Extragalactic cosmic rays modulated by the galactic wind and its implication for the origin of the ‘knee’

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Abstract

We present numerical results of the modulated energy spectrum of the hypothetical cosmic rays coming into the galaxy from just out side of the ‘galactic sphere’ where the galactic wind terminates. It is shown that the observed knee structure is reproduced well by a superposition of the modulated component and the galactic cosmic rays originating in supernova remnants. The energetics of the assumed hypothetical extragalactic cosmic rays is also discussed.

1. Introduction

Cosmic rays (CRs) spread over 11 decades of energy from ~ 10^9 eV to ~ 3×10^{20} eV (Fig. 1). The spectrum is often fitted by power laws of energy with the index of ~ -2.7 below ~ 3×10^{15} eV and ~ -3.0 above, respectively. This break in the spectrum is referred to as the ‘knee’ in the spectrum. CRs with energies below the knee have been believed to be originated in supernova remnants (SNRs) in our galaxy from general arguments about energetics and the diffusive particle acceleration mechanism in shocks (Blandford & Eichler 1987; jones & Ellison 1991). This argument of the CR origin is corroborated by recent observations of X-rays (by ASCA) and TeV gamma-rays (by CANGAROO) from two SNRs, SN1006 (Koyama et al. 1995; Tanimori et al. 1998) and RXJ1713.7-3946 (Koyama et al. 1997; Slane et al. 1999; Muraishi et al. 2000; Enomoto et al. 2002). These observations have revealed that electrons and protons are accelerated to energies of ~ 100 TeV in the SNRs, however this maximum energy does not reach the knee energy of ~ 3×10^{15} eV. A hypothesis blessed by long tradition explains the break in the spectrum at the knee by more rapid escape from the Galaxy of more energetic particles above the knee (Hillas 1984). Alternative interpretations of the knee structure are to invoke one or a few extra components of galactic origin which dominate above ~ 1 PeV (Jokipii & Morfill 1985; Fichtel & Linsley 1986; Erlykin & Wolfendale 1998). Yet the origin of CRs above the knee is still not settled.

Recently the existence of diffuse CR electrons in the intergalactic space has been suggested from the results of extreme-ultraviolet and high energy X-ray observation of clusters of galaxies (Ensslin, Lieu & Biermann 1999) and from the observation of the diffuse cosmic gamma-ray background (Loeb & Waxman 2000). If nuclear components with energies extended well above ~ 1 PeV also exist together with the diffuse electrons around our galaxy, these components 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.

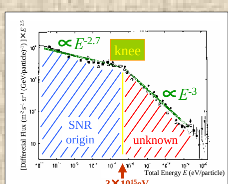


Figure 1: The overall spectrum of cosmic rays from 10^{11} – 10^{20} eV showing the observations at a wide range of particle energies (from Hillas(1984)).

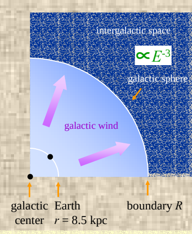


Figure 2: A schematic view of our model. We examine how the spectrum of the hypothetical CRs which is proportional to E^{-3} just out side of the galactic sphere should be modulated during propagation in our galactic halo.

2. Numerical simulations

We postulate the existence of hypothetical CRs just outside of the ‘galactic sphere’ where the galactic wind (Breitschwerdt, McKenzie & Voelk 1991) terminates (Fig. 2). The energy spectrum of these CRs is assumed to be the same as the spectrum of the CRs 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 CRs may diffuse into inner region of the galactic sphere against the expanding galactic wind. We examine how the spectrum of these CRs should be modulated during this propagation process. The transport of CRs is described by the Fokker-Planck equation for the spherical symetric case (Parker 1965; Gleeson & Axford 1967; Jokipii & Parker 1970)

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

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. Here we neglect energy change processes other than adiabatic losses. 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

$$dr=\left(V+\frac{2\kappa}{r}+\frac{\partial f}{\partial \kappa}\right)dt+\sqrt{2\kappa}dw \qquad (2) \qquad\qquad du=-\frac{2V}{3r}dt \qquad (3)$$

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 modulated spectrum can easily be obtained by solving the set of SDEs (Eqs.(2) and (3)) numerically, ‘backward in time’ (Yamada, Yanagita & Yoshida 1998; Zhang 1999) starting from the boundary of the galactic sphere to the earth (at 8.5 kpc from the Galactic Center). We integrated numerically Eqs.(2) and (3) assuming the diffusion coefficient κ as

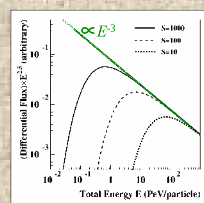
$$\kappa = S\kappa_{\mathrm{Bohm}} \approx 3.3\times10^{28}\, S\, Z^{-1}\left(\frac{E}{1\mathrm{PeV}}\right)\left(\frac{B}{1\mu\mathrm{G}}\right)^{-1}\mathrm{cm^2sec^{-1}} \qquad (4)$$

where S is the ratio of the mean free path of the particle to the Larmor radius and κ_{Bohm} is the Bohm diffusion coefficient, $\kappa_{\mathrm{Bohm}} = Ec/(3ZeB)$ (where E, Z and B are the total energy of particle, the atomic number and the magnetic field intensity, respectively).

