JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
36: 105 ~ 110, 2003

CLUSTERS OF GALAXIES: SHOCK WAVES AND COSMIC RAYS

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(Received October, 31, 2002; Accepted August 17, 2003)

ABSTRACT

Recent observations of galaxy clusters in radio and X-ray indicate that cosmic rays and magnetic fields may be energetically important in the intracluster medium. According to the estimates based on theses observational studies, the combined pressure of these two components of the intracluster medium may range between 10% ~ 100% of gas pressure, although their total energy is probably time dependent. Hence, these non-thermal components may have influenced the formation and evolution of cosmic structures, and may provide unique and vital diagnostic information through various radiations emitted via their interactions with surrounding matter and cosmic background photons. We suggest that shock waves associated with cosmic structures, along with individual sources such as active galactic nuclei and radio galaxies, supply the cosmic rays and magnetic fields to the intracluster medium and to surrounding large scale structures. In order to study 1) the properties of cosmic shock waves emerging during the large scale structure formation of the universe, and 2) the dynamical influence of cosmic rays, which were ejected by AGN-like sources into the intracluster medium, on structure formation, we have performed two sets of N-body/hydrodynamic simulations of cosmic structure formation. In this contribution, we report the preliminary results of these simulations.

Key words : acceleration of particles — cosmology: large-scale structure of universe — galaxies: clusters: general — methods: numerical — shock waves

I. INTRODUCTION

Formation and evolution of cosmic structures including clusters of galaxies have been driven by the gravity of matter, and the matter continues to accrete onto the cosmic structures as a part of hierarchical structure formation in the cold dark matter paradigm. The accreting matter has a typical velocity up to ~ a few 10^3km s^{-1}, and its baryonic component ends as accretions shocks of Mach number from a few to a few hundred (see, e.g., Ryu & Kang 1997a). The gravitational energy of the gas is dissipated via collisionless shocks, heating the intracluster gas to $10^6 - 10^8$K. Cosmic shocks, along with the hierarchical clustering of predominant dark matter, generate complex flow patterns of gas inside cosmic structures, which, in turn, induce weaker, internal shocks. As a result, shock waves formed during the large scale structure formation span a wide range of scales from a few kpc to a few Mpc, and have a wide range of Mach numbers from one to a few hundred (see, e.g., Ryu & Kang 1997b, Miniati et al. 2000). The shocks can heat up the gas to the temperature ranging from $\sim 10^4 - 10^5$ K in pancakes up to $\sim 10^8$ K in clusters (see, e.g., Kang et al. 1994, Cen & Ostriker 1999).

In addition to heating gas, the shock waves are likely to accelerate high energy particles (cosmic rays) through the so-called diffusive shock acceleration, provided that there exist weak magnetic fields in the intergalactic space (see, e.g., Blandford & Eichler 1987, Kang, Ryu, & Jones 1996). Extended regions populated by cosmic ray electrons have been observed in some clusters for more than thirty years through diffuse, nonthermal radio emissions (see e.g., Kim et al. 1989). Although cosmic ray protons produce γ-rays via π^0 decay following inelastic collisions with gas nuclei, such γ-rays have not yet been detected (Sreekumar et al. 1996). The observations of nonthermal radiations from cosmic ray electrons in clusters, however, suggest that cosmic ray protons could be energetically important, and possibly in energy equipartition with gas. Cosmic shock waves may be the main sources of such cosmic rays, while active galactic nuclei including radio galaxies should also provide a significant amount of cosmic rays to the intracluster medium.

Proceedings of the APCTP Workshop on *Formation and Interaction of Galaxies*

Cosmic shock waves could serve also as sites for generation of weak seeds of magnetic fields by the Biermann battery mechanism. It was proposed that these seeds could be amplified to strong magnetic fields of up to a few μG in clusters, if flows there can be described as the Kolmogoroff turbulence (Kulsrud et al. 1997). Although further development into coherent magnetic fields is unclear, since there is as yet no detailed theory capable of describing this process, observations suggest the existence of cluster magnetic fields of a few μG strength and $\sim$ 10 kpc coherent length (see, e.g., Clarke et al. 2001).

