X-ray spectral study of hot gas in three clusters of galaxies

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ABSTRACT

Aims. We studied the physical properties of three clusters of galaxies, selected from a BeppoSAX wide field camera (WFC) survey. These sources are identified as 1RXS J155329.7–833535, 1RXS J160147.6–754507, and 1RXS J081232.3–571423 in the ROSAT All-Sky Survey catalogue. We obtained XMM-Newton follow-up observations for these three clusters.

Methods. We fitted single and multi-temperature models to spectra obtained with the EPIC-pn camera to determine the temperature, the chemical composition of the gas and their radial distribution. Since two observations were contaminated by a high soft-proton background, we developed a new method to estimate the effect of this background on the data.

Results. We present the temperature and iron abundance of two of these three clusters for the first time. The iron abundance of 1RXS J155329.7–833535 decreases with radius. The fits to the XMM-Newton and Chandra data show that the radial temperature profile within 3′ towards the centre either flattens or lowers. A Chandra image of the source suggests the presence of X-ray cavities. The gas properties in 1RXS J160147.6–754507 are consistent with a flat radial distribution of iron and temperature within 2′ from the centre. 1RXS J081232.3–571423 is a relatively cool cluster with a temperature of about 3 keV.

Conclusions. The radial temperature and iron profiles suggest that 1RXS J155329.7–833535 is a cool core cluster. The Chandra image shows substructure which points toward active galactic nuclei (AGN) feedback in the core. The flat radial profiles of the temperature and iron abundance in 1RXS J160147.6–754507 are similar to the profiles of non-cool-core clusters.

Key words. X-rays: galaxies: clusters – galaxies: clusters: individual: 1RXS J155329.7–833535 – galaxies: abundances – galaxies: clusters: intracluster medium – galaxies: clusters: individual: 1RXS J160147.6–754507

1. Introduction

Clusters of galaxies are the largest gravitationally bound objects in the universe. They are the result of the growth of overdensities that were present in the early universe. About 80% of the mass in clusters consists of dark matter. Until now it has been impossible to directly measure it. The baryonic matter in clusters of galaxies resides in the stars and a hot di-

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Table 1. Previously known parameters for the studied sources.

| Object | WFC flux$^a$ | ROSAT flux$^b$ | Redshift$^c$ |
|--------|-------------|---------------|-------------|
| J1539  | 0.82        | 1.68$^{d,e}$  | 0.0728$^d$  |
| J1601  | 1.28        | 2.49$^f$      | 0.1530$^g$  |
| J0812  | 1.14        | 3.93$^f$      | 0.0620$^g$  |

Notes. (a) 2–10 keV, $10^{-14}$ W m$^{-2}$ for Crab-like spectrum (i.e. a power law with a photon index of 2). (b) 0.1–2.4 keV, $10^{-14}$ W m$^{-2}$. (c) Determined using optical spectroscopy. (d) From REFLEX (Böhringer et al. 2004). (e) Using a Raymond-Smith model (Raymond & Smith 1977). (f) From CIZA (Ebeling et al. 2002).

We followed up these bright sources using XMM-Newton. For one source we analysed the available Chandra archival data. Three of these six are clusters of galaxies. The physical properties of the gas in these clusters were found using the X-ray spectra.

Throughout this paper, we use $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}, \Omega_M = 0.3, \text{ and } \Omega_{\Lambda} = 0.7$. The abundances are in units of the protosolar abundances by Lodders (2003). Unless specified otherwise, quoted statistical uncertainties are at a 1σ (68%) confidence level.

2. The clusters discussed in this paper

Here, we introduce the three observed clusters and give an overview of the catalogues in which they appear. We refer to the three clusters by the first four numerals from their 1RXS-catalogue name preceded by the letter “J”. The fluxes and luminosities found by previous authors are quoted in Table 1.

2.1. J1539 (1RXS J153934.7−833535)

This source is part of the REFLEX catalogue (RXC J1539.9−8335, Böhringer et al. 2004), a cluster survey based on ROSAT data.

