Galactic modulation of extragalactic cosmic rays: Possible origin of the knee in the cosmic ray spectrum

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The existence of the spectral break around \( \sim 3 \times 10^{15} \) eV in the cosmic ray spectrum (referred to as the ‘knee’) is one of the biggest questions in cosmic ray astrophysics. At the same time, the origin of cosmic rays above the knee energies (between \( 10^{15} \) and \( 10^{18} \) eV) is also still unsettled. In this paper, we investigate how the hypothetical extragalactic CRs after modulated by the galactic wind contribute to the knee in the CR spectrum. We numerically calculate the modulated energy spectrum of the hypothetical cosmic rays coming into the galaxy from just outside of the “galactic sphere” where the galactic wind terminates. We show 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

Observations have revealed cosmic rays (CRs) spread over 11 decades of energy from \( \sim 10^9 \) eV to \( \sim 3 \times 10^{20} \) eV. The spectrum is often fitted by power laws of energy with the index of \( \sim -2.7 \) below \( 3 \times 10^{15} \) eV and \( \sim -3.0 \) above, respectively. This break in the spectrum is referred to as the ‘knee’ in the spectrum. The knee has been recognized as an important structure of the energy spectrum, which may provide constraints on the acceleration and propagation of CRs.

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.¹,²) This argument of the CR origin is corroborated by recent observations of X-rays (by ASCA) and TeV gamma-rays (by CANGAROO and HESS) from two SNRs, SN1006³,⁴) and RX J1713.7–3946.⁵–⁹) These observations have revealed that electrons and protons are accelerated to energies of \( \sim 100 \) TeV in the SNRs. ⁶) However this maximum energy does not reach the knee energy of \( \sim 3 \times 10^{15} \) 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.¹¹) Alternative interpretations of the knee structure are to invoke one or a few extra components of galactic origin which dominate above \( \sim 1 \) PeV.¹²–¹⁵) 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 galaxies¹⁶) and from the observation of the diffuse cosmic gamma-ray background.¹⁷,¹⁸) If nuclear components with energies extended well above \( \sim 1 \) PeV.

¹) For SN1006, there is discrepancy between the results of CANGAROO-I and HESS; an upper limit reported by HESS is below the flux detected by CANGAROO-I.¹⁰)
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.

§2. Numerical Simulations

We postulate the existence of hypothetical CRs just outside of the “galactic sphere” where the galactic wind 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 symmetric case

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

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 $\kappa$ 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

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

and

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

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 $r$. If we integrate the SDEs “backward in time” 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 $r_0$ from the Galactic Center. 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 boundary of the galactic sphere $R$. 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,

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

This method has been applied successfully to the investigation of the solar modulation phenomena of the galactic CRs in the heliosphere. The momentum
spectrum of the hypothetical CRs at the boundary $R$ is $f_R \propto p^{-5}$, if we assume the spectrum is proportional to $E^{-3}$ as mentioned earlier.

We integrated numerically Eqs. (2) and (3) assuming the diffusion coefficient $\kappa$ as

$$\kappa = \eta \kappa_B \sim 3.3 \times 10^{28} \eta Z^{-1} \left( \frac{E}{1 \text{ PeV}} \right) \left( \frac{B}{1 \mu \text{G}} \right)^{-1} \text{cm}^2 \text{sec}^{-1}, \quad (5)$$

where $\eta$ is the ratio of the mean free path of the particle to the Larmor radius and $\kappa_B$ is the Bohm diffusion coefficient, $\kappa_B = E_c/(3 Z e B)$ (where $E$, $Z$, and $B$ are the total energy of particle, the atomic number and the magnetic field intensity, respectively).

The resultant modulated spectrum at an arbitrary point $r_0$ depends on five parameters, $\eta$, $Z$, $R$, $V$, and $B$, where these parameters are unknown to us. According to the study of the galactic MHD wind driven by CRs in a rotating galaxy,$^{25}$ it is expected that our Galaxy is surrounded by a large galactic wind halo with a scale of the order of $R \sim 100$ kpc. Also, the resultant velocity profile reveals that it increases almost linearly with distance from the galactic disk up to $20$ kpc and then becomes a constant with about $\sim 300$ km s$^{-1}$ up to $\sim 100$ kpc. When the extragalactic CRs propagate into inner region of the galactic sphere, it will spend long times in the outer region of the galactic sphere rather than the inner region like around the galactic disk. Therefore we should select $R \sim 100$ kpc and $V \sim 300$ km s$^{-1}$ in our calculation.