We have studied the properties of cosmic shock waves and the dynamical roles of cosmic rays in clusters by high-resolution cosmological hydrodynamic simulations. For the latter, we adopted an AGN (active galactic nucleus) origin model in which cosmic ray energy is deposited into the intracluster medium by AGNs, while the cosmic rays accelerated at cosmic shocks are ignored. This is because there is yet no practical numerical scheme which can follow the non-linear diffusive shock acceleration of cosmic rays in multi-dimensional simulations. In the next section we describe a cosmological hydrodynamic simulation and discuss the statistical properties and roles of shock waves in cosmic structures. The final section briefs simulations which include the dynamical influences of cosmic rays in the course of formation and evolution of cosmic structures.

II. SHOCKS FROM A HIGH-RESOLUTION COSMOLOGY SIMULATION

The properties of shock waves associated with cosmic structures have been studied through a high-resolution cosmology simulation. For the simulation, an Eulerian hydro+N-body cosmology code (Ryu et al. 1993) has been used. The cold dark matter cosmology with a cosmological constant (ΛCDM) has been employed with the following parameters: $\Omega_{BM} = 0.043$, $\Omega_{DM} = 0.227$, and $\Omega_\Lambda = 0.73$ ($\Omega_{BM} + \Omega_{DM} + \Omega_\Lambda = 1$), $h \equiv H_0/(100\ \mathrm{km/s/Mpc}) = 0.7$, and $\sigma_8 = 0.8$. A cubic region of size $100h^{-1}$ Mpc at the current epoch has been simulated inside a computational box with 1024^3 gas and gravity cells and 512^3 dark matter particles, allowing a spatial resolution of $97.7h^{-1}$ kpc. The simulation is the largest of this kind to date.

Figure 1 illustrates typical cosmic structures found in the simulation, showing bremsstrahlung X-ray emissivity (upper-left), gas density (upper-right), gas temperature (lower-left) and shock Mach number (lower-right) distributions. It represents a slice of $(25h^{-1}\mathrm{Mpc})^2$ centered on a hot cluster in the simulation box. While X-ray clusters are scattered, gas density and temperature reveal connected structures mostly through pancakes and filaments. The outer bounds of shock waves follow closely those of gas temperature distribution. But Mach number distribution shows rich, complex network of weak shock waves inside the filaments bounded by strong accretion shocks. Note that among the protruding structures around the central cluster, thin features in T and M distribution with a thickness of $\sim 1h^{-1}$ Mpc correspond to cross sections of pancakes, while somewhat thick features with a thickness of $\sim 3 - 5h^{-1}$ Mpc belongs to filaments.

Figure 2 shows three-dimensional perspective of cosmic structures through volume rendering of gas temperature. Top panel covers the whole simulation box, while lower two panels represent two different perspectives for a $(25h^{-1}\mathrm{Mpc})^3$ portion centered on the same cluster shown in Figure 1. Images show clearly three topological features, i.e., pancakes, filaments and knots (clusters) in cosmic structures. Filaments lie on pancakes, and clusters are distributed along filaments or positioned at the intersections of filaments.

Cosmic shocks are most commonly characterized as either accretion shocks, if they result from infall of diffuse, intergalactic gas onto the perimeter of clusters, or merger shocks, if they result from collisions of two clusters. A quick glance at Figs. 1 and 2 reveal that this is an overly simplified picture. The hierarchical clustering process for structure formation produces extremely complex shock structures inside, around and outside clusters. These shock waves are neither spherical nor identifiable by simple surfaces. Indeed, they intersect each other, forming nested shock surfaces, extending from outer bounds of pancakes and penetrating deep inside clusters. In addition, collisions between flows in filaments can lead to shocks, and accretion shocks are often hard to be distinguished from merger shocks, given the complexity that accompanies the accumulation of mass in regions where clusters are forming. Dissipation at these shocks provides the basic heating of the intracluster medium, although other processes, including feedback from active galactic nuclei and galaxies may also be important contributors.

According to Miniati et al. (2000) and our analysis of the current simulation, cosmic shocks come in wide ranges of scales and strengths. Shock waves have been identified inside, around and outside clusters on scales from $\lesssim$ 100 kpc to a few Mpc. Shock Mach number depends on the gas temperature, since flow velocities tend generally to be of order 10^3 km s^{-1} both inside and outside clusters. Since shocks are found more frequently inside clusters, where gas temperature is high ($T \gtrsim 10^6$ K), there are more shocks with smaller Much number. The shock surface-area distribution shows a peak at $M = 1$. However, to the extent that the shocked gas has been virialized, moderate strength shocks with Mach number roughly in the range $2 \lesssim M \lesssim 3$ would contribute most to heating of the intracluster medium.

