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Observations of a pre-merger shock in colliding clusters of galaxies

Liyi Gu^{1,2*}, **Hiroki Akamatsu**², **Timothy W. Shimwell**^{3,4}, **Huib T. Intema**^{4,5}, **Reinout J. van Weeren**⁴, **Francesco de Gasperin**^{4,6}, **François Mernier**^{4,7,8}, **Junjie Mao**^{2,9}, **Igone Urdampilleta**^{2,4}, **Jelle de Plaa**², **Viral Parekh**^{10,11}, **Huub J. A. Röttgering**⁴ and **Jelle S. Kaastra**^{2,4}

¹RIKEN High Energy Astrophysics Laboratory, Wako, Japan. ²SRON Netherlands Institute for Space Research, Utrecht, The Netherlands. ³ASTRON, the Netherlands Institute for Radio Astronomy, Dwingeloo, The Netherlands. ⁴Leiden Observatory, Leiden University, Leiden, The Netherlands. ⁵International Centre for Radio Astronomy Research, Curtin University, Perth, Western Australia, Australia. ⁶Hamburger Sternwarte, Universität Hamburg, Hamburg, Germany. ⁷MTA-Eötvös University Lendület Hot Universe Research Group, Budapest, Hungary. ⁸Institute of Physics, Eötvös University, Budapest, Hungary. ⁹Department of Physics, University of Strathclyde, Glasgow, UK. ¹⁰Raman Research Institute, Bangalore, India. ¹¹Department of Physics and Electronics, Rhodes University, Grahamstown, South Africa. *e-mail: liyi.gu@riken.jp

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¹*RIKEN High Energy Astrophysics Laboratory, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

²*SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, the Netherlands*

³*ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA, Dwingeloo, The Netherlands*

⁴*Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, The Netherlands*

⁵*International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth, WA 6845, Australia*

⁶*Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, 21029, Hamburg, Germany*

⁷*MTA-Eötvös University Lendület Hot Universe Research Group, Pázmány Péter sétány 1/A, Budapest, 1117, Hungary*

⁸*Institute of Physics, Eötvös University, Pázmány Péter sétány 1/A, Budapest, 1117, Hungary*

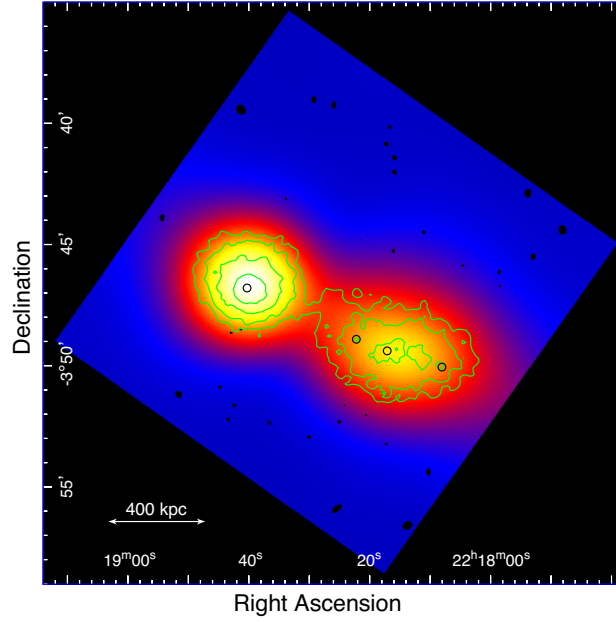
⁹*Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK*

¹⁰*Raman Research Institute, C. V. Raman Avenue, Sadashivanagar, Bangalore 560080, India*

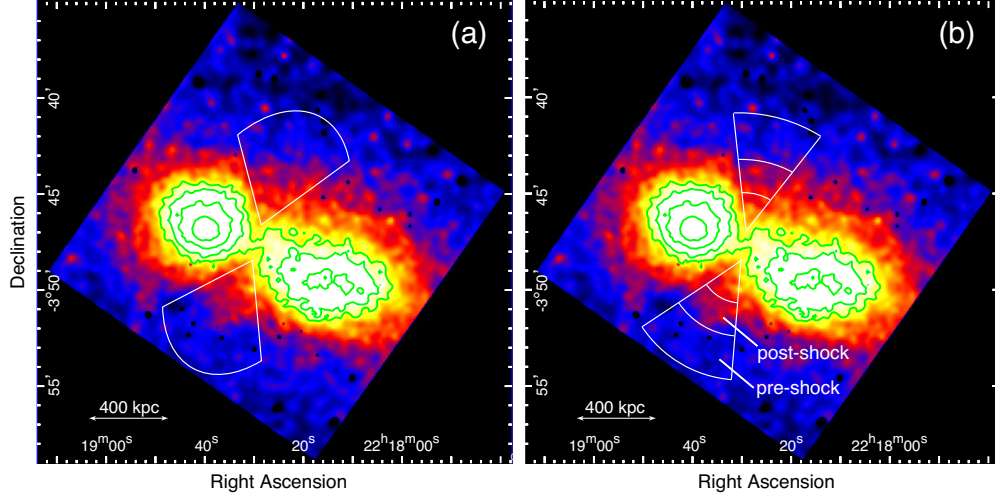
¹¹*Department of Physics & Electronics, Rhodes University, PO Box 94, Grahamstown, 6140, South Africa*

