Shocking Astrophysics in Galaxy Clusters

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in collaboration with

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1 Non-thermal emission
   - Introduction
   - Physical processes
   - Radio halos and relics

2 Cosmic ray transport
   - Observations and models
   - CR pumping, streaming, and diffusion
   - Radio and gamma-ray bimodality

3 Probes of accretion shocks
   - A puzzling radio galaxy
   - Radio galaxy-bubble system
   - Radio gischt emission
Outline

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Shocks in galaxy clusters

1E 0657-56 ("Bullet cluster")
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

Abell 3667
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)
Giant radio halo in the Coma cluster

thermal X-ray emission
(Snowden/MPE/ROSAT)

radio synchrotron emission
(Deiss/Effelsberg)
What can we learn from non-thermal emission?

- **plasma astrophysics:**
  - shock and particle acceleration
  - large-scale magnetic fields
  - turbulence

- **dynamical state → cosmology?**
  - non-thermal pressure support: hydrostatics + SZE
  - history of individual clusters: cluster archeology
  - illuminating the process of structure formation

- **consistent picture of non-thermal processes:**
  radio, soft/hard X-rays, \( \gamma \)-rays
Hadronic cosmic ray proton interaction

- $\pi^0$
- $\pi^+$
- $\mu^+$
- $e^+$
- $\nu_\mu$
- $\nu_e$
- $\nu_\mu$
- $p$
- $CRp$
Hadronic cosmic ray proton interaction

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Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

Energy sources:
- kinetic energy from structure formation
- supernovae & active galactic nuclei

Plasma processes:
- turbulent cascade & plasma waves
- shock waves

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Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons

hadronic reaction
Multi-messenger approach for non-thermal processes

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Observational diagnostics:
- radio synchrotron emission
- IC: hard X-ray & gamma-ray emission

hadronic reaction
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- $\pi^0$

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- IC: hard X-ray & gamma-ray emission
- gamma-ray emission

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Which one is the simulation/observation of A2256?

**red/yellow**: thermal X-ray emission,
**blue/contours**: 1.4 GHz radio emission with giant radio halo and relic
Observation – simulation of A2256

red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Clarke & Enßlin (2006)

C.P. & Battaglia (in prep.)
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Radio halo theory – (i) hadronic model

\[ p_{\text{CR}} + p \rightarrow \pi^\pm \rightarrow e^\pm \]

**strength:**
- all required ingredients available:
  - shocks to inject CRp, gas protons as targets, magnetic fields
- predicted luminosities and morphologies as observed without tuning
- power-law spectra as observed

**weakness:**
- all clusters should have radio halos
- does not explain all reported spectral features
- ...
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Radio luminosity - X-ray luminosity

- Radio halos
- Radio mini-halos

\[ L_X \ (0.1 - 2.4 \text{ keV}) \ [10^{44} \text{ erg s}^{-1}] \]

\[ P_{1.4 \text{GHz}} \ [10^3 \text{ erg s}^{-1} \text{ Hz}^{-1}] \]
Radio luminosity - X-ray luminosity

- **radio halos**
- **radio mini-halos**

\[ P_{1.4\text{GHz}} \left[ 10^{31} \text{ erg s}^{-1} \text{ Hz}^{-1} \right] \]

\[ L_X (0.1 - 2.4 \text{ keV}) \left[ 10^{44} \text{ erg s}^{-1} \right] \]

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Radio luminosity - central entropy

\[ P_{1.4 \text{GHz}} \left[ 10^{31} \text{erg s}^{-1} \text{Hz}^{-1} \right] \]

\[ K_0 \left[ \text{keV cm}^2 \right] \]

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Radio luminosity - central entropy

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Radio luminosity - central entropy

The graph shows the relationship between radio luminosity, $P_{1.4\text{GHz}}$, and central entropy, $K_0$, in units of $10^{31}$ erg s$^{-1}$ Hz$^{-1}$ and keV cm$^2$, respectively. The data points are plotted on a logarithmic scale, indicating a bimodal distribution. The red line represents a theoretical model or fit to the data.
Radio luminosity - central entropy