2.2. J1601 (1RXS J160147.6−754507)

J1601 is part of the ROSAT catalogue of clusters in the “zone of avoidance”, meaning a location within 20° of the Galactic plane (CIZA J1601.7−7544, Ebeling et al. 2002). That is also the first detection and identification of this source as a cluster of galaxies. The source also appears in the RXTE All-Sky Slew Survey catalogue, (XSS J16019−7548, Revnivtsev et al. 2004). Figure 1 shows intensity contours of an archival observation of this source, using the HRI aboard ROSAT.

2.3. J0812 (1RXS J081232.3−571423)

J0812 was first detected by the Einstein X-ray satellite as part of the Einstein Galactic plane survey (1E0811.5−5704, Hertz & Grindlay 1984). Furthermore, it appears in the Einstein Slew Survey (1ES0811.4−5704, Elvis et al. 1992) and is also part of the 2E catalogue (2E0811.4−5704, Harris et al. 1990). The source was identified as a cluster of galaxies by Ebeling et al. (2002) and incorporated in the CIZA catalogue (CIZA J0812.5−5714).

3. Data reduction and analysis

3.1. XMM-Newton EPIC

A log of the XMM-Newton European photon imaging camera (EPIC; Strüder et al. 2001) observations is given in Table 2. For all our observations the “medium” filter was put in place. For each observed source, we extract a lightcurve to look for soft-proton flares. Since emission from clusters of galaxies is not time dependent, we use the full energy range of the detector to extract this light curve. We compared the lightcurves within 3′ around the cluster centre to the lightcurve of the remainder of the field. Both light curves show flaring at the same time scales which excludes the possibility of a variable point source affecting the light curve. For two observations (J1539 and J1601), the residual soft-proton background was very high (see Sect. 3.3). We excluded data during the flares on top of this high background. The original and filtered observation times are listed in Table 2.

3.1.1. Standard data treatment

The data reduction is done with version 8.0.1 of the XMM-Newton science analysis software (SAS). We used the calibration version of April 1st of 2009 and the standard EPIC-pn pipeline to create event files. During the observations, EPIC-MOS was in small window mode. We did not use these data because in this mode the source is larger than the field of view. We removed the
point sources by eye using a circle with a 15″ radius around them. The next step involved correcting for the vignetting of the photons and protons. For the observation of J0812, which is not dominated by a high soft-proton background, we used the `evigweight` task to take this effect into account. This task assigns a theoretical vignetting factor to each photon based on its energy and position on the CCD. For the other two observations, we took care of the soft-proton vignetting as described in Sect. 3.1.2. We selected only the single and double events (PATTERN≤4) that were inside the field of view (FLAG=0). For each separate spectrum, we generated an ancillary response file (ARF) and a response matrix file (RMF) using a detector map. For J0812, we took the detector map to be flat (i.e. without any spatial distribution) because spatial effects are already taken care of by the vignetting correction of `evigweight`. For J1539 and J1601, we made an image of the event file and used that as a detector map.

For the spectral reduction, we rebinned the spectra, sampling the instrument FWHM by a factor of three, requiring at least 20 counts per bin to ensure the applicability of χ² statistics if needed, and checked that spectral features were not undersampled.

The next step was the background treatment. Since the sources are relatively compact, we took the background from an annulus ranging from 9′ to 12′, centred on the telescope pointing. This is the outer edge of the field of view where we did not expect any residual cluster emission. We scaled the background spectrum with the ratio of the number of illuminated pixels in the observations to the background annulus. We subtracted the scaled background spectrum from the observation. Since there is a strong instrumental copper line at 8.04 keV in the background region, we ignored the energy range from 7.8 keV to 8.4 keV for analysis of the spectra to ensure that no radiation of this line was still present. For other instrumental lines, this effect is expected to be negligible in the energy range of the fit due to the statistics of the observations.

