X-ray and radio observations of the radio relic galaxy clusters 1RXS J0603.3+4214 and RXC J1053.7+5453

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Itahana, Takizawa, Akamatsu et al. (2015), PASJ, 67, 113
Itahana, Takizawa, Akamatsu et al. (2017), PASJ, 69, 88

THE POWER OF FARADAY TOMOGRAPHY
--- TOWARDS 3D MAPPING OF COSMIC MAGNETIC FIELDS ---
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Radio Halos / Relics

- Some merging galaxy clusters have diffuse non-thermal radio emitting regions. ($E_e \sim \text{GeV}$, $B \sim \mu\text{G}$)

- Radio halos and (mini halos)
  - Located near the center, similar to X-ray morphology
  - Associated with ICM turbulence???

- Radio relics
  - Located in the outskirts, arc-like shape,
  - Likely associated with ICM shocks?
Mach Number Estimation of Shocks at Radio Relics: Two Methods

Radio Spectral index map of the relic in CIZA J2242.8+5301 (Van Weeren et al. 2010)

\[ F_\nu \propto \nu^{-\alpha} \rightarrow N(E_e) \propto E_e^{-(2\alpha+1)} \]

With a (simple) diffusive shock acceleration model,

\[ M^2 = \frac{2\alpha+2}{2\alpha-2} \]

Temperature Profile across the relic in CIZA J2242.8+5301 (Akamatsu & Kawahara 2013)

With the RH relation

\[ \frac{T_{\text{post}}}{T_{\text{pre}}} = \frac{5M^4+14M^2-3}{16M^2} \]
Akamatsu & Kawahara (2013) suggests that $M_X$ and $M_{\text{radio}}$ seem to be consistent with each other.

A simple model of diffusive shock acceleration is correct?

However, sample size is obviously too small to say something definite.
**1RXS J0603.3+4214 with “toothbrush-relic”**

Radio spectral index map (van Weeren et al. 2012)
\[ \alpha_{\text{inj}} = 0.6 - 0.7 \quad \longrightarrow \quad M_{\text{radio}} = 3.3 - 4.6 \]

Ogrean et al. (2013)
Colors: X-ray (XMM)
Contours: radio (WSRT)

X-ray surface brightness profile across the relic (Ogrean et al. 2013)
\[ M_X = 1.7^{+0.41}_{-0.42} \]
Shock is shifted outward from the relic outer edge?

\[ \frac{\rho_2}{\rho_1} = \frac{4M_X^2}{M_X^2 + 3} \]
toothbrush-relic: temperature profile across the relic (Itahana et al. 2015)

- Obtained Mach number
  \[ \frac{T_2}{T_1} = \frac{5M_X^4 + 14M_X^2}{16M_X^2} - 3 \]

  \[ 1.50^{+0.37+0.25+0.14}_{-0.27-0.24-0.15} \]

- Similar to the XMM results (Ogrean et al. 2013, surface brightness analysis), but more robust for uncertainties of line-of-sight structures.

- Inconsistent with radio results.
After our work, (van Weeren et al. 2016)

- New radio data (LOFAR+VLA) show steeper spectra.
  \[ \alpha = -0.8 \pm 0.1 \]
  \[ \mathcal{M} = 2.8^{+0.5}_{-0.3} \]

- Chandra X-ray data indicate shock is just at the outer edge of the relic, maybe XMM result is incorrect.
  \[ \mathcal{M} \approx 1.2, \text{ with an upper limit of } \mathcal{M} \approx 1.5 \]
RXC J1053.7+5453

- Elongated X-ray morphology, with radio relic (van Weeren et al. 2011)
- Two subgroups in galaxy distribution.
- No direct temperature measurements ($kT \sim 3\text{keV}$ is expected from $L_x$-$kT$ relation)
- No radio spectral information

van Weeren (2011)

Colors: X-ray(ROSAT)
Solid contours: radio(WSRT)
Dotted contours: galaxy distribution
RXC J1053: temperature profile across the relic (Itahana et al. 2017)

- Unfortunately, we do not have any radio spectral information.

\[ \frac{T_2}{T_1} = \frac{5M_X^4 + 14M_X^2 - 3}{16M_X^2} \]

\[ M_X = 1.44^{+0.48+0.14+0.03}_{-0.91-1.34-0.04} \]
We found surface brightness edge, between the cluster X-ray peak and relic.

This indicates the discontinuity in the density structure.

Shock?, contact discontinuity?, others?
RXC J1053: Surface brittleness edge (2) (Itahana et al. 2017)

Surface brightness profile

Temperature profile

\[ n(r) = \begin{cases} 
  n_1 \left( \frac{r}{R_f} \right)^{-\alpha_1}, & r < R_f \\
  n_1 \frac{1}{C} \left( \frac{r}{R_f} \right)^{-\alpha_2}, & r > R_f 
\end{cases} \]

\[ \frac{n_1}{n_2} = 2.44^{+2.50}_{-1.22} \]

\[ \frac{T_1}{T_2} = 0.72^{+0.24}_{-0.15} \]

- This is not a shock, may be a contact discontinuity.
Contact discontinuity (Cold front)
Summary

- Diffuse non-thermal radio emissions are found in some clusters of galaxies (radio halos, relics). Radio relics are likely associated with shocks in the ICM.