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Proton cooling times

\[ \tau = \frac{E}{\dot{E}} \text{ [Gyr]} \]

- Coulomb
- Hadronic

\[ n_e = 10^{-4} \text{ cm}^{-3} \]
\[ n_e = 10^{-3} \text{ cm}^{-3} \]
\[ n_e = 10^{-2} \text{ cm}^{-3} \]
Proton cooling times

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Radio halo theory – (ii) re-acceleration model

strength:

- all required ingredients available: radio galaxies & relics to inject CRe, plasma waves to re-accelerate, …
- reported complex radio spectra emerge naturally
- clusters without halos ← less turbulent

weakness:

- Fermi II acceleration is inefficient – CRe cool rapidly
- observed power-law spectra require fine tuning
- …
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Electron cooling times

\[ \tau = \frac{E}{\dot{E}} \text{[Gyr]} \]

- synchrotron + IC:
  - \( B = 1 \mu \text{G} \)
  - \( B = 3 \mu \text{G} \)
  - \( B = 10 \mu \text{G} \)

- Hubble
- Coulomb:
  - \( n_e [\text{cm}^{-3}] = 10^{-4}, 10^{-3}, 10^{-2} \)
  - total loss

\( B = 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 10^{0}, 10^{1}, 10^{2} \)
Electron cooling times

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- Total loss
Electron cooling times

Electron kinetic energy $E$ vs. electron loss timescale $\tau = E/\dot{E}$ (Gyr)

- Synchrotron + IC:
  - $B = 1 \, \mu G$
  - $B = 3 \, \mu G$
  - $B = 10 \, \mu G$

- Coulomb:
  - $n_e [\text{cm}^{-3}] = 10^{-4}, 10^{-3}, 10^{-2}$

- Hubble

Total loss
Cosmic ray transport – magnetic flux tube with CRs
Cosmic ray advection
Adiabatic expansion and compression
Cosmic ray streaming
Expanded CRs
Turbulent pumping
Turbulent pumping
Turbulent-to-streaming ratio

\[ \gamma_{tu} = \frac{u_{tu}}{u_{st}} \]

\[ \gamma_{tu} \gg 1 \]

\[ \gamma_{tu} \ll 1 \]
Are CRs confined to magnetic flux tubes?
Escape via diffusion: energy dependence

\[ \gamma_{tu} = \frac{\nu_{tu}}{\nu_{st}} \gg 1 \]

\[ \nu_{st} \ll \nu_{micro} \sim c_s \]

\[ \nu_{macro} \]

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CR transport theory

CR continuity equation in the absence of sources and sinks:

\[
\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\vec{\nu} \rho) = 0
\]

\[
\vec{\nu}_{\text{st}} = -\nu_{\text{st}} \frac{\vec{\nabla} \rho}{|\vec{\nabla} \rho|}
\]

\[
\vec{\nu}_{\text{di}} = -\kappa_{\text{di}} \frac{1}{\rho} \vec{\nabla} \rho
\]

\[
\vec{\nu}_{\text{ad}} = -\kappa_{\text{tu}} \frac{\eta \vec{\nabla} \rho}{\rho \eta}
\]

\[
\kappa_{\text{tu}} = \frac{L_{\text{tu}} \nu_{\text{tu}}}{3}
\]

CR profile due to advection

$$\eta(r) = \left( \frac{P(r)}{P_0} \right)^{\frac{3}{5}}$$
$\gamma_{tu} = \frac{v_{tu}}{v_{st}}$

$\rho(r)$ vs $r/r_c$ for different values of $\gamma_{tu}$.
CR density at fixed particle energy

\[ \gamma_{tu} = \frac{\nu_{tu}}{\nu_{st}} \]

\( r/r_c \)

\[ C(r) \]

\( \gamma_{tu} = 1, 3, 10, 30, 100 \)

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Gamma-ray emission profile

$\rho_{\text{CR}} + p \rightarrow \pi^0 \rightarrow 2\gamma$

$\gamma_{tu} = \frac{v_{tu}}{v_{st}}$

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Gamma-ray luminosity

\[ \gamma_{tu} = \frac{v_{tu}}{v_{st}} \]

\[ \rho_{CR} + p \rightarrow \pi^0 \rightarrow 2\gamma \]
Non-thermal emission
Cosmic ray transport
Probes of accretion shocks

