Radio Haloes in SPH Simulations

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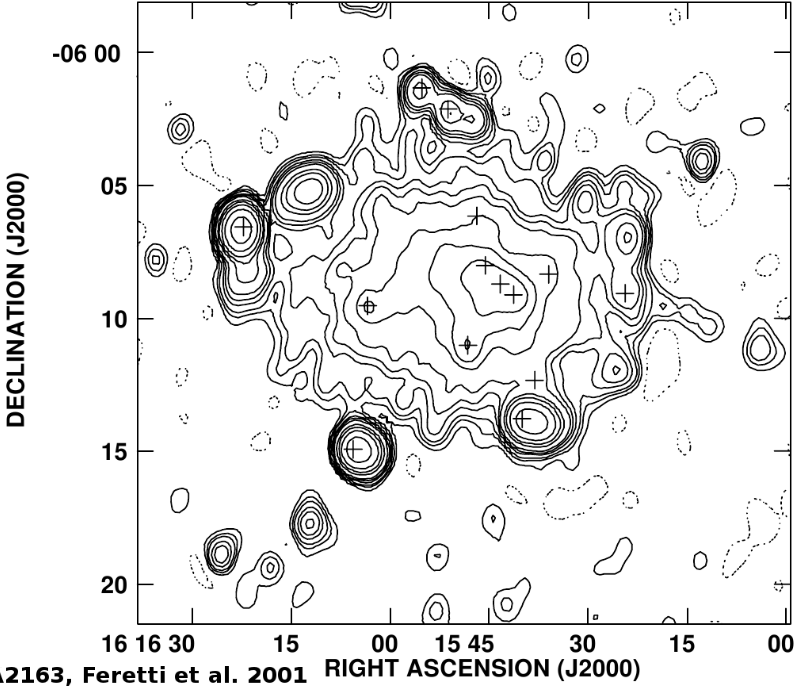


A2163, Feretti et al. 2001

Introduction

Radio Haloes

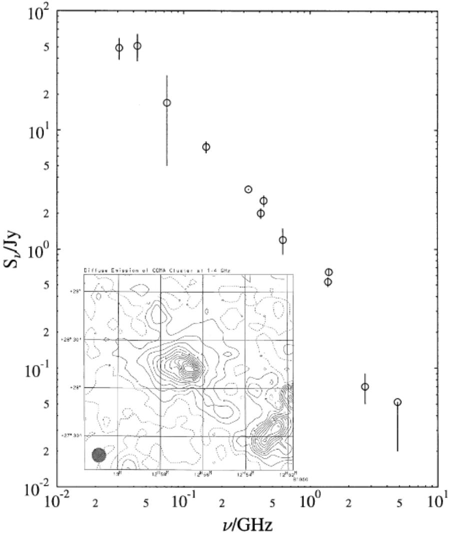
A1656 (Coma) : Deiss et al. 1997

Radio Haloes :

- steep spectrum radio sources
- synchrotron radiation from relativistic electrons ($\gamma \approx 10^4$) in *magnetic field* ($|B| \approx 1\,\mu G$)
- ≈ 50 radio haloes known today
- association with cluster merger
- 30 % in a complete sample

Why should we care ?

- probes microphysics of ICM: cosmic rays, *magnetic fields*, turbulence, thermal gas
- Main science goal of LOFAR

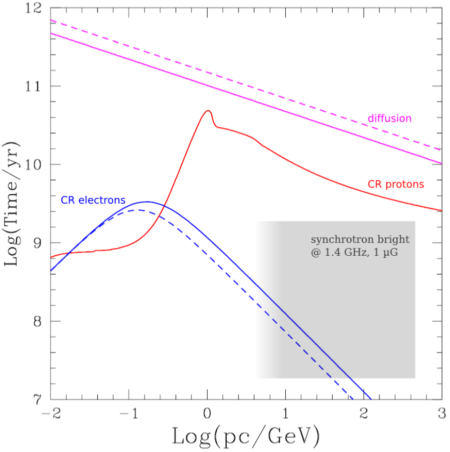


Introduction

The Diffusion Problem

Synchrotron Radiation from **CR electrons**

- losses:
  - synchrotron
  - inverse Compton
  - Coulomb scattering
- lifetime : $E/\dot{E} \approx 10^8$ yr
- local injection
- Random walk with Alvén speed (scattering , streaming inst.) effective speed $\approx$ 100 km/s
- $\Rightarrow$ diffusion length **10 kpc** (Jaffe 1977)



modified from Blasi et al. '07

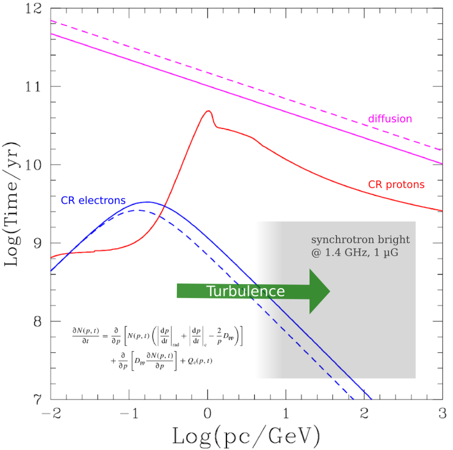
Introduction

Reacceleration Models

Solve by **stochastic reacceleration** of CR electrons (e.g.Petrosian 01):

