Cosmic Rays in Galaxy Clusters: Simulations and Perspectives

Christoph Pfrommer\textsuperscript{1}

in collaboration with

Volker Springel\textsuperscript{2}, Torsten Enßlin\textsuperscript{2}

\textsuperscript{1}Canadian Institute for Theoretical Astrophysics, Canada

\textsuperscript{2}Max-Planck Institute for Astrophysics, Germany

February, 7 2007 / Carnegie Mellon University Astrophysics Seminar
Outline

1. Introduction to galaxy clusters
   - Properties of galaxy clusters
   - Physical processes in simulations
   - Cosmic ray physics

2. Cosmic rays in cosmological simulations
   - Cosmic ray acceleration
   - Radiative high-resolution cluster simulations
   - Modified X-ray emission and Sunyaev-Zel’dovich effect

3. Non-thermal emission from clusters
   - Overview of non-thermal emission processes
   - Radio synchrotron emission
   - Gamma-ray emission
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 up-scattering of CMB photons by thermal electrons, \( F_{SZ} \propto p_{th} \rightarrow \) cluster velocity, turbulence, high-z clusters
- **radio synchrotron halos**: \( F_{\text{synchro}} \propto \varepsilon B \varepsilon_{\text{CR}} \rightarrow \) magnetic fields, CR electrons, shock waves
- **diffuse \( \gamma \)-ray emission**: \( F_{\gamma} \propto n_{th} n_{\text{CRp}} \rightarrow \) CR protons
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Coma cluster: member galaxies

optical emission,
(credit: Kitt Peak)

infra-red emission,
(credit: ISO)
Coma cluster: (non-)thermal plasma

- Thermal X-ray emission,
  (credit: S.L. Snowden/MPE/ROSAT)

- Radio synchrotron emission,
  (credit: B. Deiss/Effelsberg)
structure formation in the $\Lambda$CDM universe predicts the hierarchical build-up of dark matter halos from small scales to successively larger scales

clusters of galaxies currently sit atop this hierarchy as the largest objects that have had time to collapse under the influence of their own gravity

cluster are dynamically evolving systems that have not finished forming and equilibrating, $\tau_{\text{dyn}} \sim 1 \text{ Gyr}$

→ two extreme dynamical states of galaxy clusters: merging clusters and cool core clusters, which are relaxed systems where the central gas develops a dense cooling core due to the short thermal cooling times
Radiative simulations – flowchart

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

Physical processes in clusters:
- thermal energy
- radiative cooling
- supernovae
- shocks

loss processes
gain processes
observables
populations
Radiative simulations with cosmic ray (CR) physics

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

Physical processes in clusters:
- Radiative cooling
- Stellar populations
- Supernovae
- Shocks
- Cosmic ray energy
- Coulomb losses

Loss processes:
- Stellar populations
- Supernovae
- Shocks

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

Observables:
- Hadronic losses

Populations:
- Coulomb losses

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Cosmic Rays in Galaxy Clusters: Simulations and Perspectives
Radiative simulations with extended CR physics

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Physical processes in clusters:
- Stellar populations
  - Radiative cooling
  - Supernovae
- Cosmic ray energy
  - Hadronic losses
  - Coulomb losses
- AGN
- Heat conduction
- CR diffusion
- CR physics
- Non-thermal emission from clusters
- Physical processes in simulations
- Cosmic rays in cosmological simulations
- Properties of galaxy clusters
- Introduction to galaxy clusters
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 necessary

Assumptions:
- protons dominate the CR population
- a momentum power-law is a typical spectrum
- CR energy & particle number conservation
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Philosophy and description

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CR spectral description

\[ f(p) = \frac{dN}{dp dV} = C p^{-\alpha} \theta(p - q) \]

\[ q(\rho) = \left( \frac{\rho}{\rho_0} \right)^{\frac{1}{3}} q_0 \]

\[ C(\rho) = \left( \frac{\rho}{\rho_0} \right)^{\frac{\alpha + 2}{3}} C_0 \]

\[ n_{\text{CR}} = \frac{C q^{1-\alpha}}{\alpha - 1} \]

\[ P_{\text{CR}} = \frac{C m_p c^2}{6} B^{\frac{1}{1+q^2}} \left( \frac{\alpha - 2}{2}, \frac{3 - \alpha}{2} \right) \]
Kinetic energy per logarithmic momentum interval:

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

\[ \alpha = 2.25 \]
\[ \alpha = 2.50 \]
\[ \alpha = 2.75 \]

10 eV, 1 keV, 0.1 MeV
Radiative cooling

Cooling of primordial gas:

Cooling of cosmic rays:

\[ \tau_{\text{cool}} \quad \text{[Gyr]} \]

\[ n = 0.01 \text{ cm}^{-3} \]

\[ T \quad \text{[K]} \]

\[ q \]

\[ 0.01 \quad 0.10 \quad 1.00 \quad 10.00 \quad 100.00 \]

\[ 0.01 \quad 0.10 \quad 1.00 \quad 10.00 \]

\[ 0.0001 \quad 0.0010 \quad 0.0100 \quad 0.1000 \quad 1.0000 \quad 10.0000 \]
Cosmic rays in clusters – flowchart

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- galaxy spectra
- radio synchrotron
- gamma-ray emission

Physical processes in clusters:
- thermal energy
- radiative cooling
- supernovae
- shocks
- AGN
- Coulomb losses
- hadronic losses
- cosmic ray energy
- heat conduction
- CR diffusion
- loss processes
- gain processes
- observables
- populations

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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.)

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Cosmic Rays in Galaxy Clusters: Simulations and Perspectives
Abell 2256: giant radio relic & small halo

X-ray (red) & radio (blue, contours)  fractional polarization in colour

Clarke & Enßlin (2006)
Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:
- a collisionless shock wave
- magnetic fields to confine energetic particles
- plasma waves to scatter energetic particles $\rightarrow$ particle diffusion
- supra-thermal particles

mechanism:
- supra-thermal particles diffuse upstream across shock wave
- each shock crossing energizes particles through momentum transfer from recoil-free scattering off the macroscopic scattering agents
- momentum increases exponential with number of shock crossings
- number of particles decreases exponential with number of crossings

$\rightarrow$ power-law CR distribution
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→ power-law CR distribution
Spectral index depends on the Mach number of the shock,

\[ \mathcal{M} = \frac{\nu_{\text{shock}}}{c_s} \]

\[ \begin{align*}
\log f &\quad \text{strong shock} \\
\log f &\quad \text{weak shock}
\end{align*} \]
The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves.
Cosmological Mach numbers: weighted by $\varepsilon_{\text{diss}}$
Cosmological Mach numbers: weighted by $\varepsilon_{\text{CR}}$
Cosmological Mach number statistics

- More energy is dissipated at later times
- Mean Mach number decreases with time
more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks

non-radiative simulations: injected CR energy inside cluster makes up only a small fraction of the total dissipated energy
Radiative simulations with extended CR physics

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

Physical processes in clusters:
- Radiative cooling
- Stellar populations
- Hadronic losses
- Cosmic ray energy
- Heat conduction
- Radiative heating
- Coulomb losses
- CR diffusion
- AGN
- Shocks
- Supernovae

Loss processes:
- Red

Gain processes:
- Green

Observables:
- Yellow

Populations:
- Blue
Radiative cool core cluster simulation: gas density
Mass weighted temperature

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

\( x \) [\( h^{-1} \) Mpc]

\( y \) [\( h^{-1} \) Mpc]
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$
Relative CR pressure $P_{CR}/P_{\text{total}}$

\begin{align*}
\langle P_{CR} / P_{\text{total}} \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle
\end{align*}

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Thermal X-ray emission

large, merging cluster, $M_{\text{vir}} \sim 10^{15} M_\odot/h$

small, cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot/h$
Difference map of $S_X$: $S_{X,CR} - S_{X,th}$

large, merging cluster, $M_{\text{vir}} \approx 10^{15} M_\odot / h$

small, cool core cluster, $M_{\text{vir}} \approx 10^{14} M_\odot / h$
Softer effective adiabatic index of composite gas 

\[
\gamma_{\text{eff}} = \begin{cases} 
1.3 & \text{for radiative simulation} \\
1.4 & \text{for cosmic rays} \\
1.5 & \text{for modified X-ray emission and SZ effect} 
\end{cases}
\] 

\[ R \left[ h^{-1} \text{kpc} \right] \]
large, merging cluster, \( M_{\text{vir}} \approx 10^{15} M_{\odot} / h \)

small, cool core cluster, \( M_{\text{vir}} \approx 10^{14} M_{\odot} / h \)
Compton $y$ difference map: $y_{CR} - y_{th}$

large, merging cluster, $M_{\text{vir}} \sim 10^{15} M_\odot / h$

small, cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$
Pressure profiles with and without CRs