Observations and models
CR pumping, streaming, and diffusion
Radio and gamma-ray bimodality

\[ \gamma\text{-ray limits and hadronic predictions} \quad (\text{Ackermann et al. 2010}) \]

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Radio emission profile

\[ \rho_{\text{CR}} + \rho \rightarrow \pi^\pm \rightarrow e^\pm \rightarrow \text{radio} \]
Radio luminosity

\[ L(V) = A_y \int dV C \rho_{gas} \frac{\varepsilon_B}{\varepsilon_B + \varepsilon_{ph}} \left( \frac{\varepsilon_B}{\varepsilon_B^*} \right)^{\alpha - 2} \]

\[ \gamma_{tu} = \frac{V_{tu}}{V_{st}} \]

\[ \varepsilon_B(r) = \frac{B_0^2}{8\pi} \frac{\rho(r)}{n_0} \left( \frac{\gamma_{tu}}{10} \right)^{\delta_B} \]

\[ \rho_{CR} + \rho \rightarrow \pi^\pm \rightarrow e^\pm \rightarrow \text{radio} \]
Conclusions on cosmic ray transport

- Streaming & diffusion produce spatially flat CR profiles.
- Advection produces centrally enhanced CR profiles.
- Profile depends on advection-to-streaming-velocity ratio.
- Turbulent velocity $\sim$ sound speed $\leftarrow$ cluster merger.
- CR streaming velocity $\sim$ sound speed $\leftarrow$ plasma physics.
- Peaked/flat CR profiles in merging/relaxed clusters.
- Energy dependence of $\nu_{\text{st}}^{\text{macro}}$ $\rightarrow$ CR & radio spectral variations.
- Outstreaming CR: dying halo $\leftarrow$ decaying turbulence.
- Bimodality of cluster radio halos & gamma-ray emission!
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$\rightarrow$ Bimodality of cluster radio halos & gamma-ray emission!
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Wish list for shocks

What we would like to measure and hope to infer:

- jump conditions: shock strength
- upstream properties: infalling WHIM
- post- and pre-shock conditions: geometry, obliquity
- shock curvature: vorticity and $B$ field generation
- post-shock turbulence: power spectrum, non-thermal pressure support
- ...

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O’Dea & Owen (1986): 4.9 GHz (left) and 1.4 GHz (right)
Bipolar AGN jets in an ICM wind: magnetic field

credit: Porter, Mendygral & Jones

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Bipolar AGN jets in an ICM wind: synthetic radio

credit: Porter, Mendygral & Jones
Radio properties of NGC 1265

Sijbring & de Bruyn (1998), left: radio intensity $I_{600\,\text{MHz}}$; right: variations of $I_{600\,\text{MHz}}$ (triangles), $I_{150\,\text{MHz}}$ (squares) and spectral index (bottom) along the tail.
Requirements for any model of NGC 1265

- bright narrow angle tail radio jet: synchrotron cooling
- transition region: change of winding direction and sharp drop in $S_\nu$ and $\alpha$
- coherent properties along the dim radio ring, confined morphology

→ we are looking at 2 electron populations in projection possibly suggesting 2 different epochs of feedback:

→ active jet + detached radio bubble that recently got energized coherently across 300 kpc → shock?
Shock overruns an aged radio bubble (C.P. & Jones 2011)
Bubble transformation to vortex ring

Enßlin & Brüggen (2002): gas density (top) and magnetic energy density (bottom)
Enßlin & Brüggen (2002): total 100 MHz intensity and polarization E-vectors, strong shock/weak $B$ (left) and strong shock/strong $B$ model (right)
C.P. & Jones (2011):

Top view (not to scale):

0

1

2

3

4

NGC 1265

radio torus

head–tail jet

shock surface

plasma bubbles

to observer

NGC 1265

C.P. & Jones (2011):
NGC 1265 as a perfect probe of a shock

- **idea:**
  - galaxy velocity not affected by shock → pre-shock conditions
  - tail & torus as tracers of the post-shock flow