3.1.2. Special treatment of flared events

Normally the intervals of soft-proton flaring in the light curve are excluded from the analysis. The observations of J1539 and J1601 have a very high background. Inspection of the light curves of these observations for the region outside the 3′ around J1601 have a very high background. For the other two observations, we took care of the soft-proton vignetting as described in Sect. 3.1.2. We selected only the single and double events (PATTERN≤4) that were inside the field of view (FLAG=0). For each separate spectrum, we generated an ancillary response file (ARF) and a response matrix file (RMF) using a detector map. For J0812, we took the detector map to be flat (i.e. without any spatial distribution) because spatial effects are already taken care of by the vignetting correction of `evigweight`. For J1539 and J1601, we made an image of the event file and used that as a detector map.

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3.2. Chandra

Chandra data are available only for J1539. The 8 ks ACIS observation was taken in pointing mode on 24 June 2007. The Chandra observation does not suffer from high background. This together with a high spatial resolution allowed us to investigate the spatial properties of the object. We then performed the spectral analysis of the regions marked in Fig. 3. To compare both data sets, we also analysed the spectra based on the same annuli as used in the XMM-Newton analysis. This comparison is discussed in Sect. 4.1.

3.3. Spectral models

We fitted the spectra with the SPEX package (Kaastra et al. 1996). We employ two different models. The first is the collisionally ionised equilibrium (CIE) plasma model based on the MEKAL code (Mewe et al. 1995), implemented as the `cfe` model in SPEX. This model represents an isothermal gas, which is appropriate for low-statistics data, where we cannot distinguish between single and multi-temperature models. For data with higher statistics, a differential emission measure (DEM) type model can be used (e.g. Kaast et al. 2004). In this model the emission measure \( Y = \int n_e n_{\text{H}^1} dV \) (where \( n_e \) and \( n_{\text{H}^1} \) are the electron and...
proton densities and $V$ is the source volume) is a function of temperature. The \textit{wdem} model (Kaastra et al. 2004) is a parametrisation of this type, which provides a good empirical description of the cores of clusters of galaxies (e.g. de Plaa et al. 2004; Kaastra et al. 2004). The model consists of thermal components distributed as a truncated power law. The model is characterised by
density distribution.

\begin{equation}
dY dT = \begin{cases} cT^{1/\alpha} & \beta T_{\text{max}} \leq T < T_{\text{max}} \\ 0 & T > T_{\text{max}} \vee T < \beta T_{\text{max}} \end{cases}.
\end{equation}

The lower temperature cutoff of the distribution is located at $\beta kT_{\text{max}}$. This form of the model is chosen in a way that if $\alpha$ approaches 0, the model becomes isothermal with temperature $kT_{\text{max}}$. For this study, we empirically found that $\beta \approx 0.18$ yields a model which has negligible degeneracy between the maximum temperature ($kT_{\text{max}}$) and the power law slope ($1/\alpha$). This value agrees with earlier work (de Plaa et al. 2006; Werner et al. 2006).

For a comparison between the outcomes of the (multi-temperature) \textit{wdem} model to single-temperature-models, we employed the mean temperature, $T_{\text{mean}}$. This value is defined as

\begin{equation}
T_{\text{mean}} = \frac{\int T \frac{dT}{dT} dT}{\int \frac{dT}{dT} dT}.
\end{equation}

The evaluation of the integral between $\beta kT_{\text{max}}$ and $kT_{\text{max}}$ yields, in terms of the model parameters

\begin{equation}
kT_{\text{mean}} = \frac{(1 + 1/\alpha)(1 - \beta^{1/\alpha+2})}{(2 + 1/\alpha)(1 - \beta^{1/\alpha+1})} kT_{\text{max}}.
\end{equation}

We used a neutral absorbing gas model for the determination of the interstellar hydrogen column density. Since the hydrogen column density value from H\textsc{i} maps (e.g. Dickey & Lockman 1990; Kalberla et al. 2005) does not include molecular hydrogen, it is possibly lower than the value needed to fit the spectrum. Therefore we kept $N_{\text{H}}$ as a free parameter in our fits.

