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

Hiroshi Muraishi
Department of Radiological Sciences, Ibaraki Prefectural University of Health Sciences, 4669-2 Ami, Ami-Cho, Ibaraki 300-0394, Japan
Shohei Yanagita, and Tatsuo Yoshida
Faculty of Science, Ibaraki University, 2-1-1 Bunkyo, Mito, Ibaraki 310-8512, Japan

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.

1. Introduction

Cosmic rays (CRs) with energies below the knee ($\sim 3\times10^{15}$ eV) 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 RX J1713.7−3946 (Koyama et al. 1997; Slane et al. 1999; Muraishi et al. 2000; Enomoto et al. 2002). 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, Liew & 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. Here, we numerically examine such a possibility, and discuss their implications for the origin of the knee.

pp. 1–8

2. Numerical simulations and Results

We postulate the existence of hypothetical CRs just outside of the "galactic sphere" where the galactic wind (Breitschwerdt, McKenzie & Völk 1991) terminates. 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)

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

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

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

and

$$du = -\frac{2V}{3r}dt, \tag{3}$$

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 two functional forms for κ, $\kappa_1 P$ and $\kappa_1 E$, where κ_1, P, and E are some constant, the rigidity, and the total energy of particle, respectively.

Fig. 1. 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 $\kappa_1 = 10^{32}$, 10^{31} and 10^{30} cm^2 sec^{-1} PV^{-1}, respectively. Here we chose the values for κ_1 hinted at the Bohm diffusion coefficient $\sim 3.3 \times$

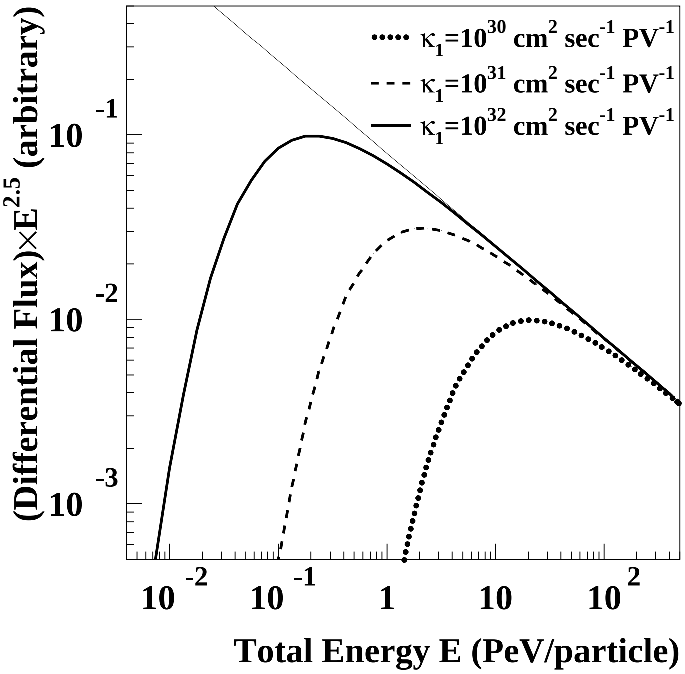

Fig. 1. Modulated energy spectra of protons at the earth.

$10^{29}(E/\mathrm{PeV})(B/0.1\mu\mathrm{G})^{-1}$ cm^2 sec^{-1} for proton. B is the magnetic field intensity in 0.1μG. For protons the resultant spectra are the same whichever functional form of κ is chosen while the same numerical value is adopted for κ_1. Here we assume the boundary is at $R = 100$ kpc from the Galactic center and also assume V is a constant of 300 km sec^{-1}. For other elements than protons, resultant spectra may differ between the two functional forms of κ even for the same value of κ_1. While κ is proportional to the total energy the break point appears at the same energy for protons, however, when κ is proportional to the rigidity, the break point is shifted to the higher energy by a factor of Z, where Z is the atomic number. For the sake of simplicity, we assume hereafter κ is proportional to the total energy of particle. The straight line indicates the assumed unmodulated spectrum 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. The break point of the spectrum should be compared with the knee. Fig. 1. suggests we can reproduce the knee by choosing an appropriate value for κ_1 even for the fixed values of V and R.