3. Results

Fig. 3 shows the calculated differential energy spectra of protons at the earth as a function of total energy E. The solid, dashed and dotted lines are the differential intensity with S = 1000, 100 and 10, respectively. Here we assume the boundary is at R = 100 kpc from the Galactic center (Zirakashvili et al. 1996), and also assume V and B are a constant of 300 km $\mathrm{sec^{-1}}$ and 1 μG, respectively (Zirakashvili et al. 1996). The straight line indicates the assumed unmodulated spectrum at the boundary of the galactic sphere. The break point of the spectrum should be compared with the knee. Fig. 3 suggests we can reproduce the knee by choosing an appropriate value for κ even for the fixed values of R and V. We can also find that if S increases 10 times, the break point is shifted to the lower energy by a factor of 10. It is important to remark how is the break point shifted when the another parameters, R, V and B are changed. If R, V and B increases 10 times, the break point is shifted to the higher energy by a factor of 10. For example, when we adopt V = 150 km $\mathrm{sec^{-1}}$ and B = 2 μG, the resultant spectra are the almost same as in Fig. 3.

In addition, we calculated the modulated energy spectra of hypothetical nuclear components instead of protons. The results are shown in Fig. 4, where each lines are the differential intensity of components labeled in the figure at the earth with, for example, S = 1000. We can find that the break point of the nuclear components is shifted to the higher energy by a factor of Z compared with that for protons. This results imply that the nuclear components of extragalactic CRs might also contribute to the origin of the knee.



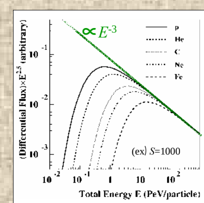
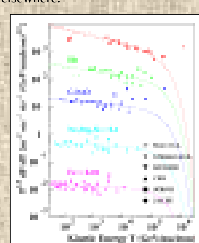


Figure 3: Modulated energy spectra of protons at the earth. The solid, dashed and dotted lines are the differential intensity of protons for R = 100 kpc, V = 300 km $\mathrm{sec^{-1}}$ and B = 1 μG with S = 1000, 100 and 10, respectively. The straight line indicates the differential energy spectrum of the hypothetical CR protons at the boundary of the galactic sphere R=100 kpc which is a power law in total energy with a spectral index of -3.0.

Figure 4: Modulated energy spectra of nuclear components at the earth. The modulated components are calculated with S = 1000 and with the same values for R, V and B as in Fig. 3.

To demonstrate how well our model reproduces the observed all particle spectrum near the knee region, we reexamined published data of CRs which are believed to originate in SNRs in our Galaxy as shown in Fig. 4 as a function of kinetic energy per nucleon T. We fit the observed spectrum of each element as a function of T as $F(T) \propto T^{-\alpha}\exp(-T/(ZE_{max}/A))$, where E_{max} is the maximum energy of protons which may come from the maximum energy attained by protons accelerated in SNRs. We assumed in this fitting E_{max} = 500 TeV and also assumed that (Z, A) are (7, 14) for CNO-group and (12, 24) for NeMgSi-group, respectively. We define the sum of these components shown in Fig. 5 as ‘SNR component’.

Fig. 6 shows the resultant all particle spectrum around the knee when we superpose the two components, namely the modulated extragalactic component and SNR component, together with the all particle data obtained by various experiments. Here we assume the galactic modulated component as the proton spectrum calculated with R = 100 kpc, V = 300 km $\mathrm{sec^{-1}}$, B = 1 μG and S = 250. As clearly seen in Fig. 6, we find our model reproduces the observed spectrum around the knee fairly well. We demonstrated our model for a simplistic case of spherical symmetric geometry with specific forms of κ. Details for much general and realistic settings will appear elsewhere.



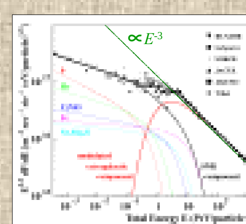


Figure 5: Differential energy spectra obtained by various direct measure-ments as a function of kinetic energy per nucleon and the best fit curves for each element. The data were adopted from Ryan, Ormes & Balasubrahman-yan (1972), Ivanenko et al. (1993), Swordy et al. (1993), Ichimura et al. (1993), Asakimori et al. (1998) and Apanasenko et al.(2001).

Figure 6: Observed all-particle spectrum and the model spectrum around the knee versus total energy of particle. The observed data were adopted from Grigorov et al. (1971), Nagano et al. (1984), Ivanenko et al. (1993), Amenomori et al. (1996), Asakimori et al. (1998) and Apanasenko et al. (2001). The thick solid line indicates the model all-particle spectrum which is the superposition of two components shown by two solid lines and labeled as ‘SNR component’ and ‘modulated extragalactic component’. The ‘SNR component’ is the sum of all nuclear components (shown by thin lines) which are presented in Fig. 5 but presented here as functions of different energy scale. The modulated component is calculated with S = 250 and with the same values for R, V and B as in Fig. 3. The numerical factor in κ was chosen so that the model spectrum reproduces best the observed spectrum.

4. Summary

The all-particle spectrum of CRs around the knee is explained by the superposition of CRs originated in SNRs in our galaxy and the hypothetical extragalactic CRs modulated by the galactic wind. The CRs above the knee region may be survivors of the extragalactic CRs in the battle against the outflowing galactic wind.