cluster may change over time, depending on a range of factors such as the mass accretion rate along the filament. It is possible that the mass inflow rate is low along those directions and, therefore, unable to penetrate deeper into the inner two-third of the cluster’s virial radius.

These results highlight the importance of having high azimuthal coverage of clusters in the outskirts. The results show that individual small sectors are not necessarily representative of the cluster as a whole, and that a spatially resolved study of the thermodynamics of the cluster in multiple sectors is needed to capture the full picture of what is happening in the outskirts.

4.2.2 Metallicity

Werner et al. (2013) found that the iron abundance in the outskirts of the nearby Perseus cluster is remarkably constant, as a function of radius and azimuth, statistically consistent with a constant value of \( Z = 0.306 \pm 0.012 Z_\odot \) out to the virial radius of the cluster. More recently, Urban et al. (2017) reported metallicity measurements outside the central regions of a sample of 10 massive, nearby galaxy clusters observed with Suzaku. Their results also revealed a uniform iron abundance in the outskirts, confirming the findings for the Perseus cluster.

In the case of the A2199 cluster, the metal abundance for all of the azimuthal sectors appears relatively uniform in the outskirts (see Fig. 12). Werner et al. (2013) argued that the homogeneous distribution of the metal-enriched gas in the outskirts requires that most of the intragalactic medium enriched by metal before galaxy clusters formed, likely more than 10 billion years ago, during the epoch of utmost star formation and black hole activity. Recent numerical simulations by Biffi et al. (2017) supported the idea that the wide spreading of the metal-enriched gas in the outskirts occurred mostly at early times \( (z > 2) \), and found that this wide and homogeneous spreading of the metal-enriched gas is mainly driven by early AGN feedback acting on small haloes at \( z > 2 \) with shallower potential wells.

5 CONCLUSIONS

We have presented a joint Suzaku and XMM–Newton analysis of the outskirts of the rich and nearby galaxy cluster A2199, the only nearby cluster to be observed with near complete azimuthal coverage with Suzaku. By combining the clumping corrected density measurements obtained from the deprojection of the XMM–Newton’s surface brightness with the deprojected temperature recovered from Suzaku, we have been able to recover the entropy and the gas mass fraction measurements out to the virial radius. We have also measured the spatial variation of the metal abundance, a powerful probe of feedback physics, of the ICM in the A2199 outskirts.

Interestingly, the azimuthal scatter in the temperature is relatively high at \( r_{500} \), where we find a value of 0.5, which is higher than the values found in the simulations of Vazza et al. (2011), which find an azimuthal scatter in the temperature in the range 0–0.2.

4.2 Thermodynamics in outskirts

4.2.1 Entropy

In the north and north-east directions (sectors 3–5), there is an apparent entropy deficit near the virial radius relative to the power-law entropy predicted from purely gravitational collapse, as shown in Figs 8 and 11. In those directions, A2199 is connected kinematically to the cluster A2197 (Rines et al. 2001) through a filamentary gas. These authors also found that two X-ray groups, positioning outside the virial radius of A2199, are connected to the A2199 cluster from the south direction. However, we find no sign of entropy decrement in this direction.

Such low-entropy gas in the north and north-east directions is consistent with what is expected for a filamentary gas stream (Zinger et al. 2016) with low entropy penetrating deep into the inner region of a cluster. However, we did not find a clear entropy deficit along those directions below \( r_{500} \). Zinger et al. (2016) argued that the penetration of a filamentary gas stream into the inner region of a cluster may change over time, depending on a range of factors such as the mass accretion rate along the filament. It is possible that the mass inflow rate is low along those directions and, therefore, unable to penetrate deeper into the inner two-third of the cluster’s virial radius.

These results highlight the importance of having high azimuthal coverage of clusters in the outskirts. The results show that individual small sectors are not necessarily representative of the cluster as a whole, and that a spatially resolved study of the thermodynamics of the cluster in multiple sectors is needed to capture the full picture of what is happening in the outskirts.

