Non thermal phenomena in Galaxy Clusters

F. Vazza
M. Bruggen, G. Brunetti
C. Gheller, A. Bonafede, +....
Summary:

- Cosmic rays protons from shocks and AGNs in simulated clusters

- (spatial location of) Radio relics

- Work in progress
Radio halo and relic → relativistic electrons, $\sim \mu G$ magnetic field

Pseudo-pressure fluctuations → turbulence with $P_{\text{turb}}/nKT \sim 0.2-0.3$

Faraday Rotation from galaxies → $B(r) = 4.7 \mu G (n/n_0)^{0.5}$

+ UPPER LIMIT ON GAMMA EMISSION by FERMI: $<10^{42}$ erg/s (Ackermann et al. 2010)

+ INVERSE COMPTON EMISSION? very debated! (FuscoFemiano + 04, Vik + 2010)
MANY EXAMPLES!

Colors:
- X-ray

Contours:
- radio

MACS J0717.5+3745
- Bullet

A2744

MACS J0717.5+3745
- 500 kpc

A3667
**Numerical challenges**

"Design and architecture" problems

Challenge 1:
- RESOLUTION: 10kpc
  - (turbulence, shocks, interplay with AGN, galaxies...)

 Challenge 2:
- VOLUME (>100 Mpc)
  - (observations: ~50 "good" objects now, >10^2 in the near future)

"Methods and developments" problems

Challenge 3:
- ICM PHYSICS (run-time)
  - (e.g. CR, magnetic field, AGN, star formation, etc...)

Challenge 4:
- CR PROTONS PHYSICS (run-time)
  - (e.g. Coulomb losses, Fermi I & II, t_loss >> △t)

Challenge 5:
- CR ELECTRONS PHYSICS
  - (post-proc: most probably fine : t_loss < △t → Fokker Planck)
**Observations:**

RADIO RELICS provide evidence for relativistic ELECTRONS acceleration at shocks → much more PROTONS should be accelerated according to DSA

**Theory & simulations:**

MINIATI+02 (see also RYU+03, PFROMMER+06)

STRUCTURE FORMATION SHOCKS can inject CR protons with high efficiency (10-50% of thermal pool)
Modelling injection and feedback of Cosmic Rays in grid-based cosmological simulations: effects on cluster outskirts.

F. Vazza\textsuperscript{1,2*}, M. Brüggen\textsuperscript{1}, C. Gheller\textsuperscript{3}, G. Brunetti\textsuperscript{2}

**Two-fluid model**

Dorfi 1984; Bell 1987; Jones & Kang 1990; etc...

\begin{align*}
\frac{d\rho}{dt} + \rho \nabla \cdot u &= 0, \\
\frac{du}{dt} &= - \frac{1}{\rho} \nabla (P_g + P_c), \\
\frac{de}{dt} &= - \frac{1}{\rho} \nabla \cdot [(P_g + P_c)u] + \frac{1}{\rho} P_c \nabla \cdot u - \frac{S}{\rho}, \\
\frac{dE_c}{dt} &= -\gamma_c E_c (\nabla \cdot u) + \nabla \cdot (\kappa \nabla E_c) + S.
\end{align*}

In cosmology:

- Miniati 2003 (fixed grid)
- Pfrommer et al 2006 & Ensslin et al. 2007 (SPH)

**Ingredients:**

- Cosmic rays pressure
- Source term (e.g. shocks)
- Equation of state $P_c = (\gamma_c - 1)E_c$ with $\gamma_c = 4/3$
- Cosmic rays diffusion
1-D tests for validation: \( M = 1.5 \) to \( M = 5 \)

Injection of CR for increasing Mach

Efficiency from theoretical works

Diffusive shock acceleration ~works in supernovae
1-D tests for validation: SHOCK TUBE

Initial conditions:

LEFT: $P_{gas}=10, P_{cr}=6, dens=9$

RIGHT: $P_{gas}=1, P_{cr}=0, dens=1$

Acceleration efficiency $\eta$ at shocks $\sim 0.5\%$
We monitor the injection of energy across shocks at run time (velocity-jump or pressure-jump algorithm)
Average radial profiles of Mach number
Same IC as in Vazza+10
Max res = 25kpc

Run at Juropa / SP6-Cineca
10-20 % longer CPU time - 10% more data
See movie (injection from $z=0.6$ on)
Non radiative clusters:

\[ P_{\text{cr/nkT}} < 5\% \text{ (core) } P_{\text{cr/nkT}} < 10\% \text{ (R}_{200}\text{)} \]

Largest effects at \( R_{200} \)

Profile of CR to thermal pressure

\[ \gamma_{\text{eff}} = \frac{(\gamma_{P_g} + \gamma_{\text{cr}} P_{\text{c}})}{P_g + P_{\text{c}}} \]

\( \gamma = 5/3 \)
Cosmic rays enhance compressibility of the ICM at $R_{200}$.
X-ray lum. and SZ are affected by 10-20%.
(small but) opposite trends in density and pressure for our implementation of CR in ENZO and SPH results.
Baseline model of CR from shocks

+ New features:
  - cooling
  - Shock-reacc.
  - Coulomb & hadronic losses
  - AGN feedback: jets (kinetic) quasar (therm.) bubbles (buoy.)
Observed CHANDRA profiles vs cooling/jet/bubbles runs

Observed CHANDRA profiles vs cooling/quasar runs
“Best” models: bubbles – feedback:

- are created as evacuated blobs in pressure equilibrium
- filled with gas ($\Gamma = 5/3$) or a mixture with CR ($\Gamma_{cr} = 4/3$)
- Initial radius $r_b = 25 \text{kpc}/h$
- Injected energy $3/2 \ PV \sim 10^{59} \text{ erg per event}$

see also: Bruggen et al. 2005; Sijacki et al. 2008 (many others!)
“Best” models: Quasar - feedback:
- Thermal energy output drives a blast wave
- Mach number $\sim 5-10$
- Injected energy $\sim 10^{59}-10^{60}$ erg per event

see also: McCarthy+04, Sijacki+07, Teyssier+10 (many others!)
“Best” models: Jets – feedback:
- Kinetic energy output from bipolar jets
- Jet velocity ~ 600–800 km/s at 50kpc/h
- Injected energy ~ $10^{59}$ erg per event

see also: Gaspari+ 11, Dubois + 11 (+ many others!)
What is the CR output of each feedback mode?

Profile of CR pressure to thermal pressure in different modes

- pure cooling produces $P_{cr} \sim nkT$
- AGN feedback increases $P_{cr}/nkT$ with respect to non-radiative
What is the CR output of each feedback mode?

Hadronic collision → γ-flux (Pfrommer&Ensslin04)

the proton spectrum must be assumed: α~2.5 (M~3)

See also: Miniati03; Pinzke&Pfrommer10; Donnert+10
• How much turbulence does each mechanism generate?

We compare with upper limits from Sanders et al.10 (XMM)

The volumetric turbulence from mergers is dominant

jets/AGN/bubbles \rightarrow \text{within core}

jets/AGN \rightarrow 300 \text{km/s intermittent}

bubbles \rightarrow 70 \text{ km/s continuous}

jets \rightarrow \text{anisotropy}
Cosmic ray (protons) from accretion, merger and AGN driven shocks:

→ various “modes” of AGN feedback seem to solve the “cooling flow” problem

→ the different modes can produce nearly identical X-ray (thermal properties), but quite different NT-ones.

→ cooling-flow models are ALWAYS rejected

→ 3 times lower FERMI limits for γ-flux will limit power/duty cycle of jets/quasar mode

→ upper limits for turbulence <100km/s will limit bubbles density contrast
Why are central radio relics so rare?

