Cosmic ray physics in AREPO

Christoph Pfrommer

in collaboration with

R. Pakmor, K. Schaal, C. Simpson, V. Springel
Heidelberg Institute for Theoretical Studies, Germany

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Puzzles in galaxy formation

- Dwarf galaxy
- Spiral galaxy
- Giant elliptical galaxy

log( stellar / halo mass ) vs log( halo mass )

20% of baryons

Moster+ (2010)
Puzzles in galaxy formation

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Active galactic nuclei feedback by stellar feedback. 20% of baryons. 

\[
\log\left( \frac{\text{stellar mass}}{\text{halo mass}} \right) \quad \log(\text{halo mass})
\]

Moster+ (2010)

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How are galactic winds driven?

observed energy equipartition between cosmic rays (CRs), thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds
Why are CRs important for wind formation?

Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface

- CR pressure drops less quickly than thermal pressure ($P \propto \rho^\gamma$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind → “CR battery”
- Poloidal (“open”) field lines at wind launching site → CR-driven Parker instability

Tüllmann+ (2000)
Introduction
Cosmic rays in AREPO
Puzzles
Galactic winds
AGN feedback

AGN feedback: M87 at radio wavelengths

\( \nu = 1.4 \text{ GHz (Owen+ 2000)} \)
\( \nu = 140 \text{ MHz (LOFAR/de Gasperin+ 2012)} \)

- high-\( \nu \): freshly accelerated CR electrons
- low-\( \nu \): fossil CR electrons \( \rightarrow \) time-integrated AGN feedback!
- LOFAR: same picture \( \rightarrow \) puzzle of “missing fossil electrons”
- solution: electrons are fully mixed with the dense cluster gas and cooled through Coulomb interactions
The gamma-ray picture of M87

- **high state** is time variable
  → jet emission

- **low state:**
  (1) steady flux
  (2) $\gamma$-ray spectral index (2.2)
    $= \text{CRp index}$
    $= \text{CRe injection index as probed by LOFAR}$
  (3) spatial extension is under investigation (?)

→ confirming this triad would be smoking gun for first $\gamma$-ray signal from a galaxy cluster!
hypothesis: low state $\gamma$-ray emission traces CRp-p interactions

- cosmic rays excite Alfvén waves that dissipate the energy $\rightarrow$ heating rate

$$\mathcal{H}_{\text{cr}} = -\mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}$$

(Loewenstein, Zweibel, Begelman 1991, Guo & Oh 2008, Enßlin+ 2011)

- calibrate $P_{\text{cr}}$ to $\gamma$-ray emission and $|\mathbf{v}_{\text{st}}| = |\mathbf{v}_{A}|$
  to radio/X-ray emission
  $\rightarrow$ spatial heating profile

$\rightarrow$ cosmic-ray heating matches radiative cooling (observed in X-rays)
and may solve the famous “cooling flow problem” in galaxy clusters!
Simulations – flowchart

ISM observables:
- X-ray, Hα, HI, ... emission
- stellar spectra

Physical processes in the ISM:
- radiative cooling
- stellar populations
  - supernovae
  - shocks
  - AGN
- thermal energy

C.P., Pakmor, Schaal, Simpson, Springel (in prep.)
Simulations with cosmic ray physics

ISM observables:

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- thermal energy
- cosmic ray energy

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Physical processes in the ISM:
- Radiative cooling
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- Supernovae
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- AGN
- Coulomb losses
- Cosmic ray energy
- Heat conduction
- CR streaming

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Simulations with cosmic ray physics

ISM observables:
- X-ray, Hα, HI, ... emission
- stellar spectra
- radio synchrotron
- gamma-ray emission

Physical processes in the ISM:
- radiative cooling
- thermal energy
- super-novae
- shocks
- AGN
- Coulomb losses
- CR streaming
- heat conduction
- hadronic losses
- cosmic ray energy

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CR shock acceleration
Comparing simulations to novel exact solutions that include CR acceleration

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Sedov explosion

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Sedov explosion with CR acceleration

C.P., Pakmor, Schaal, Simpson, Springel (in prep.)
Cosmological simulations with cosmic rays

C.P., Pakmor, Schaal, Simpson, Springel (in prep.)

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Cosmological simulations with cosmic rays

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Modeling CR streaming
A challenging hyperbolic/parabolic problem

streaming equation:

\[
\frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot [(\varepsilon_{\text{cr}} + P_{\text{cr}}) \mathbf{v}_{\text{st}}] = \mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}, \quad \mathbf{v}_{\text{st}} = -\text{sgn}(B \cdot \nabla P_{\text{cr}}) \mathbf{v}_{\text{A}}
\]

- CR streaming $\sim$ CR advection with the Alfvén speed
- at local extrema, CR energy overshoots and develops unphysical grid oscillations

Sharma+ (2010)
Modeling CR streaming
A challenging hyperbolic/parabolic problem

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\frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot \left[ (\varepsilon_{\text{cr}} + P_{\text{cr}}) \mathbf{v}_{\text{st}} \right] = \mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}, \quad \mathbf{v}_{\text{st}} = -\operatorname{sgn}(\mathbf{B} \cdot \nabla P_{\text{cr}}) \mathbf{v}_{\text{A}}
\]

- CR streaming \(\sim\) CR advection with the Alfvén speed
- at local extrema, CR energy overshoots and develops unphysical grid oscillations
- regularize equations: diffusive at extrema, advective at gradients

- **problem**: stability criterion requires \(\Delta t \propto \Delta x^3\)
  \(\Rightarrow\) implicit non-linear solver
CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtion
Additional slides
Local stability analysis (1)

- Isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

\[ T^2 h_{\text{CR}} \]
\[ T^2 c_{\text{rad}} \]

heating

cooling

\( kT \)
Local stability analysis (1)

- Isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

\[ T^2 H_{\text{CR}} \]
\[ T^2 C_{\text{rad}} \]

- Heating
- Cooling
- Unstable FP
Local stability analysis (1)

- Isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations
Local stability analysis (1)

- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations
Local stability analysis (2)
Theory predicts observed temperature floor at $kT \simeq 1$ keV

![Diagram showing instability criterion, arsinh(D), with temperature T in K and CR abundance X_{CR} = 0.31 and 0.031. The graph illustrates "islands of stability" and "ocean of instability".](image-url)
Virgo cluster cooling flow: temperature profile
X-ray observations confirm temperature floor at $kT \sim 1$ keV

Matsushita+ (2002)
Emerging picture of CR feedback by AGNs

(1) during buoyant rise of bubbles: CRs diffuse and stream outward → CR Alfvén-wave heating

(2) if bubbles are disrupted, CRs are injected into the ICM and caught in a turbulent downdraft that is excited by the rising bubbles → CR advection with flux-frozen field → adiabatic CR compression and energizing: $P_{cr}/P_{cr,0} = \delta^{4/3} \sim 20$ for compression factor $\delta = 10$

(3) CR escape and outward streaming → CR Alfvén-wave heating
Prediction: flattening of high-$\nu$ radio spectrum
Conclusions on AGN feedback by cosmic-ray heating

- LOFAR puzzle of “missing fossil electrons” solved by mixing with dense cluster gas and Coulomb cooling
- Predicted $\gamma$ rays identified with low state of M87
  $\rightarrow$ estimate CR-to-thermal pressure of $X_{\text{cr}} = 0.31$
- CR Alfvén wave heating balances radiative cooling on all scales within the radio halo ($r < 35$ kpc)
- Local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

**outlook:** simulate steaming CRs coupled to MHD, cosmological cluster simulations, improve $\gamma$-ray and radio observations . . .