Cosmological shock waves and cosmic rays in hydrodynamical cluster simulations

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in collaboration with

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Outline

1. Introduction
   - Violent structure formation
   - Cosmic rays in GADGET

2. Cosmological shock waves
   - Motivation
   - Cosmological simulations

3. Cosmic rays in cooling core clusters
   - Radiative high-resolution cluster simulations
   - Modified X-ray emission and Sunyaev-Zel’dovich effect
   - Cosmic ray induced emission processes
Gravitational heating by shocks

The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves.
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.)
Radiative simulations – flowchart

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- Galaxy spectra

Physical processes in clusters:
- Radiative cooling
- Stellar populations
- Thermal energy
- Supernovae
- Shocks

Loss processes
Gain processes
Observables
Populations
Radiative simulations with cosmic rays

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- Galaxy spectra
- Radio synchrotron
- Gamma-ray emission

Physical processes in clusters:
- Thermal energy
- Radiative cooling
- Supernovae
- Shock waves
- Coulomb losses
- Hadronic losses
- Cosmic ray energy

Processes:
- Loss processes
- Gain processes
- Observables
- Populations
An accurate description of CRs should follow the evolution of the spectral energy distribution of CRs as a function of time and space, and keep track of their dynamical, non-linear coupling with the hydrodynamics.

We seek a compromise between
- capturing as many physical properties as possible
- requiring as little computational resources as possible

Assumptions:
- protons dominate the CR population
- a momentum power-law is a typical spectrum
- CR energy & particle number conservation
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Kinetic energy per logarithmic momentum interval:

\[ \frac{dE_{\text{CR}}}{d \log p} = p T \phi(p) f(p) \text{ in } m_p c^2 \]

\[ \alpha = 2.25 \]
\[ \alpha = 2.50 \]
\[ \alpha = 2.75 \]
Motivation for studying shock waves:

- **cosmological shocks** dissipate gravitational energy into thermal gas energy: where and when is the gas heated, and which shocks are mainly responsible for it?
- **shocks accelerate cosmic rays** through diffusive shock acceleration at structure formation shocks: what are the cosmological implications of such a CR component, and does this influence the cosmic thermal history?
- **simulating realistic CR distributions** within galaxy clusters provides detailed predictions for the expected radio synchrotron and \( \gamma \)-ray emission
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.
Cosmological Mach numbers: weighted by $\varepsilon_{\text{diss}}$
Cosmological Mach numbers: weighted by $\varepsilon_{\text{CR}}$

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Cosmic rays in hydrodynamical cluster simulations
more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks
more energy is dissipated at later times
mean Mach number decreases with time
Cosmological statistics: influence of reionization

- reionization epoch at $z_{\text{reion}} = 10$ suppresses efficiently strong shocks at $z < z_{\text{reion}}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease
Cosmic rays in galaxy clusters

Cluster observables:

- Sunyaev-Zeldovich effect
- X-ray emission
- Galaxy spectra
- Radio synchrotron
- Gamma-ray emission

Physical processes in clusters:

- Radiative energy
- Stellar populations
- Supernovae
- Radiative cooling
- Hadronic losses
- Cosmic ray energy
- Coulomb losses

Loss processes
Gain processes
Observables
Populations
Radiative cool core cluster simulation: gas density

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Mach number distribution weighted by $\varepsilon_{\text{diss}}$

\[
\langle M \varepsilon_{\text{diss}} \rangle_{\text{los}} \\
\langle \varepsilon_{\text{diss}} \rangle_{\text{los}} \\
\langle M \varepsilon_{\text{CR}} / (d \log a) \rangle_{\text{los}} \\
\langle d \varepsilon_{\text{CR}} / (d \log a) \rangle_{\text{los}}
\]
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$
Relative CR pressure $P_{CR}/P_{total}$
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Phase-space diagram of radiative cluster simulation

\begin{align*}
\log[1 + \delta_{\text{gas}}] \\
\log[P_{\text{CR}} / P_{\text{th}}] \\
\text{phase space density [arbitrary units]} \\
\end{align*}
Thermal X-ray emission
Introduction
Cosmological shock waves
Cosmic rays in cooling core clusters
Radiative cluster simulations
Modified X-ray emission and SZ effect
Cosmic ray induced emission

Difference map of $S_X$: $S_{X,CR} - S_{X,th}$
Softer effective adiabatic index of composite gas

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Cosmic rays in hydrodynamical cluster simulations
Compton $y$ parameter in radiative cluster simulation

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Cosmic rays in hydrodynamical cluster simulations
Compton $y$ difference map: $y_{\text{CR}} - y_{\text{th}}$
Pressure profiles with and without CRs

\[ P_{CR}, P_{th} \text{ [Code units]} \]

\[ R [h^{-1} \text{ kpc}] \]

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Cosmic rays in hydrodynamical cluster simulations
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

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Cosmic rays in hydrodynamical cluster simulations
Hadronically induced radio mini-halo emission

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Cosmic rays in hydrodynamical cluster simulations
Hadronically induced $\gamma$-ray emission
CR physics modifies the intracluster medium in cooling core regions:

- Galaxy cluster **X-ray emission is enhanced** up to 35%, predominantly in low-mass cooling core clusters.
- Integrated **Sunyaev-Zel’dovich effect** remains largely unchanged while the Compton-y profile is more peaked.
- **Huge potential and predictive power** of **cosmological CR simulations** → provides detailed $\gamma$-ray/radio emission maps
- Understanding **non-thermal processes** is crucial for using clusters as cosmological probes (high-$z$ scaling relations).