Cosmological shock waves in SPH simulations
Exploring cosmic ray feedback

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Outline

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   - CR pressure influences Sunyaev-Zel’dovich effect
The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves.
Cosmic rays in GADGET—flowchart

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

- Existing
- New
Cosmic rays gain energy $\Delta E/E \propto \nu_1 - \nu_2$ through bouncing back and forth the shock front. Accounting for the loss probability $\propto \nu_2$ 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.)
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, $\mathcal{M} = 10$): thermodynamics

- Density
- Velocity
- Pressure
- Mach number
Shock tube (CRs & gas): Mach number statistics
Shock tube (th. gas): Mach number statistics

\[
\langle \frac{\langle d\theta \rangle}{d\log M} \rangle \quad \langle d\theta \rangle
\]

\[
\langle \frac{d\theta}{dt} \rangle \quad \langle d\theta \rangle
\]
Cosmological Mach numbers: weighted by $\varepsilon_{\text{diss}}$
Cosmological Mach numbers: weighted by $\varepsilon_{\text{CR}}$

![Cosmological Mach numbers weighted by $\varepsilon_{\text{CR}}$](image_url)
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
Adiabatic cluster simulation: gas density
Mass weighted temperature

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

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

$y [h^{-1}\text{Mpc}]$
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Cosmological shock waves in SPH simulations

Relative CR pressure $P_{CR}/P_{\text{total}}$

$P_{CR}/(P_{\text{th}} + P_{CR})$

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

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

$P_{CR}/P_{\text{total}}$
Radio halos as window for non-equilibrium processes

Coma radio halo, $\nu = 1.4$ GHz,
largest emission diameter $\sim 3$ Mpc
$(2.5^\circ \times 2.0^\circ$, credit: Deiss/Effelsberg)

Coma thermal X-ray emission,
$(2.7^\circ \times 2.5^\circ$, credit: ROSAT/MPE/Snowden)
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
$X_{\text{CRp}}(r) = \frac{\epsilon_{\text{CRp}}(r)}{\epsilon_{\text{th}}(r)}$,  $X_B(r) = \frac{\epsilon_B(r)}{\epsilon_{\text{th}}(r)} \rightarrow B_{\text{Coma, min}}(0) = 2.4^{+1.7}_{-1.0} \mu G$
Compton $y$ parameter in radiative cluster simulation

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

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

$10^{-7}$

$10^{-6}$
Compton $y$ difference map: $y_{\text{CR}} - y_{\text{th}}$
Simulated CBI observation of $\gamma_{\text{CR}} - \gamma_{\text{th}}$ (with Sievers & Bond)
Cosmological shock waves
Cosmic rays in galaxy clusters
Summary

Cluster radio halos
Energetically preferred CR pressure profiles
CR pressure influences SZ effect

Pressure profiles with and without CRs

![Graph showing pressure profiles with and without CRs](image-url)
Phase-space diagram of radiative cluster simulation

-2 0 2 4 6 8
-4
-3
-2
-1
0
1
2
-2 0 2 4 6 8
log[1 + δ_{gas}]

10^0
10^1
10^2
10^3
10^4

10^{-4}
10^{-3}
10^{-2}
10^{-1}
0
1
2

-2 0 2 4 6 8
log[P_{CR}/P_{th}]

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Cosmological shock waves in SPH simulations
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**: influence on energetic feedback, star formation, and galactic winds
- Huge potential and predictive power of **cosmological CR simulations/Mach number finder** → provides detailed $\gamma$-ray/radio emission maps
Cosmological statistics: resolution study
Differential distributions: $2 \times 256^3$ versus $2 \times 128^3$

- More energy is dissipated at later times
- Mean Mach number decreases with time
- Differential Mach number distributions are converged for $z < 3$
Cosmological statistics: resolution study

- in higher resolution simulations structure forms earlier
- more energy is dissipated in shocks internal to collapsed structures than in external shocks of pristine gas
- integrated Mach number distribution converged
Idea of the Mach number finder in SPH

- 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):

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

$$\frac{\rho_2}{\rho_1} = \frac{\left( \gamma + 1 \right) M_1^2}{\left( \gamma - 1 \right) M_1^2 + 2}$$

$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 - \left( \gamma - 1 \right)}{\gamma + 1}$$
What is the energetically least expensive distribution of non-thermal energy density $\varepsilon_{NT}$ given the observed synchrotron emissivity?

$\varepsilon_{NT} = \varepsilon_B + \varepsilon_{CRp} + \varepsilon_{CRe}$

minimum energy criterion:

$$\frac{\partial \varepsilon_{NT}}{\partial \varepsilon_B} \bigg|_{j_\nu} \equiv 0$$

defining tolerance levels: deviation from minimum by one e-fold
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.