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Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
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COSMIC RAYS AND THEIR RADIATIVE PROCESSES IN NUMERICAL COSMOLOGY

Dongsu Ryu,[1] Francesco Miniati,[2] Tom W. Jones,[2] and Hyesung Kang[3]

RESUMEN

Se describe un código hidrodinámico para cosmología, que incluye una rutina para calcular, de manera simplificada, la aceleración y el transporte de los rayos cósmicos. La rutina fue diseñada para seguir de manera explícita la aceleración difusiva en choques y la aceleración de Fermi de segundo orden con enfriamiento adiabático en flujos suaves. Se puede también seguir el enfriamiento por sincrotrón de los electrones. El código puede ser usado para estudiar, además de la emisión bremsstrahlung del gas caliente, las propiedades de la emisión sincrotrón y la dispersión de Compton inversa en cúmulos de galaxias. Se presentan los resultados de una simulación de prueba, usando una malla de 128^3, donde los rayos cósmicos y el campo magnético son tratados de forma pasiva y no se incluye la emisión sincrotrón de los electrones.

ABSTRACT

A cosmological hydrodynamic code is described, which includes a routine to compute cosmic ray acceleration and transport in a simplified way. The routine was designed to follow explicitly diffusive acceleration at shocks, and second-order Fermi acceleration and adiabatic loss in smooth flows. Synchrotron cooling of the electron population can also be followed. The updated code is intended to be used to study the properties of nonthermal synchrotron emission and inverse Compton scattering from electron cosmic rays in clusters of galaxies, in addition to the properties of thermal bremsstrahlung emission from hot gas. The results of a test simulation using a grid of 128^3 cells are presented, where cosmic rays and magnetic field have been treated passively and synchrotron cooling of cosmic ray electrons has not been included.

Key Words: **COSMIC RAYS — COSMOLOGY: LARGE-SCALE STRUCTURE OF THE UNIVERSE — GALAXIES: CLUSTERS: GENERAL — METHODS: NUMERICAL**

1. INTRODUCTION

There is growing evidence, both in observational and theoretical studies, that cosmic rays may be an important dynamical component, which affect the formation and equilibrium of clusters of galaxies (GCs) and the large scale structure of the universe (e.g., Enßlin et al. 1997). Relativistic cosmic-ray (CR) electrons have been observed in GCs through their synchrotron emission (e.g., Kim et al. 1989). In addition, many clusters possess an excess of radiation compared to that expected from the hot, thermal X-ray emitting Intra Cluster Medium (ICM), both in the extreme ultra-violet (EUV) (e.g., Fabian 1996) and in the hard X-ray band above ~ 10 KeV (e.g., Fusco-Femiano et al. 1999). One of the mechanisms proposed for the origin of this component is inverse-Compton (IC) scattering of cosmic microwave background photons by CR electrons. Based on this interpretation, and assuming diffusive shock acceleration for the origin of CR electrons, Lieu et al. (1999) concluded that a population of CR proton in equipartition of energy with the thermal gas should be present

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in the Coma cluster. However, CR protons have not been directly observed yet in GCs (e.g., Sreekumar et al. 1996).

2. CODE

As an effort to study the observational signatures and dynamical effects of CRs in numerical cosmology, we have developed a code which follows the acceleration and further evolution of CRs along with matter in the cosmological context. Here, dark matter is treated with the particle-mesh (PM) method and the gas and magnetic field are treated with a second-order accurate, conservative scheme called the total variation diminishing (TVD) scheme (Ryu et al. 1993). Special care was taken so that the code can capture accurately shocks even with very large Mach numbers, $M \gtrsim 100$. For energetic particle transport we use the conventional convection-diffusion equation for the momentum distribution function, f (e.g., Skilling 1975), which follows the spatial and momentum diffusion as well as the spatial and momentum advection of particles. However, high computational costs prohibit solving this equation through standard finite difference methods in complex flows. To circumvent this, we use a conservative finite volume approach in the momentum coordinate, taking advantage of the broad spectral character expected for $f(p)$. Particle fluxes across momentum bin boundaries are estimated by representing $f(p)$ as $f(p) \propto p^{-q(p)}$, where $q(p)$ varies in a regular way. Numerically we use the integrated number of electrons within each bin and the slope, q, within each bin. Thus, we can follow the electron spectral evolution in smooth flows with a modest number of momentum bins. Typically, we have used 8 bins to cover energies up to a few hundred GeV for electrons. In addition, diffusive acceleration of electrons to GeV energies at shocks is effectively instantaneous within a dynamical time step. Hence, we assume the analytic, steady, test particle form for the CR distribution just behind shocks. That is, the spectrum is a power law with an index, $q = 3r/r - 1$, where r is the shock compression ratio. Details for the treatment of CRs can be found in Jones, Ryu, & Engel (1999).

