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Nonthermal radiation from groups and clusters of galaxies: Numerical simulation perspective

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Abstract. Recent growing observational evidences of nonthermal activities in the intra-cluster medium have raised several questions regarding the physical processes that dominate there. Several issues are still open: the mechanism responsible for the radio halos and relics, the properties of the magnetic field, the origin of observed radiation excesses in the hard X-ray and EUV bands as compared to what is expected from the thermal emission, and the role of non-thermal pressure component including contributions from cosmic rays (CR) and magnetic fields. In this contribution we present results from a hydro + N-body cosmological simulation which includes magnetic field and direct treatments of CR protons, primary and secondary electrons - *i.e.* injection and diffusive acceleration at large scale structure shocks as well as interactions with ambient matter and radiation, and mechanical and radiative losses.

CR protons thus produced turn out to provide a potentially substantial fraction of the total pressure inside clusters of galaxies. The corresponding γ-ray flux should be readily observable by GLAST for nearby, large clusters, allowing a direct estimate of the CR content there. Such CR protons generate a population of secondary electrons through p-p inelastic collisions. Synchrotron emission from secondary electrons could account for many observed properties of radio halos, provided a magnetic field $\sim 3\mu$ G in a Coma-like cluster. Radiation power emitted from primary electrons directly injected at accretion shocks is comparable to that of the large radio relics, although low resolution effects limit our ability to reproduce all of the observed spectral properties.

1 Introduction

The large scale structure of the Universe is thought to form due to gravitational instability of "small" initial density perturbations in the otherwise uniform primordial plasma(e.g., Bahcall, 1999). Although it is most prominent as X-ray clusters of galaxies, nonthermal radio emission from these structures has recently become a much more common feature than it was thought before (Liang et al., 2000). Clusters have been proved to be invaluable for investigations of cosmological interests. The statistics of cluster masses and their dynamical properties, including, for instance, the relative proportions of baryonic and non-baryonic matter, are commonly used to test basic cosmological models (e.g., Bahcall, 1999). The existence of cosmic ray (CR) particles in at least some clusters of galaxies has been acknowledged for a while by several observations. They include the observations of radio halos (e.g., Giovannini et al., 1991) and radio relics (e.g., Deiss et al., 1997) due to synchrotron emission by CR electrons. Magnetic fields are commonly observed in the large scale structure (e.g., Kronberg, 1994; Clarke et al., 2001). They may have been amplified from week seed magnetic field in the course of structure formation up to μG level in clusters and, perhaps, also in filaments and super-clusters (Kulsrud et al., 1997; Ryu et al., 1998). Signatures of CRs are also hinted by radiation excesses with respect to the thermal emission in the hard X-ray (HXR) (Fusco-Femiano et al., 1999, e.g.,) band and possibly in the extreme ultra-violet (EUV) band (e.g., Lieu et al., 1996) due to inverse-Compton scattering of cosmic microwave background photons by CR electrons. CR protons produce γ-rays through π^0 decay following inelastic collisions with gas nuclei. While such γ-rays from clusters have not yet been detected (Sreekumar et al., 1996), they are expected to be detected by the next generation of γ-ray observatories such as GLAST.

The likely existence of strong "accretion" shocks several Mpc's from cluster cores developed in the course of the large-scale structure formation has been recognized for a long time (Ryu & Kang, 1997). Such shocks are responsible for the heating of the ICM up to temperatures of order $10^7 - 10^8$K. When cluster mergers take place, "merger" shocks associated with individual cluster form in direct response to the merging process (e.g., Markevitch et al., 1999). However, cos-

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mic structure formation simulations have demonstrated that, in addition to accretion shocks and discrete merger shocks, there exist somewhat weaker shocks "internal" to the ICM that are very common and complex (Miniati et al., 2000). Because shock waves in the presence of even modest magnetic fields are sites of efficient CR acceleration (*e.g.,* Drury, 1983), the structure formation might imply copious generation of high energy particles, including both protons and electrons. In fact, according to diffusive shock acceleration theory (Drury, 1983), as much as several tens of percent of the kinetic energy of the bulk flow associated with the shock can be converted into CR protons (Berezhko & Ellison, 1999).

In this paper we investigate the acceleration of CR particles at cosmological shocks by means of numerical calculations. For the first time, the CR population is *directly* included in the computation with particle injection, acceleration and energy losses calculated in accord with the properties of the local environment in which the particles are propagating. We note that there are other sources of CRs in clusters such as active galaxies (Enßlin et al., 1997). However, we do not attempt to include them in our current simulations, since our goal is to understand the role of cosmological shocks.

2 Numerical Simulation

The formation of the large scale structure is followed numerically by means of an Eulerian "TVD" hydro + N-body cosmological code (Ryu et al., 1993). For simplicity we explore a standard cold dark matter (SCDM) model characterized by the following parameters: *rms* density fluctuations on a scale of 8 h^{-1}Mpc to be defined by $\sigma_8 = 0.6$, spectral index for the initial power spectrum of perturbations n = 1, normalized Hubble constant $h \equiv$ H$_0$/(100 km s^{-1} Mpc^{-1}) = 0.5, total mass density $\Omega_M = 1$, and baryonic fraction $\Omega_b = 0.13$. We select a cubic comoving region of (50 h^{-1}Mpc)^3 and use 256^3 cells for baryonic matter and 128^3 dark matter particles. More detailed discussion regarding the cosmological model and numerical resolution issues can be found in Miniati et al. (2001a,b).

The CRs are evolved by our new COSMOCR code (Miniati, 2001), which computes the injection and acceleration of primary electrons and ions at shocks, production of secondary electrons in p-p inelastic collisions as well as radiative and mechanical losses of all components during spatial transport. Injection of primary CRs protons follows the thermal leakage model (*e.g.,* Kang & Jones, 1995) which results in a fraction $\eta_{inj} \simeq 10^{-4}$ of the incoming flux at the shock surface, $(\rho v)_{shock}$, being converted into CR particles. As for the injection of CR electrons, which is a physically much more complex mechanism, we simply assume that the number of injected particles amounts to a fixed, but adjustable fraction $R_{e/p} \sim 0.05 - 0.1$ of the injected protons (Mueller & et al., 1995). The energy distribution of both nonthermal populations are computed in the test particle limit of diffusive shock acceleration theory: thus a power-law in momentum space with log-slope $q = 3r/(r-1)$ where r is the shock compression ratio. Secondary electrons, on the other hand, are produced according to the collision rate of CR protons with the thermal nuclei of the intergalactic medium. They also are distributed at creation as power-law in momentum but with a log-slope determined by the properties of the parent CR proton distribution and the dominant energy loss mechanism at a given momentum. These power-law distributions extend up to $\sim 2 \times 10^2 \mathrm{GeV/c}$ for electrons and up to $\sim 10^6 \mathrm{GeV/c}$ for protons. Electrons with still higher energy are not relevant for this study and we expect that, in the test particle limit adopted here (Jones et al., 2001), the proton component above $10^6 \mathrm{GeV/c}$ to contribute negligibly. It turns out that for particles in the included energy ranges spatial transport is completely dominated by advection - as opposed to diffusion - making their numerical treatment computationally cheaper (Jones et al., 1999; Miniati, 2001). Finally the magnetic field is generated at shocks according to the Biermann battery mechanism and evolved thereafter as a passive quantity (Kulsrud et al., 1997).

3 Results

Once the simulation was carried out, collapsed objects such as groups and clusters of galaxies were identified within the computational volume with a procedure outlined in Miniati et al. (2000). Global properties of these objects, including the temperature T_x within a central region of 0.5 h^{-1}Mpc radius, the thermal and CR pressure, the emissivity at various wavelength and due to various physical mechanisms were computed thereafter (Miniati, 2000) and are discussed below.

3.1 Protons

Fig. 1 shows the ratio of CR to thermal pressure as a function of the central temperature, T_x, of the groups and small clusters produced during the simulation. These results indicate that a fraction between a few and up to several tens of percent of the total pressure in the intracluster medium could be borne by CR protons. Given the uncertainties in the assumed particle acceleration model and the numerical calculation, the result is to be taken as a qualitative estimate of the possible dynamical role of CRs. A few feature stand out from the plot. We note a large spread in the ratio P_{cr}/P_{th} even for objects of the same temperature. Although the plotted values are affected by numerical error, the spread is most probably a true reflection of the different "shock histories" undergone by the different groups/clusters. In addition we notice a slight trend on average of the ratio P_{cr}/P_{th} to decrease with the temperature T_x. This is due to both the larger adiabatic compression suffered by larger objects (which favors thermal over non-thermal pressure); and to the fact that with the adopted injection model the postshock ratio P_{cr}/P_{th} is larger for slower accretion flows which are more likely to occur in smaller (*i.e.* lower temperature) objects.

CR protons in the intracluster medium undergo inelastic p-p collisions with the thermal nuclei there. As a result, neutral

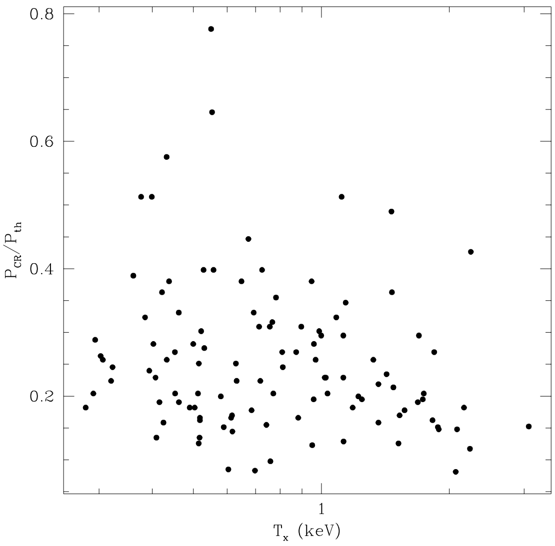

Fig. 1. Ratio of CR to thermal pressure averaged over the group/cluster volume within 0.5 h^{-1}Mpc plotted as a function of group/cluster core temperature.

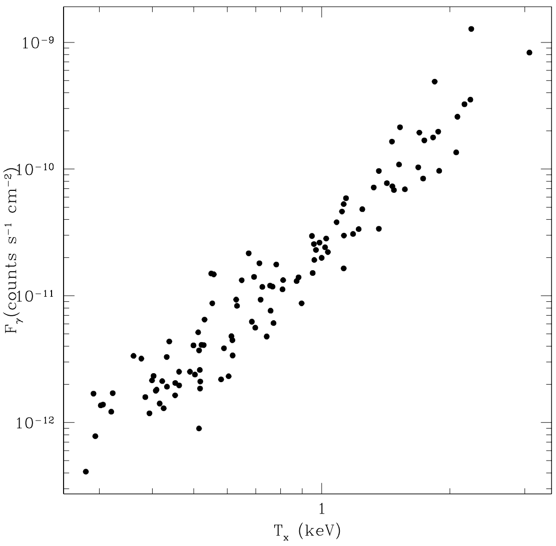

Fig. 2. γ-ray flux as a function of group/cluster core temperature.

pions are created which subsequently decay into γ-rays, thus providing an observational means to probe the CR content of the intracluster medium. In Fig. 2 we plot the expected γ-ray flux as a function of the temperature T_x of each group/cluster. The plot can be fitted well by the following power-law

$$F_\gamma = 7.4 \times 10^{-9} \left(\frac{T_x}{6.72\mathrm{keV}}\right)^{2.95} \mathrm{counts\ s^{-1}\ cm^{-2}}. \qquad (1)$$

Because of the limited computational volume, the temperature of the collapsed objects extends only up to a few keV. However, assuming the scaling law (1) can be extrapolated beyond this temperature limit, our simulation predicts a γ-ray flux above detection threshold of GLAST for nearby clusters such as Coma, Perseus and perhaps even the Virgo-M87 system (see Miniati, 2000; Miniati et al., 2001b, for detail). The advent of these observations will mark a very important step in our study and understanding of the physics of the intracluster medium.

3.2 Electrons

In this section we briefly compare the non-thermal radiation detected in clusters of galaxies in the radio, EUV, and hard X-ray (HXR) with the emission properties of CR electrons produced at cosmological shocks associated with large scale structure formation. We compute the following emissivities from CR electrons: radio synchrotron at 33, 74, 330 and 1400 MHz, inverse-Compton emission in the two HXR bands 20-80 and 0.13-100 keV, respectively, and in the EUV band 65-248 eV. We consider an emitting volume centered at each cluster within a radius of 1.3 h^{-1}Mpc. The temperature dependence of the emissivity, J, at various wavelengths is evaluated by fitting it to the following power-law,

$$J = K \left(\frac{T_x}{6.72\mathrm{keV}}\right)^{\phi}. \qquad (2)$$

where K and ϕ are the fitting parameters. The best fit parameters are then retrieved by a least χ^2 analysis. Our results are summarized in table 1.

Miniati (2000) and Miniati et al. (2001a) carried out detailed comparisons between the reported values of the non-thermal emission detected from observed clusters in the EUV and HXR bands with the prediction of the present numerical model. The purpose of this comparison is to evaluate the viability of the model, according to which the reported non-thermal emission would be produced by CR electrons produced during formation of the large scale structure, *i.e.* of cosmological origin. Once again this comparison requires one to extrapolate the emission values appropriate for the observed clusters beyond the temperature range probed by the simulation. Once the extrapolation is carried out based on table 1, we find that both primary and secondary CR electrons associated with the cosmic structure formation account at most for only a small fraction of the HXR and EUV excesses reported in the literature[1]. The discrepancy is about

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[1] The only exception is the EUV flux detected from Coma cluster by Bowyer et al. (1999).

Table 1. Fitting parameters for inverse Compton emission and synchrotron emission from groups/clusters as a function of their gas temperature T_x (cf. equation [2]). For the values reported for primary electrons $R_{e/p} = 1$ is assumed.

	secondary e$^-$		primary e$^-$	
Energy Band	K	ϕ	K	ϕ
	(erg s^{-1} cm^{-2})		(erg s^{-1} cm^{-2})	
F_{ic}HXR (20-80 keV)	2.8×10^{-13}	2.9	2.0×10^{-11}	1.5
F_{ic}HXR (0.13-10^2 keV)	7.0×10^{-12}	2.9	9.0×10^{-10}	1.9
	(erg s^{-1})		(erg s^{-1})	
L_{ic} EUV (65-248 eV)	2.2×10^{41}	2.9	3.8×10^{43}	1.9
	(W Hz^{-1})		(W Hz^{-1})	
$P_{1.4\mathrm{GHz}}$	6.3×10^{23}	4.2	7.3×10^{25}	2.6
$P_{330\mathrm{MHz}}$	2.4×10^{24}	4.1	2.1×10^{26}	2.6
$P_{74\mathrm{MHz}}$	1.2×10^{25}	4.2	7.4×10^{26}	2.7
$P_{31\mathrm{MHz}}$	2.9×10^{25}	4.2	1.6×10^{27}	2.8

one order of magnitude or more. Since our calculation is based on the assumption that an already significant fraction of the ram pressure associated with the shock flow is converted into CRs, cosmological CR electrons accelerated by the processes considered in our model are most probably *not* responsible for the reported detection of EUV and HXR radiation excesses.

On the other hand, radio emission predicted from our numerical model is much closer to the observational data. In particular, emission from secondary CR electrons resembles several general properties observed in radio halos, including the recently found $P_{1.4GHz}$ versus T_x relationship (Liang et al., 2000), which is given in table 1, the morphology and polarization of the emitting region and, although marginally, even the spectral index (Miniati, 2000; Miniati et al., 2001a). This result depends obviously on the properties of the intracluster magnetic field, in particular its strength as a function of the group/cluster size. Such properties have not been determined observationally as yet, although we know that magnetic field in the intracluster medium could range between a few 0.1μG to several μG. Our simulation indicates that, although not fully resolved, the magnetic field strength scales roughly as $T_x^{0.7}$, as expected from energy conservation and flux freezing compression arguments. The field normalization is arbitrary in the simulation, however, and we have chosen it so that for a Coma-like cluster the average magnetic field is about 3 μG.

`\balance` In addition, we find that radio synchrotron emission from primary electrons is large enough to power extended regions of radio emission resembling radio relics observed at the outskirts of clusters. Moreover, morphology and polarization fraction computed in these regions are comparable to those observed in radio relics. The spectral index inferred from the simulation is typically flatter than observed in radio relics, however, although this outcome could be due to limited spatial resolution as discussed in Miniati et al. (2001a).

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