Large-scale shocks and extragalactic cosmic rays

Christoph Pfrommer\textsuperscript{1}

in collaboration with

Torsten Enßlin, Volker Springel, Tom Jones

\textsuperscript{1}Heidelberg Institute for Theoretical Studies, Germany

Oct 28, 2015 / International Team Meeting, ISSI Bern
Outline

1. Cosmological simulations
   - Introduction
   - Physics in simulations
   - Cosmic rays in galaxy clusters

2. Cosmic-ray signatures
   - Multi messenger approach
   - Radio emission
   - Gamma rays

3. Large-scale shocks
   - Radio galaxies in clusters
   - Probing accretion shocks
   - Vision and Speculations
The structure of our Universe – a “cosmic web”

Left: projected gas density in a cosmological simulation \((L = 100 \, h^{-1} \, \text{Mpc}, \, z = 0)\).
Middle: gas temperature of the gravitationally heated intergalactic medium.
Right: structure formation shocks, color coded by Mach number.

(C.P. et al. 2006)
cluster mergers are the most energetic events in the Universe (after the Big Bang) → shocks and turbulence

'Bullet cluster'
X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; U.Arizona/D.Clowe et al.;
Lensing: NASA/STScI; ESO; U.Arizona/D.Clowe et al.
**Galaxy cluster evolution**

- **cluster mergers** are the most energetic events in the Universe (after the Big Bang) → shocks and turbulence

- accompanied by enigmatic **cluster radio halos and relics** → existence of relativistic electrons and magnetic fields

---

**giant radio halo and relic in Coma**

Effelsberg/Deiss
Cluster mergers are the most energetic events in the Universe (after the Big Bang) → shocks and turbulence

accompanied by enigmatic cluster radio halos and relics → existence of relativistic electrons and magnetic fields

laboratories for cluster formation and high-energy astrophysics:
→ particle acceleration and cosmic magnetism

giant radio relic in Abell 3667
radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.
Cosmological simulations – flowchart

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

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

C.P., Enßlin, Springel (2008)
Cosmological simulations with cosmic ray physics

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

Physical processes in clusters:
- thermal energy
- radiative cooling
- stellar populations
- supernovae
- shocks
- Coulomb losses
- cosmic ray energy

Loss processes:
- red lines
Gain processes:
- green lines
Observables:
- yellow lines
Populations:
- blue lines

C.P., Enßlin, Springel (2008)
Cosmological simulations with cosmic ray physics

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

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

Loss processes
Gain processes
Observables
Populations

C.P., Enßlin, Springel (2008)
Cosmological cluster simulation: gas density

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

Christoph Pfrommer

Large-scale shocks and extragalactic cosmic rays
Mass weighted temperature
Shock strengths weighted by dissipated energy

\[ \langle \dot{\varepsilon}_{\text{diss}} / \langle \dot{\varepsilon}_{\text{diss}} \rangle \rangle \]
Shock strengths weighted by injected CR energy
Evolved CR pressure

\[ \langle P_{\text{CR}} \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle \ [\text{erg cm}^{-3} h_{270}^{-2}] \]
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$
Multi messenger approach for non-thermal 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
Multi messenger approach for non-thermal 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

Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons
- CR protons

hadronic reaction
Multi messenger approach for non-thermal 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
- CR protons

Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons

Observational diagnostics:
- radio synchrotron emission
- IC: hard X-ray & gamma-ray emission
Multi messenger approach for non-thermal 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

Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons
- $\pi^0$

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

Christoph Pfrommer
Large-scale shocks and extragalactic cosmic rays
Structure formation shocks

\[ \langle \dot{M}_{\text{diss}} / \langle \dot{\varepsilon}_{\text{diss}} \rangle \rangle \]
Radio gischt: shock-accelerated CRe

Cosmological simulations
Cosmic-ray signatures
Large-scale shocks
Multi messenger approach
Radio emission
Gamma rays

Christoph Pfrommer
Large-scale shocks and extragalactic cosmic rays
Radio gischt + central hadronic halo = giant radio halo
Which one is the simulation/observation of A2256?

red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic
Observation – simulation of A2256

Clarke & Enßlin (2006)

red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

C.P. (in prep.)

Christoph Pfrommer

Large-scale shocks and extragalactic cosmic rays
Normalized CR spectrum shows universal concave shape → governed by hierarchical structure formation and the implied distribution of Mach numbers that a fluid element had to pass through in cosmic history.
CR proton and $\gamma$-ray spectra \cite{Pinzke2010}

- Proton spectrum
- $\pi^0$ decay
- Primary IC
- Secondary IC

Energy weighted flux [GeV cm$^{-2}$ s$^{-1}$]

Energy [GeV]
CR proton and $\gamma$-ray spectra (Pinzke & C.P. 2010)
CR proton and $\gamma$-ray spectra (Pinzke & C.P. 2010)

- Cosmological simulations
- Cosmic-ray signatures
- Multi messenger approach
- Large-scale shocks
- Radio emission
- Gamma rays