Supplementary Information

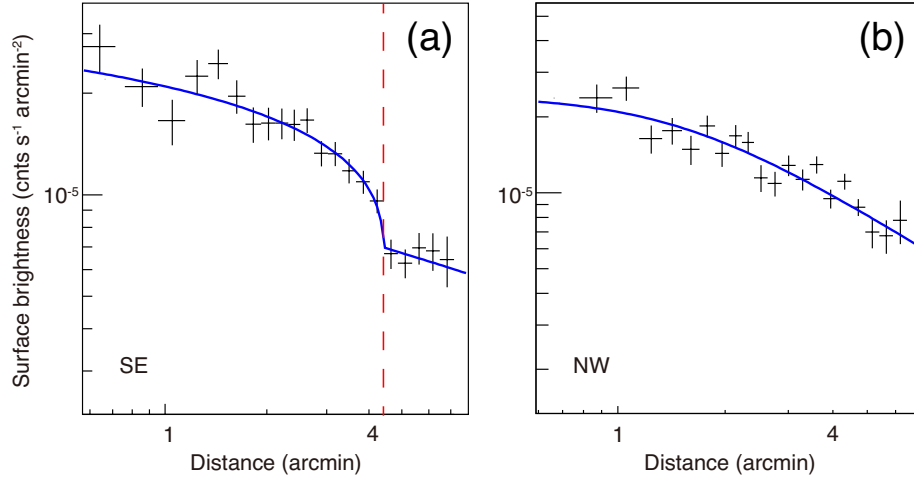
Images for shock detection in X-ray surface brightness



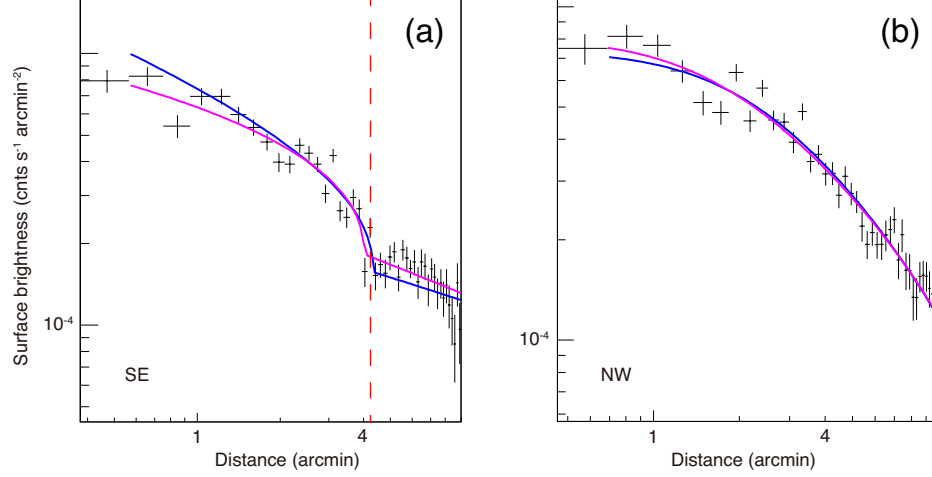
Supplementary Figure 1 **Beta model fits to the *Chandra* image.** This model image is produced by fitting the surface brightness in the 0.5 – 8.0 keV with a 2-D beta model. It is used to create the residual map in Figure 2. Green contours show the X-ray brightness of the central region. The contour levels are the same as in Figure 2. Positions of the dominant galaxies are marked with black circles.



Supplementary Figure 2 **Regions used in the shock detection.** Regions with white solid lines on the *Chandra* images are used for extracting (a) the surface brightness profiles (Supplementary Figures 3 and 4) and (b) the X-ray temperature profiles (Supplementary Figure 5). Green contours show the X-ray brightness of the central region. The contour levels are the same as in Figure 2.

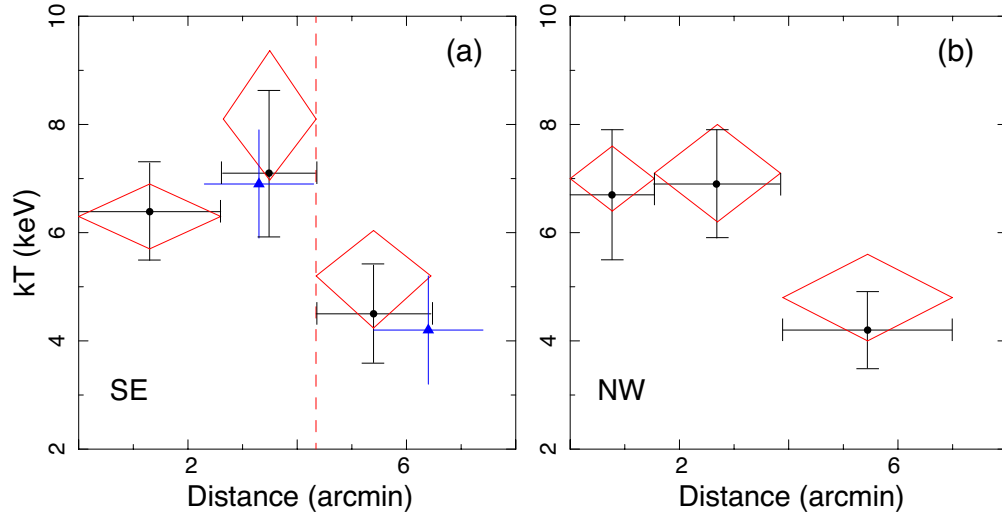


Supplementary Figure 3 **Chandra surface brightness profiles along the merger equator.** (a) *Chandra* surface brightness profile in the 0.5 – 8.0 keV band across the SE equatorial shock in an elliptical sector. (b) Surface brightness profile in the NW region. Errors are given at the 1σ level. The blue line in panel a shows the best-fit broken power law model with the compression factor $C = 2.1$, and the blue line in panel b shows the best-fit *beta* model. The vertical red dashed line shows the surface brightness jump at a distance of $\sim 4.3'$ from the collision axis.