\section*{4. Results}

A summary of the parameters fitted to the data from the $3\prime$ around the centre of the three clusters (which we will hereafter refer to as the “integrated” spectrum) is given in Table 3. The nominal statistical uncertainties of the fits are shown, as well as the lower and upper limits for the temperature of the surrounding gas of 3\textsc{kpc}.

\begin{table}[h]
\centering
\begin{tabular}{c c c}
\hline
Region & $kT$ (keV) & Fe abundance (proto-solar) \\
\hline
1 & 3.02 $\pm$ 0.13 & 0.9 $\pm$ 0.3 \\
2 & 2.7 $\pm$ 0.2 & 0.41 $\pm$ 0.14 \\
res. & 3.28 $\pm$ 0.14 & 0.52 $\pm$ 0.11 \\
\hline
\end{tabular}
\caption{Summary of the fits to the \textit{Chandra} ACIS spectra of J1539.}
\end{table}

\section*{Notes.}

\begin{itemize}
\item \textsuperscript{(a)} The regions are shown in Fig. 3. \textsuperscript{(b)} For this spectrum, regions “1” and “2” are excluded.
\end{itemize}

(\textsuperscript{(a)} \textsuperscript{(b)}) (in brackets) the uncertainty associated with the statistical uncertainty of the subtracted background. In Fig. 5, optical and X-ray images of the sources are shown. We also fitted the spectra of different annuli employing the same model as for the integrated spectrum (Figs. 6 and 7). In the following sections we describe the results for each source.

\subsection*{4.1. J1539}

The integrated spectrum of our brightest source, J1539, is shown in Fig. 4. As shown in the plot, the background is high compared to the source (see also Sect. 3.1.2). The effect is noticeable for the part of the spectrum above 2.5 keV. We fitted a \textit{wdem} model to the background-subtracted spectrum. The mean temperature of the source is 3.03 $\pm$ 0.15 keV.

Visual inspection of the \textit{Chandra} image of J1539 (see Fig. 3) shows complexity in the cluster morphology: a compact bubble-shaped region and an extended structure in the upper part of it stand out from the weaker diffuse emission of the cluster. The three regions indicated in the image yield the parameters cited in Table 4. Due to the relatively low statistics, we fitted a single-temperature model to these spectra. The region labelled “2” has a temperature of 2.7 $\pm$ 0.2 keV, which is slightly below the temperature of the surrounding gas of 3.28 $\pm$ 0.14 keV. This is consistent with the values found in the XMM-\textit{Newton} analysis. Fits to the 0–3\textquoteleft region of the \textit{Chandra} observation yield a hydrogen column density of $(17.2 \pm 1.3) \times 10^{24}$ m$^{-2}$. This is consistent with the best-fit column density derived for the XMM-\textit{Newton} data, $(20.0 \pm 0.4 \text{ (0.2)}) \times 10^{24}$ m$^{-2}$. Here, the uncertainty between parentheses is due to the uncertainty in the background

Fig. 3. \textit{Chandra} image of J1539, based on a 8 ks observation using the ACIS instrument. There are no X-ray point sources in the region shown. The image is smoothed using a Gaussian with a standard deviation of 2.5 pixels. The white circle represents the position of the central cD galaxy in this cluster. In the left panel, a hint of sub-structure is visible. The regions we used to fit the different parts of the spectrum are shown in the right panel. The projected radii of the elliptical “res.” region are 97 kpc (width) and 89 kpc (height).

Fig. 4. The EPIC-pn spectrum of J1539 (crosses) with subtracted background level (histogram) as explained in Sect. 3.1.2 and the fitted model (connected line). The part above 2 keV is rebinned with a factor two for presentational purposes.

Table 4. Summary of the fits to the \textit{Chandra} ACIS spectra of J1539.