Cosmic shocks are capable of accelerating cosmic rays efficiently, so deserve a close scrutiny in that regard. It is important to remember that, since cosmic rays are effectively tied to the intracluster medium up to pretty high energies, the integrated shock history of the intracluster medium determines the character of the cosmic ray population. So, one would not expect

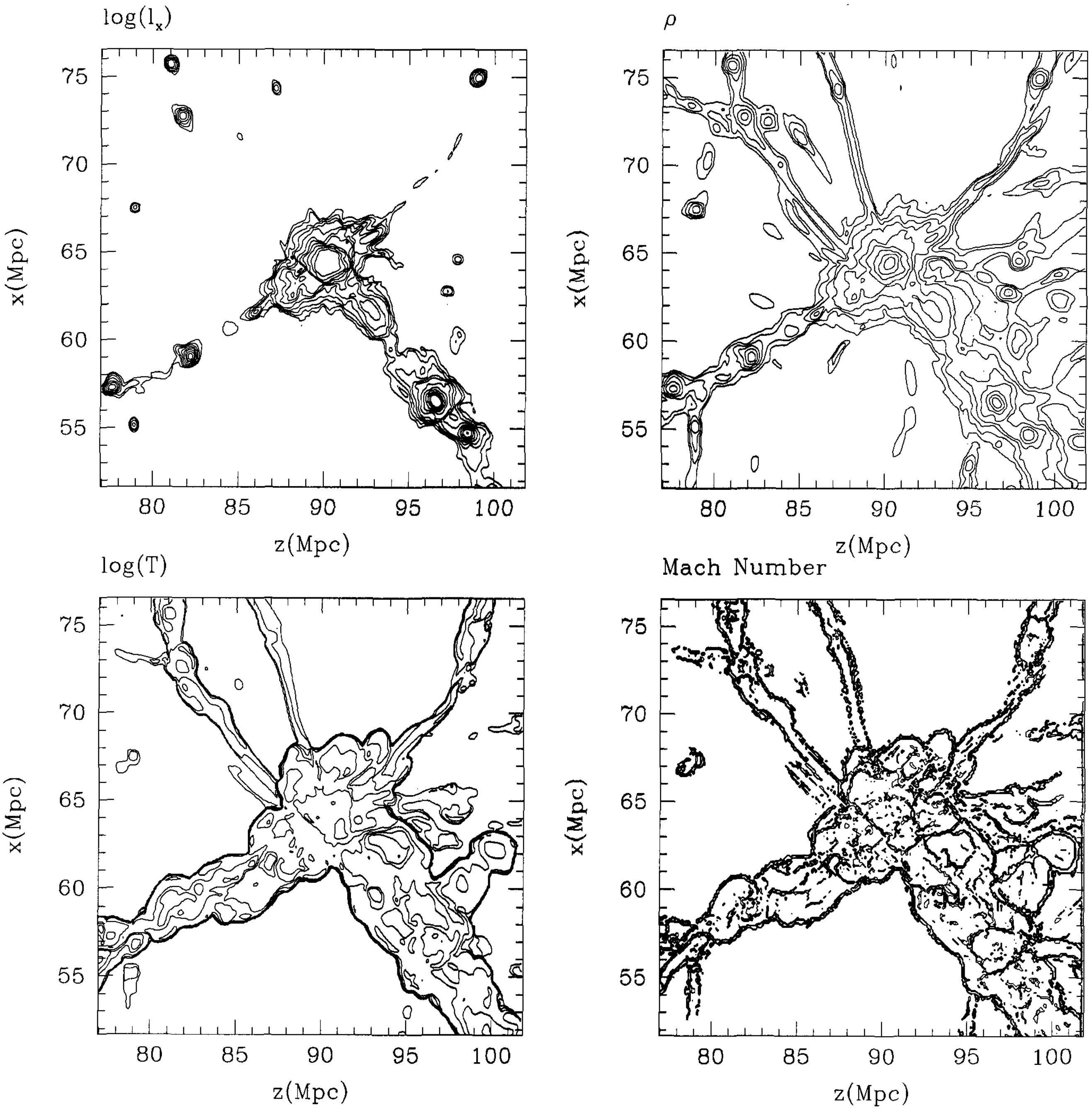

Fig. 1.— Typical cosmic structures through a two-dimensional slice of $(25h^{-1}\mathrm{Mpc})^2$ out of the whole $(100h^{-1}\mathrm{Mpc})^3$ box in the ΛCDM simulation with 1024^3 grid cells. Bremsstrahlung X-ray emissivity, gas density, gas temperature and shock Mach number distributions are shown.