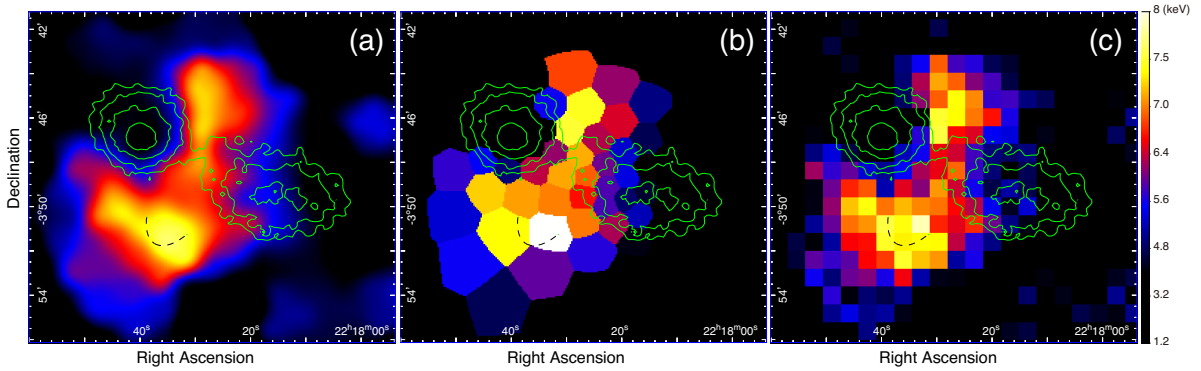


Supplementary Figure 4 **XMM-Newton surface brightness profiles along the merger equator.** (a) *XMM-Newton* surface brightness profile in the 0.5 – 8.0 keV band across the SE equatorial shock in an elliptical sector. (b) The surface brightness profile in the NW region. Errors are given at the 1σ level. Magenta lines show the best-fit models to the *XMM-Newton* profiles, and the blue lines show the *Chandra* models from Supplementary Figure 3. The vertical red dashed line shows the distance of $\sim 4.1'$ from the collision axis.

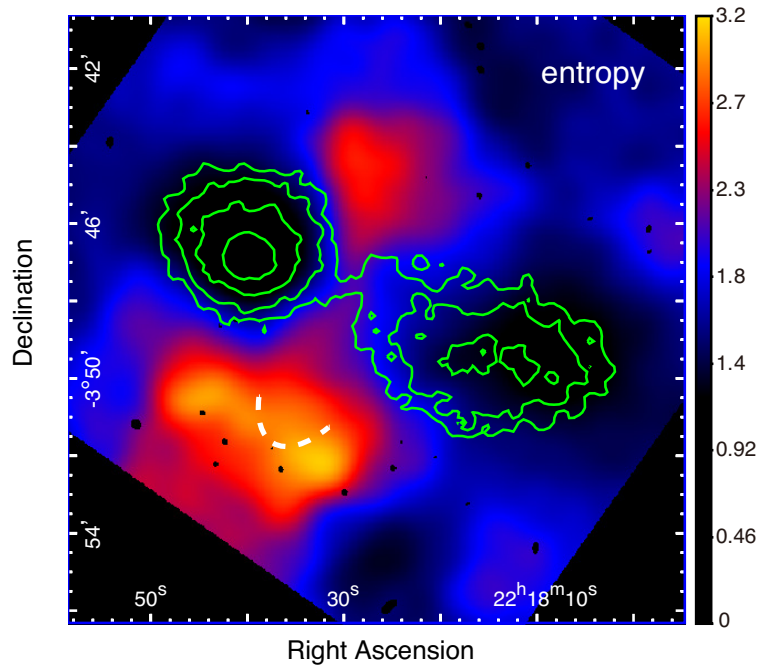
Images for shock detection in X-ray temperature



Supplementary Figure 5 **X-ray temperature profiles along the merger equator.** (a) Projected temperature profiles obtained with *Chandra* (black) and *Suzaku* (blue), and deprojected profile with *XMM-Newton* (red), for the SE equatorial region. The vertical line marks the location of the surface brightness jump. (b) Projected temperature profile from *Chandra* (black) and deprojected profile from *XMM-Newton* (red) for the NW equatorial region. Errors are given at the 1σ level.



Supplementary Figure 6 **Temperature maps of 1E 2216.0-0401 and 1E 2215.7-0404 with three different algorithms.** Temperature map obtained through (a) the fits and interpolation (Eq. 1 in the Method section) are compared with the maps obtained through (b) the WVT algorithm and (c) the ACB method. Green contours show the X-ray distribution (same as in Figure 2), and the black dashed curve indicates the position of the wedge.



Supplementary Figure 7 **Distribution of ICM entropy in the merger.** Pseudo entropy map in arbitrary units, created from the *XMM-Newton* temperature map (Figure 3) and a smoothed *Chandra* image. Green contours show the X-ray distribution (same as in Figure 2), and the white curve indicates the edge of the wedge-like feature.