**Normalized CR spectrum**

**Emission components**

- Primary IC
- Secondary IC
- $\pi^0$-decay

**Energy weighted flux** [GeV cm$^{-2}$ s$^{-1}$]

**Energy [GeV]**

**Proton spectrum**

$R < R_{\text{vir}}$

$\text{CRp} + p \rightarrow \pi^\pm \rightarrow \ldots \rightarrow e^\pm + \ldots$
An analytic model for the cluster $\gamma$-ray emission

Comparison: simulation vs. analytic model, $M_{\text{vir}} \sim (10^{14}, 10^{15}) M_\odot$

Spatial $\gamma$-ray emission profile

Pion decay spectrum
Constraining CR physics with $\gamma$-ray observations

- Non-detections constrain $P_{CR}/P_{th} < 1.7\%$ in Coma and Perseus and to $\lesssim 1\%$ in a stacked sample of 50 Fermi clusters.
- Constrains maximum shock acceleration efficiency to $< 50\%$.
- Hydrostatic cluster masses not significantly biased by CRs: important for cluster cosmology!
Conclusions on non-thermal signatures in clusters
Exploring the memory of structure formation

- **primary, shock-accelerated CR electrons** resemble current accretion and merging shock waves

- **CR protons/hadronically produced CR electrons** trace the time integrated non-equilibrium activities of clusters that is modulated by the recent dynamical activities

- *Fermi, MAGIC, VERITAS* non-detections of $\gamma$ rays from clusters start to limit CR acceleration efficiencies to < 50% (or tell us about CR transport processes)

→ Multi-messenger approach from the radio to $\gamma$-ray regime!
What we would like to measure and hope to infer:

- jump conditions: shock strength
- upstream properties: infalling warm-hot intergalactic medium
- post- and pre-shock conditions: geometry, obliquity
- shock curvature: vorticity and $B$ field generation
- post-shock turbulence: power spectrum, non-thermal pressure support
- ...
What we would like to measure and hope to infer:

- jump conditions: shock strength
- upstream properties: infalling warm-hot intergalactic medium
- post- and pre-shock conditions: geometry, obliquity
- shock curvature: vorticity and $B$ field generation
- post-shock turbulence: power spectrum, non-thermal pressure support

X-rays give limited insight → new complementary tools!
Radio galaxies in merging clusters

A2256, Owen+ (2014)
Total synchrotron intensity of NGC 1265

NGC 1265 – a radio galaxy in the Perseus cluster at 4.9 GHz (left) and 1.4 GHz (right)
O’Dea & Owen (1986)
Bipolar AGN jets in an ICM wind: magnetic field

credit: Porter, Mendygral & Jones

Christoph Pfrommer

Large-scale shocks and extragalactic cosmic rays
Bipolar AGN jets in an ICM wind: synthetic radio

credit: Porter, Mendiagral & Jones
Radio properties of NGC 1265

Sijbring & de Bruyn (1998): *left*: radio intensity $I_{600\text{ MHz}}$; *right*: variations of $I_{600\text{ MHz}}$ (triangles), $I_{150\text{ MHz}}$ (squares) and spectral index (bottom) along the tail.
Previous models of NGC 1265 and why they fail

1. chance superposition of several independent head-tail galaxies
   \[\rightarrow \text{lack of observed strong radio sources in this field}\]
Previous models of NGC 1265 and why they fail

1. chance superposition of several independent head-tail galaxies
   → lack of observed strong radio sources in this field

2. re-acceleration of electrons in the turbulent wake of a galaxy
   → contrived projection probabilities and implausible energetics
   (re-acceleration efficiency \( \sim 3\% \))
Previous models of NGC 1265 and why they fail

1. Chance superposition of several independent head-tail galaxies → lack of observed strong radio sources in this field

2. Re-acceleration of electrons in the turbulent wake of a galaxy → contrived projection probabilities and implausible energetics (re-acceleration efficiency $\sim 3\%$)

3. ‘Radio tail’ traces a helical cluster wind → wind needs special alignment with LOS, fine-tuned re-acceleration that balances electron cooling and avoids fanning out the well-confined radio emission along the arc
Previous models of NGC 1265 and why they fail

1. chance superposition of several independent head-tail galaxies → lack of observed strong radio sources in this field

2. re-acceleration of electrons in the turbulent wake of a galaxy → contrived projection probabilities and implausible energetics (re-acceleration efficiency ∼ 3%)

3. ‘radio tail’ traces a helical cluster wind → wind needs special alignment with LOS, fine-tuned re-acceleration that balances electron cooling and avoids fanning out the well-confined radio emission along the arc

4. ‘radio tail’ outlines ballistic orbit of NGC 1265 → requires dark object with $M \gtrsim M_{NGC\ 1265} \sim 3 \times 10^{12} M_\odot$ orbiting the galaxy, no explanation of change of orbit and same challenges regarding electron cooling and re-acceleration
Requirements for any model of NGC 1265