§3. Results

3.1. Galactic Modulated Spectrum

Fig. 1(a) shows the calculated differential energy spectra of protons ($Z=1$) at the earth ($r_0 = 8.5$ kpc) as a function of total energy $E$. The solid, dashed, and dotted lines are the differential intensity with $\eta = 1000$, 100, and 10, respectively. Here we assume $V = 300$ km sec$^{-1}$, $R = 100$ kpc, and $B = 1 \mu$G. 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. We can find that the spectrum is break around the knee energy. We also find that if $\eta$ increases by some factor, the break point is shifted to the lower energy by the same factor. We also calculated the modulated energy spectra of hypothetical nuclear components instead of protons. The results are shown in Fig. 1(b), where each lines are the differential intensity of components labeled in the figure at the earth with $\eta = 1000$ as an example. We 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. It may also be worth remarking how is the break point shifted when the other parameters, $B$, $R$, and $V$ are changed. The resultant spectra are shown in Fig. 1(c)-(e). Here if we define the breaking energy $E_{\text{break}}$ as the energy in which the modulated spectrum shown in Fig. 1 becomes a maximum, it is approximately shown as

$$E_{\text{break}}(Z, \eta, B, R, V) \sim 6 \times 10^{15} Z \eta^{-1} B_\star R_\star V_\star \text{eV}, \quad (6)$$
Fig. 1. Expected energy spectra of the hypothetical CRs modulated by the galactic wind. The straight line indicates the differential energy spectrum of the hypothetical CRs with $Z$ at the boundary of the galactic sphere $R$, which is a power law in total energy with a spectral index of $-3.0$. (a) the differential intensity of protons ($Z=1$) at the earth ($r_0 = 8.5$ kpc) for $R = 100$ kpc, $V = 300$ km sec$^{-1}$, and $B = 1 \mu G$ with $\eta = 1000$ (solid line), 100 (dashed line), and 10 (dotted line), respectively. (b) Same as (a) but with five values of $Z$ for $\eta = 1000$, $R = 100$ kpc, $V = 300$ km sec$^{-1}$, and $B = 1 \mu G$. (c) Same as (a) but with four values of $R$ for $\eta = 100$, $Z=1$, $R = 100$ kpc, $V = 300$ km sec$^{-1}$, and $B = 1 \mu G$. (d) Same as (a) but with four values of $V$ for $\eta = 100$, $Z=1$, $R = 100$ kpc, and $B = 1 \mu G$. (e) Same as (a) but with four values of $B$ for $\eta = 100$, $Z=1$, $R = 100$ kpc, and $V = 300$ km sec$^{-1}$. (f) Same as (a) but at four values of an arbitrary point $r_0$ for $\eta = 100$, $Z=1$, $R = 100$ kpc, $V = 300$ km sec$^{-1}$, and $B = 1 \mu G$. 

- $\eta = 1000$, $\eta = 100$, $\eta = 10$
- $p$, $\cdot \cdot \cdot$ He, $\cdot \cdot \cdot$ C, $\cdot \cdot \cdot$ Ne, $\cdot \cdot \cdot$ Fe
- $R = 25$ kpc, $\cdot \cdot \cdot$ R = 50 kpc, $\cdot \cdot \cdot$ R = 100 kpc, $\cdot \cdot \cdot$ R = 200 kpc
- $V = 30$ km sec$^{-1}$, $\cdot \cdot \cdot$ V = 100 km sec$^{-1}$, $\cdot \cdot \cdot$ V = 300 km sec$^{-1}$, $\cdot \cdot \cdot$ V = 600 km sec$^{-1}$
- $B = 0.1 \mu G$, $\cdot \cdot \cdot$ B = 0.3 $\mu G$, $\cdot \cdot \cdot$ B = 1 $\mu G$, $\cdot \cdot \cdot$ B = 3 $\mu G$
- $r_0 = 8.5$ kpc, $\cdot \cdot \cdot$ r$_0$ = 35 kpc, $\cdot \cdot \cdot$ r$_0$ = 60 kpc, $\cdot \cdot \cdot$ r$_0$ = 85 kpc
where $\eta_*=\eta/(100)$, $B_*=B/(1\mu G)$, $R_*=R/(100\text{kpc})$, and $V_*=V/(300 \text{ km s}^{-1})$, respectively. This results indicate clearly that we can reproduce the knee by choosing an appropriate values for these parameters.

