Mem. S.A.It. Vol. 82, 623

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Simulating cosmic rays in turbulent galaxy clusters

J. Donnert[1], K. Dolag[1], R. Cassano[2], and G. Brunetti[2]

[1] Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, P.O. Box 1317, 85741 Garching, Germany, e-mail: `jdonnert@mpa-garching.mpg.de`
[2] Istituto di Radioastronomia Via Gobetti, 101 40129 Bologna, Italy

Abstract. We present results from numerical simulations of radio haloes, which are diffuse non-thermal sources in galaxy clusters. We use constrained cosmological MHD SPH simulations to compare in detail predictions and observations assuming hadronic models and physically motivated magnetic fields in clusters. This way we find a number of issues regarding size, non-thermal pressure and statistics in purely secondary models. We present our new Fokker-Planck code and study the evolution of non-thermal emission in a direct cluster simulation. Assuming a magneto-turbulent model for CR electron evolution we are able to show that re-acceleration indeed plays a significant role in the formation of radio haloes.

Key words. Galaxy: clusters

1. Introduction

The thermal emission from galaxy clusters is well understood through observations in the X-ray band. However, radio observations reveal Mpc-scale diffusion emission (radio haloes), which is attributed to relatistic electrons (CR electrons) interacting with the magnetic field frozen into the thermal plasma.The size and diffuse nature of radio haloes pose a problem to the injection and evolution of the underlying CR electron population. The CR electrons are believed to cool too quickly to produce a diffuse Mpc-scale source when injection happens locally by shocks and galactic outflows. Two classes of models have been proposed to circumvent this problem: The ubiquitous CR protons are long-living at the relevant energies and may diffuse throughout the whole cluster within a Hubble time. In *hadronic models* this may circumvent the cooling problem by in-situ injection of the CR electron population from hadronic interactions of CR protons with the ICM (e.g. Blasi & Colafrancesco 1999; Keshet & Loeb 2010). However, observations suggest a link between non-thermal emission and cluster mergers (e.g. Buote 2001; Cassano et al. 2010). In *re-acceleration models*, merger-induced turbulence accelerates a dormant population of mildly relativistic CR electrons to synchrotron-bright momenta (e.g. Brunetti & Lazarian 2007, and references therein).

2. Hadronic models in MHD simulations

There have been attempts to simulate radio haloes using a description of CR protons in

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Send offprint requests to: J. Donnert

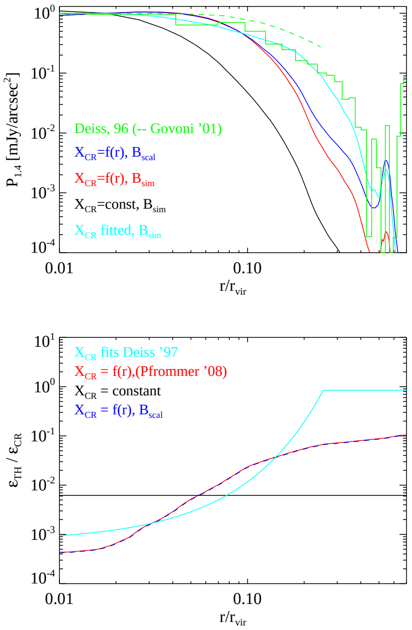

Fig. 1. Top: Normalised radial profile of the observed Coma cluster (green) and predictions for different hadronic models. Bottom: Radial profile of the energy density ratio of CR protons and thermal protons for the same models as on the left. (Donnert et al. 2010)

hydrodynamic cosmological simulations and hadronic models (Pfrommer et al. 2008). These simulations find a spatially increasing CR proton fraction relative to the thermal gas. For the first time we use constrained cosmological MHD simulations with GADGET-3 (Dolag & Stasyszyn 2009) to compare the non-thermal emission predicted from hadronic models with recent observations of radio haloes. We employed a self-consistent model of CR seeding and evolutionary processes (Donnert et al. 2009) to simulate the underlying magnetic field.

