Low-frequency Radio Observations of Galaxy Cluster Merger Shocks

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Small fraction of the energy can be channeled into the production of Cosmic Rays.

- Internal merger shocks
- Accretion shocks

Millennium Simulation, Springel+ 2005

blue: X-rays
red: radio synchrotron
QUESTIONS

- Physics of shocks & turbulence
- Origin of Cosmic Rays (CR) and magnetic fields in the ICM
  - Particle acceleration mechanisms
  - Acceleration efficiency of shocks/turbulence
  - Magnetic field amplification
- Contribution of CRs and B-fields to the ICM pressure budget
DIFFUSE CLUSTER RADIO EMISSION

latest review paper: Brunetti & Jones 2014

MACS J1752.0+4440 (van Weeren+ 2012; Bonafede+ 2012)

Radio (WSRT) + X-rays (XMM)

GIANT RADIO RELICS:

• Cluster outskirts, elongated
• Radio emission traces merger shocks
• Particle acceleration mechanism:
  • diffusive shock acceleration? (Ensslin+ 1998)

GIANT RADIO HALOS:

• Smooth, centrally located
• Particle acceleration mechanism:
  • Radio emission generated via turbulent re-acceleration mechanism? (Brunetti+01, ...)
  • Radio emission from secondary electrons (products of hadronic collisions)? (Dennison 1980, ...)

Abell 2744; Feretti+ 2012, Govoni+ 2001

Radio Halo

Radio Relics

1 Mpc

Radio image + radio contours
DIFFUSE CLUSTER RADIO EMISSION

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BACKGROUND: RADIO SPECTRAL INDEX

Acceleration produces power-law particle distribution

\[ n(E) \propto E^{-p}, \quad p = 1 - 2\alpha \]

“injection spectral index” \( \alpha \) set by acceleration mechanism/source physical condition
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Energy losses radiating electrons:
- synchrotron losses
- Inverse Compton losses

“Spectral ageing”/“electron cooling”

\[ \frac{dE}{dt} \propto -E^2 \]

→ spectrum steepens and curves with time
Origin of the radiating electrons?

- Radiative lifetime of electrons is $10^8$ yr $<<$ diffusion timescale (Jaffe 1977) $\rightarrow$ electrons are **accelerated in-situ** in the ICM.
- Merger connection: giant radio relics and halos are **only** found in disturbed galaxy clusters.
- ICM: Particle acceleration poorly understood in this regime.

**Relics: Diffusive shock acceleration (DSA)?**

- Particles accelerated by multiple crossings of a shock front (first order Fermi process).
- Recent PIC simulations show efficient electron acceleration for low-Mach number shocks.

**Re-acceleration?**

- Relativistic particles accumulated over the lifetime of a cluster.
Non-thermal component of the ICM (cosmic rays)

IRXS J0603.3+4214 (z=0.225)
Found by inspecting 1.4 GHz NVSS & 325 MHz WENSS radio survey images
Non-thermal component of the ICM (cosmic rays)

1 Mpc

GMRT radio image (325 MHz)

Radio Relic ("Toothbrush")
Radio Halo

1RXS J0603.3+4214 (z=0.225)
Found by inspecting 1.4 GHz NVSS & 325 MHz WENSS radio survey images

XMM X-ray image (+radio contours)

Thermal component of the ICM

Follow-up XMM observations by Ogrean+2013:
• $L_X \sim 10^{45}$ erg s$^{-1}$, $T = 7.5$ keV
• main merger event in the NS direction
• evidence for shocks (M$\sim$1.5) via surface brightness jumps

Ogrean+2013; van Weeren+2012
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LOFAR

• New radio telescope operating at 10-250 MHz

• About 50 antenna stations
  • 40 stations in the Netherlands
  • stations in Germany, UK, Sweden, France, Poland

• Large range of baselines (100 m - 1,000 km)

• Phased-array technology (multi-beaming)
LOFAR 120-180 MHz

One pointing full FOV
4 x 4 degr
LOFAR results

120-180 MHz, 95 microJy/beam rms noise

LOFAR vs GMRT

LOFAR
resolution: 7 arcsec
noise: 95 microJy/beam

GMRT
resolution: 22 arcsec
noise: 1100 microJy/beam

emphasize large-scale emission with weighting

(6 arcsec)

(35 arcsec)

(22 arcsec)
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Chandra + LOFAR

(35 arcsec)
(22 arcsec)
GMRT 610 MHz image

shock: particle injection

energy losses

Spectral index
GMRT 610 MHz image

shock: particle injection

energy losses

energy losses

GMRT 610 MHz - LOFAR 150 MHz

Spectral index
shock: particle injection

energy losses

GMRT 610 MHz - LOFAR 150 MHz

Spectral index

JVLA 1.5 GHz - LOFAR 150 MHz

Re-acceleration due to turbulence ??

energy losses
Puzzles

- North: Mismatch between relic emission and shock location
- South: Shock but no bright radio relic

Chandra 0.5-2.0 keV

best fit shock position

Ogrean+ 2013
Puzzles

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Ogrean+ 2013

Chandra 0.5-2.0 keV
SUMMARY

• First ultra-deep LOFAR cluster image
• Radio halos: CR electrons from shocks re-accelerated by merger induced turbulence?
• Puzzle: Shock without clear radio relic?
• Puzzle: Mismatch between relic and shock location?