Notes. \textsuperscript{(a)} The regions are shown in Fig. 3. \textsuperscript{(b)} For this spectrum, regions “1” and “2” are excluded.
Table 3. Best-fit parameters for spectra of the 3’ around the centre of the galaxy clusters.

| Parameter                      | J1539 (XMM-Newton)
|--------------------------------|-----------------------|
| Background scaling factor      | 0.99 ± 0.02           |
| Hydrogen column density (10^{24} m^{-2}) | 20.0 ± 0.4           |
| Hydrogen 21 cm column density (10^{24} m^{-2}) | 8.38               |
| Emission measure (10^{53} m^{-3}) | 2.57 ± 0.04           |
| Temperature (keV)              | 3.03 ± 0.15           |
| 1/α                           | 0.48 ± 0.09           |
| Fe abundance                   | 0.61 ± 0.03           |
| Si/Fe abundance                | 0.65 ± 0.12           |
| Ni/Fe abundance                | 2.81 ± 0.56           |
| Flux (0.1–2.4 keV) [10^{-14} W m^{-2}] | 1.03 ± 0.02         |
| Flux (2–10 keV) [10^{-14} W m^{-2}] | 1.11 ± 0.02          |
| C-stat / d.o.f.                | 270/229               |
| χ^2 / d.o.f.                   | –                    |

Notes. (a) The first quoted uncertainty is the statistical uncertainty on the value. The uncertainty between parentheses is due to the uncertainty in background estimation (Sect. 3.1.2). (b) For this source, we fitted a “wdem” model. (c) The emission measure is defined as $Y = \int n_e n_H dV$, see also Sect. 3.3. (d) Deduced from the 21 cm map by Dickey & Lockman (1990). (e) For wdem: “mean temperature”, see Eq. (3). (f) As defined in Eq. (1).

Fig. 5. X-ray (top) and optical (bottom) images of the studied clusters. Top and bottom image are at the same scale and the length of the scale bars is 30’. J1539 and J0812 both have a clear cD galaxy in the centre. In J1601 there are three bright foreground stars in the field of view, which makes any optical central structure in this cluster hard to see.

determination by comparing the values of maximum and minimum background scaling factors.

4.2. J1601

The temperature fitted for the integrated spectrum of this source is 8.24 ± 0.58(±0.97) keV (see Table 3). The fit is acceptable (see Table 3). We did not find significant multi-temperature structure for this source. Figure 7 shows that there is a flat radial temperature and iron abundance distribution. Silicon and nickel abundances were not measured in any significant way.

4.3. J0812

This is the only source for which the background during the observation was not high. Because we multiplied the counts in the image with the theoretical vignetting weighting, the uncertainties are not the square root of the measured counts anymore. In
5. Discussion and conclusions

We reported the spectral properties of three moderately bright clusters, which were selected from WFC data. Radial temperature and abundance profiles of the cores of J1539 and J1601 were obtained. In addition, the temperature and iron abundance in the highly absorbed cluster J0812 are measured. We were able to derive accurate temperatures and abundances, despite the high soft-proton background in two of our cluster observations. In Sect. 3.1.2, we described a novel method to estimate the vignetting factor of soft protons for EPIC-pn. The systematic uncertainties introduced by this new method are mostly similar to or smaller than the statistical uncertainties found in our spectral fits. From the plots in Figs. 6 and 7, it is clear that the effect of the background subtraction becomes more important further away from the centre of the field of view due to the distribution of the source brightness. Especially in the 2–3′ region of the upper panel of Fig. 6 it is clear that this effect is non-negligible when measuring temperatures.

The difference we fitted between the 0.1–2.4 keV fluxes we found as well as the fluxes from both the ROSAT all sky survey (Voges et al. 1999) and the REFLEX catalogue (Böhringer et al. 2004) are typically 20–30%. A comparison of the fluxes with catalogue values is however not straightforward. The measured flux depends on the model used and the extraction region (in our case 3′). Furthermore, the hydrogen column density used in these catalogues is based on the H i data from Dickey & Lockman (1990). The value we used is found by fitting the spectra. We found a higher column density in two of our cases. For J1539, the higher column density is also found with the Chandra data.

