Systematic X-Ray Analysis of Radio Relic Clusters with Suzaku

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Abstract

We undertook a systematic X-ray analysis of six giant radio relics in four clusters of galaxies using the Suzaku satellite. The sample included CIZA 2242.8+5301, Zwcl 2341.1−0000, the South-East part of A 3667 and previously published results of the North-West part of A 3667 and A 3376. Especially, we first observed the narrow (50 kpc) relic of CIZA 2242.8+5301 by the Suzaku satellite, which enabled us to reduce the projection effect. We report on X-ray detections of shocks at the positions of the relics in CIZA 2242.8+5301 and A 3667 SE. At the positions of the two relics in ZWCL 2341.1−0000, we did not detect shocks. From spectroscopic temperature profiles across the relic, we found that the temperature profiles exhibit significant jumps across the relics for CIZA 2242.8+5301, A 3376, A 3667 NW, and A 3667 SE. We estimated the Mach number from the X-ray temperature or pressure profile using the Rankine-Hugoniot jump condition, and compared it with the Mach number derived from the radio spectral index. The resulting Mach numbers (\(M = 1.5–3\)) are almost consistent with each other, while the Mach number of CIZA 2242.8+5301, derived from the X-ray data, tends to be lower than that of the radio observation. These results indicate that the giant radio relics in merging clusters are related to the shock structure, as suggested by previous studies of individual clusters.

Key words: galaxies: clusters — galaxies: intergalactic medium — shock waves — X-rays: galaxies: clusters

1. Introduction

The formation theory of galaxy clusters and groups is now well established: the high-density peaks that exist within the primordial matter distribution later grow to groups and clusters by both accretion of surrounding matter, and the mergers of clumps. In the growth history of haloes, major mergers have a significant effect on the internal structure of clusters. X-ray observations have revealed a lot about the merging phenomena of haloes from the massive clusters scale (e.g., Markevich et al. 2002) to galaxy groups (e.g., Kawahara et al. 2011), mainly by studying X-ray morphology. Shock structures induced by mergers were clearly found in the Bullet cluster using Chandra (Markevich et al. 2002). In general, however, the identification of a shock structure in X-ray images is difficult, except in major mergers, including 1E 0657−56, A 520, A 2146, and A 754 (Clowe et al. 2006; Markevitch et al. 2005; Russell et al. 2010; Macario et al. 2011).

Recent progress in radio astronomy has revealed interesting arc structures in merging clusters, called radio relics (Ferrari et al. 2008). Radio relics are believed to be tracers of shock structures through synchrotron radiation. Finoguenov et al. (2010) used XMM-Newton data of the well-known radio relic cluster A 3667, and found a sharp temperature decrement across the radio relic. Akamatsu et al. (2012a) confirmed their result using data from the Suzaku satellite.

Here, we present a systematic X-ray analysis of 6 radio relics in 4 clusters observed using Suzaku, including a new observation of a strong radio relic cluster, CIZA 2242.8+5301 (hereafter CIZA2242), which was recently discovered in a Giant Metrewave Radio Telescope (GMRT) observation (Swarup 1991). New analyses of archival data of Zwc 2341.1−0000 (hereafter Zwcl2341), A 3667 SE, and a compilation of previous results of A 3667 NE (Akamatsu et al. 2012a) and A 3376 (Akamatsu et al. 2012b) are also discussed.

We use \(H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}, \Omega_M = 0.27, \) and \(\Omega_{\Lambda} = 0.73,\) respectively. We use solar abundances as given by Anders and Grevesse (1989). Unless otherwise stated, the errors correspond to the 68% confidence level for a single parameter. The rest of this paper is organized as follows. In section 2, we describe the target selection, data reduction, and the X-ray spectral analysis. In section 3 we derive the temperature across the relic to estimate the Mach number. In section 4 we summarize the results.

