Cosmic rays in galaxy clusters and cosmological shock waves
Going beyond gas physics

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Outline

1. Non-equilibrium processes in clusters
   - Introduction
   - Cluster radio halos
   - Minimum energy condition

2. Cosmic rays in GADGET
   - Importance of cosmic ray feedback
   - Philosophy and description

3. Cosmological shock waves
   - Observations of cluster shocks
   - Mach number finder
   - Cosmological simulations
   - Cluster simulations
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Cluster non-equilibrium processes
Cosmic rays in GADGET
Cosmological shock waves
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Galaxy clusters are dynamically evolving dark matter potential wells:

- protons and electrons
- shock waves inject CR
- CRe: ~ 10 GeV
- gas: ~ 3 keV
- B: ~ 3 μG
- synchrotron emission
- diffuse radio (GHz)
- Space
Each frequency window is sensitive to different processes and cluster properties:

- **optical**: gravitational lensing of background galaxies, galaxy velocity dispersion measure gravitational mass
- **X-ray**: thermal plasma emission, \( F_X \propto n_{th}^2 \sqrt{T_{th}} \rightarrow \) thermal gas with abundances, cluster potential, substructure
- **Sunyaev-Zel’dovich effect**: IC upscattering of CMB photons by thermal electrons, \( F_{SZ} \propto p_{th} \rightarrow \) cluster velocity, turbulence, high-z clusters
- **radio synchrotron halos**: \( F_{sy} \propto \varepsilon_B \varepsilon_{CRE} \rightarrow \) magnetic fields, CR electrons, shock waves
- **diffuse \( \gamma \)-ray emission**: \( F_{\gamma} \propto n_{th} n_{CRp} \rightarrow \) CR protons
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Coma cluster: optical emission
Coma cluster: infra-red emission
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Coma cluster: X-ray emission
Coma cluster: radio synchrotron emission
Models for radio synchrotron halos in clusters

Halo characteristics: smooth unpolarized radio emission at scales of 3 Mpc.
Different CR electron populations:

- **Primary accelerated CR electrons**: synchrotron/IC cooling times too short to account for extended diffuse emission
- **Re-accelerated CR electrons** through resonant interaction with turbulent Alfvén waves: possibly too inefficient, no first principle calculations (Jaffe 1977, Schlickeiser 1987, Brunetti 2001)
Hadronic cosmic ray proton interaction
Cosmic rays in clusters of galaxies
What do we know about CRs?

- predictions for the CR pressure span between 10% and 50% of the cluster’s pressure budget
- escape of cosmic ray protons only possible for energies $E_{\text{CRp}} > 2 \times 10^{16} \text{ eV}$
- energy losses (for particles with $E \sim 10$ GeV):
  - $\text{CRe}$: synchrotron, inverse Compton: $\tau \sim 10^8 \text{ yr}$
  - $\text{CRp}$: inelastic collisions, Coulomb losses: $\tau \sim 10^{10} \text{ yr} \sim \text{Hubble time}$

Coma cluster: radio halo, $\nu = 1.4$ GHz, $2.5^\circ \times 2.0^\circ$

(Credit: Deiss/Effelsberg)
Cooling core clusters are efficient CRp detectors

ROSAT observation: Perseus galaxy cluster

Credit: NASA/LoA/A. Fabian et al.
Credit: ROSAT/PSPC

Chandra observation: central region of Perseus

Credit: NASA/LoA/A. Fabian et al.
Credit: ROSAT/PSPC
Cooling core cluster model of CRp detection

Perseus galaxy cluster

\[ \epsilon_{\text{CRp}} = \chi_{\text{CRp}} \epsilon_{\text{th}} \]
Gamma-ray flux of the Perseus galaxy cluster
IC emission of secondary CRs ($B = 0$), $\pi^0$-decay induced $\gamma$-ray emission:

\[ \frac{dF_\gamma}{dE_\gamma} \propto [X_{\text{CRp}}] \gamma \text{ cm}^{-2} \text{s}^{-1} \text{GeV}^{-1} \]

\[ \alpha_p = 2.1, 2.3, 2.5, 2.7 \]
Upper limits on $X_{CRp}$ using EGRET limits

![Graph showing upper limits on $X_{CRp}$ using EGRET limits for various clusters.]