2.1. The Coma cluster

We study the non-thermal emission of the Coma cluster using a simulated cluster with comparable properties. We investigate four models for the spatial distribution of CR protons and magnetic fields: a model with constant CR protons density and self-consistent magnetic field from the simulation (Fig. 1, black), two models (red, blue) with spatially increasing CR proton density from Pfrommer et al. (2008) and with simulated and upscaled magnetic field and a fourth model to fit the observed brightness profile of Coma (Deiss et al. 1997). We find that the first three models fail in reproducing the non-thermal emission beyond 0.15 $r_{\rm vir}$ (Fig. 1). The fourth model, however, fits the profile by construction, but predicts up to 50% non-thermal pressure at $r > 0.2 r_{\rm vir}$, assuming realistic magnetic fields (Fig. 1), and this is in not observed.

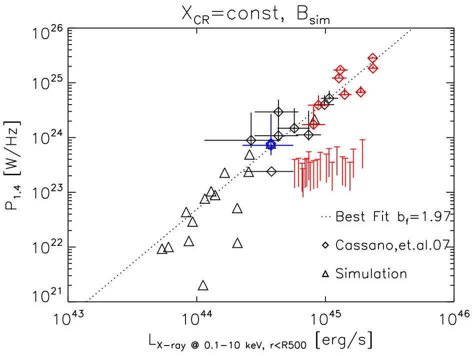

Fig. 2. Radio power at 1.4GHz of a sample of 16 simulated galaxy clusters from a secondary model (black triangles). Observed radio haloes (black diamonds, $z < 0.2$ red) from Cassano et al. (2006). Lower limits of observed non-detections (red lines) (Venturi et al. 2008).

2.2. Cluster sample

Radio haloes are found within 30% of all massive clusters, their synchrotron luminosity correlates with the soft X-ray luminosity (Bacchi et al. 2003; Cassano et al. 2006). In Fig. 2 we show the observed correlation and non-detections with the expected correlation from our simulations. The simulated clusters follow the observed correlation, but fail to reproduce the observed bimodality.

3. Simulating CR electrons

Given the above issues with purely hadronic models, a more complete description of the CR electron spectrum is required to incorporate the effects of turbulence and re-acceleration. The governing equation for the evolution of a population of CR electrons with number density n(**r**. **p**) is given by (Borovsky & Eilek 1986; Brunetti & Lazarian 2007):

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial p}\left(D_{\mathrm{pp}}\frac{\partial n}{\partial p} + H(p)n\right) - \frac{n}{T(t)} + Q(t), \quad (1)$$

where D_{pp} describes the resonant coupling of the spectrum to magnetosonic turbulence and $H(p)$ cooling processes due to synchrotron, IC and diffusion losses. This provides a lower limit to re-acceleration effects. To model these effects in our SPH simulations, we use a subgrid model of turbulence, where we estimate the local turbulent energy by the RMS velocity dispersion of the SPH particles with the kernel. Given the turbulent velocity v_{turb} on a scale h_{sml}, the magnetosonic re-acceleration coefficient can be estimated (Donnert et al. in prep.): $D_{\mathrm{pp}} \propto v_{\mathrm{turb}}^4/h_{\mathrm{sml}}/c_{\mathrm{sound}}^2$. We consider cooling by synchrotron and inverse Compton losses (e.g. Cassano & Brunetti 2005) and need solve the above Fokker-Planck equation for every particle in our simulation.

4. Fokker-Planck code

We have implemented the description of CR electrons given above in a new Fokker-Planck code to be run in postprocessing with MHD-GADGET-3. The code is written in C, fully MPI-parallel and reads GADGET format 2 input. We use the method of Chang & Cooper (1970) to solve the Fokker-Planck equation. This method ensures conservation of particle number, positivity and the correct stationary solution by construction on a logarithmic grid, being first-order accurate. It allows us to run the code on a relatively coarse grid (100 points) providing the speed-up needed for cosmological simulations. We implemented open and closed boundary condition following the description in Borovsky & Eilek (1986).