2. Observations and Data Preparation

2.1. Targets

In table 1 and figure 1, we summarize the information about the relics and clusters that we analyze. Four relics (CIZA2242, A 3667 SE, Zwcl2341N, and Zwcl2341S) are newly analyzed in this paper, and our previous analyses are used for two relics (A 3667 NW, A 3376). We examine these clusters one by one. CIZA2242 (\(z = 0.192\)) was discovered in Clusters in the Zone of Avoidance (CIZA) survey (Kocevski et al. 2007). van Weeren et al. (2010) reported a Mpc scale radio relic located in the Northern outskirts, at a distance of 1.2 Mpc from the cluster center. The radio relic is extremely narrow with a width of 55 kpc. The spectral index at the front of...
Table 1. Basic properties of the clusters.

| Cluster     | Redshift | Physical length for 1' (kpc) | Temperature (keV) | $N_H$ (10$^{20}$ cm$^{-2}$) | Radio references                                      |
|-------------|----------|------------------------------|-------------------|-----------------------------|------------------------------------------------------|
| CIZA2242    | 0.192    | 193                          | 8.4               | 33.4                        | van Weeren et al. (2010)                             |
| A 3376      | 0.046    | 54                           | 4.2               | 5.8                         | Bagchi et al. (2006), Kale et al. (2012)             |
| A 3667 NW$^*$| 0.056    | 66                           | 6.0               | 4.7                         | Röttgering et al. (1997)                             |
| A 3667 SE   | 0.056    | 66                           | 6.0               | 4.7                         | Röttgering et al. (1997)                             |
| Zwcl2341N   | 0.270    | 250                          | 5.7               | 3.4                         | Bagchi et al. (2002), van Weeren et al. (2009)       |
| Zwcl2341S   | 0.270    | 250                          | 5.7               | 3.4                         | Bagchi et al. (2002), van Weeren et al. (2009)       |

* Akamatsu et al. (2012a).
† Akamatsu et al. (2012b).

Fig. 1. X-ray image of (a) CIZA2242, (b) A 3376, (c) A 3667, and (d) Zwcl2341 in the energy band 0.5–8.0 keV, after subtraction of the NXB without vignetting correction and after smoothing by a 2-dimensional Gaussian with $\sigma = 16$ pixel $= 17''$. White and Yellow annuli indicate the spectrum analysis regions and the radio relic region. Magenta annuli in panel (a) is used for analysis of the region perpendicular to the merger axis.
the relic is $-0.6 \pm 0.05$, which corresponds to a Mach number of $M = 4.5^{+1.3}_{-0.9}$. Although this shock wave is the strongest of all shocks in this sample, only X-ray data from ROSAT have been available so far. We obtained a 120 ks Suzaku observation of CIZA2242, performed on 2011 September 28 with an additional 60 ks offset observation.

A 3376 ($z = 0.046$) is considered to be experiencing a binary subcluster merger. Previous BeppoSAX/PDS observations showed a 2.7$\sigma$ detection of a hard X-ray signal (Nevalainen et al. 2004). However, Suzaku XHD observations gave an upper limit, which did not exclude the BeppoSAX flux (Kawano et al. 2009). The detection of a hard X-ray signal is still controversial. Another striking feature of A 3376 is a pair of Mpc-scale radio relics (Bagchi et al. 2006; Kale et al. 2012). Using Suzaku data, Akamatsu et al. (2012b) confirmed evidence for the presence of shock fronts across the west radio relic.

A 3667 ($z = 0.0556$) is well known as a merging cluster with an irregular X-ray morphology, and has two large extended radio relics at the North-West (A 3667NW) and the South-East (A 3667SE) (Röttgering et al. 1997). The overall spectral index of North-West relic gradually varies $-1.1$ to $-1.5$ toward the southeast direction. A 3667 exhibits an elongated X-ray shape to the North-West direction with an average temperature of $7.0 \pm 0.5$ keV (Knopp et al. 1996; Briel et al. 2004). Recent XMM-Newton and Suzaku observations of the North-West radio relic have revealed a significant jump in temperature and surface brightness across the relic (Finoguenov et al. 2010; Akamatsu et al. (2012a)). The observed ICM properties indicate the presence of a shock front with Mach number $M \sim 2.4$. The South-East radio relic has not yet been studied in X-rays.