- Comparison with X-ray and radio observation results provide us with implications of diffusive shock acceleration model.

- In toothbrush relic, there is a hint of inconsistency between X-ray and radio Mach number estimates.

- In RXC J1053, we measure ICM temperature for the first time and estimate Mach number of shock candidate at the relic and found a feature like a contact discontinuity.
Radio relic Mach number problem: updated version

- Sample size becomes slightly larger.
- Some radio results has been changed.
- Basically, $M_x$ and $M_{\text{radio}}$ seems to be consistent with each other, but some outliers like "toothbrush" may exist.

Akamatsu & Kawahara (2013)
Magnetic field strength (Toothbrush relic)

- Non-thermal X-ray (0.3\text{–}10\,\text{keV}) upper limit

\[ F_{IC}[0.3\text{–}10\text{keV}] < 2.24 \times 10^{-13}\,\text{erg/cm}^2/\text{s}(90\% \text{信頼度}) \]

- Radio flux corresponding to X-ray (0.3\text{–}10\,\text{keV})

\[ F_{\text{sync}}[0.3\text{–}10\text{keV}] = 6.8 \times 10^{-15} \left( \frac{B}{G} \right)^{-0.1} \]

\[ S_{1382\text{MHz}} = 319.5 \pm 20.8 \, mJy \]

\[ F_{\text{sync}} / F_{IC} = \frac{B^2}{8\pi} / U_{\text{CMB}} \]

\[ B > 1.6 \mu G \]

(van Weeren et al. 2012)
Energy density (toothbrush relic)

- Magnetic field

\[ U_B = \frac{B^2}{8\pi} \]

\[ > 1.0 \times 10^{-13} \text{ erg/cm}^3 \]

- Thermal ICM

\[ U_{th} = \frac{3}{2} \frac{n_e kT}{\mu} \]

\[ = 8.6 \times 10^{-12} \text{ erg/cm}^3 \]

- Non-thermal electrons

\[ U_e = \int C \left( \frac{E}{m_e c^2} \right)^{1-p} dE \]

\[ < 3.6 \times 10^{-14} \text{ erg/cm}^3 \]

\[ \frac{U_B}{U_{th}} > 1.2 \times 10^{-2} \]

\[ \frac{U_e}{U_{th}} < 4.3 \times 10^{-3} \]
Magnetic Field Strength (RXC J1053 relic)

\[
\frac{S_{\text{Synch}}}{S_{\text{IC}}} \propto \frac{B^{(p+1)/2} \nu_{\text{Synch}}^{-(p-1)/2}}{(kT_{\text{CMB}})^{(p+5)/2} \nu_{\text{IC}}^{-(p-1)/2}}
\]

\[
S_{1382 \text{ MHz}} = 15 \pm 2 \text{ mJy}
\]

(van Weeren et al. 2011)

- $\Gamma=2.0$

\[
S_{\text{IC}} < 2.22 \times 10^{-10} \text{ Jy at 10 keV (}\nu_{\text{IC}} = 2.4 \times 10^{18} \text{ Hz})
\]

\[
B > 0.73 \mu \text{G}
\]

- $\Gamma=3.8$

\[
S_{\text{IC}} < 1.11 \times 10^{-8} \text{ Jy}
\]

\[
B > 2.00 \mu \text{G}
\]
Energy Density (RXC J1053 relic)

\[ U_{th} = 1.52^{+1.10}_{-0.45} \times 10^{-13} \text{ erg/cm}^3 \]

\[ n_e = 3.12^{+0.78}_{-1.08} \times 10^{-5} \text{ cm}^{-3} \]

In case of \( \Gamma = 2.0 \)

\[ U_{\text{mag}} > 2.1 \times 10^{-14} \text{ erg/cm}^3 \]
\[ U_e < 7.8 \times 10^{-16} \text{ erg/cm}^3 \]

In case of \( \Gamma = 3.8 \)

\[ U_{\text{mag}} > 1.6 \times 10^{-13} \text{ erg/cm}^3 \]
\[ U_e < 5.6 \times 10^{-12} \text{ erg/cm}^3 \]

\[ U_{\text{mag}}/U_{th} > 0.14 \]
\[ U_e/U_{th} < 5.1 \times 10^{-3} \]

\[ U_{\text{mag}}/U_{th} > 1.00 \]
\[ U_e/U_{th} < 36.7 \]

❖ Unlikely???
A Simple DSA is not correct?
The spectrum is not a single power-law??
Temperature in the central region of RXC J1053

\[ kT = 1.38^{+0.17}_{-0.11} + 0.04 - 0.04 - 0.01 \text{ keV} \]

- **Lx – kT relation**
  
  (Hilton et al. 2012)

\[
\log\left( \frac{L_x}{E(z) \text{ erg/s}} \right) = (44.67 \pm 0.09) \\
+ (3.04 \pm 0.16) \log\left( \frac{kT}{5 \text{ keV}} \right) \\
- (1.5 \pm 0.5) \log(1 + z)
\]

\[ L_x[0.1-2.4keV] = 0.96 \times 10^{44} \text{ erg/s} \]

\[ z = 0.0704 \]

\[ \sigma = 665^{+51}_{-45} \text{ km/s} \]

\[ kT = 3.04 \pm 1.08 \text{ keV} \]