- **assumptions:**
  - shock surface $\parallel$ gravitational equipotential surface of Perseus
  - recent jet launched shortly after shock crossing

- **method:**
  - extrapolating position and velocity back in time
  - employing conservation laws at oblique shock
  - iterate until convergence
Derived geometry for NGC 1265

C.P. & Jones (2011)
Shock strength and jump conditions

- Shock compresses relativistic bubble adiabatically: \( P_2 / P_1 = C^{4/3} \)

- Bubble compression factor:

\[
C = \frac{V_{\text{bubble}}}{V_{\text{torus}}} = \frac{\frac{4}{3} \pi R^3}{2 \pi^2 R r_{\text{min}}^2} = \frac{2}{3 \pi} \left( \frac{R}{r_{\text{min}}} \right)^2 \approx 10
\]

- Assuming pressure equilibrium → shock jumps:

\[
\frac{P_2}{P_1} \approx 21.5, \quad \frac{\rho_2}{\rho_1} \approx 3.4, \quad \frac{T_2}{T_1} \approx 6.3 \quad \text{and} \quad M \approx 4.2
\]

C.P. & Jones (2011)
Perseus accretion shock and WHIM properties

- jet has low Faraday RM $\rightarrow$ NGC 1265 on near side of Perseus
  - NGC 1265 redshifted w/r to Perseus $\rightarrow$ infalling system
  - shock likely the accretion shock

- extrapolating X-ray $n$- and $T$-profiles to $R_{200}$ & shock jumps:
  - upper limits on infalling warm-hot intergalactic medium

\[
\begin{align*}
kT_1 & \lesssim 0.4 \text{ keV} \\
n_1 & \lesssim 5 \times 10^{-5} \text{ cm}^{-3} \\
P_1 & \lesssim 3.6 \times 10^{-14} \text{ erg cm}^{-3}
\end{align*}
\]

C.P. & Jones (2011)
ellipticity of radio torus (magnitude and orientation) & bending direction of tail
→ excludes projection effects
→ evidence for post-shock shear flow

shock curvature injects vorticity that shears the gas westwards:

\[
\frac{\varepsilon_{\text{shear}}}{\varepsilon_{\text{th,2}}} = \frac{\mu m_p v^2}{3kT_2} \approx 0.14,
\]

with \( kT_2 \approx 2.4 \text{ keV} \) and \( v_\perp \approx 400 \text{ km/s} \).

C.P. & Jones (2011)
Structure formation shocks triggered by a recent merger of a large galaxy cluster.

red/yellow: shock-dissipated energy,
blue/contours: 150 MHz radio gischt emission from shock-accelerated CRe

Combining the low-frequency radio observables of relics, we can probe

- strength and coherence scale of cluster magnetic fields
- diffusive shock acceleration of electrons
- existence and properties of the WHIM
- dynamical state of the cluster
Population of faint radio relics in merging clusters
Probing the large scale magnetic fields

Finding radio relics with an FOF-finder that links radio emission instead of DM → relic luminosity function:

radio map with GMRT emissivity threshold

“theoretical” threshold (towards SKA)
Relic luminosity function → magnetic field behaviour and dynamical state:

- Varying magnetic decline with radius
- Varying overall magnetic strength
**Rotation measure (RM)**

RM maps and power spectra have the potential to infer the magnetic pressure support and discriminate the nature of MHD turbulence in clusters:

Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.

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Conclusions on probes of accretion shocks

- **radio galaxies** are perfect probes of pre- and post-shock flows:
  - hydrodynamic jumps and Mach numbers
  - statistical properties of the infalling WHIM (+ X-rays)
  - estimating the curvature radius of shocks and induced shear flows

- **radio gischt emission** in cluster outskirts probes
  - strength and coherence scale of magnetic fields
  - diffusive shock acceleration of electrons
  - nature of magnetic and hydrodynamic turbulence
  - dynamical cluster state
Non-thermal emission
Cosmic ray transport
Probes of accretion shocks

A puzzling radio galaxy
Radio galaxy-bubble system
Radio gischt emission

Literature for the talk