Zwcl2341 ($z = 0.270$) has two Mpc-scale structures of diffuse radio emission, which were discovered in a 1.4 GHz New VLA All the Sky Survey (NVSS) (Bagchi et al. 2002) at the North (Zwcl2341N) and South (Zwcl2341S) of the clusters. These radio relics are located at Northern (Zwcl2341N $\sim 860$ kpc) and Southern (Zwcl2341S $\sim 1100$ kpc) directions from the cluster center (Bagchi et al. 2002). Recently, GMRT observations revealed that those radio emissions exhibit "arc"-like shapes (van Weeren et al. 2009). The spectral indices of the relics are $-0.49 \pm 0.18$ for Zwcl2341N and $-0.76 \pm 0.17$ for Zwcl2341S, corresponding to Mach numbers $M > 3.57$ and $2.95 \pm 1.39$, respectively. Previous Chandra and XMM-Newton observations (van Weeren et al. 2009) show that the X-ray emission extends over $\sim 3.3$ Mpc in the North-South direction. Due to its low X-ray surface brightness, the X-ray information around these radio relics is still limited.

## 2.2. Data Reduction

All Suzaku observations of CIZA2242, CIZA2242OFFSET, A 3667 SE, and Zwcl2341 were performed with the XIS in either the normal $5 \times 5$ or $3 \times 3$ clocking mode. The detailed information about these observations is summarized in table 2. For all data, 3 out of the 4 CCD chips were available: XIS0, XIS 1, and XIS 3. XIS 1 is the back-illuminated chip with high sensitivity in the soft X-ray energy range.

We used HEAsoft version 6.11 and the calibration database (CALDB), dated 2011-06-30. We performed event screening with cut-off rigidity (COR) $> 6$ GV to increase the signal-to-noise ratio. For CIZA2242, we set the Earth rim ELEVATION to be $> 10^\circ$ so as to avoid contamination by scattered solar X-rays from the day Earth limb. Furthermore, we applied additional processing for XIS 1 to reduce NXB level, which increased after changing the amount of charge injection. The detailed processing procedure was the same as that described in XIS analysis topics.1 Regions affected by the calibration sources were masked out using the calmask CALDB file. We used data in the energy range between 0.5–10 keV for the FI detectors, and between 0.5–8 keV for the BI detector. For CIZA2242, we used the energy range between 0.75–10 keV for the FI detectors and 0.6–8 keV for the BI detector.

## 2.3. X-Ray Spectrum Analysis

In the current work, we followed the same spectral fitting procedure as for the Suzaku observations of A 3667 and A 3376 (Akamatsu et al. 2012a, 2012b). The basic method of the spectral fit is described in subsection 4.1 of Akamatsu et al. (2012a).

### 2.3.1. Background and foreground emissions

An accurate measurement of the background components is crucial for an ICM study in the cluster outskirts. We considered three sky background components: the local hot bubble (LHB), the Milky way halo (MWH), and the cosmic X-ray background (CXB). We analyzed the offset region for CIZA2242OFFSET (ID:806002010), which is one degree away from the main target. For the A 3667 SE observation, we used a background model reported in table 3 in Akamatsu et al. (2012a) and for Zwcl2341, we used the outer region where there is negligible ICM emission.

The non X-ray background (NXB) subtracted spectra were fitted by summation of the LHB ($\sim 0.1$ keV), the MWH ($\sim 0.3$ keV), and the CXB as $apec + wabs (apec + powerlaw)$. We fixed the redshift and abundance of all $apec$ components

| Name (ObsID)       | (RA, Dec)       | Observation start time | Exp. time* |
|-------------------|-----------------|------------------------|------------|
| CIZA2242 (806001010) | (340°74, +53°16) | 2011-07-28             | 102.1      |
| CIZA2242OFFSET (806002010) | (339°29, +52°67) | 2011-07-30             | 52.4       |
| A 3667 SE (805036010)       | (303°44, −57°03) | 2010-04-12             | 45.0       |
| Zwcl2341 (803001010) | (355°90, +00°34) | 2008-06-27             | 41.0       |

* COR2 $> 6$ GV.
to zero and unity, respectively. The NXB component was estimated from the dark Earth database by the *xissxbgen* FTOOLS (Tawa et al. 2008), and was subtracted from the data before the spectral fit. We used the XIS response while assuming uniform brightness on the sky by *xissimarfgen* (Ishisaki et al. 2007).

