Cosmic ray heating in cool core clusters

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Aug 13, 2014 / 3rd ICM Theory and Computation Workshop, NBI Copenhagen
Galactic cosmic ray spectrum

- power-law momentum spectrum with 33 decades in flux and 12 decades in energy
- likely origin: diffusive shock acceleration at supernova remnants ($E \lesssim 10^{17}$ eV)

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data compiled by Swordy

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Galactic cosmic ray spectrum

- power-law momentum spectrum with 33 decades in flux and 12 decades in energy
- likely origin: diffusive shock acceleration at supernova remnants \( (E \lesssim 10^{17} \text{ eV}) \)
- pressure of cosmic rays (CRs), magnetic fields, and turbulence in the interstellar gas all similar:
  - CR pressure in cluster cores?
  - impact of CRs on cooling gas and star formation in ellipticals?

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Cosmic ray feedback
Cosmic ray physics
Observations of M87
Alfvén-wave heating

data compiled by Swordy
CRs scatter on magnetic fields → isotropization of CR momenta

CR streaming instability: Kulsrud & Pearce 1969
- if $v_{\text{cr}} > v_{\text{waves}}$ with respect to the gas, CR excite Alfvén waves
- scattering off this wave field limits the CRs’ bulk speed $\ll c$
- wave damping: transfer of CR energy and momentum to the thermal gas

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Interactions of CRs and magnetic fields
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  - wave damping: transfer of CR energy and momentum to the thermal gas

$\rightarrow$ CRs exert a pressure on the thermal gas by means of scattering off Alfvén waves and heat the surrounding gas

$\rightarrow$ **cool-core heating** (Loewenstein+ 1991, Guo & Oh 2008, C.P. 2013)
CR transport

- total CR velocity $\mathbf{v}_{cr} = \mathbf{v} + \mathbf{v}_{st} + \mathbf{v}_{di}$ (where $\mathbf{v} \equiv \mathbf{v}_{gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\mathbf{B}$):

\[
\mathbf{v}_{st} = -\mathbf{v}_A \frac{\nabla P_{cr}}{|\nabla P_{cr}|} \quad \text{with} \quad \mathbf{v}_A = \sqrt{\frac{B^2}{4\pi \rho}}, \quad \mathbf{v}_{di} = -\kappa_{di} \frac{\nabla P_{cr}}{P_{cr}},
\]
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\]

- energy equations with \( \varepsilon = \varepsilon_{\text{th}} + \rho \mathbf{v}^2 / 2 \) (neglecting CR diffusion):

\[
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \left[ (\varepsilon + P_{\text{th}} + P_{\text{cr}}) \mathbf{v} \right] = P_{\text{cr}} \nabla \cdot \mathbf{v} + |\mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}|
\]
\[
\frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot (\varepsilon_{\text{cr}} \mathbf{v}) + \nabla \cdot \left[ (\varepsilon_{\text{cr}} + P_{\text{cr}}) \mathbf{v}_{\text{st}} \right] = -P_{\text{cr}} \nabla \cdot \mathbf{v} - |\mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}|
\]
Messier 87 at radio wavelengths

\( \nu = 1.4 \text{ GHz (Owen+ 2000)} \)

- expectation: low frequencies sensitive to fossil electrons \((E \sim 100 \text{ MeV}) \rightarrow \text{time-integrated activity of AGN feedback!} \)
Messier 87 at radio wavelengths

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- **LOFAR**: halo confined to same region at all frequencies and no low-\(\nu\) spectral steepening → puzzle of “missing fossil electrons”
Solutions to the “missing fossil electrons” problem

solutions:

- special time: M87 turned on
  ~ 40 Myr ago after long silence
  ⇔ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
Solutions to the “missing fossil electrons” problem