Fig. 2. shows the model spectrum around the knee when we superpose the two components, namely 'modulated extragalactic component' and 'SNR component', together with the all particle data obtained by various experiments. Here we assume the modulated extragalactic component as the proton spectrum calcu-

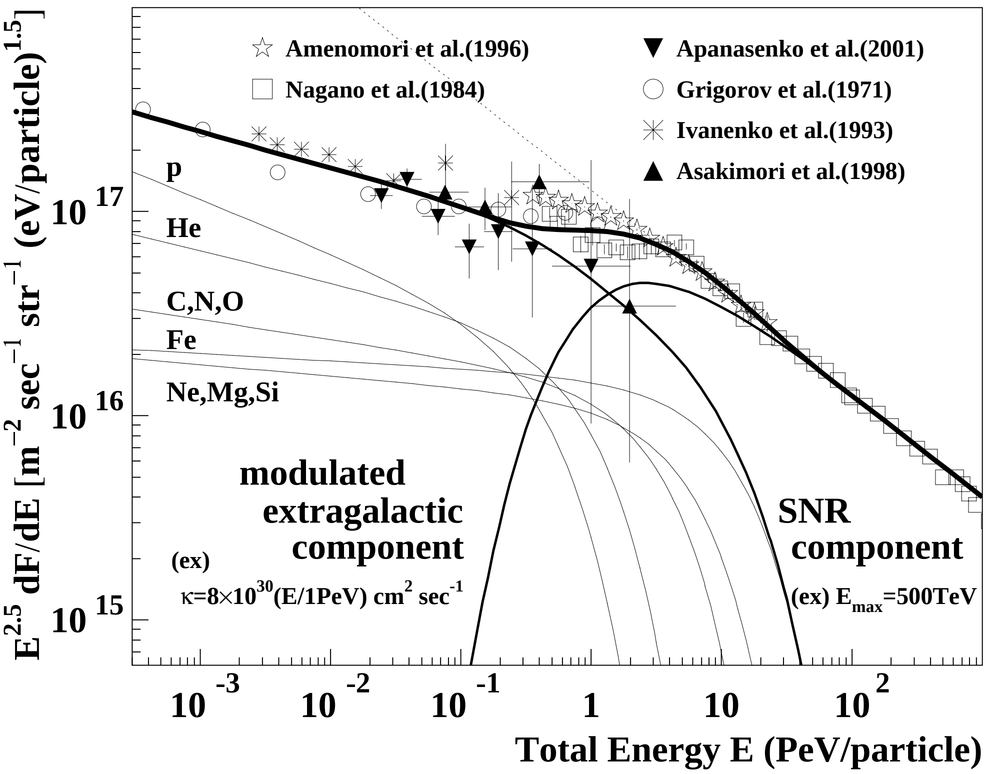

Fig. 2. The model spectrum around the knee versus total energy of particle. The modulated component is calculated with $\kappa = 8 \times 10^{30}$ $(E/1\mathrm{PeV})$ cm^2 sec^{-1} and with the same values for V and R as in Fig. 1..

lated with $V = 300$ km sec^{-1}, $R = 100$ kpc and $\kappa = 8 \times 10^{30}$ $(E/1\mathrm{PeV})$ cm^2 sec^{-1}. The SNR component is defined as follows by using published data of CRs in TeV region which are believed to originate in SNRs in our Galaxy. We fit the observed spectrum of each element as a function of E as $F(E) \propto E^{-\alpha} \exp\left(-E/(ZE_{\mathrm{max}})\right)$, where E_{max} is the maximum energy of protons which may come from the maximum energy attained by protons accelerated in SNRs. The resultant fitted curves for p, He, CNO-group, NeMgSi-group and Fe are shown by the thin solid lines. In this fitting, we assumed $E_{\mathrm{max}} = 500$ 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 as SNR component. As clearly seen in Fig. 2., we find our model reproduces the observed spectrum around the knee fairly well.

On inspection of Fig. 2., we also find the mean mass of the CRs around the knee should change with energy in complicated manner, because SNR component diminishes gradually depending on its charge and the modulated component creeps in as energies go up. Notice that the spectral shape of the modulated