X-ray surface brightness profile of the equatorial shock

To verify the wedge-like structure seen in the flux image, we study the *Chandra* surface brightness profile along the equatorial direction of the merger. To avoid the contamination from the cluster main body, we extract the profiles in two elliptical sector regions (Supplementary Figure 2), one towards southeast and another towards northwest, with an opening angle of 70 degree and a bin size of about $10''$. To fit the observed shape of the wedge, we set the major axes of the elliptical sectors on the equatorial plane. As shown in Supplementary Figure 3, the surface brightness profile is calculated as a function of the mean distance from the collision axis, which is defined as a straight line connecting the X-ray peaks of the two clusters. The profiles are fit with the latest version of Proffit [1] (<https://www.isdc.unige.ch/~deckert/newsite/Proffit.html>).

The surface brightness in the northwest sector decreases smoothly with the distance from the collision axis. It can be described by a standard β model, with a best-fit $\beta = 0.31 \pm 0.03$ and core radius $r_c = 1.5' \pm 0.5'$. The southeast region shows a clear jump at around $4.3'$, which appears to agree well with the shock front detected by eye. The profile is modelled with a broken power-law density distribution,

$$n(R) = \begin{cases} Cn_0R^{-\alpha_1} & R \leq R_{\text{edge}}, \\ n_0R^{-\alpha_2} & R > R_{\text{edge}}, \end{cases} \quad (1)$$

where R is the 3-D radius, C is the compression factor of the shock, n_0 is the normalization, α_1 and α_2 are the power law indexes for the up and downstream regions, respectively, and R_{edge} is the position of the jump. To project the 3-D density model into 2-D, we assume that the shock surface is a doughnut-like structure around the merger axis, and the wedge-like surface morphology holds for the other parts of the doughnut.

The projected broken power law model provides a reasonable fit to the southeast profile. The best-fit power law indexes α_1 and α_2 are 0.35 ± 0.05 and 0.62 ± 0.04 , respectively, the cut-off radius $R_{\text{edge}} = 4.3' \pm 0.1'$, and the compression factor $C = 2.1 \pm 0.5$. The shock Mach number $\mathcal{M}$ can be obtained from the compression factor,

$$\mathcal{M} = \sqrt{\frac{2C}{\gamma + 1 - (\gamma - 1)C}} = \sqrt{\frac{3C}{4 - C}}, \quad (2)$$

where the rightmost equation refers to the adiabatic index $\gamma = 5/3$ for the thermal plasma. By error propagation, the uncertainty in the Mach number can be calculated as

$$\delta\mathcal{M} = \frac{6}{(4 - C)^2\mathcal{M}}\delta C \quad (3)$$

Therefore, the Mach number estimated from the *Chandra* surface brightness profile is 1.8 ± 0.5 .

To further test how the results vary with the region selection, we extract the surface brightness profile in small bin size ($6''$), and run the fit again. The compression factor remains intact with $C = 2.1$. The profile is also extracted in a spherical sector instead of the elliptical one, although the latter appears to better describe the morphology of the shock structure. The best-fit C becomes 2.0, which is still consistent with the original value. The position of the edge also remains the

same. We further change the opening angle of the extraction sector from 70 degree to 50 degree or 90 degree, and find that both the compression factor and edge position are consistent with the original value within errors. Therefore the obtained properties of the southeast shock are nearly independent on the detailed region selection.

To verify the surface brightness discontinuity found in the *Chandra* image, we extract the *XMM-Newton* surface brightness profiles in the southeast and northwest cone regions (Supplementary Figure 2). The radial binning is set to $10''$, and the radial distance is calculated from the collision axis of the merging system. The observed profiles and the best-fit models are shown in Supplementary Figure 4, as well as the models obtained with the *Chandra* profiles. For the northwest region, the *XMM-Newton* profile can be fit with the β model. The best-fit parameters of the β model agree well with the *Chandra* results. The southeast profile shows a discontinuity at $r = 4' - 5'$. By fitting the southeast profile with a broken power law model (Eq. 1 in the Supplementary Information), the position of the discontinuity R_{edge} is $4.1' \pm 0.2'$, and the compression factor $C = 2.0 \pm 0.4$, indicating a shock front with $\mathcal{M} = 1.7 \pm 0.3$. These values are all consistent with the *Chandra* results within the uncertainties. In both southeast and northwest regions, the *XMM-Newton* profiles show surface brightness excess over the best-fit model at $r \sim 6'$, which is not seen in the *Chandra* plot. The nature of the excess is unclear. Ignoring the excess does not affect the fits.

The above *XMM-Newton* analysis is based on the surface brightness profiles extracted in the 0.5 – 8.0 keV. We have repeated the surface brightness fits with the profiles extracted in the 0.5 – 2.0 keV so as to enhance the source-to-background ratio. The best-fit compression factor and shock Mach number are consistent with the original values.