- **Cool core cluster:**
  - A85
  - Perseus
  - A2199
  - Centaurus
  - Ophiuchus
  - Triangulum Australis
  - Virgo

- **Non-cool core cluster:**
  - Coma
  - A2256
  - A2319
  - A3571

The graph illustrates the upper limits on $X_{CRp}$ for various clusters, with $X_{CRp} = \varepsilon_{CRp}/\varepsilon_{th}$, where $\alpha_p$ values are indicated for different clusters:

- $\alpha_p = 2.1$
- $\alpha_p = 2.3$
- $\alpha_p = 2.7$
- $\alpha_p = 2.3$, radio

The magnetic field strength $B = 10 \mu G$ is also shown.
Radio halos: Coma and Perseus

Coma radio halo, $\nu = 1.4$ GHz, 
largest emission diameter $\sim 3$ Mpc 
(Credit: Deiss/Effelsberg)

Perseus mini-halo, $\nu = 1.4$ GHz, 
largest emission size $\sim 0.5$ Mpc 
(Credit: Pedlar/VLA)
Minimum energy criterion (MEC): the idea

\[ \varepsilon_{NT} = \varepsilon_B + \varepsilon_{CRp} + \varepsilon_{CRe} \]

\[ \rightarrow \text{minimum energy criterion: } \left. \frac{\partial \varepsilon_{NT}}{\partial \varepsilon_B} \right|_{j_\nu} \equiv 0 \]

- classical MEC: \( \varepsilon_{CRp} = k_p \varepsilon_{CRe} \)
- hadronic MEC: \( \varepsilon_{CRp} \propto (\varepsilon_B + \varepsilon_{CMB}) \varepsilon_B^{-(\alpha_\nu + 1)/2} \)

defining tolerance levels: deviation from minimum by one e-fold
Classical minimum energy criterion

\[ X_{\text{CRp}}(r) = \frac{\varepsilon_{\text{CRp}}(r)}{\varepsilon_{\text{th}}}, \quad X_{B}(r) = \frac{\varepsilon_{B}(r)}{\varepsilon_{\text{th}}(r)} \]

Coma cluster: classical minimum energy criterion

Perseus cluster: classical minimum energy criterion

\[ B_{\text{Coma}}(0) = 1.1^{+0.7}_{-0.4} \mu G \]

\[ B_{\text{Perseus}}(0) = 7.2^{+4.5}_{-2.8} \mu G \]
$X_{\text{CRp}}(r) = \frac{\varepsilon_{\text{CRp}}(r)}{\varepsilon_{\text{th}}(r)}$, $X_B(r) = \frac{\varepsilon_B(r)}{\varepsilon_{\text{th}}(r)}$

Coma cluster: hadronic minimum energy condition

Perseus cluster: hadronic minimum energy condition

$B_{\text{Coma}}(0) = 2.4^{+1.7}_{-1.0} \mu G$

$B_{\text{Perseus}}(0) = 8.8^{+13.8}_{-5.4} \mu G$
A galactic outflow seen at high redshift. Left: the projected gas density around some of the first star forming galaxies. Right: generated bubbles of hot gas, as seen in the temperature map (Springel & Hernquist 2002).
Potential effects of cosmic ray feedback

Mostly speculations so far

- **Feedback on galactic scales:**
  - Regulation of star formation efficiency due to extra CR pressure.
  - Driving Galactic outflows due to buoyant rise of CRs in star forming regions.
  - Radiative cooling losses of galaxies altered by different CR cooling times → gas flow in halos might be affected.

- **Feedback on larger scales:**
  - Changing the total baryonic fraction that ends up in collapsed structures due to effects of different CR cooling times and equation of state.
  - CRs might change the absorption properties at high redshift.
Potential effects of cosmic ray feedback
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Our model describes the CR physics by three adiabatic invariants:

1. CRs are coupled to the thermal gas by magnetic fields.
2. We assume a single power-law CR spectrum: momentum cutoff $q$, normalization $C$, spectral index $\alpha$ (constant).
3. $q$ determines CR energy density and pressure.

In adiabatic processes, $q$ and $C$ scale only with the density. Non-adiabatic processes are mapped into changes of the adiabatic constants $q_0$ and $C_0$. 
Cosmic rays and cosmological shock waves

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Cosmic rays in GADGET—flowchart

Thermal Energy

- Radiative cooling
- Shocks
- Supernovae

- Thermal Conduction
- Coulomb losses
- CR Diffusion

Cosmic Ray Energy

- Catastrophic losses

Existing

New
Diffusive shock acceleration – Fermi 1 mechanism

Cosmic rays gain energy $\Delta E/E \propto v_1 - v_2$ through bouncing back and forth the shock front. Accounting for the loss probability $\propto v_2$ of particles leaving the shock downstream leads to power-law CR population.
Observations of cluster shock waves

1E 0657-56 ("Bullet cluster")
(NASA/SAO/CXC/M.Markevitch et al.)