4.2.2 Metallicity

Werner et al. (2013) found that the iron abundance in the outskirts of the nearby Perseus cluster is remarkably constant, as a function of radius and azimuth, statistically consistent with a constant value of \( Z = 0.306 \pm 0.012 Z_\odot \) out to the virial radius of the cluster. More recently, Urban et al. (2017) reported metallicity measurements outside the central regions of a sample of 10 massive, nearby galaxy clusters observed with Suzaku. Their results also revealed a uniform iron abundance in the outskirts, confirming the findings for the Perseus cluster.

In the case of the A2199 cluster, the metal abundance for all of the azimuthal sectors appears relatively uniform in the outskirts (see Fig. 12). Werner et al. (2013) argued that the homogeneous distribution of the metal-enriched gas in the outskirts requires that most of the intragalactic medium enriched by metal before galaxy clusters formed, likely more than 10 billion years ago, during the epoch of utmost star formation and black hole activity. Recent numerical simulations by Biffi et al. (2017) supported the idea that the wide spreading of the metal-enriched gas in the outskirts occurred mostly at early times \( (z > 2) \), and found that this wide and homogeneous spreading of the metal-enriched gas is mainly driven by early AGN feedback acting on small haloes at \( z > 2 \) with shallower potential wells.

5 CONCLUSIONS

We have presented a joint Suzaku and XMM–Newton analysis of the outskirts of the rich and nearby galaxy cluster A2199, the only nearby cluster to be observed with near complete azimuthal coverage with Suzaku. By combining the clumping corrected density measurements obtained from the deprojection of the XMM–Newton’s surface brightness with the deprojected temperature recovered from Suzaku, we have been able to recover the entropy and the gas mass fraction measurements out to the virial radius. We have also measured the spatial variation of the metal abundance, a powerful probe of feedback physics, of the ICM in the A2199 outskirts.

Interestingly, the azimuthal scatter in the temperature is relatively high at \( r_{500} \), where we find a value of 0.5, which is higher than the values found in the simulations of Vazza et al. (2011), which find an azimuthal scatter in the temperature in the range 0–0.2.

4.2 Thermodynamics in outskirts

4.2.1 Entropy

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We find that the azimuthally averaged, clumping corrected entropy profile is consistent in the outskirts with the baseline entropy profile, and the average gas mass fraction in the outskirts is consistent with the mean cosmic baryon fraction. When split into 10 sectors however, the entropy and temperature demonstrate significant azimuthal variation. We perform an azimuthally resolved study of the outskirts metal abundance and find it to be consistent with being uniform with an average value of $0.29_{-0.03}^{+0.03} Z_\odot$, which agrees well with previous findings by Werner et al. (2013) and Urban et al. (2017), and supports the hypothesis that the gas accreting on to galaxy clusters has been pre-enriched with metals.

ACKNOWLEDGEMENTS

We thank the referee for helpful comments that improved the paper. Based on observations obtained with Suzaku, a joint JAXA and NASA mission, and XMM–Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

DATA AVAILABILITY

The Suzaku data used in the paper are publicly available from the High Energy Astrophysics Science Archive Research Centre (HEASARC) Archive. The XMM–Newton Science Archive (XSA) stores the archival data used in this paper, from which the data are publicly available for download. The XMM data were processed using the XMM–Newton Science Analysis System (SAS). The software packages HEASOFT and XSPEC were used, and these can be downloaded from the HEASARC software web page. Analysis and figures were produced using Python version 3.7.

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APPENDIX A: SUZAKU AND XMM–NEWTON OBSERVATIONS OF A2199
Table A1. *Suzaku* observations of A2199.