The best-fit parameters and spectrum of CIZA2242OFFSET are given in table 3 and figure 2, respectively.

### 2.3.2. Spectrum fitting

We extracted spectra from regions defined by their distances from the center (22\(^h\)42\(^m\)41\(^s\), 50\(^°\)03’00’’), 2\(^°\)5, 5\(^°\)0, 7\(^°\)7, 10\(^°\)3, 12\(^°\)8, 16\(^°\)7 (figure 1a) for CIZA2242, 16\(^°\)8, 21\(^°\)0, 25\(^°\)2 centered on (20\(^h\)12\(^m\)31\(^s\), 56\(^°\)49’12’’) (figure 1b) for A 3667 SE, 1\(^°\)5, 4\(^°\)4, 8\(^°\)5, 10\(^°\)0 centered on (23\(^h\)43\(^m\)41\(^s\), 00\(^°\)18’19’’

![Fig. 2](image)

**Fig. 2.** Spectrum of CIZA2242OFFSET used for a background estimation, after subtracting of NXB and the source. XIS BI (Black) and FI (Red) spectra were fitted with CXB + Galactic components (LHB, MWH) [apec+wabs (apec + powerlaw)]. The CXB spectrum is shown with a black curve, and the LHB and MWH components are indicated by green and blue curves, respectively.

![Fig. 3](image)

**Fig. 3.** NXB subtracted spectra of six annuli of CIZA2242 (corresponding to white annuli in figure 1). The XIS BI (Black) and FI (Red) spectra were fitted with the ICM model (wabs + apec), along with the sum of the CXB and the Galactic emission [apec + wabs (apec + powerlaw)]. The ICM components are shown in magenta. The CXB component is shown with a black curve, and the LHB and MWH emissions are indicated by green and blue curves, respectively. The total background components are shown by the orange curve.
for Zwcl2341, 1.5, 4.0, 7.0 centered on (23h43m41s, +00°18′19″) (figure 1d) for Zwcl2341S, respectively. For CIZA2242, the center was determined by visually fitting a circle to the radio relics. For other clusters, the center was determined from their X-ray surface brightness peaks.

The response matrix files (RMFs) and ancillary response files (ARFs) were generated using xisrmfgen and xissimarfgen (Ishisaki et al. 2007). Since the Galactic and CXB components can be regarded as being spatially uniform in the XIS field of view, we used a uniform ARF for these components. For the ICM emission, we needed to put the flux distribution into xissimarfgen. For A 3667 and A 3376, we adopted the $\beta$-model distribution with $\beta = 0.54, r_c = 2'97$ and $\beta = 0.40, r_c = 2'03$, respectively. For CIZA2242 and Zwcl2341, we used the Suzaku XIS image (0.5–8.0 keV).

The spectral fitting of each region was performed as described below. We modeled the NXB-subtracted spectrum as the sum of the ICM emission and each background component discussed in sub-subsection 2.3.1. The intensity, temperature, photon indices of CXB and galactic components were all fixed at the values determined in offset observations. The interstellar absorption was kept fixed using the twenty-one centimeter line measurement of the hydrogen column, $N_H = 33.4 \times 10^{20} \text{ cm}^{-2}, 4.7 \times 10^{20} \text{ cm}^{-2}$, and $3.4 \times 10^{20} \text{ cm}^{-2}$ for CIZA2242, A 3667 SE, and Zwcl2341, respectively (Dickey & Lockman 1990). We simultaneously fitted both the BI and FI spectra with XSPEC ver12.7. For the inner regions of the radio relic, the free parameters were the temperature, $kT$, the normalization, $norm$, and the metal abundance, $Z$, of the ICM component. Otherwise, we fixed the ICM metal abundance to the typical value in the cluster outskirts, $Z = 0.2 Z_\odot$ (e.g., Fujita et al. 2008). The relative normalization between the two sensors was a free parameter in this fit so as to compensate for any cross-calibration errors.