3. RESULTS

As a test, a standard cold dark matter (CDM) model universe with total $\Omega_M = 1$ of matter has been simulated in a periodic box with $(32h^{-1}\mathrm{Mpc})^3$ volume using 128^3 cells and 64^3 particles from $z_i = 20$ to $z_f = 0$. The values of other parameters used are $\Omega_b = 0.06$, $h = 1/2$, and $\sigma_8 = 1.05$. Synchrotron cooling of CR electrons has *not* been included. Since it is important in real situations, later simulations with synchrotron cooling are expected to produce results somewhat different.

With the simulated CRs along with the magnetic field distribution we can study the properties of nonthermal synchrotron emission and IC emissivity in CGs, in addition to the properties of thermal bremsstrahlung emission from hot gas. Figure 1 shows sliced maps of synchrotron emission (left panel) and bremsstrahlung emission (right panel) around a cluster identified in the simulation. The distribution of synchrotron emission roughly follows that of bremsstrahlung emission, but it shows more fine structures. This is because the regions of strong synchrotron emission typically correspond to the regions of strong magnetic field. Figure 2 plots the average magnetic field strength, the ratio of CR-proton to gas pressure, the IC and synchrotron emissivity from clusters as a function of cluster core temperature. Both synchrotron and IC emissivity are larger in hotter cluster. In addition, larger and hotter clusters have stronger magnetic field. As a result, the slope of synchrotron emissivity is steeper than that of the IC. With an injection rate $\epsilon_{inj} \sim 10^{-2}$ or so, the top-right panel shows that the CR pressure becomes comparable to the gas pressure. Hence, we expect that CRs play important dynamical roles in the formation of large scale structures and clusters.

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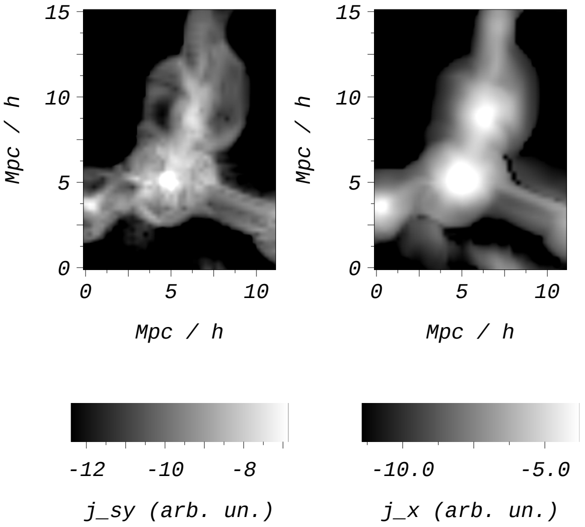

Fig. 1. *(Left)* Sliced maps of synchrotron emission and *(Right)* bremsstrahlung emission around a cluster identified in the simulation.

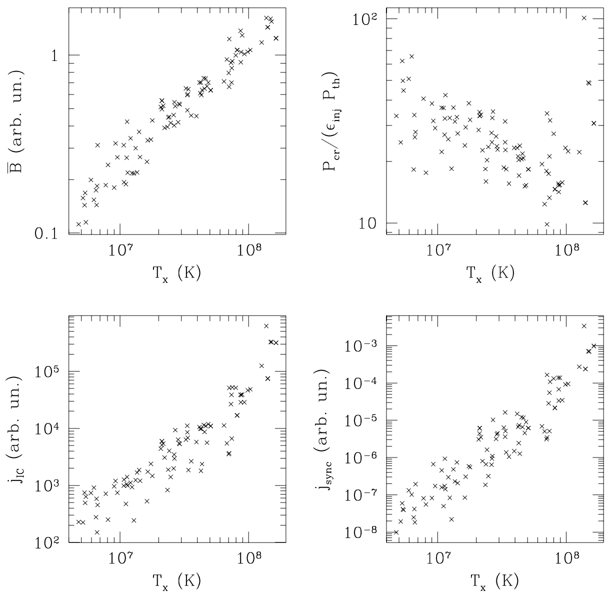

Fig. 2. Average magnetic field strength, the ratio of CR-proton to gas pressure, the IC and synchrotron emissivity from clusters as a function of cluster core temperature.

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