Shock X-ray temperature jump

To rule out the presence of a cold front at the surface brightness discontinuity, and to obtain more constraints on the shock Mach number, we measure the ICM temperature profiles of the southeast equatorial region. First, we extract *Chandra* spectra from the regions defined in Supplementary Figure 2. Each spectrum is fit by one absorbed *cie* component, with temperature, emission measure, and redshift free to vary. The average metallicity is fixed to 0.3 solar as it cannot be constrained with the *Chandra* spectrum. The temperature profile is shown in Supplementary Figure 5. The best-fit temperatures for the pre- and post-shock regions are $T_{\text{pre}} = 4.5 \pm 0.9$ keV and $T_{\text{post}} = 7.1 \pm 1.5$ keV, respectively. The resulting temperature jump $T_{\text{post}}/T_{\text{pre}}$ is 1.6 ± 0.5 . We can therefore confirm the presence of a shock by ruling out the possibility of a cold front at the surface brightness discontinuity.

The standard Rankine-Hugoniot shock model [2] predicts the temperature jump condition,

$$\frac{T_{\text{post}}}{T_{\text{pre}}} = \frac{[2\gamma\mathcal{M}^2 - (\gamma - 1)][(\gamma - 1)\mathcal{M}^2 + 2]}{(\gamma + 1)^2\mathcal{M}^2} = \frac{5\mathcal{M}^4 + 14\mathcal{M}^2 - 3}{16\mathcal{M}^2}, \quad (4)$$

where the right hand expression assumes $\gamma = 5/3$. Therefore, the Mach number can be obtained

from the temperature jump,

$$\mathcal{M} = \sqrt{\frac{\left(8 \frac{T_{\text{post}}}{T_{\text{pre}}} - 7\right) + \sqrt{\left(8 \frac{T_{\text{post}}}{T_{\text{pre}}} - 7\right)^2 + 15}}{5}}, \quad (5)$$

and the error in the Mach number is

$$\delta \mathcal{M} = \frac{4\mathcal{M}}{\sqrt{\left(8 \frac{T_{\text{post}}}{T_{\text{pre}}} - 7\right)^2 + 15}} \delta \left(\frac{T_{\text{post}}}{T_{\text{pre}}} \right). \quad (6)$$

The best-fit Mach number for the southeast shock is 1.6 ± 0.4 . It is well consistent with the Mach number estimated from the *Chandra* surface brightness profile. We then prove the presence of a weak shock propagating towards outskirts along the equatorial direction of the early merger system.

The above temperature jump is obtained from the projected spectra. The post-shock temperature might be underestimated as the cooler gas at temperature T_{pre} is projected on the post-shock region. However, the current *Chandra* data do not allow a deprojected analysis, which requires spectra with high total counts. The deprojected analysis needs to be done with the *XMM-Newton* data.

Next we measure the temperature jump at the southeast shock with the *XMM-Newton* data, accounting for the projection effect. The spectra are extracted from the regions shown in Supplementary Figure 2. The direct deprojection model presented in [3] (<https://www-xray.ast.cam.ac.uk/papers/dsdeproj/>) is used to correct the projection effect for the inner regions. For each region, the ICM component is modelled by one SPEX *cie* component, absorbed by the Galactic neutral material. The temperature, metallicity, redshift, and the emission measure of the thermal component are left free in the fits. As shown in Supplementary Figure 5, the best-fit temperatures are 5.2 ± 0.9 keV and 8.1 ± 1.4 keV for the pre- and post-shock regions, respectively. Both temperatures are consistent, within the statistical uncertainties, with the *Chandra* values based on a projected analysis. Using Eqs. 5 and 6 in the Supplementary Information, the shock Mach number with the temperature jump is 1.6 ± 0.4 . This value is identical to the *Chandra* result, and in good agreement with the Mach numbers based on the surface brightness discontinuity measured with both instruments.

We further investigate the temperature jump by using *Suzaku*, which has low and stable background hence enables us to investigate the regions of low X-ray surface brightness. We extract *Suzaku* spectra from the post-shock region as shown in Supplementary Figure 2. To reduce the photon contamination from the bright post-shock region, the pre-shock region is moved 1 arcmin to the southeast. As shown in Supplementary Figure 5, the resulting temperature is $T_{\text{pre}} = 4.2 \pm 1.0$ keV and $T_{\text{post}} = 6.9 \pm 1.1$ keV for the pre- and post-shock regions, respectively. With the observed temperature jump and Eqs. 5 and 6 in the Supplementary Information, the Mach number is estimated to be 1.7 ± 0.4 . These values are consistent with the results obtained with *Chandra* and *XMM-Newton*.

Although the surface brightness at the northwest of the merger axis does not show an apparent discontinuity (Supplementary Figures 3 and 4), given the hot spot in X-ray temperature and the

radio spectrum flattening (Figure 3), naturally we would expect the presence of a shock northwest on the equatorial plane. Here we also measure the temperature profile for the northwest equatorial region. Spectra are extracted from the regions defined in Supplementary Figure 2. As shown in Supplementary Figure 5, the projected *Chandra* analysis gives $T_{\text{post}} = 6.9 \pm 1.0$ keV and $T_{\text{pre}} = 4.2 \pm 0.7$ keV, the temperature ratio is then 1.6 ± 0.4 , and the shock Mach number can be estimated using Eqs. 5 and 6 in the Supplementary Information as $\mathcal{M} = 1.6 \pm 0.3$. The *XMM-Newton* data allow a deprojection analysis. The best-fit temperatures with the *XMM-Newton* spectra are $T_{\text{post}} = 7.1 \pm 0.9$ keV and $T_{\text{pre}} = 4.8 \pm 0.9$ keV, which give a shock Mach number of $\mathcal{M} = 1.5 \pm 0.3$. We skip the *Suzaku* data as it does not cover the pre-shock region. Therefore, if the northwest shock exists, it would have nearly the same speed as the observed equatorial shock at southeast.