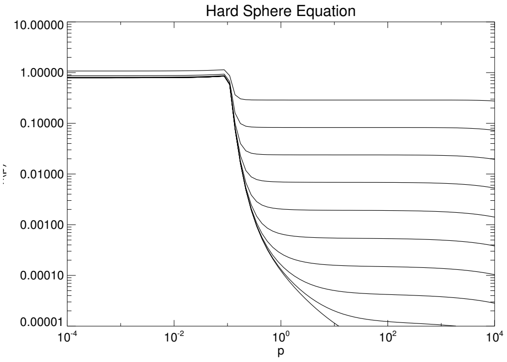

Fig. 3. Evolution of a CR population with $p = 0.1$ at $t = 0$ (compare to Park & Petrosian 1996).

We present solutions to the hard-sphere equation (see Park & Petrosian 1995, 1996) :

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial p}\left(p^2\frac{\partial n}{\partial p} - pn + n\right) - n + \delta(p - 0.1)\Theta(t)$$

as a test case. Starting from a delta distribution at $p = 0.1$. The code converges to the analytic solution. The calculation of the spectral evolution takes a fraction of a second. This is mandatory for us, as we need to calculate the evolution of more than 10^6 spectra for our simulation.

As a first application we use our Fokker-Planck code to follow the evolution of a CR electron population in a direct cluster collision using the MHD implementation in GADGET-3 (Dolag & Stasyszyn 2009) and a low viscosity scheme. We assume constant injection of a power-law spectrum at synchrotron dark momenta. The collision is set up with a total mass of $2.5 \times 10^{15} M_{\odot}$ and mass ratio of 1:4. We use 64^3 particles. Both cluster are put on a zero energy, heads-on orbit. The DM component is modeled as a Hernquist profile with a concentration parameter of 500 kpc. We initialise the magnetic field from a random vector potential on a grid, assuming a radial beta model, motivated from observations (Bonafede et al. 2010). We evolve the simulation for 4 Gyr, run our FKP code in postprocessing and project the synchrotron brightness for every particle.

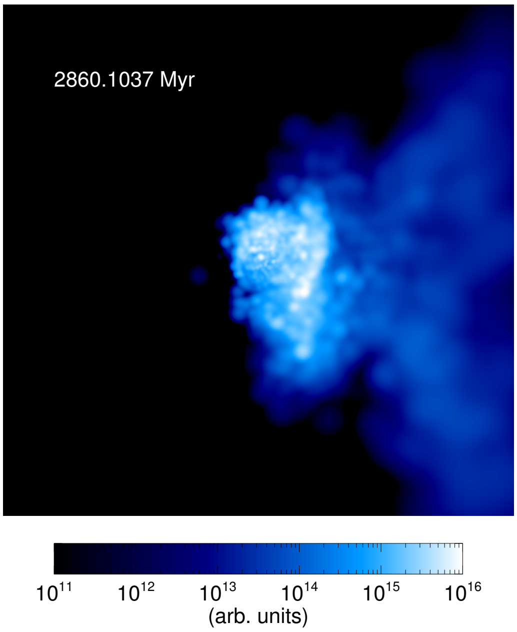

Fig. 4. Synchrotron emission of a direct cluster collision. CR electrons are followed by solving a Fokker-Planck equation numerically, assuming constant injection.

We find no emission before the cluster collision at around 1 Gyr, then emission from particles in the shock region at the contact zone of the clusters. Later we see (Fig. 4) emission in a $\approx$ 1 Mpc-sized region at the center of the merger.

5. Summary

We have presented a comparison of the non-thermal emission from hadronic models in simulated galaxy clusters. We find a number of issues related to pure hadronic models, in terms of size, non-thermal pressure and abundance of radio haloes. To investigate the validity of re-acceleration models we presented a Fokker-Planck code to follow a CR electron population in postprocessing to astrophysical SPH MHD simulations. This code is accurate, stable and fast enough to pursue this task even for large particle numbers. We show that turbulent re-acceleration of CR electrons plays an important role in the formation of radio haloes in cluster mergers.

Acknowledgements. J.D. thanks the SOC for the opportunity to present his work at the conference. K.D. acknowledges the support by the DFG Priority Programme 1177 and additional support by the DFG Cluster of Excellence "Origin and Structure of the Universe".

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