Cosmic ray feedback in hydrodynamical simulations of galaxy and structure formation

Christoph Pfrommer

Canadian Institute for Theoretical Astrophysics, Toronto

April, 13 2006 / Workshop ‘Dark halos’, UBC Vancouver
Outline

1. Motivation
   - Cosmic rays in galaxies
   - Violent structure formation
   - Gravitational heating by shocks

2. Cosmic rays and structure formation shocks
   - Cosmic rays in GADGET
   - Mach number finder
   - Cosmological simulations

3. Cosmic rays in galaxy clusters
   - Cluster radio halos
   - CR pressure influences Sunyaev-Zel’dovic effect
   - Generic CR pressure profile
M51: cosmic ray electron population

Fletcher, Beck, Berkhuijsen und Horellou, in prep.
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.)

Christoph Pfrommer
Cosmic ray feedback in hydrodynamical simulations
The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves.
The talk is based on the following papers:


Philosophy and description

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
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
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
CRs are coupled to the thermal gas by magnetic fields.

We assume a single power-law CR spectrum: momentum cutoff $q$, normalization $C$, spectral index $\alpha$ (constant).

→ determines CR energy density and pressure uniquely.

The CR spectrum can be expressed by three adiabatic invariants, which scale only with the gas density. Non-adiabatic processes are mapped into changes of the adiabatic constants using mass, energy and momentum conservation.
Cosmic rays in GADGET—flowchart

- Radiative cooling
- Thermal Energy
- Thermal Conduction
- Shocks
- Supernovae
- Coulomb losses
- Cosmic Ray Energy
- Catastrophic losses
- CR Diffusion

Existing

New
Kinetic energy per logarithmic momentum interval:

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

\(\alpha = 2.25\)
\(\alpha = 2.50\)
\(\alpha = 2.75\)
Radiative cooling

Cooling of primordial gas:

\[
\tau_{\text{cool}} \text{ [Gyr]} = \frac{1}{\frac{\rho}{2.386 \times 10^{-25}}} \text{ g/cm}^3
\]

where \( T \) is the temperature in Kelvin.

Cooling of cosmic rays:

\[
\tau_{\text{cool}} \text{ [Gyr]} = \frac{1}{\frac{\rho}{10^{-25}}} \text{ g/cm}^3
\]

where \( q \) is the ratio of cosmic ray density to gas density.

Christoph Pfrommer

Cosmic ray feedback in hydrodynamical simulations
Cosmic rays in GADGET—flowchart

1. Radiative cooling
2. Thermal Energy
3. Thermal Conduction
4. Shocks
5. Supernovae
6. Coulomb losses
7. Cosmic Ray Energy
8. CR Diffusion
9. Catastrophic losses

Existing

New
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.
Motivation for the Mach number finder

- **cosmological shocks** dissipate gravitational energy into thermal gas energy: where and when is the gas heated, and which shocks are mainly responsible for it?

- **shock waves are tracers** of the large scale structure and contain information about its dynamical history (warm-hot intergalactic medium)

- **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
Shock tube (CRs & gas, \( M = 10 \)): thermodynamics
**Shock tube (CRs & gas): Mach number statistics**

<table>
<thead>
<tr>
<th>log (M)</th>
<th>(d\mu/dt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1·10^8</td>
</tr>
<tr>
<td>10</td>
<td>2·10^8</td>
</tr>
<tr>
<td>100</td>
<td>3·10^8</td>
</tr>
<tr>
<td>1000</td>
<td>4·10^8</td>
</tr>
<tr>
<td>10000</td>
<td>5·10^8</td>
</tr>
<tr>
<td>100000</td>
<td>6·10^8</td>
</tr>
<tr>
<td>1000000</td>
<td>7·10^8</td>
</tr>
<tr>
<td>10000000</td>
<td>8·10^8</td>
</tr>
<tr>
<td>100000000</td>
<td>9·10^8</td>
</tr>
<tr>
<td>1000000000</td>
<td>1·10^9</td>
</tr>
</tbody>
</table>
Shock tube (th. gas): Mach number statistics

Motivation
Cosmic rays and structure formation shocks
Cosmic rays in galaxy clusters
Cosmic rays in GADGET
Mach number finder
Cosmological simulations