- minimum of cooling processes at $\gamma \approx 200$
- cluster merger injects turbulence in the ICM
- CR electrons couples to MHD turbulence (TTD)
- induces non-linear momentum diffusion to higher energies

$\Rightarrow$ complex physics.
Put into astrophysical simulations



modified from Blasi et al. '07

Simulations & Reacceleration Models

- Implementation as a subgrid model to SPH simulations:
  1. Model SPH turbulent energy at the scale of the smoothing length.
  2. Specify sub-grid model of reacceleration.
  3. Numerically solve Fokker-Planck equation.
- Direct simulation of a cluster merger with MHD-GADGET (Dolag & Stasyzyn 2009).
- CR dynamics in postprocessing on 8 Million particles

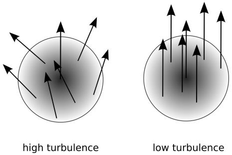
Simulations & Reacceleration Models

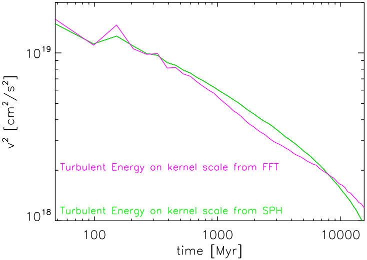
SPH Turbulence

Estimate turbulence as **RMS velocity dispersion** inside SPH kernel.

Idealised simulation:

- Ideal decaying subsonic turbulence
- Periodic box
- Homogeneous density field
- Map velocity to a grid
- Inspect power spectra from grids FFT
- Correct for CIC kernel & shot-noise





Donnert et al. in prep.

Simulations & Reacceleration Models

CR Dynamics

Fokker-Planck equation of isotropic CR electron spectrum N(p); Stochastic diffusion in momentum space

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial p}\left(N \cdot \left[\left|\frac{dp}{dt}\right|_{loss} - \frac{2}{p}D_{\mathrm{pp}}\right]\right) + \frac{\partial}{\partial p}\left(D_{\mathrm{pp}}\frac{\partial N}{\partial p}\right) + Q(p,t) - \frac{N(p,t)}{T_{esc}}$$

Competing Mechanisms in momentum space:

- losses: Synchrotron, IC, Coulomb $\left|\frac{dp}{dt}\right|_{loss}$
- systematic gain: $\frac{2}{p}D_{\mathrm{pp}}$
- stochastic gain (broadening): $\frac{\partial}{\partial p}\left(D_{\mathrm{pp}}\frac{\partial N}{\partial p}\right)$
- injection (power law), leakage (neglect): $+Q(p,t) - \frac{N(p,t)}{T_{esc}}$

Wave-particle coupling, Fermi 2 acceleration:
Model D_{pp} from turbulent energy

Simulations & Reacceleration Models

Resonant Coupling of Turbulence and CRs: TTD

Modelling of $\mathbf{D_{pp}}$ uncertain, ICM plasma physics not testable in laboratory. $\Rightarrow$ *least efficient model*

- Resonant wave-particle interaction:

$$\omega - k_{\|} v_{\|} - n\Omega = 0$$

- Fast magnetosonic (compression) waves: $\mathbf{k} \perp \mathbf{B}$, $n = 0$
- Assume turbulence is Kolmogorov: $W(\mathbf{k}) \propto k^{-5/3}$
- Formulate balance equation, CRe damp a fraction η:

$$\int E \left(\frac{\partial f(p)}{\partial t} \right) d^3 p = \eta \int d\mathbf{k} \Gamma(k) W(\mathbf{k})$$

- (Brunetti & Lazarian 2007):

$$D_{pp} \propto \eta \frac{E^2_{turb}}{scale \times c^2_{sound}}$$

Solve Fokker-Planck numerically ...

Simulations & Reacceleration Models

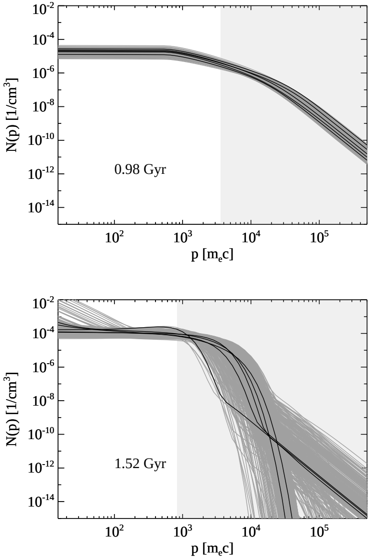
A numerical Fokker-Planck Solver

Solve Fokker-Planck for $> 10^6$ particles.

Advantage of Chang & Cooper 1970 Method:

- Unconditionally Stable
- Ensures Positivity
- Reproduces Equllibrium
- Logarithmic p Grid
- Large timesteps
- Small Number of gridcells (100)

Donnert et al. in prep.

