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Origin of the knee in the cosmic ray spectrum

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Abstract. Recent results of extreme-ultraviolet and high energy X-ray observation from clusters of galaxies have suggested the existence of diffuse cosmic ray electrons in the cluster which would have a profound impact on cosmology. If nuclear components also exist around our own galaxy, these components with an energy above $\sim 10^{15}$ eV (1 PeV) after modulated by the galactic wind might be directly observable. We report on the numerical results of the modulated energy spectrum of the hypothetical cosmic rays and discuss their implications for the origin of the "knee".

1 Introduction

Cosmic rays spread over 11 decades of energy with an almost featureless power law spectrum. The spectrum steepens rather suddenly from differential spectral index $\gamma \sim 2.7$ below $\sim$ 3 PeV to $\gamma \sim 3.0$ above. This break in the spectrum is often referred to as the "knee" in the spectrum. Knee has been recognized as an important structure of the energy spectrum, since it can provide constraints on the acceleration mechanism and the source of cosmic rays.

A major source of cosmic rays below knee energies is currently believed to be supernova remnants (SNRs) in our galaxy from the arguments of energetics, shock acceleration mechanisms (Blandford & Eichler, 1987; Jones & Ellison, 1991), and the elemental abundances in the source of galactic cosmic rays (Yanagita et al., 1990; Yanagita & Nomoto, 1999). Arguably the recent results of X-ray (ASCA) and TeV gamma-ray (CANGAROO) observation from SNRs, SN1006 (Koyama et al., 1995; Tanimori et al., 1998) and RX J1713.7−3946 (Koyama et al., 1997; Slane et al., 1999; Muraishi et al., 2000), are the best evidence for the existence of shock accelerated relativistic electrons with energies near the knee.

However, the origin of cosmic rays above knee energies is still unsettled. An attractive possibility is that the steepening of the spectrum is a rigidity dependent effect (Peter, 1959). Such a steepening could be a consequence of the breakdown of an acceleration mechanism at this energy range or due to an increased rate of escape from our galaxy at this high energy. In this scenario, the relative fraction of heavy nuclei would increase with energy. Hillas (1984) points out, however, that the break appears to be rather too sharp for this explanation to work. On the other hand, some other scenarios predict that there is a new component that dominates above $\sim$ 1 PeV (Jokipii & Morfill, 1985; Fichtel & Linsley, 1986; Erlykin & Wolfendale, 2000).

Recently the Extreme Ultraviolet Explorer satellite has revealed that some clusters possess an excess of EUV radiation which is higher than what is expected from the hot, thermal X-ray-emitting intracluster medium (ICM) (Lieu et al., 1996; Fabian, 1996; Mittaz et al., 1998; Kaastra, 1998). Further evidence for non-thermal activity in the ICM comes from the detection of excess emission of X-rays above $\sim$ 10 keV (Henriksen, 1998; Fusco-Femiano et al., 1999; Vilinia et al., 1999; Sarazin et al., 1999). The mechanism proposed for the origin of these components is the inverse-Compton scattering of cosmic microwave background photons by diffuse cosmic ray electrons (Ensslin et al., 1999). Such detections suggest the possibility that nonthermal activities in the ICM are much higher than previously expected (Sarazin & Lieu, 1998; Lieu et al., 1999).

If nuclear components with energies extended well above $\sim$ 1 PeV also exist together with the diffuse electrons around our galaxy, these components after modulated by the galactic wind might be directly observable at the earth. In this paper, we numerically examine such a possibility, and discuss their implications for the origin of the knee.