Abell 3667
(Radio: Austr.TC Array. X-ray: ROSAT/PSPC.)
Applications for a shock finder in SPH simulations

- **Cosmological shocks** dissipate gravitational energy into thermal gas energy
- **Shock waves are tracers** of the large scale structure and contain information about its dynamical history (warm-hot intergalactic medium)
- **Shocks accelerate energetic particles** (cosmic rays) through diffusive shock acceleration at structure formation shocks
- **Cosmic ray injection** by supernova remnants (when combined with radiative dissipation and star formation)
- **Shock-induced star formation** in the interstellar medium
Idea of the Mach number finder

- SPH shock is broadened to a scale of the order of the smoothing length $h$, i.e. $f_h h$, and $f_h \sim 2$
- approximate instantaneous particle velocity by pre-shock velocity (denoted by $v_1 = M_1 c_1$)

Using the entropy conserving formalism of Springel & Hernquist 2002 ($A(s) = P \rho^{-\gamma}$ is the entropic function):

\[
\frac{A_2}{A_1} = \frac{A_1 + \frac{dA_1}{dt}}{A_1} = 1 + \frac{f_h h}{M_1 c_1 A_1} \frac{dA_1}{dt} = \frac{P_2}{P_1} \left( \frac{\rho_1}{\rho_2} \right) \gamma
\]

\[
\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1) M_1^2}{(\gamma - 1) M_1^2 + 2}
\]

\[
\frac{P_2}{P_1} = \frac{2 \gamma M_1^2 - (\gamma - 1)}{\gamma + 1}
\]
Complications of the numerical implementation

- **Broad Mach number distributions**
  \[ f(\mathcal{M}) = \frac{d u_{th}}{d t \, d \log \mathcal{M}} \]
  because particle quantities within the (broadened) shock front do not correspond to those of the pre-shock regime.
  **Solution**: introduce decay time \( \Delta t_{\text{dec}} = f_h h / (\mathcal{M}_1 c) \), meanwhile the Mach number is set to the maximum (only allowing for its rise in the presence of multiple shocks).

- **Weak shocks imply large values of \( \Delta t_{\text{dec}} \):**
  **Solution**: \( \Delta t_{\text{dec}} = \min[f_h h / (\mathcal{M}_1 c), \Delta t_{\text{max}}] \)

- **Strong shocks with \( \mathcal{M} > 5 \) are slightly underestimated**
  because there is no universal shock length.
  **Solution**: recalibrate strong shocks!
Shock tube ($\mathcal{M} = 10$): thermodynamics

- **Density**
- **Velocity**
- **Pressure**
- **Mach number**

Observations
Mach number finder
Cosmological simulations
Cluster simulations

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Cosmic rays and cosmological shock waves
Shock tube: Mach number statistics

\[ \left\langle \frac{du_{\text{th}}}{dt} \frac{d\log M}{dM} \right\rangle \]

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Shock tube (CRs & gas, $M = 10$): thermodynamics

Density

Velocity

Pressure

Mach number
Shock tube (CRs & gas): Mach number statistics
Cosmological Mach numbers: weighted by $\varepsilon_{\text{diss}}$
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Cosmological Mach numbers: weighted by $\varepsilon_{\text{CR}}$
Cosmological statistics: resolution study

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Cosmic rays and cosmological shock waves
Cosmological statistics: influence of reionization

\[ \frac{d^2 \epsilon_{\text{diss}}(a, M)}{d \log a \, d \log M} [10^{50} \text{ergs} (h^{-1} \text{Mpc})^3] \]

\[ \frac{d \epsilon_{\text{diss}}(a) \, d \log M}{d \log a} [10^{50} \text{ergs} (h^{-1} \text{Mpc})^3] \]

\[ \frac{d \epsilon_{\text{diss}}(M)}{d \log M} : \]
- with reionization
- without reionization

\[ \frac{d \epsilon_{\text{CR}}(M)}{d \log M} : \]
- with reionization

\[ \frac{d \epsilon_{\text{diss}}(a)}{d \log a} \]
- with reionization
Adiabatic cluster simulation: gas density
Mass weighted temperature

![Mass weighted temperature](image)

- **Cluster non-equilibrium processes**
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Cosmic rays and cosmological shock waves
Observations

Mach number finder

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Cluster non-equilibrium processes

Cosmic rays in GADGET

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Summary

Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Relative CR pressure $P_{CR}/P_{total}$

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Cosmic rays and cosmological shock waves
Equation of state for CRs

\[
\log \left( \frac{P_{CR}}{P_{th}} \right) = \log \left( 1 + \delta_{\text{gas}} \right)
\]

Probability density [arbitrary units]
Understanding **non-thermal processes** is crucial for using clusters as cosmological probes (high-$z$ scaling relations).

- Radio halos might be of hadronic origin as our simulations suggests.

- Huge potential and predictive power of cosmological CR simulations/Mach number finder $\rightarrow$ provides detailed $\gamma$-ray/radio emission maps

**Outlook**

- Galaxy evolution: influence on energetic feedback, star formation, and galactic winds
- Exploring the CR influence on the absorption properties at high redshift.
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