3. Results

3.1. ICM Properties of Individual Clusters

3.1.1. CIZA2242

We first performed spectral fitting within the radio relic ($\sim$1.2 Mpc = 6.5'): the temperature and the metal abundance are $kT = 7.88 \pm 0.20 \text{ keV}$ and $Z = 0.28 \pm 0.03$, respectively. The unabsorbed flux and luminosity within the radio relic in the 0.5–10 keV band are $F_{0.5–10.0\text{keV}} = 1.4 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ and $L_{0.5–10.0\text{keV}} = 1.4 \times 10^{45} \text{ erg s}^{-1}$, respectively.

We then performed spectral fittings for each annulus examined in sub-subsection 2.3.2. Figure 3 displays the spectra of six annuli. Figure 4a shows the radial profile of the ICM temperature in CIZA2242. The temperature within 6/5 (1.25 Mpc) from the cluster center shows a fairly constant value of $\sim$8–9 keV. As mentioned in section 1, van Weeren et al. (2010) reported a sharp radio relic at that radius, which is indicated by the vertical dashed line in panel (a). We found that the temperature profile exhibits a significant jump from 8.3 keV to 2.1 keV across the radio relic. Because the ICM emission is lower than the background level in the outer bins ($r > 7'7$), we considered the variability of the CXB as being a systematic error. The fluctuation of the CXB intensity was estimated based on our previous work (Akamatsu et al. 2011). The estimated fluctuations span 15%–25%. The resultant parameters after taking into account the systematic error are shown by blue dotted lines in figure 4a. The temperature jump is consistent with the prediction of a numerical simulation by van Weeren et al. (2011). For a reference, we plotted the “universal” temperature profile expected from the scaled temperature profiles (Burns et al. 2010) as a gray dotted line.

As shown in figure 5a, we could not see the surface brightness jump across the relic directly in the profile. However, in the Appendix we show that this is caused by the limited Suzaku spatial resolution, and the observed profile is in fact consistent with the expected density jump.

3.1.2. A 3376

Previous studies of A 3376 found that the global mean temperature is 4.0 keV, and showed the presence of a pair of Mpc-scale radio relics consistent with 1.4 GHz VLA NVSS observations (Bagchi et al. 2006). A detailed study of the A 3376 radio relic has already been published by Akamatsu et al. (2012b). We refer to that paper for the images and X-ray information, and we will include A 3376 in the discussion section.

3.1.3. A 3667 NW

Suzaku performed 3 pointing observations of A 3667 along the North-West merger axis in 2006 May. Figure 1c displays the NXB-subtracted X-ray image of A 3667. A detailed study of the A 3667 NW radio relic has already been published by Akamatsu et al. (2012a). We refer to that paper for the images and X-ray information, and we will include A 3667 NW in the discussion section.

3.1.4. A 3667 SE

Figure 4d indicates the radial profile of the ICM temperature in the South-East direction of A 3667, respectively. The innermost 2 bins of the cluster are identical to that of A 3667 NW. The temperature within the SE radio relic ($\sim$1.3 Mpc) from the cluster center shows a fairly constant value of 7 keV, which is consistent with the NW direction (Akamatsu et al. 2012a). Our temperature profile exhibits a jump across the SE radio relic region. Although we could not see the surface brightness jump (figure 5d), the pressure profiles (figure 6d) exhibit a slight drop due to the temperature jump.

3.1.5. Zwcl2341N and Zwcl2341S

We first extracted the spectrum within $3'$ ($\sim$740 kpc) and fixed the redshift value to 0.270. The spectrum was well fitted with the above model ($\chi^2_r = 1.04$ for 473 degrees of freedom). We found a temperature and metal abundances of $kT = 5.16 \pm 0.32 \text{ keV}$ and $Z = 0.25 \pm 0.08$, respectively. The unabsorbed flux and luminosity in the 0.5–10 keV band are $F_{0.5–10.0\text{keV}} = 1.0 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ and $L_{0.5–10.0\text{keV}} = 2.2 \times 10^{44} \text{ erg s}^{-1}$, respectively. The derived temperature is consistent with previous Chandra observations ($\sim$5 keV) (van Weeren et al. 2009).