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- Coulomb cooling removes fossil electrons
  → efficient mixing of CR electrons and protons with dense cluster gas
  → predicts γ rays from CRp-p interactions:

\[ p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots \]

\[ p = \bar{p}/m_e c \]

\[ \tau = E/\dot{E} \text{ [Myr]} \]

\[ B = 10 \mu G \]

\[ B = 20 \mu G \]

\[ n_e [\text{cm}^{-3}] = 10^{-2} \]

\[ \text{Coulomb} \]

\[ \text{total loss} \]

C.P. (2013)
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)
    = CRp index
    = 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!
Estimating the CR pressure in M87

hypothesis: low state of $\gamma$-ray emission traces $\pi^0$ decay in ICM:

- X-ray data $\rightarrow$ $n$ and $T$ profiles
- assume $X_{cr} = P_{cr}/P_{th} = \text{const.}$ (self-consistency requirement)
- $F_\gamma \propto \int dV P_{cr} n$ enables to estimate $X_{cr} = 0.31$
  (allowing for Coulomb cooling with $\tau_{Coul} = 40$ Myr)

$\rightarrow$ in agreement with non-thermal pressure constraints from dynamical potential estimates (Churazov+ 2010)

Rieger & Aharonian (2012)
Cosmic-ray heating vs. radiative cooling (1)

**CR Alfvén-wave heating:**

\[ \mathcal{H}_{cr} = -v_A \cdot \nabla P_{cr} = -v_A \left( X_{cr} \nabla_r \langle P_{th} \rangle \Omega + \frac{\delta P_{cr}}{\delta l} \right) \]

- Alfvén velocity \( v_A = B / \sqrt{4\pi \rho} \) with \( B \sim B_{eq} \) from LOFAR and \( \rho \) from X-ray data
- \( X_{cr} \) calibrated to \( \gamma \) rays
- \( P_{th} \) from X-ray data
- pressure fluctuations \( \delta P_{cr} / \delta l \) (e.g., due to weak shocks of \( M \sim 1.1 \))

\( C_{rad} = n_e n_i \Lambda_{cool}(T, Z) \)

cooling function \( \Lambda_{cool} \) with \( Z \sim Z_* \), all quantities determined from X-ray data
Cosmic-ray heating vs. radiative cooling (1)

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**Radiative cooling:**

\[ C_{rad} = n_e n_i \Lambda_{cool}(T, Z) \]

- Cooling function \( \Lambda_{cool} \) with \( Z \sim Z_{\odot} \), all quantities determined from X-ray data
Cosmic-ray heating vs. radiative cooling (2)
Global thermal equilibrium on all scales in M87

\[ C_{\text{rad}}, H_{\text{CR}} \ [\text{ergs cm}^{-3} \text{s}^{-1}] \]

radial extent of radio halo:

\[ H_{\text{CR}}, P_{\text{smooth}} + \delta P \]

\[ H_{\text{CR}}, P_{\text{smooth}} \]

\[ C_{\text{rad}}(0.7 Z_\odot \lesssim Z \lesssim 1.3 Z_\odot) \]
Cosmic-ray heating vs. radiative cooling (3)

is this global thermal equilibrium a coincidence in Virgo?
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- CCs typically show a steep central density profile: $n \propto r^{-1}$
- central temperature profile rises slowly: $T \propto r^\alpha$, with $\alpha \lesssim 0.3$
- assume $v_A = \text{const.}$ and $P_{\text{cr}} \propto P_{\text{th}}$ (required for self-consistency):

$$\mathcal{H}_{\text{cr}} \propto \frac{\partial}{\partial r} P_{\text{th}} \propto \frac{\partial}{\partial r} r^{\alpha - 1} \propto r^{\alpha - 2}$$

$$C_{\text{rad}} \propto n^2 \propto r^{-2}$$
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\]

(1) identical radial profiles expected for \( T \simeq \text{const.} \) (\( \alpha \simeq 0 \))
(2) for a smoothly rising temperature profile, heating is slightly favored over cooling at larger radii \( \rightarrow \) onset of cooling is smoothly modulated from the outside in
Cosmic-ray heating vs. radiative cooling

