Cosmic Rays in Galaxy Clusters

Joshua Wiener, University of Wisconsin
SNOWCLUSTER March 21
Acknowledgements

Ellen Zweibel
UW Madison

Peng Oh
UC Santa Barbara

Fulai Guo
Shanghai Astronomical Observatory
Outline

I. Models of CRs in Radio Halos
II. A Brief Introduction to CR Transport
III. Simulation Results
IV. High Beta Effects
V. Future Work - Streaming in the Steady State
Radio Haloes

Brown and Rudnick 2011

1 Mpc
How can radio emission drop so quickly?
Synchrotron Radiation

Brown and Rudnick 2010
Hadronic Model

CR

Accelerated during structure formation, stream out quickly when cluster relaxes

Produce synchrotron radiation

Gamma rays are also produced from neutral pion decay
Reacceleration Model

CR electrons are accelerated directly (must be accelerated continuously)

No gamma rays from pion decay (still some from inverse Compton emission)
Cosmic Ray Transport – a (very) brief introduction
Alfvén Waves

Resonance condition

\[ k_{\parallel} = \frac{1}{\mu r_L}, \quad r_L = \gamma r_0 \]
Streaming Instability

Resonance condition

\[ k_\parallel = \frac{1}{\mu r_L}, \quad r_L = \gamma r_0 \]

Compare bulk CR drift speed \( v_D \) with Alfvén speed \( v_A \):

\[ \vec{v}_D P_c \equiv \vec{F}_c \]

- \( v_D > v_A \) \quad waves generated
- \( v_D < v_A \) \quad waves damped
- \( v_D = v_A \) \quad neutral stability
Self Confinement

no waves, no scattering  →  \( v_D \sim c \)

*but* CRs generate waves via streaming instability, so

waves, scattering  →  \( v_D \sim v_A \)

More accurately, the bulk motion of CRs is determined by

\[
\Gamma_{\text{growth}}(v_D) = \Gamma_{\text{damping}}
\]
MHD Turbulence Damping

\[ \Gamma_{\text{turb}} \sim \frac{1}{t_{\text{cascade}}(\lambda_\perp)} \sim \frac{v_{\lambda_\perp}}{\lambda_\perp} \sim \frac{v_A}{L_{\text{MHD}}^{1/3} \lambda_\perp^{2/3}} \sim \frac{\epsilon^{1/3}}{\lambda_\perp^{2/3}}. \]

\[ \Gamma_{\text{turb, min}} \sim \left( \frac{\epsilon}{r_L v_A} \right)^{1/2}; \]

*Farmer and Goldreich 2004
Evolution Equation

\[ \frac{\partial f_p}{\partial t} + (\mathbf{u} + \mathbf{v}_A) \cdot \nabla f_p = \]

- Compression/expansion
  \[ \frac{1}{3} \rho \frac{\partial f_p}{\partial p} \nabla \cdot (\mathbf{u} + \mathbf{v}_A) \]

- Super-Alfvenic streaming
  \[ + \frac{1}{\rho^3} \nabla \cdot \left( \frac{\Gamma_{\text{damp}} B^2 n}{4 \pi^3 m_p \Omega_0 \nu_a} \frac{n \cdot \nabla f_p}{|n \cdot \nabla f_p|} \right) \]

- Turbulent mixing
  \[ - \nabla \cdot \left[ \frac{\nu_{L_{\text{MHD}}}}{3} \rho^{1.5} \nabla \left( \frac{f_p}{\rho^{1.5}} \right) \right] \]
Goal:

With the above simple physics, what happens to radio and gamma emission in galaxy clusters over time?

Method:

Spherically symmetric 1D simulations of CR streaming in individual galaxy clusters using ZEUS
Coma Cluster Radio Emission

*Wiener, Oh, and Guo 2013 
MNRAS, 434, 2209

*Observations from Deiss et al 1997 
(Effelsberg 100-m telescope)
Coma Cluster γ-ray Emission

*Upper limits from Arlen et al 2012 (Fermi and VERITAS)
New ingredient: Wave damping in high Beta environments

\[ \Gamma_{\text{growth}}(v_D) = \Gamma_{\text{damping}} \]

\[ \Gamma_{\text{turb, min}} \sim \left( \frac{\epsilon}{r_L v_A} \right)^{1/2} \]

Turbulent cascade rate

Relativistic gyroradius
Dispersion relation from Foote and Kulsrud 1979:

For small $l$:

$$\nu = l - \frac{i\alpha}{4l} \pm \frac{1}{4l} \left( l^6 - \alpha^2 + \frac{4i\alpha^3}{l^2} \right)^{1/2}$$

$$\alpha = \pi^{1/2}\beta^{1/2}l^2 \tan^2 \theta.$$

Turbulence implies a minimum propagation angle:

$$\tan \theta_{min} = \left( \frac{\lambda_\parallel}{\lambda_\perp} \right) \sim \left( \frac{r_L}{L_{\text{MHD}}} \right)^{1/4} \sim \left( \frac{r_L \epsilon}{v_A^3} \right)^{1/4}$$
Result: Linear Landau damping rate is

$$\Gamma_{\text{damp}} \approx \frac{\sqrt{\pi}}{4} \beta^{1/2} \left( \frac{\epsilon}{r_L v_A} \right)^{1/2}$$

Compare with rate used in original work:

$$\Gamma_{\text{turb}, \text{min}} \sim \left( \frac{\epsilon}{r_L v_A} \right)^{1/2}$$

Damping is stronger in high beta environments – streaming is faster by $\beta^{1/2}$!

($\sim 10$ in the center of our model cluster)
Faster Streaming

Faster Dimming

The graph shows the luminosity $L_{\text{AGN}}$ (erg s$^{-1}$ Hz$^{-1}$) as a function of time $t$ (Myr). The plot includes three lines:

- Blue line: No Damping
- Green line: $L_{\text{MHD}} = 100$ kpc
- Red line: $L_{\text{MHD}} = 100$ kpc, High Beta Correction

The luminosity decreases over time, with different slopes for each case.
Faster Dimming

Caveat: We still have 1D symmetry with radial fields.

Non-linear effects may exaggerate the “speed boost” we get from the high beta.
Conclusions

1. Alfven wave damping in high beta plasmas is stronger than previously considered
2. This effect results in significantly faster streaming speeds in our simplified system

Limitations

1. Assumptions made about $B$-field strength and topology strongly affect results
2. Low frequency data cannot be explained by secondary CRe alone
3. Gamma ray non-detections are getting more and more restrictive (or are they?)
Steady State Streaming (PRELIMINARY)

Steady CR injection
Steady State Streaming (PRELIMINARY)
Steady State Streaming (PRELIMINARY)