The radial profiles of the ICM temperature are shown in figures 4e and 4f for Zwcl2341N and Zwcl2341S, respectively. The temperature drops from 4 keV to 1 keV toward the Northern direction, or from 4 keV to 2 keV toward the Southern direction. Figures 5e, 5f, 6e, and 6f show the surface brightness and the pressure profiles of Zwcl2341N and Zwcl2341S. We could not see any jump in our wide radial bins for the temperature, surface brightness, and pressure profiles of this cluster.
Fig. 4. X-ray temperature profiles for the six radio relics. Vertical dashed lines indicate the position of the radio relics. Gray dotted lines indicate the "universal" temperature profile expected from the scaled temperature profiles (Burns et al. 2010). The red and blue horizontal bars show the pre and post shock quantities we use to derive Mach number (subsection 3.3). The vertical bars indicate a 1σ error. In (a) CIZA2242, the gray crosses show the data for a reference sector as shown in figure 1a magenta annuli. The uncertainty range due to the fluctuations of CXB intensity are shown by two blue dotted lines.

Fig. 5. Surface brightness profiles (0.5–10 keV). Vertical dashed lines indicate the positions of radio relics.
Fig. 6. Pressure profiles derived by the deprojection technique, as described in Akamatsu et al. (2011). Vertical dashed lines indicate the position of radio relics. The vertical bars are 1σ errors.

3.2. The Scaled Temperature Profiles

We normalized the radial temperature profile of each cluster by the flux-weighted average temperature. The resulting scaled temperature profiles are shown in figure 7. We find that the temperature profiles of four relics, including the previous two results, exhibit significant discontinuities across the radio relic. These discontinuities can be associated with the shock front found in the radio relics. For the other two samples (Zwcl2341N, S), we could not see any jump in the temperature profiles. The angular resolution of Suzaku was not sufficient to check the presence of a discontinuity. Therefore, we focus on these four examples of temperature discontinuity.

Another remarkable point concerning the scaled temperature profile is its flatness within the radio relic. Recent X-ray results show that the ICM in relaxed clusters has the “universal” decline temperature profile up to the virial radius (Markevitch et al. 1998; De Grandi & Molendi 2002; Vikhlinin et al. 2005; Pratt et al. 2007; Akamatsu et al. 2011). The flatness of the temperature within the radio relic might need a heating mechanism, such as shock heating.

As mentioned above, the temperature of relaxed clusters tends to have the “universal” profile. It is natural that the flat temperature profiles of merging clusters will settle to the “universal” profile in less than the Hubble time. In our samples, the locations of the radio relic are far from the cluster center, typically $r_{\text{shock}} \sim 0.5r_{200}$. Due to the low density...
Here, $T_1$ and $T_2$ are the pre-shock and post-shock temperatures, and $\mathcal{M}_{X, kT}$ is the estimated Mach number. The post and pre-quantities we use are marked by red and blue horizontal bars in figure 4.

We compared our results with the Mach number derived from previous radio observations. Based on Diffusive Shock Acceleration (DSA) theory, we estimate the Mach number based on the radio spectrum to be

\begin{equation}
\frac{T_2}{T_1} = \frac{5 \mathcal{M}_{X, kT}^4 + 14 \mathcal{M}_{X, kT}^2 - 3}{16 \mathcal{M}_{X, kT}^2}.
\end{equation}

Here, $T_1$, $T_2$ are the pre-shock and post-shock temperatures, and $\mathcal{M}_{X, kT}$ is the estimated Mach number. The post and pre-quantities we use are marked by red and blue horizontal bars in figure 4.

We compared our results with the Mach number derived from previous radio observations. Based on Diffusive Shock Acceleration (DSA) theory, we estimate the Mach number based on the radio spectrum to be

\begin{equation}
\alpha = -\frac{3 \mathcal{M}_{\text{radio}}^{-2} + 1}{2 - 2 \mathcal{M}_{\text{radio}}^{-2}},
\end{equation}

where $\alpha$ is the radio spectral index and $\mathcal{M}_{\text{radio}}$ is the Mach number from the radio observations. For strong shocks, the radio spectral index will be flat, about $-0.5$. We used radio spectral indices from the radio observations summarized in table 1. The resulting Mach numbers are given in table 4. Figure 8 displays the Mach number based on the X-ray temperature and radio observations. As shown in this figure, we find that the two different methods give consistent results within the current observational noise.