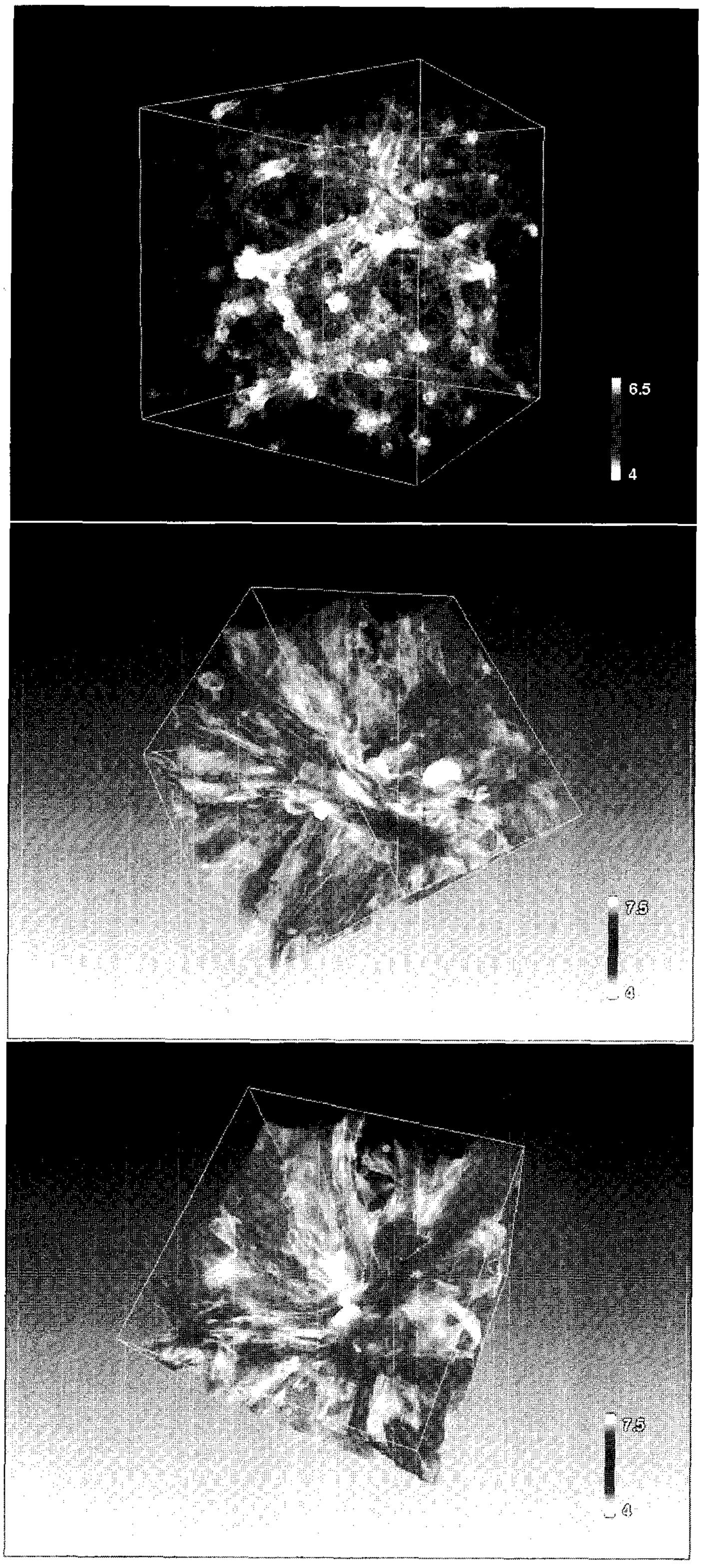

Fig. 2.— Three-dimensional volume rendering of gas temperature in the ΛCDM simulation with 1024^3 grid cells. Top: The box of $(100h^{-1}\mathrm{Mpc})^3$. Middle and Bottom: Two different perspective views of a $(25h^{-1}\mathrm{Mpc})^3$ portion which encompasses the slice in Figure 1.

cosmic rays produced in this way to be only associated with recent merger events, for example. Our analysis of the simulation indicates the shocks, which contribute most to acceleration of cosmic rays, would be those in the range $3 \lesssim M \lesssim 4$. Miniati et al. (2001) and our analysis show such shock waves can accelerate cosmic ray protons with pressure up to $\sim 50\%$ of gas thermal pressure.

Details of the simulation in this section will be reported elsewhere (Ryu et al. 2002b; Kang et al. 2002).

III. COSMOLOGY SIMULATIONS WITH COSMIC RAY DYNAMICS

The simulations used to study the dynamical effects of cosmic rays have also employed the ΛCDM cosmology with the parameters same as those in the previous section, and have been performed with the same cosmology code. However, a cubic region of smaller comoving size, $75h^{-1}$ Mpc, has been chosen for computational domain, and smaller numbers of cells and particles, 512^3 cells for gas and gravity and 256^3 particles for dark matter, have been used. Two simulations have been done, one with cosmic ray dynamics included and the other without cosmic rays.

The following equation for cosmic ray pressure has been solved in addition to the usual standard set of equations for dark matter and gas (Ryu et al. 1993),

$$\frac{\partial p_{CR}}{\partial t}+\frac{1}{a}u_k\frac{\partial P_{CR}}{\partial x_k}+\frac{\gamma_{CR}}{a}P_{CR}\frac{\partial u_k}{\partial x_k}=-3(\gamma_{CR}-1)\frac{\dot{a}}{a}p_{CR}. \tag{1}$$

Here, a is the expansion parameter, x_k is the comoving length, p_{CR} is the comoving pressure of cosmic rays, u_k is the proper peculiar velocity, and γ_{CR} is the adiabatic index of cosmic rays which has been assumed to be 4/3. Diffusion of cosmic rays has been ignored, since the diffusion length is much shorter than the computational cell size for most of cosmic rays. The dynamical feedback of cosmic rays to gas has been incorporated by including the $(1/a)(\partial P_{CR}/\partial x_k)$ term in the momentum equation, along with the $(1/a)u_k(\partial P_{CR}/\partial x_k)$ term in the energy equation.

It has been assumed that the sources, which deposit cosmic ray energy into the intracluster medium, form at 40 different epochs after the redshift $z = 10$, if the following criteria are satisfied in each grid cell

$$M_{gas} \geq \frac{3 \times 10^{10}}{1+z} h^{-1} M_{\odot}, \quad \frac{\partial u_k}{\partial x_k} < 0, \tag{2}$$

where M_{gas} is the total gas mass inside the cell. It has been further assumed that each source ejects the following amount of cosmic ray energy into the intracluster medium

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

Note that at $z = 0$ this translates into the cosmic ray efficiency, $E_{CR}/M_{gas}c^2 = 10^{-6}$.

Bottom panel of Figure 3 shows that the source formation history, which has been realized by the criteria (2), increases first, and then stays more or less constant after $z \sim 2$. Total of $\sim 4 \times 10^4$ sources have formed in the simulation box of $(75h^{-1}\mathrm{Mpc})^3$. Middle panel shows the resulting mass averaged densities of gas kinetic energy, gas thermal energy and cosmic ray energy, which reflect mostly the averaged energy densities inside clusters with high mass density. In clusters the cosmic ray energy dominated over the gas thermal energy before $z \sim 2$ in our model, during which the gas thermal energy was still small. After $z \sim 2$, the ratio of cosmic ray to gas thermal energies has decreased. The cosmic ray energy density has become and stays $\sim 50\%$ of the gas thermal energy density after $z \sim 1$. With such amount of cosmic ray energy, the gas density perturbation has reduced by $\sim 20\%$ at the present epoch, while the density perturbation of dark matter has been hardly affected, as shown in top panel.

Figure 4 shows the power of density perturbation at three different epochs. It has been decreased by $\sim 25\%$ at $z = 2$, by $\sim 35\%$ at $z = 1$, and by $\sim 45\%$ at $z = 0$ on the cluster scale of $\sim 1h^{-1}$ Mpc, due to the dynamical effects of cosmic ray pressure. However, the structures of scales larger than the cluster scale have been less disturbed, since sources form mostly at the highest density peaks within clusters.

To study the dynamical effects of cosmic ray pressure on individual clusters, we have randomly identified several clusters in the computational box, and compared their properties in the cases with/without cosmic ray dynamics. Cosmic ray pressure provides additional support against infalling flows. As a result, the intracluster medium becomes less concentrated with cosmic rays, and the virial temperature reduces to lower values. The clusters with $E_{CR} \sim 1/2E_{th}$ have been significantly modified. Their X-ray bremsstrahlung emission and temperature decreased by $\sim 50\%$.

Further details of the simulations in this section will be reported in Ryu et al. (2002a).

This work was supported by grant No. R01-1999-000-00023-0 from the Korea Science & Engineering Foundation. Simulations have been made through a support by the Grand Challenge Program of KISTI Supercomputing Center.

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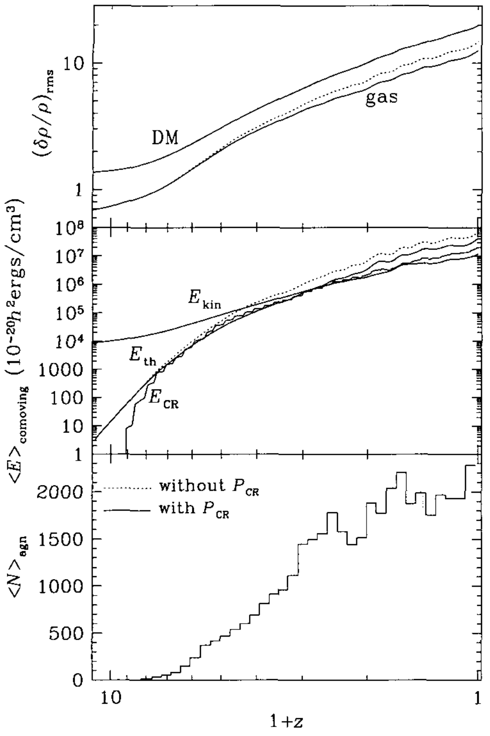

Fig. 3.— Top: Temporal evolution of the root-mean-square density perturbations of dark matter and gas in the 512^3 ΛCDM simulations with (solid line) or without (dotted line) cosmic ray energy ejection from AGN-like sources. Middle: Temporal evolution of the mass-averaged energy per unit comoving volume. E_{kin} is the gas kinetic energy, E_{th} is the gas thermal energy, and E_{CR} is the cosmic ray energy. Bottom: Formation history of cosmic ray sources. Sources are assumed to form at 40 logarithmically spaced epochs after $z = 10$.

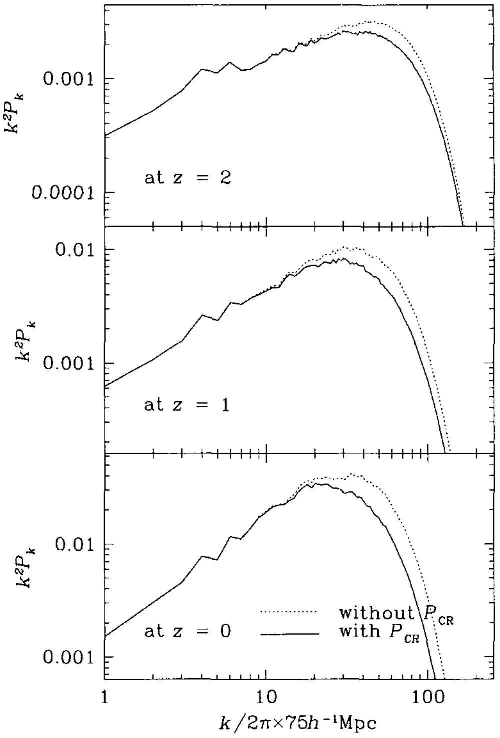

Fig. 4.— Power spectrum of gas density perturbations at three different epochs in the 512^3 ΛCDM simulations with (solid line) or without (dotted line) cosmic ray energy ejection from AGN-like sources.

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