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Radio emission of galaxy clusters

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We use a simplified numerical model for the relativistic electron population originating from hadronic proton decays inside a galaxy cluster to calculate its characteristic radio synchrotron emission under the influence of strong accretion and merger shocks. Earlier investigations showed that during structure formation the ICM magnetic field can be substantially magnified. We therefore expect the cluster dynamics to manifest itself in the observable synchrotron emission. Comparison to observations will help us gain better insight into the physics of cluster formation.

1 Introduction

Large-scale magnetic fields are widely observed in galaxy clusters using Faraday rotation measurements and studies of X-ray and radio emission. Depending on the measuring technique and the location within the cluster their strengths vary from ~ 0.1 up to $10\,\mu$G in the cores of cooling flow clusters (Carilli & Taylor, 2002). While magnetic structures are common in galaxy clusters, radio halos are rare. There are strong hints that the appearance of radio halos is directly related to the dynamical state of a cluster as most of the observed clusters hosting a radio halo show signs of recent merger events (Feretti, 2005). The energetics of such core-core encounters is adequate to amplify the plasma magnetic field to the required level to explain the observations.

We seek to find the connection between merger events and their impact on the observable physical quantities of galaxy clusters, focussing on radio emission as a direct measure of the magnetic field strength of the ICM. For this purpose we perform numerical simulations of cosmological structure formation including merger processes. Our model for the relativistic electron population in the ICM was adopted from Enßlin et al., who developed a simplified formalism for the description of cosmic ray physics and the resulting radio emission (Enßlin et al., 2006).

2 Numerical model

Theoretical studies of high-energy relativistic electrons in galaxy clusters favour two distinct injection mechanisms: The first involves “primary electrons” originating from AGN activity that are subsequently spread throughout the cluster's atmosphere. Due to their short lifetime (about 10^8 yr) the electrons should be reaccelerated by turbulence or shocks in order to explain the spatial extent of radio halos (Brunetti et al., 2001).

A second population of “secondary electrons” is believed to result from inelastic collisions between CR protons and the thermal nuclei of the ICM followed by a subsequent charged pion decay (Dennison, 1980):

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu/\bar{\nu}_\mu \rightarrow \mathrm{e}^{\pm} + \nu_\mathrm{e}/\bar{\nu}_\mathrm{e} + \nu_\mu + \bar{\nu}_\mu\,. \quad (1)$$

In our model, we assume all synchrotron emitting electrons to be secondary, neglecting any contribution coming from the primary electron population. A detailed description of the analytical formalism for the treatment of CRs in the context of cosmological simulations can be found in Enßlin et al. (2006). In their work, the CRp momentum spectrum is approximated by a single power-law above the minimum momentum p_min:

$$f(p) = \frac{\mathrm{d}N}{\mathrm{d}p\mathrm{d}V} = C p^{-\alpha}\Theta(p - p_\mathrm{min}), \qquad \alpha = 2...3\,, \quad (2)$$

where $p = P_\mathrm{p}/(m_\mathrm{p}c)$ and p_min may correspond to proton energies of $\approx 1\,\mathrm{GeV}$. The normalization C ist determined by CR cooling processes (Coulomb losses and inelastic collisions) and injection processes. For the latter we adopted a very simplified model where we inject CRs with a fixed energy efficiency at structure formation shocks (assuming $\alpha = 2.3$ regardless of the Mach number of these shocks).

Starting from Eq. (2), expressions for the basic cosmic ray variables such as the energy density can be derived. Employing a steady-state approximation for the CR secondary electron spectrum and averaging over an isotropic distribution of electron pitch angles, the hadronically induced synchrotron emissivity j_ν at frequency ν and per steradian yields (Dolag & Enßlin, 2000)

$$j_\nu \;\propto\; \epsilon_\mathrm{CRe}\, B^{\alpha_\nu+1}\, \nu^{-\alpha_\nu}, \quad \text{where} \quad \alpha_\nu = \alpha/2. \quad (3)$$

