Fermi I and II (re)acceleration of cosmic rays in the ICM

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Signs of non-thermal activity in galaxy clusters

A 3667
Radio: Johnston-Hollitt.
X-ray: ROSAT/PSPC.

A 2163
Radio: Feretti et al, 2004
A radio relic poster child: A2256

$\alpha_v = 0.85 \rightarrow$ Mach = 2.6

How is this possible???
Biggest unknown: Shock acceleration efficiency

Outskirts dominated by low Mach number shocks. These shocks have low acceleration efficiency.
Diffusive shock acceleration – reacceleration through Fermi I

- super thermal tail - accelerated
- Maxwellian
- aged CR population - all particles reaccelerated
- strong shock
- weak shock

Fermi I reacceleration:

CRe cooling times

Plasma processes:
Relativistic particle pop.:

\[ m_e \]
Fossil CR electron population

$M-\alpha R$

$P = P_e / m_e c$

Median spectrum w/ cooling:
- Individual clusters
- Median all clusters

Median spectrum w/o cooling:
- Individual clusters
- Median all clusters

Pinzke+ 2013
Fermi-I re-acceleration in radio relics

\[ f_{\text{reaccel}}(p) = \int_{p_{\text{inj}}}^{\infty} (\alpha + 2) \left( \frac{p}{p'} \right)^{-\alpha} f_0(p') H(p - p') d(\log p') \]

Fossil contribution comparable to direct injection at high \( M \)

Dominates at low \( M \)

Pinzke+ 2013

Fossil contribution comparable to direct injection at high \( M \)
Giant radio halo – Fermi II reacc.

Relativistic populations and radiative processes in clusters:

Energy sources:
- kinetic energy from structure formation
- supernovae & active galactic nuclei

Plasma processes:
- relativistic particle pop.

Relativistic particle pop.:
- shock waves - Fermi I
- turbulent cascade & plasma waves - Fermi II
- re-accelerated CRs - Fermi II

Observational diagnostics:
- radio synchrotron emission
- hard X-ray
- gamma-ray emission


Fermi II reacc. - CRs

Acceleration mechanism: Compressible MHD turbulence

$L_{\text{inj}} = 300$ kpc, $(V_{\text{turb}}/C_s)^2 = 0.22$, $\tau_{\text{reacc}} = 650$ Myr, isotropic Kraichnan turbulence

$$D_{pp}(p, t) = \frac{\pi}{8} \frac{\beta}{c} \frac{|B_k|^2}{16\pi W} \left( \frac{2I_0(V_{ph})}{7\rho} \right)^{\frac{1}{2}} k_{\text{cut}}(t)^{\frac{1}{2}} \int_0^{\pi/2} d\theta V_{ph}^2 \frac{\sin^3(\theta)}{|\cos(\theta)|} \mathcal{H} \left( 1 - \frac{V_{ph}/c}{\cos \theta} \right) \left( 1 - \left( \frac{V_{ph}/c}{\cos \theta} \right)^2 \right)^2$$

Fermi II reacc. - uncertainties

- flat CR profile (out to ~0.4 R_{200})
  - strong tension with simulations

Possible solutions:

- CRp streaming
- d\epsilon_{turb} /dR << d\epsilon_{th} /dR
- primary CRs
- alpha_B << 0.5

Pinzke+ 2015
Fermi II reacc. - uncertainties

- flat CR profile (out to \( \sim 0.4 R_{200} \))
  - strong tension with simulations

Possible solutions:
- CRp streaming
- \( d\epsilon_{\text{turb}} / dR \ll d\epsilon_{\text{th}} / dR \)
- primary CRes
- \( \alpha_B \ll 0.5 \)

Realistic cluster simulations with relevant physics need to fully establish Fermi II reacceleration models!
Streaming and diffusion – CR protons


Small anisotropy in CRs (frame of waves) ➞ momentum transfer CRs ➔ waves ➞ wave growth rate

\[ \Gamma_{CR}(k_{\parallel}) \sim \Omega_0 \frac{n_{CR}(>\gamma)}{n_i} \left( \frac{v_s}{v_A} - 1 \right) \]

\[ k_{\parallel} \sim \frac{1}{\mu r_L} \]

Kulsrud and Pearce 1969

⇒ grows until scattering renders CRs isotropic,

\[ V_{D} \sim V_A \]

⇒ self-confinement

Turbulence damps growth of waves since waves cascade to smaller scales before scattering CRs Farmer and Goldreich 2004

Adopt steady state, \( \Gamma_{grow} = \Gamma_{damp} \)

\[ v_D = v_A \left( 1 + 1.2 \frac{B^{1/2}_{\mu G} n_{i, -3}^{1/2}}{L_{MHD, 100}^{1/2} n_{CR, -10}^{3.5}} \gamma_{100}^{-3.5} 10^{2(n-4.6)} \right) \]

Wiener+ 2013

CR protons in clusters stream outward faster than inward turbulent advection

Wiener+ in prep.
Fermi II reacc. - three scenarios

1) **Flat turbulent profile** \((M\text{-turbulence}, \alpha_{tu} = 0.66)\)
   - secondary CRes and CRps, reaccelerated by flat turbulent profile
   - \(\alpha_{tu} < 1\) motivated by cosmological simulations, *Lau et al. 2009; Shaw et al. 2010; Battaglia et al. 2012*

2) **Streaming CRps** \((M\text{-streaming}, \alpha_{tu} = 0.81)\)
   - secondary CRes and streamed CRps, reaccelerated

3) **Primary CRes** \((M\text{-primary}, \alpha_{tu} = 0.88)\)
   - primary CRes with \(K_{ep} = 0.1\), reaccelerated
   - high \(K_{ep}\) motivated by radio relics and lack of \(\gamma\)-ray emission, e.g. *Vazza & Brüggen 2014*

\[
e_{turb}(R) \propto \varepsilon_{th}(R)
\]
\[
E_{turb}(< R_{RH}) = 0.2 E_{th}(< R_{RH})
\]
All three proposed scenarios reproduce observed radio spectrum.

Pure hadronic model (DSA only) can not reproduce spectrum

Pinzke+ 2015
Fermi II reacc. – radio profiles

COMA

Pinzke+ 2015
Fermi II reacc. – gamma-rays

Fermi-LAT can probe M-streaming and M-turbulence in near future!
Take home messages

Radio relics
- *Fermi I reaccelerated* fossil CR electrons in cluster outskirts can explain radio emission from low Mach number shocks

Giant radio halos
- *Classical hadronic models* ruled out by radio observations
- *Fermi II reacceleration* preferred, however, tension between initial CR distribution and simulations
  - 3 different solutions to the problem
    - *primary CRes* (large $K_{ep}$)
    - *streaming CRps* that produce secondary CRes
    - CRps and secondary CRes reaccelerated by *flat turbulent profile*

*Fermi I & II reacc. can reproduce both radio and gamma-ray observations in halos and relics!*
Thank You