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CONTRIBUTIONS TO THE COSMIC RAY FLUX ABOVE THE ANKLE: CLUSTERS OF GALAXIES

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ABSTRACT

Assuming that particles can be accelerated to high energies via diffusive shock acceleration process at the accretion shocks formed by the infalling flow toward the clusters of galaxies, we have calculated the expected spectrum of high-energy protons from the cosmological ensemble of the cluster accretion shocks. The model with Jokipii diffusion limit could explain the observed cosmic ray spectrum near 10^{19}eV with reasonable parameters and models if about 10^{-4} of the infalling kinetic energy can be injected into the intergalactic space as the high energy particles.

Key Words : Cosmic Rays, Particle Acceleration, Clusters of Galaxies

I. INTRODUCTION

Above the "ankle" at about 3 EeV (UHECR), a simultaneous change in spectrum and composition of the cosmic rays as well as the large Larmor radius of such particles call for extragalactic sources (Bird et al. 1994). Among various models of extragalactic origins, we focus here on diffusive shock acceleration by the accretion shocks which form as a result of gravitational infall of background matter onto clusters of galaxies (Kang, Ryu, & Jones 1996).

II. MODEL

(a) Accretion Shock

The accretion flow toward a cluster is modeled by an 1D self-similar solution of Bertschinger 1985 in an $\Omega_0 = 1$ universe. Then the radius and velocity of the accretion shock can be related with the ICM temperature as follows.

$$r_s = 2.12 h^{-1}\,\mathrm{Mpc}\left(\frac{kT_{\mathrm{obs}}}{6\mathrm{keV}}\right)^{1/2}(1+z)^{-3/2} \qquad (1)$$

$$V_s = 1.75\times10^3\,\mathrm{kms}^{-1}\left(\frac{kT_{\mathrm{obs}}}{6\mathrm{keV}}\right)^{1/2}. \qquad (2)$$

We further assumed the magnetic field is in rough equipartition with the thermal energy of the gas. The particle diffusion is modeled either by the Bohm diffusion (Drury 1983) in parallel shocks ($\kappa_B = 1/3 r_g v$) or by the Jokipii diffusion (Jokipii 1987) in perpendicular shocks ($\kappa_J = r_g V_s$).

(b) Injection Spectrum

The maximum energy E_{max} is found by the condition that the energy gain rate for diffusive shock acceleration is balanced by the loss rate due to the interactions with the cosmic background radiation (Greisen 1996, Rachen & Biermann 1993). The proton spectrum at the shock is assumed to be a power law of α and with an exponential cutoff at the maximum energy as follows.

$$f(T,z,p) = A(T,z)\,p^{-\alpha}\exp\left[-\frac{p}{p_c(T,z)}\right], \qquad (3)$$

where $A(T,z)$ is a normalization constant. It is chosen by assuming that a small fraction (ϵ) of the kinetic energy density of the infalling matter in the shock rest frame ($\rho_1 V_s^2$) is converted to CR energy and then injected into IG space. Then the injected particle spectrum at the cluster is integrated over the cosmological distance to earth by considering the energy loss due to the interactions with the cosmic background radiation.

(c) Cluster Distribution Function

In order to model the distribution of cosmological population of clusters, first we adopted a temperature distribution function of clusters given by Henry and Arnaud (1991) which was derived from the observed local clusters. The number density in unit comoving volume at the present is given by for $kT = 1$–$10\,\mathrm{keV}$, $n_o(kT) = 1.8\times10^{-3}\,h^3\,\mathrm{Mpc}^{-3}\,\mathrm{keV}^{-1}\left(\frac{kT}{\mathrm{keV}}\right)^{-4.7}$. Secondly, we made a simple assumption that the comoving density of cluster evolves as a power-law of a scale factor, $(1+z)$, that is, $n(kT,z) = n_o(kT)(1+z)^m$.

III. RESULTS

Fig. 1 shows the expected proton spectrum from the cluster accretion shocks. In all models we set $m = 0$, $\Omega_b = 0.06$ and $h = 0.75$. Different values of the injection energy fraction ϵ is assumed for each value of the spectral index α to obtain the better fit with the observation around 10 EeV for Jokipii models and around 1 EeV for Bohm models, respectively. The data points represent the all-experiment data set collected

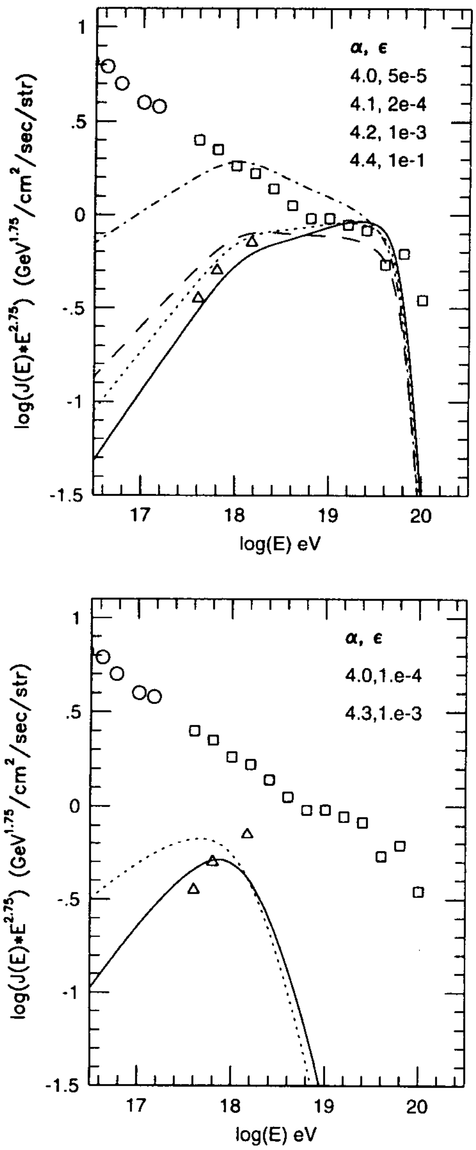

Fig. 1.— Estimated proton flux from a cosmological ensemble of cluster accretion shocks. The top panel shows the models with Jokipii diffusion. The solid line is for $\alpha=4.0. \epsilon=5\times10^{-5}$, dotted line for $\alpha=4.1$, $\epsilon=2\times10^{-4}$ dashed line for $\alpha=4.2$, $\epsilon=10^{-3}$ and dot-dashed line for $\alpha=4.4$, $\epsilon=10^{-1}$. The bottom panel shows the results for Bohm diffusion. The solid line is for $\alpha=4.0$, $\epsilon=10^{-4}$, and dotted line for $\alpha=4.3$, $\epsilon=10^{-3}$. See text for symbols for the observed data sets

by T. Stanev (squares, see Rachen, Stanev & Biermann 1993), and the light component inferred from the Fly's Eye composition measurements (triangles). As expected, higher ϵ is required for steeper spectra. For the Jokipii diffusion, the models with $4.0 \leq \alpha \leq 4.2$ show good fits to the data, while the models with Bohm diffusion produce too few particles above 1 EeV.

The required injection efficiency at a level of order 10^{-4} could be understood as follows. The CR shock can transfer typically 1-10 % of its kinetic energy to the CR component. If 1-10 % of the CR energy can leak out from the shock and be injected into the intergalactic space, then the final fraction of the infall kinetic energy which comes out from the cluster shock as UHECRs would be order of $10^{-4} - 10^{-3}$.

Even though the model is quite successful in explaining the observed spectrum of UHECRs, several assumptions on the magnetic field outside of clusters, the particle diffusion, and escape processes needs further investigations.

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