Shock heating and the ICM thermal/ionization equilibrium

Combining the *Chandra*, *XMM-Newton*, and *Suzaku* results for the southeast region, the mean pre-shock temperature weighted by their errors is 4.6 ± 0.7 keV, and the mean post-shock temperature is 7.4 ± 1.3 keV. This temperature jump indicates a Mach number of 1.6 ± 0.3 , and a compression factor $C = 1.9 \pm 0.4$ at the shock front. The pressure jump at the shock is 3.1 ± 0.9 , marginally consistent with the observed value in the pseudo-pressure map (Figure 3). These are adopted as the best values. The measured emission measure indicates a mean electron density $n_e = 2.0 \times 10^{-4}(l/2 \text{ Mpc})^{-1/2} \text{ cm}^{-3}$ in the pre-shock region, where l is the line-of-sight depth of the cluster volume. Assuming $l = 2$ Mpc, and given the observed surface brightness jump at the shock front, the electron density in the post-shock region is $\sim 3.8 \times 10^{-4} \text{ cm}^{-3}$. As the shock has a low Mach number, the electrons are heated by adiabatic compression,

$$n_{\text{e,post}}^{1-\gamma} T_{\text{post}} = n_{\text{e,pre}}^{1-\gamma} T_{\text{pre}}, \quad (7)$$

the adiabatic heating gives an expected $T_{\text{post}}/T_{\text{pre}} = 1.5$. Therefore, the observed temperature jump at the surface brightness discontinuity can be roughly explained by the adiabatic compression from the equatorial shock.

Converting the pre-shock temperature to the sound speed ($c_s = 1088 \text{ km s}^{-1}$), the observed shock velocity v_s is then $\sim 1740 \text{ km s}^{-1}$. The velocity of the post-shock gas relative to the shock is $v_p = c_s/C = 566 \text{ km s}^{-1}$. Assuming that the shock propagates with a uniform speed from the collision axis, the age of the shock is then about 250 Myr. In reality, the propagation time is probably longer, because the speed of equatorial shock is expected to increase in time as the two subclusters approach [4]. Therefore, the current age estimate should be treated as a lower limit.

It is still uncertain how fast the equilibrium between the electron and ion temperatures is reached after the merger shocks. Assuming that the electrons are not heated effectively in the collisionless shock, given the low ICM density at cluster outskirts and high shock speed, it is possible that the post-shock region has not had enough time to equilibrate via Coulomb collisions [5–10]. The timescale for collisional thermal equilibrium is

$$t_{\text{eq}} \approx 2 \times 10^9 \left(\frac{T}{10^8 \text{ K}} \right)^{3/2} \left(\frac{n_p}{10^{-4} \text{ cm}^{-3}} \right)^{-1} \left(\frac{\ln \Lambda}{40} \right)^{-1} \text{ yr}, \quad (8)$$

where n_p is the proton density ($n_p \approx 0.83n_e$), and $\ln\Lambda \approx 40$ is the Coulomb logarithm. Adapting the measured post-shock proton density and temperature, the time to reach thermal equilibrium is $t_{\text{eq}} \sim 500$ Myr. Given the uncertainty in the shock age estimate, it is not clear if an overall electron-ion thermal equilibrium is reached in the post-shock region. Locally, the thickness of the possible non-thermal-equilibrium region can be approximated as $v_p t_{\text{eq}} = 290$ kpc (or $\sim 2.9'$ if the shock is propagate along the plane of the sky).

Another possible non-equilibrium effect is the departure from collisional ionization equilibrium, as the charge state distribution of the ions might lag behind the electron temperature increase due to the low collisional frequency at the shock. The equilibrium ionization timescale is $t_{\text{ie}} = 3 \times 10^9 (n_e/10^{-4} \text{ cm}^{-3})^{-1}$ yr. Given the post-shock density $n_{e,\text{post}} = 3.8 \times 10^{-4} \text{ cm}^{-3}$, it would take about 790 Myr for the ionization equilibrium.

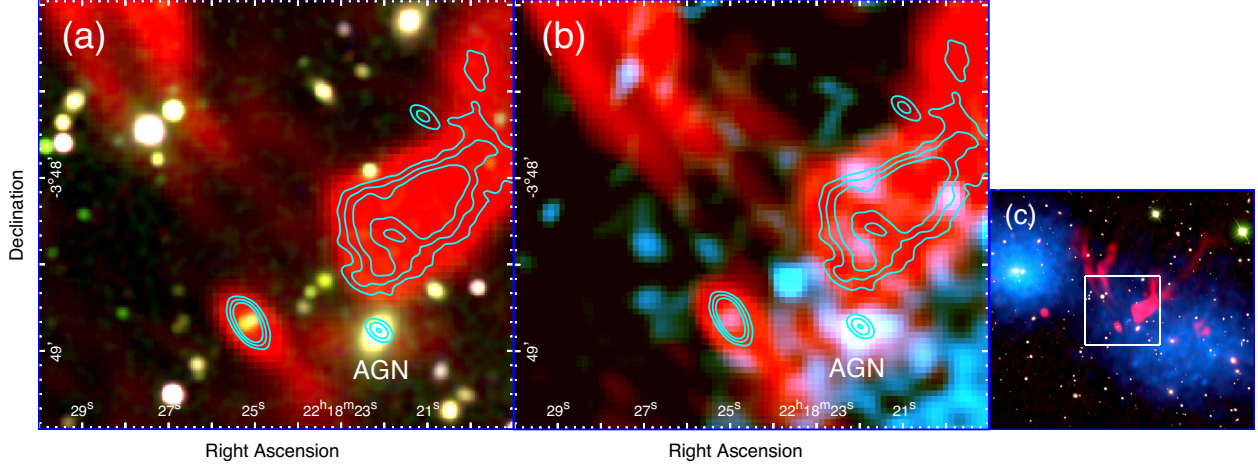
If exists, the non-ionization-equilibrium might affect the X-ray spectrum [9]. We refit the deprojected *XMM-Newton* spectrum of the post-shock region, and allow the rt parameter to vary during the fit. rt is the ratio between the ionization temperature and the electron temperature, $rt = 1$ indicates an ionization equilibrium. The best-fit rt is 0.92 ± 0.26 , suggesting that the post-shock ICM is not strongly biased from equilibrium. A deep observation with future high-resolution X-ray spectrometers (e.g., XRISM, Athena) will be required to accurately determine the gas ionization state at the shock.