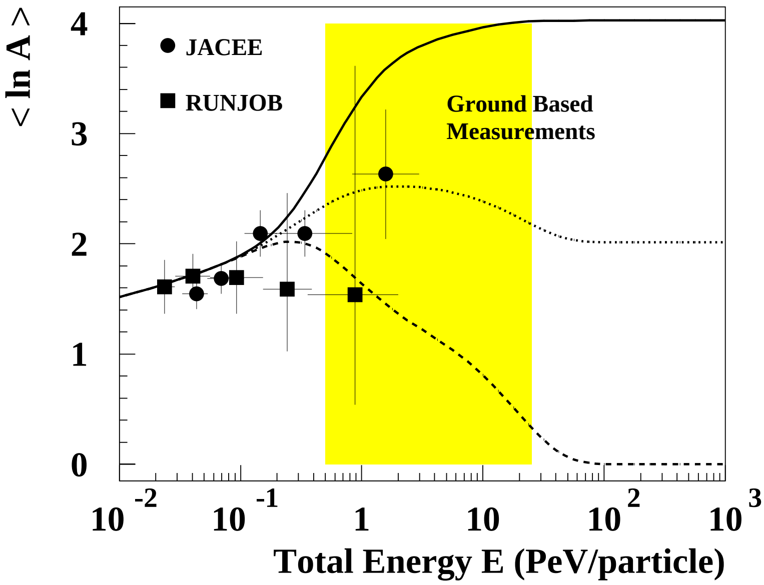

Fig. 3. Mean mass of cosmic rays around the knee as a function of total energy of particle. Symbols indicate the values obtained by direct measurements (Asakimori et al. 1998; Apanasenko et al. 2001). The hatched region shows schematically the range of mean mass values versus total energy of particle by various ground-based measurements (Swordy et al.2002).

component shown in Fig. 2. does not depend on its chemical composition, as we have shown above, because here we assume κ is proportional to the total energy of particle. We have to estimate the expected mean mass to be compared with measurements by assuming the chemical composition of the hypothetical CRs, because we do not know it. The results for three extreme cases are shown in Fig. 3. by three lines together with the mean mass determined by direct measurements in regions below the knee; dashed, solid, and dotted lines indicate the three cases of, 100 % proton, 50 % proton and 50 % iron, and 100 % iron, respectively. Experimental determinations of the mean mass in the region above the knee are, however, scattered in rather wide range (hatched region shown schematically in Fig. 3.) for various cause depending on the methods in ground-based measurements and also on the interaction models of hadrons in the data analysis (for details see Swordy et al.(2002)). Our model predicts the mean mass above $\sim$ 50 PeV would tend to that of the hypothetical extragalactic CRs as inferred from Figs. 2. and 3.. Our model should be testified by future experiments in the energy range much higher than the knee.

3. 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 expected mean mass of CRs around the knee is calculated as a function of energy which should be testified by future measurements. Details for much general and realistic settings will appear elsewhere.

4. References

1. Amenomori M. et al. 1996, ApJ 461, 408
2. Apanasenko A. et al. 2001, Astropart. Phys. 16, 13
3. Asakimori K. et al. 1998, ApJ 502, 278
4. Blandford R., Eichler D. 1987, Phys. Rep. 154, 1
5. Breitschwerdt D., McKenzie J., Völk H. 1991, A&A 245, 79
6. Burles S., Nollett K., Turner M. 2001, ApJ 552, L1
7. Enomoto R. et al. 2002, Nature 416, 823
8. Ensslin T., Lieu R., Biermann P. 1999, A&A 344, 409
9. Erlykin A., Wolfendale A. 1998, Astropart. Phys. 8, 265
10. Fichtel C., Linsley J. 1986, ApJ 300, 474
11. Grigorov N. et al. 1971, Proc. 12th Int. Cosmic Ray Conf.(Tasmania) 5, 1746, 1752, 1760
12. Hillas A. 1984, Ann. Revs. Astron. Astrophys. 22, 425
13. Ivanenko I. et al. 1993, Proc. 23rd Int. Cosmic Ray Conf.(Calgary) 2, 17
14. Jokipii J., Morfill G. 1985, ApJ 290, L1
15. Jones F., Ellison D. 1991, Space Sci. Rev. 58, 259
16. Koyama K. et al. 1995, Nature 378, 255
17. Koyama K. et al. 1997, Publ. Astron. Soc. Japan 49, L7
18. Loeb A., Waxman E. 2000, Nature 405, 156
19. Muraishi H. et al. 2000, A&A 354, L57
20. Nagano M. et al. 1984, J. Phys. G 10, 1295
21. Parker E. 1965, Planetary Space Science 13, 9
22. Slane P. et al. 1999, ApJ 525, 357
23. Swordy S. et al. 2002, astro-ph/0202159
24. Tanimori T. et al. 1998, ApJ 497, L25
25. Yamada Y., Yanagita S., Yoshida T. 1998, Geophys. Res. Lett. 25, 2353
26. Zhang M. 1999, ApJ 513, 409
27. Zirakashvili V. et al. 1996, A&A 311, 113