Acceleration and Transport of High Energy Particles in Galaxy Clusters

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Focus of this talk

$$r_g(p) = \frac{pc}{eB} \approx 3 \times 10^{12} \left( \frac{pc}{\text{GeV}} \right) \left( \frac{B}{\mu\text{G}} \right) \text{cm}$$

= $10^{-6}$ pc

Microscale-Astrophysics of Galaxy Clusters
Cluster Shocks

Structure formation shocks have high Mach numbers (Miniati+ 2000, Ryu+ 2003, Pfrommer+ 2005, Skillman+ 2008)

Shocks classes:
- Internal $M \sim 4-5$
- External $M \geq 10$

Collisionless shocks dissipate into CRs (Krymsky 1977, Skadron+ 1977, Bell 1978, Balndford & Ostriker 1978)
Non-thermal Emission

Straightforward Predictions:

\[ p_{CR} p_{ICM} \]

\[ \pi^0 + \ldots \rightarrow \gamma \gamma + \ldots \]
\[ \pi^\pm + \ldots \rightarrow \mu^\pm + \ldots \rightarrow e^\pm + \ldots \]

i) gamma-ray emission

ii) radio emission

gamma-ray upper limits from
Fermi, H.E.S.S, MAGIC

Miniati 2003
Bullet Cluster at Radio WL
Bimodality in Cluster Diffuse Radio Emission

Brunetti et al. (2007)
What’s wrong?

Simulation results based on following simple assumptions:

A. Accretion shocks accelerate CR protons
B. Magnetic fields are seeded at high-z more or less uniformly
C. CRs diffusion negligible (CRs tied up to ICM by B)
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(A): Accretion shocks accelerate CR protons (?)

- SNRs
- Radio relics show that $e^-$ are accelerated at cosmic shocks
- Particle-in-Cell simulations indicate that at least relativistic collision-less shocks produce suprathermal particles even if initially unmagnetized (e.g. Spitsosky 2008)

CR are accelerated at filament termination shocks
Relic Radio Emission

Abell 3667

Infalling column of galaxies

Synchrotron shock

2 Mpc

Bown & Rudnick 2010

credits to M. Johnston-Hollitt
CRs from Galaxies

For example, Voelk et al (1996) find $P_{\text{CR}}/P_{\text{th}} \sim 5\text{-}10\%$

Bouwens et al 2010
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Bimodality in B-field

\[ j_{\text{synch}} \propto n_{\text{CR}}(E) \frac{B^2}{B^2 + B_{\text{CMB}}^2} \]

- non radio-halos GCs have \( \mu \text{G} \) magnetic fields (RM, from Clarke et al. 2001, 2004)

CR current, $j_{cr}$, drives a return current in the thermal plasma, $j_{th}$, that tends to cancel $j_{cr}$ itself.

\[ \tilde{E}' = \frac{\tilde{j}_{th}}{\sigma}, \]

\[ \sigma_{Spitzer} \approx 10^7 \left( \frac{T}{K} \right)^{3/2} \text{ S}^{-1} \]

\[ \frac{\partial \tilde{B}}{\partial t} = -c \tilde{\nabla} \times \tilde{E} \approx 10^{-16} \frac{G}{\text{Gyr}} \]
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Voelk et al (1996):

- fluctuations \( \frac{\delta B}{B} \sim 1 \) driven by galaxy motions
- fluctuations extend down to the gyration radius of CR particles, i.e.:

\[
r_g(p) = \frac{pc}{eB} \approx 3 \times 10^{12} \left( \frac{pc}{\text{GeV}} \right) \left( \frac{B}{\mu\text{G}} \right) \text{cm}
\]
However, this neglects damping of the waves by plasma effects, e.g. transit-time damping, cyclotron resonance, non-linear Landau damping...

For example during a merger when the turbulent motions are high, Brunetti & Lazarian (2007) estimate a cutoff of the power spectrum of the magnetosonic waves:

\[ \lambda_{\text{cutoff}} = \frac{1}{3} \text{kpc} \gg r_g \sim 10^{-9} \text{kpc} \]
After the merger has relaxed, the turbulence level decreases significantly and things get even worse, i.e. damping significant at even larger wavelengths.

At this two effects are important:

i) streaming of CRs generates the necessary scattering (Achterberg 1981, Foote&Kulsrud 1979, Yan&Lazarian 2008)

ii) mirroring from bent magnetic fields lines

(C:) CR diffusion negligibly small?
Rolling Flux-tubes
turbulent to streaming ratio

\[ \gamma_{tu} = \frac{u_{tu}}{u_{st}} \]
CR profile due to advection

\[ \eta(r) = \left( \frac{P(r)}{P_0} \right)^{\frac{2}{5}} \]
CR profile

\[ f_{CR} : x_1 \rightarrow x_2 \quad \rho_{CR}(x_1) \rightarrow \rho_{CR}(x_2) = \rho_{CR}(x_1) \left( \frac{P_2}{P_1} \right)^{1/\gamma} \]

\[ \frac{\rho_{CR}(x_2)}{\rho_{CR}(x_1)} = \left( \frac{P_2}{P_1} \right)^{1/\gamma} \]
CR transport model

\[ \frac{\partial \rho_{CR}}{\partial t} = \vec{\nabla} \cdot (\rho_{CR} \vec{u}_{CR}) \]

\[ \vec{u}_{st} = -u_{st} \frac{\vec{\nabla} \rho_{CR}}{\left| \vec{\nabla} \rho_{CR} \right|} \]

\[ \vec{u}_{ad} = -\kappa_{tu} \vec{\nabla} \ln \frac{\rho_{CR}}{\eta} \]

\[ \vec{u}_{si} = -\kappa_{di} \vec{\nabla} \ln \rho_{CR} \]

\[ \vec{u}_{CR} = \vec{u}_{st} + \vec{u}_{ad} + \vec{u}_{di} \]

\[ \kappa_{tu} = \frac{\nu_{tu}}{3} \]
CR Spatial Distribution

CR normalisation profile

$C(r)$

$r/r_c$

$\gamma_v = 30$

$\gamma_v = 10$

$\gamma_v = 3$

$\gamma_v = 1$
Gamma-ray, Synchrotron Emissivities

gamma ray emissivity

radio emissivity
Summary

A. Not yet in a position to rule out acceleration of CR protons at structure formation shocks

B. no problem with seeding the magnetic field

C. Assumption that CR diffusion in GCs is negligibly small is most likely an oversimplification. CR transport in ICM needs important revision, with essential input from both theory and simulations.

D. Radio halo emission powered by hadronic interactions switch-off timescales depend on streaming of CRs and magnetic field lines topology after the merger has settled