AGN feedback: mechanical versus cosmic-ray heating

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Outline

1. Cosmic ray feedback
   - Observations of M87
   - Cosmic rays
   - Heating

2. Diversity of cool cores
   - Cool core sample
   - Bimodality
   - Conclusions
Radio mode feedback by AGN: open questions

- **energy source:**
  release of non-gravitational accretion
  energy of a black hole

- **jet-ICM interaction and rising bubbles:**
  1.) magnetic draping → amplification
  2.) CR confinement vs. release
  3.) excitation of turbulence

- **heating mechanism:**
  1.) self-regulated to avoid overcooling
  2.) thermally stable to explain $T$ floor
  3.) low energy coupling efficiency

- **cosmic ray heating:**
  1.) are CRs efficiently mixed into the ICM?
  2.) is the CR heating rate sufficient to balance cooling?
  3.) how universal is this heating mechanism in cool cores?
Messier 87 at radio wavelengths

- high-$\nu$: freshly accelerated CR electrons
- low-$\nu$: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!

- LOFAR: halo confined to same region at all frequencies and no low-$\nu$ spectral steepening $\rightarrow$ 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)

- Coulomb cooling removes fossil electrons
  → efficient mixing of CR electrons and protons with dense cluster gas
  → predicts $\gamma$ rays from CRp-p interactions:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$
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 of $\gamma$-ray emission traces $\pi^0$ decay in ICM:

- X-ray data $\rightarrow$ $n$ and $T$ profiles
- assume steady-state CR streaming: $P_{\text{cr}} \propto \rho^{\gamma_{\text{cr}}/2} \propto P_{\text{th}}$
- $F_\gamma \propto \int dV P_{\text{cr}}n$ enables to estimate $X_{\text{cr}} = P_{\text{cr}}/P_{\text{th}} = 0.31$ (allowing for Coulomb cooling with $\tau_{\text{Coul}} = 40$ Myr)

$\rightarrow$ in agreement with non-thermal pressure constraints from dynamical potential estimates (Churazov+ 2010)
Interactions of cosmic rays and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta

- **CR streaming instability:** Kulserud & Pearce 1969
  - if $v_{cr} > v_A$, CR current provides steady driving force, which amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs’ bulk speed $\sim v_A$
  - wave damping: transfer of CR energy and momentum to the thermal gas

→ CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves
Cosmic-ray transport

- total CR velocity $v_{cr} = v + v_{st} + v_{di}$ (where $v \equiv v_{gas}$)
- CRs are advected with the flux-frozen $B$ field in the gas
- CRs stream adiabatically down their own pressure gradient relative to the gas:

$$v_{st} = -v_A \frac{b \cdot \nabla P_{cr}}{|b \cdot \nabla P_{cr}|} \quad \text{with} \quad b = \frac{B}{|B|} \quad \text{and} \quad v_A = \sqrt{\frac{B^2}{4\pi \rho}}$$

- CRs diffuse in the wave frame due to pitch angle scattering by MHD waves:

$$v_{di} = -\kappa_{di} \frac{b \cdot \nabla P_{cr}}{P_{cr}}$$
Cosmic-ray heating vs. radiative cooling (1)

**CR Alfvén-wave heating:**
(Loewenstein, Zweibel, Begelman 1991, Guo & Oh 2008, Enßlin+ 2011)

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

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

**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

Radial extent of radio halo:
Local stability analysis (1)

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

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

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

\[ kT \]

heating

cooling

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Local stability analysis (1)

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

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

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

unstable FP

heating

stable FP

cooling
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 $kT \simeq 1 \text{ keV}$

![Graph showing instability criteria and regions]

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

"islands of stability"  
"ocean of instability"
Virgo cluster cooling flow: temperature profile
X-ray observations confirm temperature floor at $kT \sim 1$ keV

$kT$ (keV) vs. $R$ (arcmin)

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

![Graph showing the prediction of flattening of high-$\nu$ radio spectrum with different emission scenarios: radio data, continuous injection, continuous injection with switch off, and hadronically induced emission. The graph plots flux density in Jy against frequency in MHz.](image-url)
How universal is CR heating in cool core clusters?

- no $\gamma$ rays observed from other clusters $\rightarrow P_{cr}$ unconstrained

**strategy**: construct sample of 24 cool cores

1. assume $H_{cr} = C_{rad}$ at $r = r_{cool}$, 1 Gyr
2. assume steady-state CR streaming: $P_{cr} \propto \rho \gamma_{cr}/2$
3. adopt $B$ model from Faraday rotation studies:
   $$B = 40 \mu G \times \left( n/0.1 \text{ cm}^{-3} \right)^{\alpha_B}$$
   where $\alpha_B \in \{2/3, 1\}$
4. calculate hadronic radio and $\gamma$-ray emission and compare to observations

**consequences**:

$\Rightarrow$ if $H_{cr} = C_{rad}$ $\forall$ $r$ and hadr. emission below observational limits:
successful CR heating model that is locally stabilized at $\sim 1$ keV

$\Rightarrow$ otherwise CR heating ruled out as dominant heating source
Cosmic-ray heating in cool core clusters (1)

Jacob & C.P. (in prep.)