- bright narrow angle tail radio jet: synchrotron cooling
- transition region: change of winding direction and sharp drop in $S_\nu$ and $\alpha$
- coherent properties along the dim radio ring, confined morphology

→ we are looking at 2 electron populations in projection possibly suggesting 2 different epochs of feedback:

→ active jet + detached radio bubble that recently got energized coherently across 300 kpc → shock?
Shock overruns an aged radio bubble (C.P. & Jones 2011)
Bubble transformation to vortex ring

Enßlin & Brüggen (2002): gas density (top) and magnetic energy density (bottom)
Enßlin & Brüggen (2002): total 100 MHz intensity and polarization E-vectors, strong shock/weak B (left) and strong shock/strong B model (right)
Cartoon of the time evolution of NGC 1265

Top view (not to scale):

0 1 2 3 4

plasma bubbles

NGC 1265

radio torus

head−tail jet

C.P. & Jones (2011)
NGC 1265 as a perfect probe of a shock

**idea:**
- galaxy velocity not affected by shock → pre-shock conditions
- tail & torus as tracers of the post-shock flow

**assumptions:**
- shock surface \parallel gravitational equipotential surface of Perseus
- recent jet launched shortly after shock crossing

**method:**
- extrapolating position and velocity back in time
- employing conservation laws at oblique shock
- iterate until convergence
Derived geometry for NGC 1265

Top view:
- x-axis
- y-axis (to observer)
- z-axis
- vorticity
- active shear layer
- curved shock surface
- orbit of NGC 1265

Plane of the sky:
- 0 0
- 100 kpc = 4.6'
- orbit of NGC 1265
- tangent surface @ shock crossing of NGC 1265
- curved shock surface
- LOS (out of plane)

C.P. & Jones (2011)
A 3D model for NGC 1265
A 3D model for NGC 1265

3D model:

observer’s view:

Christoph Pfrommer

Large-scale shocks and extragalactic cosmic rays
Shock strength and jump conditions

- Shock compresses relativistic bubble adiabatically: \( \frac{P_2}{P_1} = C^{4/3} \)

- Bubble compression factor:

\[
C = \frac{V_{\text{bubble}}}{V_{\text{torus}}} = \frac{\frac{4}{3} \pi R^3}{2 \pi^2 R^2 r_{\text{min}}^2} = \frac{2}{3 \pi} \left( \frac{R}{r_{\text{min}}} \right)^2 \approx 10
\]

- Assuming pressure equilibrium \( \rightarrow \) shock jumps:

\[
\frac{P_2}{P_1} \approx 21.5, \quad \frac{\rho_2}{\rho_1} \approx 3.4, \quad \frac{T_2}{T_1} \approx 6.3, \quad \text{and} \quad M \approx 4.2
\]

C.P. & Jones (2011)
Perseus accretion shock and WHIM properties

- jet has low Faraday RM → NGC 1265 on near side of Perseus
- NGC 1265 redshifted w/r to Perseus → infalling system
- shock likely the accretion shock

- extrapolating X-ray $n$- and $T$-profiles to $R_{200}$ & shock jumps:
  → upper limits on infalling warm-hot intergalactic medium

\[
\begin{align*}
  kT_1 & \lesssim 0.4 \text{ keV} \\
  n_1 & \lesssim 5 \times 10^{-5} \text{ cm}^{-3} \\
  P_1 & \lesssim 3.6 \times 10^{-14} \text{ erg cm}^{-3}
\end{align*}
\]

C.P. & Jones (2011)
Shear flows and shock curvature

- Ellipticity of radio torus (magnitude and orientation) & bending direction of tail → excludes projection effects → evidence for post-shock shear flow

- Shock curvature injects vorticity that shears the gas westwards:

\[
\frac{\varepsilon_{\text{shear}}}{\varepsilon_{\text{th},2}} = \frac{\mu m_p v_\perp^2}{3 k T_2} \approx 0.14,
\]

with \( k T_2 \approx 2.4 \) keV and \( v_\perp \approx 400 \text{ km/s} \)

C.P. & Jones (2011)
Cosmological simulations
Cosmic-ray signatures
Large-scale shocks

Radio galaxies in clusters
Probing accretion shocks
Vision and Speculations

Vision and Speculations

A2256, Owen+ (2014)

Christoph Pfrommer

Large-scale shocks and extragalactic cosmic rays
The Universe is full of . . .

- Smoke rings . . .
  - in air
  - over Mt. Etna
  - in water

- in galaxy clusters

Christoph Pfrommer

Large-scale shocks and extragalactic cosmic rays
Conclusions on radio galaxies as probes of shocks

- consistent 3D model of NGC 1265
- prediction of a very interesting source class for LOFAR/SKA
- radio galaxies as perfect probes of pre- and post-shock flows:
  - hydrodynamic jumps and Mach numbers
  - statistical properties of the infalling WHIM (+ X-rays)
  - estimating the curvature radius of shocks and induced shear flows

→ implications for intra-cluster turbulence as well as generation and amplification of large-scale magnetic fields!
Cosmic rays in clusters:


Large-scale shocks: