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Cosmic Rays Accelerated at Cosmological Shock Waves

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Abstract. Based on hydrodynamic numerical simulations and diffusive shock acceleration model, we calculated the ratio of cosmic ray (CR) to thermal energy. We found that the CR fraction can be less than ~ 0.1 in the intracluster medium, while it would be of order unity in the warm-hot intergalactic medium.

Key words. Cosmic rays—large-scale structure of universe—methods: numerical—shock waves.

1. Introduction

During the formation of large-scale structure of the universe, matters condense into structures such as cluster of galaxies, filaments and sheets (Springel *et al.* 2006). The temperature of gas in the intracluster medium (ICM) is above 10^7 K, while it is in the range of 10^5–10^7 K in filaments and the outskirt of clusters, i.e., the so-called warm-hot intergalactic medium (WHIM) (Cen & Ostriker 1999). Cosmological shocks are induced abundantly around and inside structures as a consequence of accretion, merger and turbulent flow motions. They are mostly responsible for the heating of the intergalactic medium (IGM). At the same time, cosmological shocks accelerate a large amount of cosmic rays (CRs) (Kang & Jone 2005; Ryu *et al.* 2008). Observationally, the non-detection of γ-ray from the ICM constrains the fraction of CR energy to be less than ~ 0.1 (Reimer *et al.* 2003). We theoretically calculated the ratio of CR to thermal energy in the ICM and WHIM based on numerical simulations and diffusive shock acceleration (DSA) model.

2. Simulations

The results are based on simulations that has been presented in Cen & Ostriker (2006). The simulations include radiative processes of heating/cooling and galactic superwind feedback. The WMAP1-normalized ΛCDM cosmology was employed with the following parameters: $\Omega_b = 0.048$, $\Omega_m = 0.31$, $\Omega_\Lambda = 0.69$, $h \equiv H_0/(100\ \text{km s}^{-1}\ \text{Mpc}^{-1}) = 0.69$, $\sigma_8 = 0.89$, and $n = 0.97$. A cubic box of comoving size $85h^{-1}$ Mpc was simulated using 1024^3 grid zones. The details of shock wave identification are described in Kang *et al.* (2007).

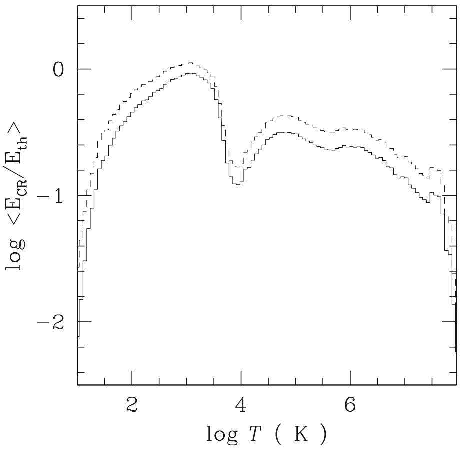

Figure 1. The averaged ratio of CR to thermal energy in the IGM of different temperature at $z = 0$. The dashed and solid lines correspond to different CR acceleration efficiencies.

3. Results

In clusters, weak shocks are energetically important and the CR acceleration efficiency is low. On the other hand, in filaments and outskirts of clusters, shocks are stronger and so the acceleration efficiency is higher. Thus, the CR fraction is small for the ICM, but high for the WHIM, as shown in Fig. 1. By integrating from $z = 5$ to $z = 0$, we calculated the total kinetic energy that passed through all the shock waves and thus the total CR and thermal energies dissipated into the IGM. The ratio of the total CR to thermal energy is about 0.1 for the ICM. In cluster cores where the gas density is highest, the CR fraction can be even smaller. This is consistent with observations. However, in the WHIM, the CR energy density is comparable to the thermal energy density. Hence, the nonthermal radiation of CRs may provide us a way to investigate the WHIM.

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