Christoph Pfrommer
Cosmic ray feedback in hydrodynamical simulations
Cosmological Mach numbers: weighted by $\varepsilon_{\text{diss}}$
Cosmological Mach numbers: weighted by $\varepsilon_{\text{CR}}$
Cosmological Mach number statistics

- 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.
Radio halos as window for non-equilibrium processes
Exploring complementary methods for studying cluster formation

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, $F_{SZ} \propto \rho_{th} \rightarrow$ cluster velocity, turbulence, high-$z$ clusters
- **radio synchrotron halos**: $F_{sy} \propto \varepsilon B \varepsilon_{CR} \rightarrow$ magnetic fields, CR electrons, shock waves
- **diffuse $\gamma$-ray emission**: $F_{\gamma} \propto n_{th} n_{CRp} \rightarrow$ CR protons
Adiabatic cluster simulation: gas density

Christoph Pfrommer
Cosmic ray feedback in hydrodynamical simulations
Motivation
Cosmic rays and structure formation shocks
Cosmic rays in galaxy clusters
Cluster radio halos
CR pressure influences SZ effect
Generic CR pressure profile

Mass weighted temperature

\[ \langle 1 + \delta_{\text{gas}} \rangle T \text{ [K]} \]

\[ x \text{ [h}^{-1}\text{Mpc]} \]

\[ y \text{ [h}^{-1}\text{Mpc]} \]

\[ \times 10^3 \times 10^4 \times 10^5 \times 10^6 \]
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$
Coma radio halo, $\nu = 1.4$ GHz, 
largest emission diameter $\sim 3$ Mpc

(2.5° × 2.0°, credit: Deiss/Effelsberg)

Coma thermal X-ray emission,

(2.7° × 2.5°, credit: ROSAT/MPE/Snowden)
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
Energetically preferred CR pressure profiles

Coma cluster: hadronic minimum energy condition

\[ X_{\text{CRp}}(r) = \frac{\varepsilon_{\text{CRp}}}{\varepsilon_{\text{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\text{th}}}(r) \rightarrow B_{\text{Coma, min}}(0) = 2.4^{+1.7}_{-1.0} \mu G \]
Compton $y$ parameter in radiative cluster simulation

$y$ [$h^{-1}\text{Mpc}$]

$x$ [$h^{-1}\text{Mpc}$]

$10^{-7}$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$

$10^1$

$10^2$

$10^3$
Compton $y$ difference map: $y_{CR} - y_{th}$
Simulated CBI observation of $\gamma_{CR} - \gamma_{th}$ (with Sievers & Bond)
Pressure profiles with and without CRs
Preliminary emerging picture

Importance of central CR pressure relative to the gas pressure seems to depend on subtle interplay of the following effects:

- Presence of well developed **cool core region**
- **Violent merger history** of the cluster → resulting flat effective spectral index of CRs
- Cluster mass: ratio of CR-to-thermal **cooling times** changes with the cluster’s virial temperature
Non-radiative simulation: entropy profile

\[ A_{th} \text{ [Code units]} \]

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

\[ 10^6 \]
\[ 10^7 \]
\[ 10^8 \]
\[ 10^9 \]
\[ 10^{10} \]
Radiative simulation: entropy profile

**Motivation**
Cosmic rays and structure formation shocks
Cosmic rays in galaxy clusters
Cluster radio halos
CR pressure influences SZ effect
Generic CR pressure profile

**Christoph Pfrommer**
Cosmic ray feedback in hydrodynamical simulations
Radiative simulation: Schwarzschild criterion

Cluster profile unstable with respect to convection $\rightarrow$ effective mixing?
Motivation
Cosmic rays and structure formation shocks
Cosmic rays in galaxy clusters

Cluster radio halos
CR pressure influences SZ effect
Generic CR pressure profile

Generic CR pressure profile

Christoph Pfrommer
Cosmic ray feedback in hydrodynamical simulations
Summary

- 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 → tracer of structure formation
- Dynamical CR feedback influences Sunyaev-Zel’dovic effect

Outlook
- Galaxy evolution: CRs might influence energetic feedback, galactic winds, and disk galaxy formation
- Huge potential and predictive power of cosmological CR simulations/Mach number finder → provides detailed γ-ray/radio emission maps