2 Numerical simulations and Results

We postulate the existence of hypothetical cosmic rays just outside of "the galactic sphere" where the galactic wind (Breitschwerdt et al., 1991) terminates. The energy spectrum of

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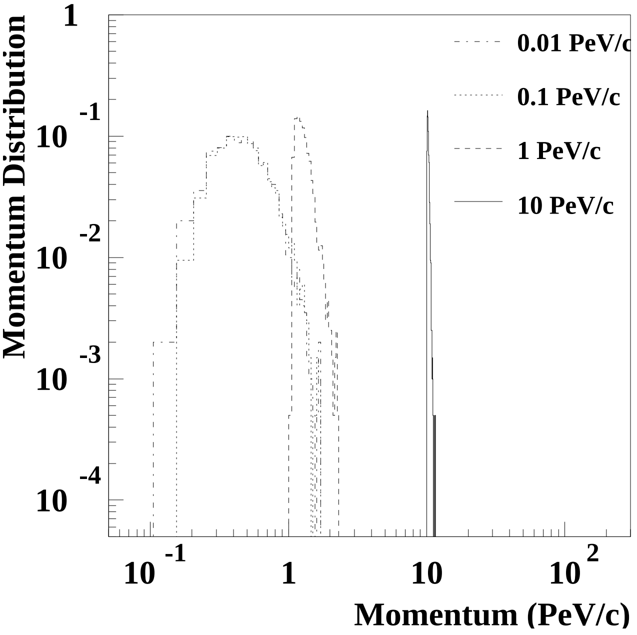

Fig. 1. The momentum distribution at the galactospheric boundary R = 100 kpc, for protons observed at 8 kpc with a value of momentum from 0.01 to 10 PeV/c, with $\kappa_1 = 10^{31}$ cm^2 sec^{-1} PV^{-1}.

these cosmic rays is assumed the same as the spectrum of the cosmic rays observed at the earth with energies higher than the knee region but extrapolated to much lower energy range; namely the spectrum is proportional to E^{-3} where E is the total energy of a particle.

These cosmic rays may diffuse into inner region of the galactic sphere against the expanding galactic wind. We examine how the spectrum of these cosmic rays should be modulated during this propagation process. The transport of cosmic rays is described by the Fokker-Plank equation (FPE) for the spherical symetric case (Parker, 1965; Gleeson & Axford, 1967; Jokipii & Parker, 1970)

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\kappa\frac{\partial f}{\partial r}) - V\frac{\partial f}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V)\frac{p}{3}\frac{\partial f}{\partial p}, \qquad (1)$$

where f is the phase space distribution function, t is the time, r is the radial distance, V is the speed of galactic wind, p is the particle momentum, and κ is the diffusion coefficient for radial propagation.

It is known that Eq.(1) is equivalent to the coupled stochastic differential equations (SDEs). The SDEs equivalent to Eq.(1) are written using new quantities $u = \ln(p/mc)$ (where m is the particle mass and c is the speed of light) as (Gardiner, 1989; Yamada, Yanagita & Yoshida, 1998)

$$dr = (V + \frac{2\kappa}{r})dt + \sqrt{2\kappa}\,dW_r, \qquad (2)$$

and

$$du = -\frac{2V}{3r}dt, \qquad (3)$$

where dW_r is a Wiener process given by the Gaussian distribution, $P(dW_r)$ = $(2\pi dt)^{-1/2}$ $\exp(-dW_r^2/2dt)$. Here we assume that V does not depend on r. The set of SDEs are integrated by a simple Euler method.

If we integrate the SDEs "backward in time" (Yamada, Yanagita & Yoshida, 1998), we can obtain a probability function $F(p, R|p_0, r_0)$ which is necessary to calculate the modulated energy spectrum at an arbitrary point of galactocentric distance r_0. The probability function describes the probability of which a particle observed with momentum p_0 at r_0 would have had momentum p at the galactospheric boundary R. Once we have calculated $F(p, R|p_0, r_0)$, the modulated energy spectrum $f_{r_0}(p_0)$ at a point r_0 is calculated with the energy spectrum $f_R(p)$ at R as,