Global thermal equilibrium on all scales in M87

radial extent of radio halo:

C.P. (2013)

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Local stability analysis (1)

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

\[ T^2 \mathcal{H}_{\text{CR}} \]
\[ T^2 C_{\text{rad}} \]

heating
cooling

\[ kT \]
Local stability analysis (1)

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- 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

![Graph of instability criterion, $\text{arsinh}(D)$ vs. temperature $T$ (K)]

- $X_{CR} = 0.31$
- $X_{CR} = 0.031$

“islands of stability”
“ocean of instability”
Virgo cluster cooling flow: temperature profile

X-ray observations confirm temperature floor at $kT \simeq 1$ keV

(Matsushita+ 2002)
Critical length scale of the instability ($\sim$ Fields length)

- CR streaming transfers energy to a given gas parcel
- Line and bremsstrahlung emission radiate energy from the parcel
- **limiting size of unstable gas parcel** since CR Alfvén-wave heating smooths out temperature inhomogeneities on small scales:

$$\lambda_{\text{crit}} = \frac{f_s v_A P_{\text{cr}}}{C_{\text{rad}}}$$

- However: unstable wavelength needs to be supported by the system $\rightarrow$ constraint on magnetic suppression factor $f_s$
Critical length scale of the instability ($\sim$ Fields length)

Critical instability length ($\lambda_{\text{crit}}$) vs. radius ($r$) for different values of $f_{\text{sup}}$ and $Z$.

- $f_{\text{sup}} = 1.0$, $Z = 0.7 \, Z_\odot$
- $f_{\text{sup}} = 1.0$, $Z = 1.3 \, Z_\odot$
- $f_{\text{sup}} = 0.3$, $Z = 0.7 \, Z_\odot$
- $f_{\text{sup}} = 0.3$, $Z = 1.3 \, Z_\odot$
- $\lambda_{\text{crit}} = r$

Unstable wavelength larger than system

Stabilized by CR streaming

Thermally unstable

C.P. (2013)
CR heating dominates over thermal conduction
Prediction: flattening of high-$\nu$ radio spectrum

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Radio spectrum data and models.}
\end{figure}
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: \( \frac{P_{\text{cr}}}{P_{\text{cr},0}} = \delta^{4/3} \sim 20 \) for compression factor \( \delta = 10 \)

(3) CR escape and outward streaming → CR Alfvén-wave heating
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 $X_{cr} = 0.31$
- 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 $kT \sim 1$ keV

Outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, improve $\gamma$-ray and radio observations . . .
AGN feedback by cosmic rays:

Self-consistent CR pressure in steady state

- CR streaming transfers energy per unit volume to the gas as

\[
\Delta \varepsilon_{th} = -\tau_A \mathbf{v}_A \cdot \nabla P_{cr} \approx P_{cr} = X_{cr} P_{th},
\]

where \( \tau_A = \delta l / v_A \) is the Alfvén crossing time and \( \delta l \) the CR pressure gradient length.

- comparing the first and last term suggests that a constant CR-to-thermal pressure ratio \( X_{cr} \) is a necessary condition if CR streaming is the dominant heating process.

→ thermal pressure profile adjusts to that of the streaming CRs!
Impact of varying Alfvén speed on CR heating

global thermal equilibrium:

local stability criterion:

parametrize $B \propto \rho^{\alpha_B}$, which implies $v_A = B/\sqrt{4\pi\rho} \propto \rho^{\alpha_B-1/2}$:

- $\alpha_B = 0.5$ is the geometric mean, implying $v_A = \text{const.}$
- $\alpha_B = 0$ for collapse along $B$, implying $v_A,\parallel \propto \rho^{-1/2}$
- $\alpha_B = 1$ for collapse perpendicular to $B$, implying $v_A,\perp \propto \rho^{1/2}$