5.1. J1539

J1539 is the brightest source of our cluster sample. We found a hydrogen column density that is a factor 2.4 higher than the value from Dickey & Lockman (1990). This value is consistent between XMM-Newton and Chandra. The mean temperature of the integrated spectral region for this cluster is about 3 keV, which indicates that J1539 is a relatively cool cluster. This source also had a significant multi-temperature structure when we fitted the spectrum with a differential emission measure (DEM) model. The strong radial iron gradient in J1539 is similar to abundance gradients found in cool-core clusters (De Grandi et al. 2004; Tamura et al. 2004). In the Chandra data, no clear trend is visible, which is due to the large error bars of the outer data points.
The Chandra image shows structure in the core (see Fig. 3). The central elliptic region (labelled “1”) is cooler than its surroundings, and the top region (labelled “2”) is cooler than the rest of the gas, which is at comparable distances from the core (labelled “res.”). The Fe abundance is consistent with the value derived from the XMM-Newton observation. There is a slight hint for a higher Fe abundance in the region “1”. The morphology looks similar to other examples of cool-core clusters where bubbles were observed, for example in Abell 2052 (Blanton et al. 2001) and Hydra A (McNamara et al. 2000). The bubbles in clusters are thought to be caused by AGN outbursts in the central galaxy (for a review on this topic see McNamara & Nulsen 2007). These outbursts are detected in the radio domain and create cavities in the X-ray emission of the gas. These AGN also seem to provide the energy needed to keep the gas from cooling below ~0.5 keV. Gas at these temperatures is not observed in clusters of galaxies (Tamura et al. 2001; Kaasstra et al. 2001; Peterson et al. 2001, 2003; Kaasstra et al. 2004), therefore a reheating process of the gas is needed.

In the top panel of Fig. 6 we present the temperature profiles derived from our fits, and compared them to the profile derived by Cavagnolo et al. (2009). Both our radial XMM-Newton and Chandra temperature profiles are significantly different from their profile because they keep the hydrogen column density fixed to the H I value. We let the hydrogen column density free in our fits, and found a value which is 2.4 times higher in both the Chandra and the XMM-Newton data sets.

The radial temperature profile derived from the XMM-Newton data shows a strong decline in the 1–3′ region. The Chandra data however show a much weaker decline. We compared the radial temperature profiles with a profile, based on average profiles compiled by Leccardi & Molendi (2008). They show profiles for the cooling-core, unidentified cooling core and non-cooling core clusters. This classification is based on the radial behaviour of temperature in the cluster core. Since we did not measure a significant temperature decrease with XMM-Newton in this region, we compare our results with the average of the unidentified cooling core clusters.

The temperature $kT_{\text{mean}}$ in Leccardi & Molendi (2008) is defined by fitting a single temperature model to the region between 0.1 $R_{180}$ and 0.6 $R_{200}$. However, the annuli we fitted extend only to 0.2 $R_{200}$. Therefore we could not use this range for our mean temperature. To compare the two data sets with the trend, we scaled the relative temperature to the value of the innermost bin. This results in the plot shown in Fig. 8.

Since the shape of the Chandra and XMM-Newton temperature profiles are different, the scaling on the innermost bin results in more significant deviations between the profiles at larger radii (see Fig. 8). The absolute temperatures in the three inner bins lie within 2.1σ. Furthermore, the scaled XMM-Newton data point at 0.17 $R_{200}$ is 4.7σ below the average profile of Leccardi & Molendi (2008).

The difference in profile shapes between XMM-Newton, Chandra and the average profile can be explained in multiple ways. The cooler temperature of the innermost bin as measured by Chandra may be partly due to point spread function (PSF) effects. The larger PSF of XMM-Newton may cause photons from the second radial bin to scatter into the central bin and subsequently raise the derived temperature. In addition, the subtracted soft-proton background may not exactly represent the true soft-proton spectrum as measured in the annuli. This is because the soft-proton spectrum in the inner annuli might have a slightly different slope compared to the soft-proton spectrum in the outermost annulus on which the subtracted background is based. The slope of the subtracted background can have a significant influence on the measured temperature, especially in the outer annuli where the background is high with respect to the source spectra.