If we assume in the case of CIZA2242 that the Mach number derived from the radio observations is correct, the expected post shock temperature would reach $kT = 15$ keV. Although our results are well reproduced by a 1 temperature model, we also fit 2 temperature models to the spectrum extracted from the $50–70$ annulus, which is located in the region where the shock just passed. The metal abundances of the two apec components were tied to be the same, and only the temperature and normalization were set free. We then obtained a statistically acceptable fit with $\chi^2$/d.o.f. = 228/244 compared with the single-temperature case of 231/246. The rather low statics of the spectrum hampered us to distinguish between the $2kT$ and $1kT$ models. The hot-component temperature was derived to be $kT_{\text{high}} = 11.5^{+4.65}_{-3.26}$ keV, and the cool one to be $kT_{\text{low}} = 2.05^{+1.53}_{-0.20}$ keV. The intensity of the cool component is about an order lower than the hot one. Based on those analyses, there were no strong signatures for the presence of high-temperature components.

### 3.3. Mach Number at Discontinuity

We estimate the Mach numbers using temperature jumps across the relics. The Mach number can be obtained by applying the Rankine-Hugoniot jump condition, assuming the ratio of specific heats as $\gamma = 5/3$ to be

\begin{equation}
\frac{T_2}{T_1} = \frac{5 \mathcal{M}_{X, kT}^4 + 14 \mathcal{M}_{X, kT}^2 - 3}{16 \mathcal{M}_{X, kT}^2}.
\end{equation}

Here, $T_1$, $T_2$ are the pre-shock and post-shock temperatures, and $\mathcal{M}_{X, kT}$ is the estimated Mach number. The post and pre-quantities we use are marked by red and blue horizontal bars in figure 4.

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\begin{equation}
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where $\alpha$ is the radio spectral index and $\mathcal{M}_{\text{radio}}$ is the Mach number from the radio observations. For strong shocks, the radio spectral index will be flat, about $-0.5$. We used radio spectral indices from the radio observations summarized in table 1. The resulting Mach numbers are given in table 4. Figure 8 displays the Mach number based on the X-ray temperature and radio observations. As shown in this figure, we find that the two different methods give consistent results within the current observational noise.

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### 4. Summary

From simulations of the structure formation of the Universe (Enßlin & Brüggen 2002; Vazza et al. 2009), large accretion shocks and low merger shocks around clusters of galaxies are expected. To understand the physics of cluster evolution, cluster merger events are important processes. Suzaku XIS is the best suited instrument for measuring the ICM emission beyond the radio relics, thanks to its low and stable detector background. In the present work, we analyzed six radio relics of four clusters with Suzaku XIS, and measured their temperature profiles. We found clear temperature jumps across four relics, and derived the Mach number from the pre and post temperatures. The derived Mach number is almost consistent with that from the radio observation. These results strongly suggest that a shock structure exists at the radio relic.
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Appendix. Surface Brightness Jump in CIZA2242

Because of the non-detection of a surface brightness jump in CIZA2242, we performed an additional check. Based on previous work (e.g., Markevich et al. 2002), we modeled the electron density profile switching at the radio relic ($r = 6.5$) from the beta model to a power law. In this model, we assume that two cases of the jump amplitude, corresponding to the Mach numbers $\mathcal{M} = 2.0$ (our lower limit including the systematic uncertainty, see table 4) and $\mathcal{M} = 4.5$ (the radio value). Assuming spherical symmetry, we calculated the square of the density as the surface brightness, and convolved it with the Suzaku PSF. The profile was binned with the same size as the observed surface brightness. Because the jump in the surface brightness is important, we selected the profile across the radio relic ($r = 5.0^\circ - 10.3^\circ$). Finally, we normalized the profile to the observed value at the post shock region ($r = 5.0^\circ - 7.7^\circ$). The resulting profiles are shown in figure 9b (blue and black). The observed brightness profile, shown by red crosses, is consistent with the interval of $\mathcal{M}$ obtained from our temperature measurements.

For the CIZA2242 case, the PSF of Suzaku corresponds to 380 kpc, which is probably much larger than the length of the shock. Hence, the surface brightness jump should be significantly diluted by another area in the bin. We need more observations with a higher angular resolution to confirm the shock structure in the surface brightness profile.

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