Evolution and Properties of the Intracluster Medium in the Presence of Cosmic Ray Sources

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Abstract

There are lines of evidence that the intracluster medium is permeated by strong magnetic fields and filled with a large number of cosmic rays as the interstellar medium. Here we report the study of dynamical roles of such nonthermal components on the evolution and properties of the intracluster medium, focusing on cosmic rays. N-body/hydrodynamic simulations for the large scale structure formation of the Universe have been performed, where cosmic rays were deposited from individual sources such as radio galaxies, and their dynamical effects were followed explicitly. The additional pressure due to the deposited cosmic rays slows down the growth of the large scale structure. It also reduces the temperature, mass, and luminosity of X-ray clusters/groups. The quantitative results are presented.

1. Introduction

Clusters of galaxies have the intracluster medium (ICM), which actually dominates in baryonic mass over the stars in galaxies. Recently, it has been recognized that in the ICM, magnetic fields and cosmic ray (CR) particles are important in the overall energetics, in the overall pressure, and in the emission. Rather strong magnetic fields of $5-10\mu$G were detected through rotational measures [1]. A number of clusters of galaxies have been found with diffuse synchrotron radio halos and relic sources [3] or/and with excess EUV and hard X-ray radiations [4] from CR electrons. Although CR protons in the ICM have yet to be confirmed by observations, there may very well exist CR proton populations whose pressure is comparable to the gas thermal pressure. Radio galaxies and cosmological shock waves are likely to provide the main sources for both magnetic fields and CRs [2,5]. The total "nonthermal" pressure of these components would range probably from 1/10 up to equipartition of the thermal pressure of gas.

In this contribution, we study the dynamical importance and influence of

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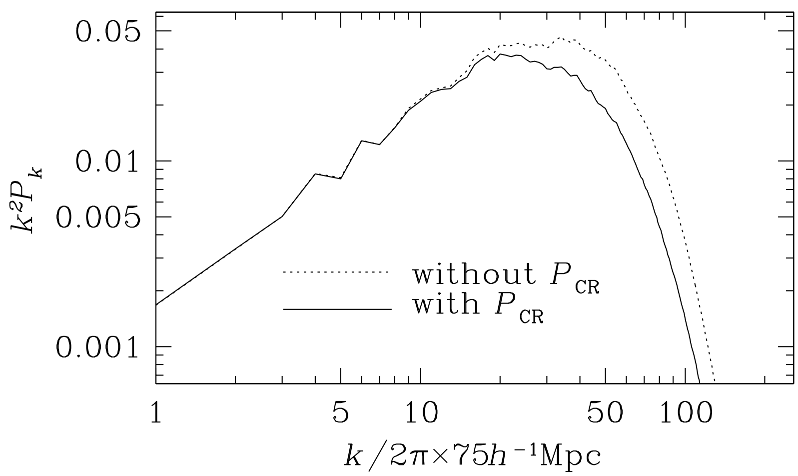

Fig. 1. Power spectrum of gas density perturbations at $z = 0$ without (dotted line) and with (solid line) CR deposit from sources.

the nonthermal component, focusing on CR protons which are modeled to have been deposited to the ICM from sources formed during the large scale structure formation in the Universe.

2. Simulations

The simulations employed the ΛCDM cosmology with the following parameters: $\Omega_{BM} = 0.043$, $\Omega_{DM} = 0.227$, $\Omega_\Lambda = 0.73$, $h \equiv H_0/(100$ km/s/Mpc$)$ $= 0.7$, and $\sigma_8 = 0.8$. A cubic region of size $75h^{-1}$ Mpc at the current epoch was simulated inside a computational box with 512^3 gas, CR and gravity cells and 256^3 dark matter particles, allowing a spatial resolution of $146h^{-1}$ kpc. Two simulations were done, one with CRs included and the other without CRs.

The equation for the CR pressure was solved explicitly, in addition to the standard set of equations for dark matter and gas. It was assumed that the sources, which deposit CRs into the ICM, form at 40 different epochs after the redshift $z = 10$, if the following criteria are satisfied in each grid cell

$$M_{gas} \geq \frac{4 \times 10^{10}}{(1+z)^{1/5}} h^{-1} M_\odot, \quad \frac{\partial u_k}{\partial x_k} < 0, \tag{1}$$

where M_{gas} is the total gas mass inside the cell. It was further assumed that each source ejects the following amount of CR energy into the ICM

$$E_{CR} = 3 \times 10^4 h^{-1} M_\odot \times c^2. \tag{2}$$

Note that at $z = 0$ this translates into the CR efficiency, $E_{CR}/M_{gas}c^2 = 7.5\times10^{-7}$. With the above model for CR deposit, the CR energy density in the ICM becomes $\sim 1/2$ of the gas thermal energy density at $z \sim 1$ and stays constant afterwards.

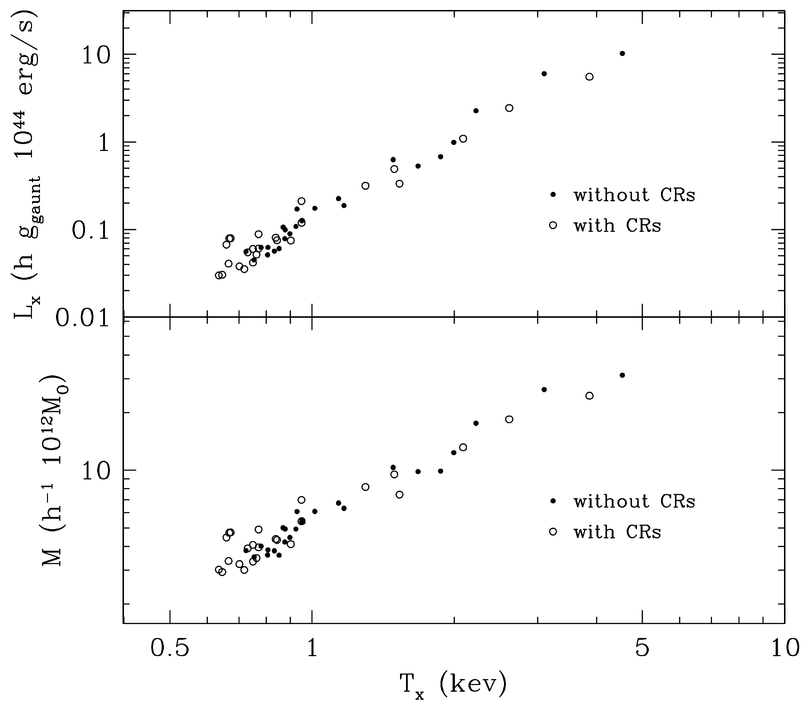

Fig. 2. X-ray luminosity-temperature relation (upper panel) and mass-temperature relation of 25 hottest clusters/groups in the simulations without CRs (filled circles) and with CRs (open circles).

3. Results

The global effect of CRs on the growth of the large scale structure is exhibited in Fig. 1. With $E_{CR} \sim 1/2E_{th}$ on average, the power of density perturbation was decreased by $\sim 50\%$ at the present epoch on the cluster scale of $\sim 1h^{-1}$ Mpc. However, the structures of scales larger than the cluster scale have been less affected, since the sources form mostly at the highest density peaks within clusters/groups.

In order to examine the dynamical effect of CRs on individual clusters/groups of galaxies, we identified them in the simulation data and calculated their properties, such as X-ray luminosity, L_x, gas mass, M_{gas}, temperature, T_x, gas thermal energy, E_{th} and CR energy E_{CR}. Fig. 2 plots the $L_x - T_x$ and $M_{gas} - T_x$ relations for clusters without and with CRs. The slopes of the relations do not change noticeably. However, CRs reduce L_x, M_{gas}, and T_x of identified clusters. As a result, the positions of individual clusters are shifted to the lower left along the $L_x - T_x$ and $M_{gas} - T_x$ relations.

Quantitative estimates of changes in these cluster properties can be made from Fig. 3, which shows the ratios of L_x, M_{gas}, and T_x for the same clusters without/with CRs, as a function of E_{CR}/E_{th}. Here, E_{th} is the gas thermal energy of clusters with CRs. Clusters have the values of E_{CR}/E_{th} between 0.1 to 2 due to statistical fluctuation of CR sources. In the clusters with $E_{CR}/E_{th} \sim 1/2$, we

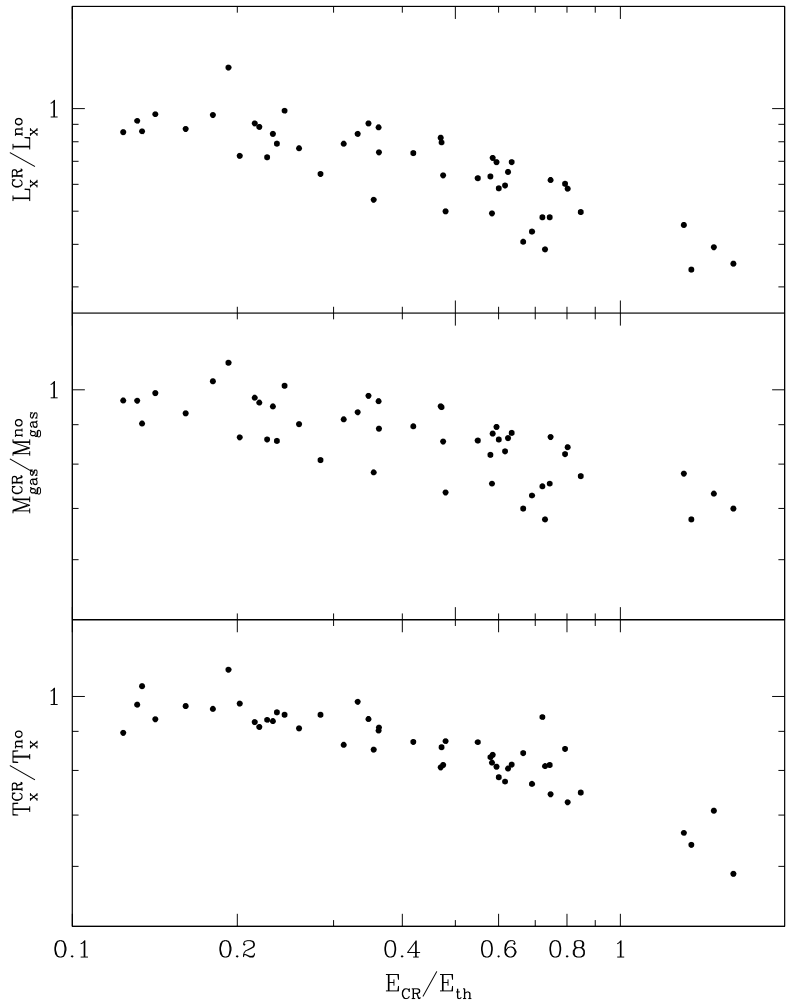

Fig. 3. Ratios of X-ray luminosity (upper panel), mass (middle panel) and temperature (lower panel) for the same clusters/groups but with/without CRs, as a function of the ratio of CR to gas thermal energies. 50 hottest clusters/groups of galaxies are shown.

can see that M_{gas} and T_x are reduced by $\sim 15\%$ due to CRs, while L_x is reduced by $\sim 30\%$.

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1. Clarke, T. E., Kronberg, P. P. & Böhringer, H. 2001, ApJ, 547, L111
2. Enßlin, T. A., Biermann, P. L., Kronberg, P. & Wu, X.-P. 1997, ApJ, 447, 560
3. Giovannini, G. & Feretti, L. 2000, New Astronomy, 5, 335
4. Lieu, R., Mittaz, J. P. D., Bowyer, S., Lockman, F. J., Hwang, C.-Y. & Schmitt, J. H. M. M. 1996, ApJ, 458, L5
5. Ryu, D., Kang, H., Hallman, E. & Jones, T. W. 2003, ApJ in press (astro-ph/0305164)