5.2. J1601

The hydrogen column density that we fitted for J1601 is consistent with the value based on the H I maps of Dickey & Lockman (1990). We derived a temperature for the integrated spectrum, which is rather high for clusters of galaxies. Clusters with high temperatures have less prominent spectral lines, and the fit of the temperature is mostly dependent on the continuum. Therefore, the uncertainty on the background scaling factor introduces a large systematic uncertainty on the temperature.

The flat temperature and iron abundance profiles suggest however that J1601 is a non-cooling core cluster. This means either that the core of the cluster has not cooled yet or was recently reheated. The rate at which the cluster core cools can be estimated by the cooling time. This is the typical time scale during which the core should have radiated all its energy away. Sarazin (1988) gives for the cooling time of a cluster of galaxies

$$t_{\text{cool}} = 8.5 \times 10^{10} \left( \frac{n_p}{10^3 \text{ m}^{-3}} \right)^{-1} \left( \frac{T_g}{10^8 \text{ K}} \right)^{1/2} \text{ yr.}$$

In this equation, $T_g$ is the gas temperature and $n_p$ represents the proton density. The volume is calculated with the Cosmology Calculator by Wright (2006). We used the emission measure that we found for the innermost 30″ of the cluster core ((1.98 ± 0.08) × 10$^{53}$ m$^{-3}$) and the temperature of the same region (7.4 ± 0.7 keV), assuming that this region is a sphere with 1

In Leccardi & Molendi (2008), $R_{200}$ is used. Based on their definition of that radius and the definition of the $R_{500}$ from Arnaud et al. (2005) we find that $R_{500} = 1.012 R_{180}$. Y. G. Grange et al.: X-ray spectral study of hot gas in three clusters of galaxies
constant density. We took the electron density to be a factor 1.2 higher than the proton density. The cooling time we compute is 4.9 ± 0.2 Gyr, which is about 1/2 of the Hubble time at the redshift of J1601, which indicates that the cluster has had enough time to cool.

A merger at an early stage of the clusters life could cause shocks, which would reheat the gas. This could explain the absence of a cool core when the cooling time is more than ~0.1 Hubble times (e.g. Burns et al. 1997; Gómez et al. 2002). The image of this cluster made using XMM-Newton (top-middle panel of Fig. 5) and the intensity contours of the ROSAT HRI (Fig. 1) hint towards an elongation of the X-ray cluster emission. This hint is however not statistically strong enough to pinpoint a merger. The bottom-middle panel of Fig. 5 shows three very bright foreground stars, which make it hard to state whether there is one central galaxy or if the core consists of multiple galaxies, which could indicate a merger history.

5.3. J0812

The 0.1–2.4 keV flux we derived for this source is 60% lower than the ROSAT value of Voges et al. (1999). The integrated temperature is relatively low and the iron abundance is slightly lower than the average of larger cluster samples (e.g. Tamura et al. 2004; De Grandi et al. 2004; de Plaa et al. 2006). The hydrogen column density we fitted is high, 36% higher than the value of Dickey & Lockman (1990). Although this is the only observation for which the soft-proton background is very low, it is also the dimmest of the three sources. Therefore, the statistical quality of this observation is limited.