$$f_{r_0}(p_0) = \int f_R(p)F(p, R|p_0, r_0)dp. \qquad (4)$$

This method has been applied successfully to the investigation of the solar modulation phenomena of the galactic cosmic rays in the heliosphere (Yamada, Yanagita & Yoshida, 1998) and is based on the theory of Kolmogorov (Gardiner, 1989; Risken, 1989), and the insight of Kóta (1977). The momentum spectrum of the hypothetical cosmic rays at the boundary of the galactosphere is $f_R \propto p^{-5}$, if we assume the spectrum is proportional to E^{-3} as mentioned earlier. In the numerical integration of Eqs.(2) and (3), we need κ and V which are unknown to us. The functional form of κ is assumed as $\kappa_1\beta P$, because κ should be $\sim r_L c\beta$ if we assume the Bohm diffusion, where κ_1, β, P, and r_L are some constant, the speed of particle in unit of the speed of light, the rigidity of particle, and the Larmor radius of the particle, respectively. For proton with momentum p, the Bohm diffusion coefficient is estimated as $\sim 10^{30}(p/\mathrm{PeV/c})(B/0.1\mu\mathrm{G})^{-1}$ cm^2 s^{-1}.

Figure 1 shows normalized distribution function $F(p, R|p_0, r_0)$ for protons at $r_0 = 8$ kpc with four values of p_0, where we adopt $V = 300$ km sec^{-1}, $R = 100$ kpc, and $\kappa_1 = 10^{31}$ cm^2 sec^{-1} PV^{-1}. It is seen that $F(p, R|p_0, r_0)$ is zero for $p \le p_0$ in general as expected, because particles observed with p_0 at 8 kpc should have started from the boundary of the galactosphere with some p much higher than p_0. It is remarkable that the distribution functions for two distinctively different values of p_0 of 0.01, and 0.1 PeV/c are almost indistinguishable. This means difficulty in prediction of the spectrum of our hypothetical cosmic rays at the boundary of the galactosphere in relatively low energy range from observations at inner region of the sphere. It is also remarkable that the distribution function shown for p_0 = 0.01 PeV/c particles indicate that particles observed at the earth with p_0 = 0.01 PeV/c have loosed more than 90 % of the energy which the particles have possessed at the galactospheric boundary. In other words cosmic ray protons with momentum below $\sim$ 0.1 PeV/c at the boundary could not almost arrive at the earth. Of course cosmic rays observed at the earth with momentum below $\sim$ 0.01 PeV/c are dominated by the particles accelerated by shocks in SNRs. The SDE method allows us to deduce another suggestive information for understanding the origin and the propagation of the hypothetical cosmic rays.

Figure 2 shows the distribution functions of arrival time

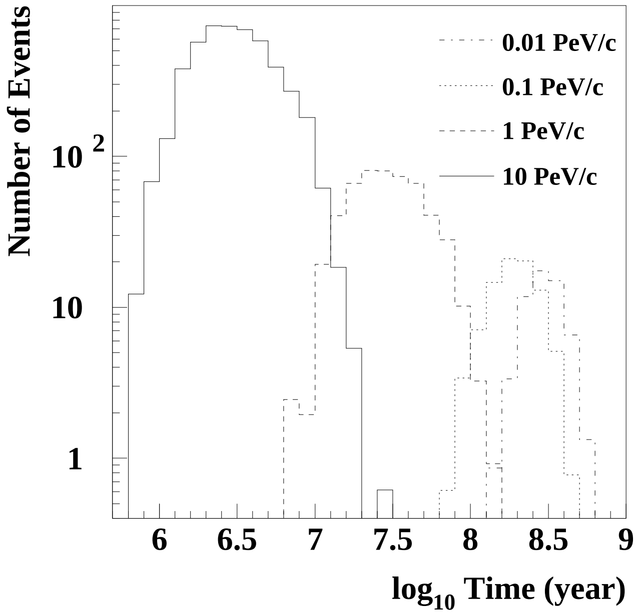

Fig. 2. The distribution of arrival time from the galactospheric boundary to 8 kpc for protons at 8 kpc, with $\kappa_1 = 10^{31}$ cm^2 sec^{-1} PV^{-1}.