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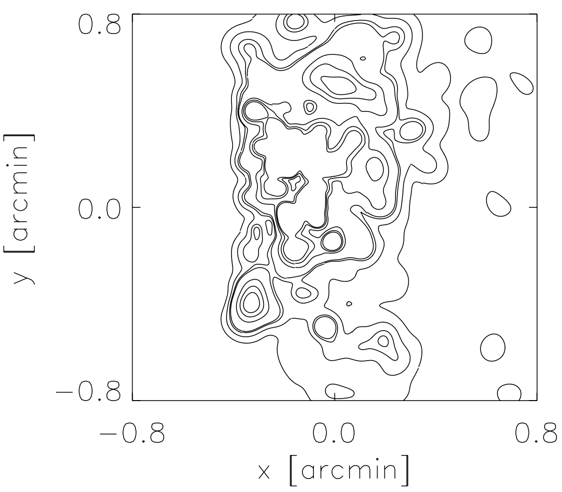

Fig. 1 Projected radio emissivity of a simulated galaxy cluster at $1.4\,\mathrm{GHz}$ and redshift $z = 0.3$. Contour levels are 0.1, 0.4, 0.8, 1.0, 3.0, 5.0 and 7.0 $\mathrm{mJy/arcmin^2}$.

To obtain a sample of magnetised galaxy clusters, we performed simulations of structure formation in a $\Lambda\mathrm{CDM}$ universe using the cosmological MHD code GADGET-2 (Springel, 2005). Non-adiabatic processes like radiative cooling and star formation were neglected. Furthermore, the magnetic field and CR physics were treated in two independent simulations of the same cluster.

In a last step we combined the obtained 3D-distributions of the magnetic field and the CR proton population to calculate the radio emission of the cluster according to Eq. (3).

3 Simulation results

Figure 1 shows a synthetic radio map of a galaxy cluster of mass $\sim 4\,10^{14}\,\mathrm{M_\odot}/h$ at $1.4\,\mathrm{GHz}$ for $z = 0.3$. Starting from a homogeneous seed field of $0.89\,10^{-2}\,\mu\mathrm{G}$ at redshift $z = 60$, the magnetic field strength has reached values ranging from $\sim 3\,10^{-6}$ to $3\,\mu\mathrm{G}$ in the presented snapshot. The strong amplification is due to the adiabatic compression and magnetic induction caused by accretion shocks and merger events.

The chosen value of the initial field represents an upper limit for seed fields, which have been tested to reproduce today's highest observed field strengths in numerical simulations of structure formation (Dolag et al., 1999).

Despite the crude assumptions of our model, we obtain reasonable values for the surface brightness of typical radio halos with a brightness of 7 $\mathrm{mJy/arcmin^2}$ in the center and 0.1 $\mathrm{mJy/arcmin^2}$ in the peripheral regions of Fig. 1. Observed clusters with radio halos like Coma show $\sim 3.5\,\mathrm{mJy/arcmin^2}$. However, with an extent of $\leq 300\,\mathrm{kpc}$ the size of our synthetic radio map is considerably smaller than that of typically observed radio halos ($\sim 1\,\mathrm{Mpc}$) possibly because of its relatively low mass.

4 Summary and outlook

We carried out MHD simulations of cosmological structure formation including the merging of galaxy clusters to obtain a sample of model clusters. In a post-processing procedure, we calculated the radio halo generated by secondary electrons resulting from hadronic collisions in the ICM. Assuming a CR injection from structure formation shocks in our simulations with $\alpha = 2.3$, we were able to reproduce the correct orders of magnitude for the surface brightness of radio halos typically found in galaxy clusters after merging.

We are currently improving our numerical model, including a more realistic shock model that will allow stronger CR energy injection at the cluster periphery due to strong accretion shocks (Pfrommer et al., 2005). Moreover, we wish to realize a parallel simulation of magnetic fields and CR dynamics in order to take their impact on thermal hydrodynamics into account.

Future comparisons of improved simulations with observations may shed light on the dynamical history of radio emitting clusters. Finally, we hope to reveal correlations of the radio emission with other diagnostics of cluster dynamics such as strong lensing and X-ray emission.

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