F. Vazza\textsuperscript{1,2*}, M. Brüggen\textsuperscript{1}, R. van Weeren\textsuperscript{3}, A. Bonafede\textsuperscript{1}, K. Dolag\textsuperscript{4}, G. Brunetti\textsuperscript{2}

\textsuperscript{1}ASTRON,\textsuperscript{2}Erasmus University,\textsuperscript{3}University of Groningen,\textsuperscript{4}University of Bonn
34 clusters

$0 \leq z \leq 0.3$

Cumulative radial distribution of observed radio relics from the clusters centre

(it should be noted: not a complete distribution!)

NO relics inside 200 kpc!
- We measure Mach numbers in the 3D
- Flux of kinetic energy across the shock:

\[ F_{KE} = \frac{\rho u v_s^3}{2} \Delta S, \]

- Injection efficiency \( \eta(M) \)
- Different magnetic field profiles \( B(n) \)
- Compression factor \( R(n) \)

\[ P_{radio} = F_{KE} \cdot \eta(M) \cdot B(n) \cdot R(M) \]

(\text{Pfrommer+07, Hoeft+08, Skillmann+10})

\( B = \text{constant} \)
\text{No amplification}

\( B = B_0 \left( \frac{n}{n_0} \right)^{0.5} \)
\text{Isotropic amplification}

\( B = B_0 \left( \frac{n}{n_0} \right)^{0.5} \)
\text{radial amplification}
“Detectable” radio relics $\rightarrow$ relics catalogue

Radial distribution functions for Simulated radio relics (5 models)

Regardless of the assumed model for $B(n)$ and amplification, the lack of central relics is naturally explained if they originate from shocks.
3D profiles of average Mach number (weighted by all models)

3D profiles of energy flux across shocks (all models)

Dissipated kinetic power

Emission models

Kin
KJ
KJ_BtangledRadial, B_0 = 5 μG
KJ_BparallelRadial, B_0 = 5 μG
Radio-halos CANNOT be face-on relic (from shocks)

- We studied projection effects for each cluster

- If the relics is seen face-one, we would need a dynamical range of $\sim 100$ in radio images to detect emission

- The emission would have a very “flat” spectrum $\alpha \approx -1$
We suggest that:

1) shocks in the ICM dissipate most of the kinetic energy at R>0.2Rvir

2) geometry makes the probability of seeing a relics projected onto the centre very small, <1%

3) a relic seen face-on is too dim to be detected (Flux_{face-on} < 0.01-01 Flux_{edge-on})
Work in progress: VLA observation of Abell1497 (z=0.11)
(FV, Bonafede, Bruggen in prep..)

A1497:
z=0.11
$Lx \sim 3 \times 10^{44}$ erg/s

Radio observation:
VLA Array D
Observing time = 10 hr

A1497 with Chandra
(dirty image)
Work in progress: VLA observation of Abell1497 (z=0.11)
(FV, Bonafede, Bruggen in prep..)

A1497:
- $z=0.11$
- $L_{x} \sim 3 \times 10^{44}$ erg/s

Radio observation:
- VLA Array D
- Observing time = 10 hr
- Noise $\sim 70 \mu$J/beam

A1497 with Chandra
(image after cleaning...preliminary)
Work in progress: VLA observation of Abell1497 (z=0.11) (FV, Bonafede, Bruggen in prep..)

VanWeeren+10

CIZA J2242.8+5301

A1497
Radio beam

UV coverage

Real map relics/halos/radio galaxies

Map in Fourier space relics/halos/radio galaxies

Simulated Radio (Images)

Initial VLA configuration

$t=10$ hours

Radio beam
**Radio power in baselines**

**SIMULATED RADIO (IMAGES)**

- **Realistic** mock radio images (hopefully)
- Can process any 2D image from sim.
- Test models under realistic conditions
- Useful for proposal (hopefully)

**Cleaning (minor cycles)**

**Thermal noise added**

**Final cleaned image components + residual**
danke!