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References

Abell, G. O. 1958, ApJS, 3, 211
Allen, S. W., Schmidt, R. W., & Fabian, A. C. 2002, MNRAS, 334, L11
Arnaud, M., Pointecouteau, E., & Pratt, G. W. 2005, A&A, 441, 893
Blanton, E. L., Sarazin, C. L., McNamara, B. R., et al. 2001, ApJS, 558, L15
Boella, G., Butler, R. C., Perola, G. C., et al. 1997, A&A, 122, 299
Bohringer, H., Schuecker, P., Guzzo, L., et al. 2004, A&A, 425, 367
Bravo, Mayer, W., Naranan, S., Rappaort, S., & Spada, G. 1967, ApJ, 150, L199
Burns, J. O., Loken, C., Gomez, P., et al. 1997, in Galactic Cluster Cooling Flows, ed. N. Sokera (San Francisco: ASP), PASPC, 115, 21
Byram, E. T., Chubb, T. A., & Friedman, H. 1986, Science, 152, 66
Cash, W. 1979, ApJ, 228, 939
Cavagnolo, K. W., Donahue, M., Voi, G. M., et al. 2009, A&JS, 182, 12
Cavaliere, A. G., Gursky, H., & Tucker, W. H. 1971, Nature, 231, 437
David, L. P., Arnaud, K. A., Forman, W., et al. 1990, ApJ, 356, 32
De Grandi, S., Ettori, S., Longhetti, M., et al. 2004, A&A, 419, 49
de Plaa, J., Kaasstra, J. S., Tamura, T., et al. 2004, A&A, 423, 492
de Plaa, J., Werner, N., Bykov, A. M., et al. 2006, A&A, 452, 397
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Ebeling, H., Mullis, C. R., & Tully, R. B. 2002, ApJ, 580, 774
Elvis, M., Plummer, D., Schachter, J., et al. 1992, ApJS, 80, 257
Gómez, P. L., Loken, C., Rottgering, K., et al. 2002, ApJ, 569, 122
Harris, D. E., Forman, W., Gioia, I. M., et al. 1990, in Imaging X-Ray Astronomy. A Decade of Einstein Observatory Achievements, ed. M. Elvis (Cambridge: Cambridge Univ. Press), 309
Hertz, P., & Grindlay, J. E. 1984, ApJ, 278, 137
Jager, R., Mels, W. A., Brinkman, A. C., et al. 1997, A&AS, 125, 557
Kaasstra, J. S., Mewe, R., & Nieuwenhuijzen, H. 1996, in UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas, ed. K. Yamashita, & T. Watanabe (Tokyo: Univ. Acc. Press), 411
Kaastra, J. S., Ferrigno, C., Tamura, T., et al. 2001, A&A, 365, L99
Kaastra, J. S., Tamura, T., Peterson, J. R., et al. 2004, A&A, 413, 415
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Kellogg, E., Gursky, H., Leong, C., et al. 1971, ApJ, 165, L49
Kuntz, K. D., & Snowden, S. L. 2008, A&A, 478, 575
Leccardi, A., & Molendi, S. 2008, A&A, 486, 359
Lodders, K. 2003, ApJ, 591, 1220
McNamara, B. R. & Nulsen, P. E. J. 2007, ARA&A, 45, 177
McNamara, B. R., Wise, M., Nulsen, P. E. J., et al. 2000, ApJ, 534, L135
Mewe, R., Kaasstra, J. S., & Liedahl, D. A. 1995, Legacy, 6, 17
Peterson, J. R., Paerels, F. B. S., Kaasstra, J. S., et al. 2001, A&A, 365, L104
Peterson, J. R., Kahn, S. M., Paerels, F. B. S., et al. 2003, ApJ, 590, 207
Raymond, J. C., & Smith, B. W. 1977, ApJ, 214, 51
Reiprich, T. H., & Bohringer, H. 2002, ApJ, 567, 116
Revnivtsev, M., Sazonov, S., Jahoda, K., et al. 2004, A&A, 418, 297
Sarazin, C. L. 1988, X-ray emission from clusters of galaxies, ed. C. L. Sarazin (Cambridge: Cambridge Univ. Press)
Strüder, L., Briell, U., Dennerl, K., et al. 2001, A&A, 365, L18
Tamura, T., Kaasstra, J. S., Peterson, J. R., et al. 2001, A&A, 365, L87
Peterson, J. R., Kaasstra, J. S., den Herder, J. W. A., Bleecker, J. M. A., & Peterson, J. R. 2004, A&A, 420, 135
Verrecchia, F., in’t Zand, J. J. M., Gioini, P., et al. 2007, A&A, 472, 705
Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389
Werner, N., Bohringer, H., Kaasstra, J. S., et al. 2006, A&A, 459, 353
Wood, K. S., Meeks, J. F., Yentis, D. J., et al. 1984, ApJS, 56, 507
Wright, E. L. 2006, PASP, 118, 1711