Re-accelerated radio tails associated with a member AGN

The low-frequency radio sky of the pre-merger cluster is dominated by a pair of 330 kpc-long radio tails (source A in Figure 2), and a bright patch with a 450 kpc-long collimated narrow extension towards the northwest (source B). As shown in Supplementary Figure 8, the radio tails are likely fueled by the host radio galaxy 2MASX J22182217-0348539 at RA = 22h18m22.19s, Dec = -03d48m54.0s. This galaxy also exhibits a compact radio source at the 610 MHz. The optical spectrum of the host galaxy was taken in the 6dF galaxy survey [11], which gives a spectroscopic redshift of 0.09434 ± 0.00015 . Therefore the host galaxy is likely a member of the merger system. The radio galaxy also hosts a small diffuse gas halo visible in the X-ray. The *Chandra* image further shows a hint for a narrow gaseous extension that leads from the AGN towards the northeast. Spectral analysis of the radio galaxy is not plausible with the current X-ray data.

The LOFAR 144 MHz, GMRT 235 MHz and 325 MHz images are used to calculate the spectral index map. The radio images at 610 MHz and higher are not deep enough to detect the majority of the steep spectrum emission. To correct for different sampling densities in the uv-plane, we use a uniform weighting, and apply inner uv-range cuts to image only the common uv-range. The images are convolved to the lowest resolution. A power-law model is used to fit the image pixels where all the three data are significant above $5\sigma_{\text{rms}}$. Any possible curvatures are ignored in the fits.

The very steep ($-1.8 \sim -2.5$) spectrum of the radio tails indicate that the plasma has experienced significant synchrotron and inverse Compton losses. Naturally, one might expect that more aged plasma would show a steeper radio spectrum. However, as seen in Supplementary Figure 9, there is no evidence for the expected spectral steepening towards the tips of the tails, where the older relativistic electrons reside. The right tail of source A has a relatively constant spectral index of -1.8 ± 0.1 , while the left one seems to be systematically steeper, and exhibits a patchy

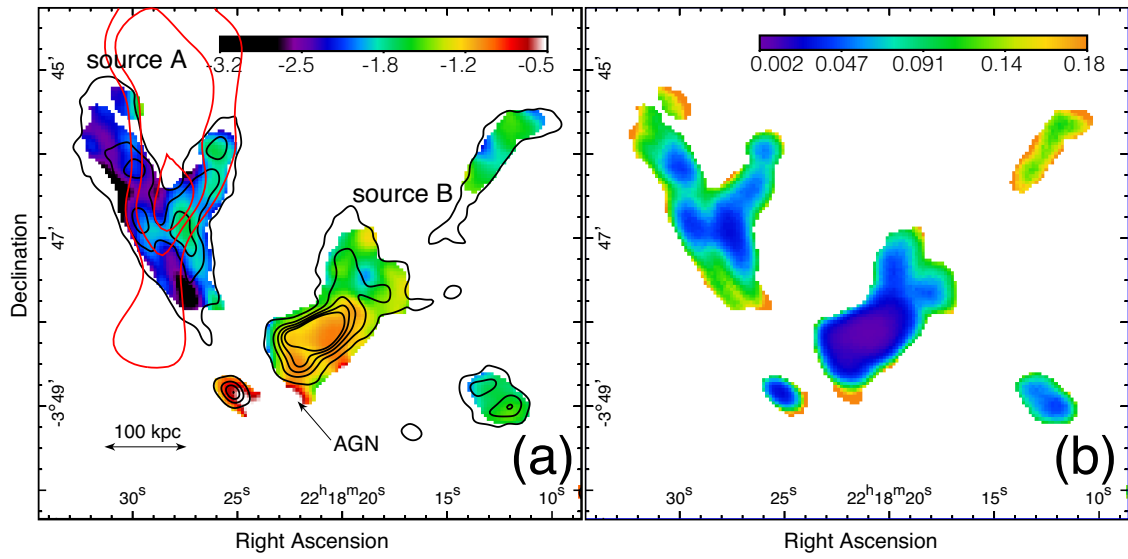


Supplementary Figure 8 **Composite images of the region between 1E 2216.0-0401 and 1E 2215.7-0404.** (a) Composite SDSS *gri* image overlaid with the 235 MHz GMRT (red) and 610 MHz GMRT (contour) showing the possible connection between the radio tails and the radio AGN. (b) *Chandra* image of the same field overlaid with the 235 MHz GMRT (red) and 610 MHz GMRT (contour) showing the diffuse gas halo associated with the radio galaxy. The radio contours are given at the levels of $\sqrt{[1, 8, 64]} \times 4\sigma_{\text{rms}}$, with σ_{rms} being the map noise. (c) The white rectangle shows the field of view of panels (a) and (b).