Cosmic ray feedback
Diversity of cool cores

Cool core sample
Bimodality
Conclusions

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HITS
Cosmic-ray heating in cool core clusters (2)
Cosmic-ray heating in Hydra A vs. Perseus

2 populations of cool cores emerging:

- **pop 1** (Hydra A, Virgo, ...): $\mathcal{H}_{\text{cr}} = C_{\text{rad}} \rightarrow$ CR heated?
- **pop 2** (Perseus, Ophiuchus, ...): $\mathcal{H}_{\text{cr}} \neq C_{\text{rad}}$: host radio-mini halos!

Jacob & C.P. (in prep.)
Non-thermal pressure balance

- define $X_{cr} = \frac{P_{cr}}{P_{th}}$ and $X_B = \frac{P_B}{P_{th}}$
- CR heating rate: $\mathcal{H}_{cr} = -v_A \cdot \nabla P_{cr} \propto X_B^{0.5} X_{cr}$
- non-thermal pressure at fixed heating rate:
  \[ X_{nt} \equiv (X_B + X_{cr}) \mathcal{H}_{cr} = AX_{cr}^{-2} + X_{cr} \rightarrow X_{cr,min} = (2A)^{1/3} \]
Hadronic emission: radio and $\gamma$ rays

$X_{\text{cr}} = C_{\text{rad}}$

Jacob & C.P. (in prep.)

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Hadronic emission: radio and $\gamma$ rays

$X_{cr}$

$C_{rad} = H_{cr}$

$\gamma$-ray obs., $r_{max} = r_{cool,1Gyr}$

Jacob & C.P. (in prep.)

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AGN feedback: mechanical versus cosmic-ray heating
Hadronic emission: radio and $\gamma$ rays

$X_{cr} = H_{cr}$

- $\gamma$-ray obs., $r_{max} = r_{cool,1Gyr}$
- NVSS data, $r_{max} = r_{cool,1Gyr}$

Jacob & C.P. (in prep.)

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AGN feedback: mechanical versus cosmic-ray heating
Hadronic emission: radio and $\gamma$ rays

CR heating solution ruled out in radio mini-halos ($H_{cr} \neq C_{rad}$)!

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possibly cosmic ray-heated cool cores vs. radio mini halo clusters:

- $F_{\nu, \text{obs}} > F_{\nu, \text{pred}}$: strong radio source = abundant injection of CRs
- peaked CC profile ($r_{\text{cool}} \lesssim 20$ kpc) and simmering star formation: cosmic-ray(?) heating is effectively balancing cooling
- large star formation rates: heating out of balance
Conclusions on AGN feedback by cosmic-ray heating

cosmic-ray heating in M87:

- LOFAR puzzle of “missing fossil electrons” in M87 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 central radio halo ($r < 35$ kpc)
- Local thermal stability analysis predicts observed temperature floor at $kT \approx 1$ keV

Diversity of cool cores:

- *Peaked cool cores*: possibly stably heated by cosmic rays
- *Radio mini halo clusters*: cosmic-ray heating ruled out
  systems are strongly cooling and form stars at large rates
AGN feedback by cosmic rays:


- Jacob & Pfrommer, *Diversity in cool core clusters: implications for cosmic-ray heating*, in prep.
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 $v_{A,\perp} \propto \rho^{1/2}$
CR heating dominates over thermal conduction

\[ \frac{H_{\text{CR}}}{H_{\text{cond}}} \]

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

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

radius [kpc]

C.P. (2013)
CR streaming transfers energy to a gas parcel with the rate

\[ \mathcal{H}_{cr} = -v_A \cdot \nabla P_{cr} \sim f_s v_A |\nabla P_{cr}|, \]

where \( f_s \) is the magnetic suppression factor.

- line and bremsstrahlung emission radiate energy with a rate \( C_{rad} \)
- limiting size of unstable gas parcel since CR Alfvén-wave heating smoothes out temperature inhomogeneities on small scales:

\[ \lambda_{crit} = \frac{f_s v_A P_{cr}}{C_{rad}} \]

- however: unstable wavelength must be supported by the system
  \[ \rightarrow \text{constraint on magnetic suppression factor } f_s \]
Critical length scale of the instability ($\sim$ Fields length)

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

$\lambda_{\text{crit}} = r$

- Unstable wavelength larger than system
- Thermally unstable
- Stabilized by CR streaming

C.P. (2013)
CR streaming transfers energy per unit volume to the gas as

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

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 \( X_{\text{cr}} \) is a necessary condition if CR streaming is the dominant heating process.

→ thermal pressure profile adjusts to that of the streaming CRs!