| Name             | RA    | Dec.    | Obs. date    | Obs. ID  | Exposure (ks) | Offset (arcmin) |
|------------------|-------|---------|--------------|----------|---------------|-----------------|
| A2199 EAST OFFSET| 16 27 | + 40 14 | 2010-09-19   | 805042010| 58.44         | 46.350          |
| A2199 NE         | 16 30 | + 39 47 | 2014-01-04   | 808050010| 44.16         | 22.849          |
| A2199 FE         | 16 33 | + 39 38 | 2014-01-05   | 808051010| 40.35         | 52.760          |
| A2199 OFFSET8    | 16 29 | + 39 40 | 2011-08-23   | 806154010| 30.71         | 41.275          |
| A2199 OFFSET6    | 16 29 | + 38 47 | 2011-08-19   | 806152010| 29.79         | 44.657          |
| A2199 OFFSET7    | 16 31 | + 39 03 | 2011-08-19   | 806153010| 28.98         | 43.336          |
| A2199 OFFSET13   | 16 30 | + 39 59 | 2011-09-11   | 806159010| 28.65         | 30.444          |
| A2199 OFFSET16   | 16 31 | + 39 41 | 2011-10-06   | 806162010| 28.32         | 31.551          |
| A2199 OFFSET15   | 16 25 | + 39 53 | 2011-09-19   | 806161010| 28.17         | 37.962          |
| A2199 OFFSET9    | 16 26 | + 38 54 | 2011-09-12   | 806155010| 28.13         | 44.286          |
| A2199 OFFSET14   | 16 25 | + 39 31 | 2011-09-21   | 806160010| 27.44         | 41.366          |
| ABELL 2199 OFFSET3 | 16 29 | + 39 18 | 2006-10-04   | 801059010| 25.25         | 15.695          |
| ABELL 2199 CENTER | 16 28 | + 39 29 | 2006-10-01   | 801056010| 24.93         | 2.998           |
| ABELL 2199 OFFSET1 | 16 28 | + 39 39 | 2006-10-01   | 801057010| 24.63         | 9.578           |
| ABELL 2199 OFFSET4 | 16 28 | + 39 18 | 2006-10-04   | 801060010| 24.45         | 13.770          |
| ABELL 2199 OFFSET12 | 16 27 | + 39 55 | 2011-09-16   | 806158010| 23.59         | 26.527          |
| ABELL 2199 OFFSET2 | 16 29 | + 39 38 | 2006-10-03   | 801058010| 22.71         | 12.189          |
| ABELL 2199 OFFSET3 | 16 26 | + 39 33 | 2011-08-17   | 806149010| 21.37         | 24.640          |
| ABELL 2199 OFFSET11 | 16 26 | + 39 13 | 2011-09-11   | 806157010| 20.65         | 30.964          |
| ABELL 2199 OFFSET1 | 16 29 | + 38 59 | 2011-08-16   | 806147010| 20.30         | 34.720          |
| ABELL 2199 OFFSET2 | 16 28 | + 38 40 | 2011-08-17   | 806148010| 20.29         | 32.371          |
| ABELL 2199 OFFSET4 | 16 31 | + 39 22 | 2011-08-18   | 806150010| 18.71         | 29.836          |

Table A2. *XMM–Newton* observations of A2199.

| Name           | RA    | Dec.    | Obs. date    | Obs. ID  | Exposure (ks) | Offset (arcmin) |
|----------------|-------|---------|--------------|----------|---------------|-----------------|
| A2199 1        | 16 28 | + 39 33 | 2002-07-04   | 0008030201| 22.98         | 1.69            |
| A2199 2        | 16 30 | + 39 23 | 2011-09-08   | 067190010| 31.02         | 23.85           |
| A2199 3        | 16 26 | + 39 00 | 2013-02-22   | 069101010| 47.83         | 38.12           |
| A2199 4        | 16 25 | + 39 26 | 2013-02-28   | 0691010901| 31.91         | 33.87           |
| A2199 5        | 16 26 | + 39 00 | 2013-02-26   | 0691011001| 33.92         | 38.12           |
| A2199 6        | 16 28 | + 39 33 | 2013-08-12   | 072380110| 57.00         | 1.58            |
| A2199 7        | 16 26 | + 39 26 | 2017-03-03   | 078452110| 40.00         | 22.28           |
| A2199 8        | 16 30 | + 39 44 | 2017-03-07   | 0784521201| 40.00         | 25.88           |
| A2199 9        | 16 28 | + 39 58 | 2017-03-18   | 0784521301| 30.00         | 26.80           |
| A2199 10       | 16 30 | + 40 06 | 2017-03-21   | 0784521401| 37.80         | 42.33           |
| A2199 11       | 16 26 | + 39 53 | 2017-03-21   | 0784521501| 32.00         | 30.57           |
| A2199 12       | 16 24 | + 39 06 | 2017-03-22   | 0784521701| 31.90         | 49.37           |

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