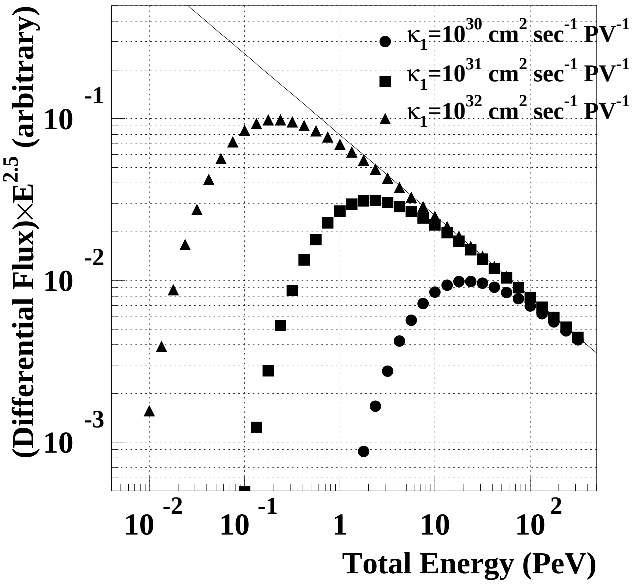

Fig. 3. The modulated energy spectra of protons at 8 kpc. The filled circles, squares and triangle are the differential intensity of protons at 8 kpc for $V = 300$ km sec^{-1} and $R = 100$ kpc with $\kappa_1 = 10^{30}$, 10^{31} and 10^{32} cm^2 sec^{-1} PV^{-1} respectively. The solid line indicate a differential energy spectrum of the hypothetical cosmic ray protons at the galactospheric boundary $R = 100$ kpc which is a power law in total energy with a spectral index of -3.0.

of protons from the galactospheric boundary to 8 kpc for the same series of values of p_0 at 8 kpc which led to Figure 1. The arrival time is distributed in a wide range even for particles with the same momentum at 8 kpc. The distribution depends strongly on the momentum observed at the earth, in a sense the mean value is the longer the lower the momentum is, as expected. The arrival time is shorter than 10^9 y even for particles with momentum of 0.01 PeV/c which could barely reach the earth. This time is much shorter than the confinement time of hadronic components of cosmic rays in galactic clusters (Völk & Atoyan, 2000). Accordingly the flux level of cosmic rays at the earth with energies higher than $\sim$ 1 PeV would be expected to be in a quasi-steady state.

Figure 3 shows the calculated differential energy spectra versus total energy E at 8 kpc. The filled circles, squares and triangle are the differential intensity of protons at 8 kpc, which is calculated by Eq.(4), with $\kappa_1 = 10^{30}$, 10^{31} and 10^{32} cm^2 sec^{-1} PV^{-1} respectively. The solid line indicate the assumed unmodulated spectrum at $R = 100$ kpc. The break point of the spectrum should be compared with the knee. As clearly seen in Figure 3, by choosing an appropriate value for the parameters κ, V, and R, we can reproduce the knee in the observed energy range.

3 Discussion

We have shown the existence of the knee is reproduced fairly well by the spectrum of the hypothetical cosmic rays modulated by the galactic wind, although our model is still a toy. In our model, we simply assume the existence of a population of cosmic rays without any specification of its origin. Many authors accept without any direct evidence the galactic origin of cosmic rays with 10^{15} eV $\leq$ E $\leq$ 10^{18} eV (Gaisser, 2001). Recently the AGASA group reported that the origin of cosmic rays around 10^{18} eV might be galactic from the result of a large first harmonic anisotropy around 10^{18} eV which was apparently caused by an excess in direction close to the Galactic Centre, with a possible smaller excess from the direction of the Cygnus region of the galactic plane (Hayashida et al., 1999; Yoshida, 1999). But the SUGAR group have shown that the signal is consistent with that from a point source, and no evidence for an excess of cosmic rays coming from the direction of the Galactic Centre itself (Bellido et al., 2001). It may be premature to conclude the galactic origin of cosmic rays with energy of 10^{15} eV $\leq$ E $\leq$ 10^{18} eV.

On the other hand, Völk & Atoyan (2000) discuss the existence of non-thermal hadronic components in the cluster of galaxy in terms of early starbursts and magnetic field generation in galaxy clusters. They suggest that relativistic particles would be confined in galaxy clusters over times longer than the age of the universe. Therefore if these hypothetical components truly exist around our own galaxy, the observed cosmic ray spectrum around the knee might be able to be explained by the sum of these component and the component generated at SNRs in our galaxy.

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