morphology in the spectral index map. It is hence difficult to explain the tails by radiative cooling alone. Provided that the radio tails further coincide, in projection, with the heated thermal structure in the ICM, we speculate that the present radio source is revived from faded electrons, by either a passing weak shock or an adiabatic compression caused by the merger. The spectral index and morphology of source A seem to be generally consistent with a radio phoenix [12–16], or some sort of old AGN tails re-energized through more gentle processes [17].

As ICM heating and particle (re-)acceleration at source A might have the same origin, it would be interesting to compare the observed thermal energy excess with the energy that powered the relativistic electrons. Assuming that the heated ICM structure at source A has an ellipsoid shape in 3-D, the thermal energy excess is $\sim 1 \times 10^{59}$ erg. Taking the shock speed estimated from the temperature jump in the northwest region (Supplementary Figure 5), the heating time is ~ 100 Myr, and the heating rate is $\sim 3 \times 10^{43}$ erg s $^{-1}$. The total energy spent in accelerating electrons can be approximated by the combined radio and inverse Compton radiation power. The observed flux of source A at 144 MHz is 0.94 Jy, and the average radio spectral index is -2.3. Ignoring the possible curvature, the radio spectrum has the form of $S_\nu = 0.94 \text{ Jy } (\nu/144 \text{ MHz})^{-2.3}$. The bolometric luminosity is therefore $\sim 7 \times 10^{41}$ erg s $^{-1}$, including a typical inverse Compton component might increase the luminosity to double that amount [18]. The small radio-to-thermal-excess ratio implies that little energy goes into accelerating electrons relative to heating the ICM.

The radio structure to the west, source B, gives rise to a number of questions. The origin of the source is uncertain. Does it originate from the same AGN as the radio tails, or some other objects?



Supplementary Figure 9 **Radio spectral index map and spectral index uncertainty map of the radio sources.** (a) Spectral index map at a resolution of $17.6'' \times 10.7''$ calculated between 144 MHz and 325 MHz. Black contours show the 325 MHz GMRT image (same as in Figure 2), and the red contours are the heated ICM structure from the *XMM-Newton* temperature map (same as in the inset of Figure 3). Pixels with values below $5\sigma_{\text{rms}}$ are blanked. (b) Spectral index uncertainty (1σ) map of the same region.

If it is indeed a part of the merger, how was the 450 kpc-long collimated extension formed in such a dynamic system? Is the radio spectrum shaped by re-acceleration, which manages to keep a relatively flat spectral index along the collimated structure? Answering these questions requires further deep radio and X-ray observations. We defer the discussion on the source B to a follow-up paper, since it is not apparently related to the equatorial shocks.

Energetics of the equatorial shocks

The rate of kinetic energy flow through the southeast shock front can be estimated as

$$\Delta F_K = \frac{1}{2} \rho_{\text{pre}} v_s^3 \left(1 - \frac{1}{C^2} \right), \quad (9)$$

where ρ_{pre} is the pre-shock ICM mass density. Adopting $n_e = 2.0 \times 10^{-4} \text{ cm}^{-3}$ in the pre-shock region, shock speed $v_s = 1740 \text{ km s}^{-1}$, and $C = 1.9$, the energy flux is then about $6.5 \times 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1}$. The surface area of the shock depends on the assumption of its shape. As a simple approximation, we may treat the equatorial shock as a conical structure, with a radius $r_c \sim 130 \text{ kpc}$, and height $h_c = 180 \text{ kpc}$. The shock surface area can be estimated as $\pi r_c \sqrt{r_c^2 + h_c^2} \sim 0.1 \text{ Mpc}^2$. With this size, the total rate of the shock kinetic energy is about $6.2 \times 10^{44} \text{ erg s}^{-1}$. Instead, if the shock has an ellipsoid shape, the surface area becomes $\sim 0.13 \text{ Mpc}^2$, and the total kinetic energy flow is then $\sim 8.1 \times 10^{44} \text{ erg s}^{-1}$. The shock power is about two times of the combined radiative X-ray luminosity of the two clusters.

The thermal energy excess in the post-shock region can be estimated as $\Delta E = n_{g,\text{post}}(kT_{\text{post}} - kT_{\text{pre}})V_{\text{post}}$, where $n_{g,\text{post}}$ is the post-shock gas density and V_{post} is the volume of the post-shock region. Using the values determined from the shock jump condition, and assuming an ellipsoid shape of the post-shock region, the shock energy dissipated in the post-shock region is $\sim 2.6 \times 10^{59} \text{ erg}$. Assuming a shock cross time of $h_c/v_s \approx 100 \text{ Myr}$, the heating rate is then about $8.2 \times 10^{43} \text{ erg s}^{-1}$. Therefore, the shock energy thermalized in the current post-shock region ($r \leq 500 \text{ kpc}$ from the collision axis) is only 10% of the total kinetic energy. The main bulk of the shock energy is expected to be dissipated at a large radius.

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