Cosmic ray feedback in cool cores

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Local thermal imbalance
Precipitation conditions

$\frac{t_{\text{cool}}}{t_{\text{ff}}} = 10$

$\frac{t_{\text{cool}}}{t_{\text{ff}}} = 1/10$

McCourt, Sharma, Quataert, Parrish 2012
Sharma, McCourt, Quataert, Parrish 2012
Gaspari, Ruszkowski, Oh 2013
Gaspari, Ruszkowski, Sharma 2012
Yang & Reynolds 2016a,b
Li, Ruszkowski, Bryan 2017
LOFAR radio

CR

de Gasperin et al. (2012)
Microphysics of CR streaming

Streaming instability (Kulsrud & Pearce, 1969)

- CR generate waves
- waves are coupled to the ionized gas (frozen in)
- CR interact with these waves
- CR push the gas & lose energy to the gas
Cosmic ray Advection
Cosmic ray Transport (2\textsuperscript{nd} order effect)
Cosmic rays generate waves that transfer momentum to the gas.
\[
\frac{\partial (\rho u)}{\partial t} = [...] - \nabla P_{CR}
\]

extra pressure force

\[
\frac{\partial e_{CR}}{\partial t} = [...] - \nabla \cdot F
\]

streaming
\[ \frac{\partial (\varrho u)}{\partial t} = [...] - \nabla P_{CR} \]

**extra pressure force**

\[ \frac{\partial e_{CR}}{\partial t} = [...] - \mathbf{v}_{Alfven} \cdot \nabla p_{CR} \]

**heating**
Hydro

Efficient heating by mixing
hydro
efficient heating by mixing

MHD, hadronic + Coulomb
mixing partially suppressed by B-fields
inefficient heating by hadronic/Coulomb
hydro

efficient heating by mixing

MHD, hadronic + Coulomb
mixing partially suppressed by B-fields
inefficient heating by hadronic/Coulomb

MHD, hadronic + Coulomb + streaming/heating
improved mixing;
efficient transfer of CR energy to the ICM
CR energy density maps

Coulomb + hadronic

Ruszkowski, Yang, Reynolds 2017

Coulomb + hadronic streaming heating streaming transport
CR pressure support
Coulomb + hadronic Coulomb + hadronic
streaming heating & transport

Ruszkowski, Yang, Reynolds 2017
steady state models do not violate gamma-ray constraints
(ignore models to the right; may be out of equilibrium/accreting)

CR fractions ~ 10%

Jacob & Pf frommer (2017)
streaming heating

no gamma-ray flux

hadronic + Coulomb heating
Jet power

Coulomb + hadronic streaming heating & transport

Ruszkowski, Yang, Reynolds 2017
no CR streaming

- heating more centrally-peaked
no CR streaming
• heating more centrally-peaked

CR streaming
• heating more distributed
• central cool timescale shorter
• AGN fueling and feedback intermittent
fast streaming
(perturbations smoothed out)

streaming inhibited
(by perturbations)
Coulomb + hadronic streaming heating
super-Alfvenic streaming transport

\[ \frac{\Gamma_L}{\Gamma_t} \sim \beta^{1/2} > 1 \]

Ruszkowski, Yang, Reynolds 2017
Wiener, Oh, Zweibel 2017

CR heating is less LOCAL
Coulomb + hadronic streaming heating
super-Alfvenic streaming transport

\[ \frac{\Gamma_L}{\Gamma_t} \sim \beta^{1/2} > 1 \]

Ruszkowski, Yang, Reynolds 2017
Wiener, Oh, Zweibel 2017
\[ \frac{r}{2}(-v_A \cdot \nabla P_{cr}) \equiv \hat{c}_i c s_0 n k_b T \]

\[ -v_A \cdot \nabla P_{cr} \sim 2v_{A \perp} \frac{\partial P_{cr}}{\partial x} + v_{A \parallel} \frac{\partial P_{cr}}{\partial z} \]

\[ \epsilon_{M87} \sim 0.073 \]

\[ \beta \gg 1 \]

\[ P_{th} \gg P_{cr} \]

\[ P_{th} \sim P_{cr} \]

Ruszkowski, Yang, Reynolds 2018
only a **small amount of CR pressure** is needed to heat the ICM

**CR transport** is essential for self-regulation

**CR streaming instability heating** $\rightarrow$ Coulomb/hadronic heating

(no gamma-rays)

simulations with streaming show **AGN variability**