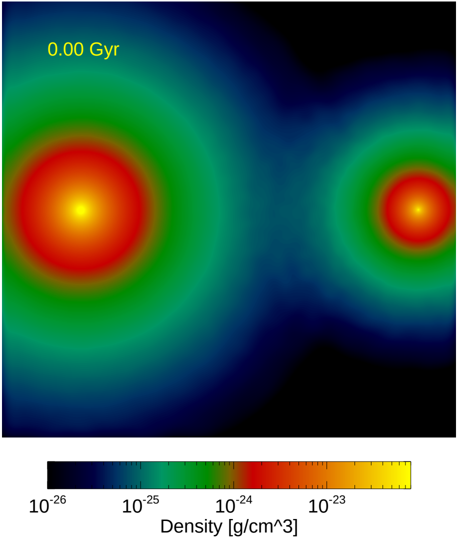


Simulations & Reacceleration Models

Cluster collision, Setup

Setup **Toymodel Cluster collision**:

- Masses $2 \times 10^{15} M_\odot$ and $5 \times 10^{14} M_\odot$
- 128^3 particles
- Zero energy orbit
- Heads on collision
- DM profile: Hernquist with scale 500 kpc
- Random magnetic field from vector potential with $5\mu G$ in the core.
- Radial decline of B like COMA (Bonafede et al. 2010)



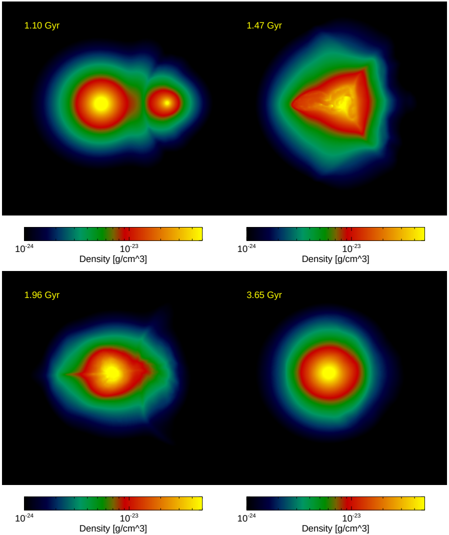
Simulations & Reacceleration Models

Cluster collision, Movies

Evolution

- Core of small cluster is disrupted
- Shock waves in directions of collision
- Amplification and decay of magnetic field
- Several DM core passages
- Turbulence "brightens" spectra

Movie

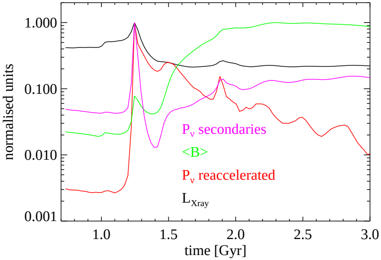


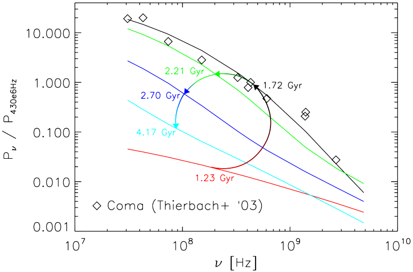
Run Fokker Planck code

- Constant injection of secondary CR electrons
- Momentum Grid of 100 points

Evolution

- Infall shock leads to first peak
- Small DM core stirrs big cluster
- Turbulence "brightens" spectra
- Radio Halo is switched off after 0.5Gyr
- Pure hadronic model $j_\nu \propto \rho^2 B^\alpha$





Summary

- Radio haloes are large scale, diffuse, non-thermal emission from galaxy clusters
- Reacceleration models light up clusters through turbulence
- First simulation of reacceleration in clusters.

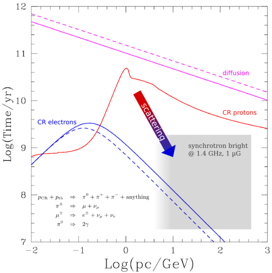
Reacceleration can not be neglected in radio halo models

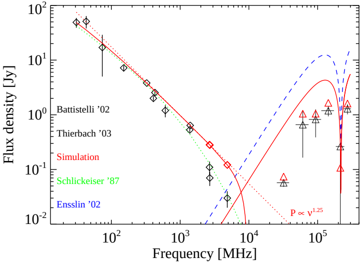
Thank You !

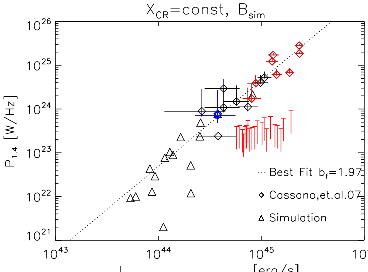
Introduction

Simple hadronic approaches

(Donnert et al. 2010a,b)







- CR proton population leads to *global* injection of CR electrons
- ?? Break in synchrotron spectrum ??
- ?? Bimodality ??

$\Rightarrow$ more complete models needed