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

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

0.001 0.010 0.100 1.000 10.000 100.000

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Cosmic Rays in Galaxy Clusters: Simulations and Perspectives
So far, we were asking how the CR pressure modifies thermal cluster observables such as the X-ray emission and the Sunyaev-Zel’dovich effect of clusters. These processes tell us only very indirectly (if at all) about the history of structure formation. In contrast, non-thermal processes retain their cosmic memory since their particle population is not in equilibrium.

How can we read out this information about non-thermal populations? → new era of multi-frequency experiments, e.g.:

- **LOFAR**: European interferometric array of radio telescopes at low frequencies ($\nu \simeq (10 - 240)$ MHz)
- **Astrosat**: Indian satellite that images soft and hard X-rays ($E \simeq (0.3 - 100)$ keV)
- **Glast**: international high-energy $\gamma$-ray space mission ($E \simeq (0.02 - 300)$ GeV)
Introduction to galaxy clusters
Cosmic rays in cosmological simulations
Non-thermal emission from clusters

Overview of non-thermal emission processes
Radio synchrotron emission
Gamma-ray emission

Hadronic cosmic ray proton interaction

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Cosmic Rays in Galaxy Clusters: Simulations and Perspectives
Expected hadronic $\gamma$-ray flux of the Perseus cluster

IC emission of secondary CRes ($B = 0$), $\pi^0$-decay induced $\gamma$-ray emission:

$dF_{\gamma}/dE_{\gamma}$ [X_EGRET $\gamma$ cm$^{-2}$ s$^{-1}$ GeV$^{-1}$]

$E_{\gamma}$ [GeV]

$\alpha_p = 2.1$
$\alpha_p = 2.3$
$\alpha_p = 2.5$
$\alpha_p = 2.7$
Cosmic rays and radiative 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
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:

Energy sources:
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- CR protons

Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:

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

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Cosmic rays and radiative processes

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- $\pi^0$

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Cosmic Rays in Galaxy Clusters: Simulations and Perspectives
Abell 2256: giant radio relic & small halo

X-ray (red) & radio (blue, contours)  fractional polarization in colour

Clarke & Enßlin (2006)
Cosmic web: density
Cosmic web: Mach number

\[ \langle M \dot{\varepsilon}_{\text{diss}} / \langle \dot{\varepsilon}_{\text{diss}} \rangle \rangle \]
Radio web: primary CRe (1.4 GHz)
Radio web: primary CRe (150 MHz)
Radio web: primary CRe (15 MHz), slower magnetic decline
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)

Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:

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- primary CR electrons
- secondary CR electrons

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

hadronic reaction
Radio halos: secondary CRe (150 MHz)

\[ S_\nu \text{ [mJy arcmin}^{-2} \text{h}^{-3}\text{]} \]
Radio web + halos 150 MHz

\[ S_\nu \left[ \text{mJy \ arcmin}^{-2} h^3 \right] \]

\( x \left[ h^{-1} \text{Mpc} \right] \)

\( y \left[ h^{-1} \text{Mpc} \right] \)
Radio web + halos: spectral index

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Cosmic Rays in Galaxy Clusters: Simulations and Perspectives
Thermal X-ray emission
Hadronic $\gamma$-ray emission, $E_\gamma > 100$ MeV
Inverse Compton emission, $E_{IC} > 100$ MeV

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Inverse Compton emission, $E_{IC} > 10$ keV
CR physics modifies the intracluster medium in merging clusters and cooling core regions:

- Galaxy cluster **X-ray emission is enhanced** up to 35%, systematic effect in low-mass cooling core clusters.
- Integrated **Sunyaev-Zel’dovich effect** remains largely unchanged while the Compton-y profile is more peaked.
- **LOFAR** is expected to see the **radio web emission**: origin of cosmic magnetic fields.
- **Glast** should see hadronic $\gamma$-ray emission from clusters: measurement of CR protons and origin of radio halos.

→ exciting experiments allow a **complementary view on structure formation as well as fundamental physics**!