In addition, in order to investigate how the spectrum is modulated in arbitrary points other than the earth, we calculated the modulated spectra at four values of $r_0$. The results are shown in Fig. 1(f). We found that if $r_0$ approaches the boundary $R$, the break point of the spectrum shifts to low energy more and the modulated spectrum diminishes more rapidly as energies go down at the same time. This result indicates that the hypothetical extragalactic CRs with energy lower than at least TeV cannot penetrate into the inner region of our galactic sphere due to the effect of modulation by the galactic wind.

3.2. Model Spectrum (Two Components Model)

In this section, to demonstrate how well our model reproduces the observed all-particle spectrum near the knee region, we consider a simple model which is mentioned below. We assume that the all-particle spectrum observed at the earth $F_{\text{total}}(E)$ is superposition of the two components, namely the modulated extragalactic component $F_{\text{modul}}(E)$ and the component originated in SNRs in our Galaxy $F_{\text{SNR}}(E)$ as

$$F_{\text{total}}(E) = F_{\text{SNR}}(E) + F_{\text{modul}}(E),$$

(7)
and $F_{\text{SNR}}(E)$ and $F_{\text{modul}}(E)$ are represented as

$$F_{\text{SNR}}(E) = \sum_Z f_Z^{\text{SNR}}(E)$$

(8)

$$F_{\text{modul}}(E) = \sum_Z f_Z^{\text{modul}}(E),$$

(9)

where $f_Z^{\text{SNR}}(E)$ and $f_Z^{\text{modul}}(E)$ are each nuclear components, respectively. Now we consider that $F_{\text{SNR}}(E)$ consists of the sum of components after propagated in interstellar space from each of SNRs in our Galaxy, in which particles are accelerated to a power law by shock acceleration. Thus we simply assume that each nuclear component observed at the earth $f_Z^{\text{SNR}}(E)$ is represented by a power law with each spectral index of $\alpha$ as

$$f_Z^{\text{SNR}}(E) \propto E^{-\alpha}\exp(-E/(ZE_{\text{max}})),$$

(10)

where $E_{\text{max}}$ is the maximum energy of protons which may come from the maximum energy attained by protons accelerated in SNRs. Here we reexamined published data of CRs which are believed to originate in SNRs in our Galaxy as shown in Fig. 2 as a function of kinetic energy per nucleon $T$. Here we fit with $f_Z^{\text{SNR}}(T) \propto T^{-\alpha}\exp(-T/(ZE_{\text{max}}/A))$ because the published data is represented as a function of $T$. We assumed in this fitting $E_{\text{max}} = 500$ TeV for example, 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. 2 as SNR component $F_{\text{SNR}}(E)$.

Fig. 3 show the resultant model spectrum $F_{\text{total}}(E)$ around the knee for two example cases with the all-particle data obtained by various experiments. Fig. 3(a) shows a model spectrum when we adopt $F_{\text{modul}}(E)$ for the modulated proton spectrum $f_p^{\text{modul}}(E)$ calculated with $\eta = 250$, $R = 100$ kpc, $V = 300$ km sec$^{-1}$, and $B = 1$ $\mu$G. As clearly seen in Fig. 3(a), we find our model reproduces the observed spectrum around the knee fairly well. We emphasize that we can replace the modulated proton spectrum $f_p^{\text{modul}}(E)$ with another nuclear component $f_Z^{\text{modul}}(E)$ calculated with the values according to the roles shown in Eq.(6). For example, if we adopt $\eta = 500$, $R = 100$ kpc, $V = 300$ km sec$^{-1}$, and $B = 0.077$ $\mu$G, we can replace $f_p^{\text{modul}}(E)$ with the modulated iron spectrum $f_{\text{Fe}}^{\text{modul}}(E)$.

On the other hand, we don’t know the chemical composition of the hypothetical extragalactic CRs. As an extreme example, we assume compound $F_{\text{modul}}(E)$ which consists of the same spectrum of $f_p^{\text{modul}}(E)$, $f_{\text{He}}^{\text{modul}}(E)$, $f_{\text{CNO}}^{\text{modul}}(E)$, $f_{\text{NeMgSi}}^{\text{modul}}(E)$, and $f_{\text{Fe}}^{\text{modul}}(E)$ at the boundary. The result is shown in Fig. 3(b), where we adopt $\eta = 250$, $R = 100$ kpc, $V = 300$ km sec$^{-1}$, and $B = 1$ $\mu$G, and each abundance ratio at the boundary is five times smaller than that for the case in Fig. 3(a). We can also reproduce a spectrum by using the model with compound of $F_{\text{modul}}(E)$. We demonstrated our model for a simplistic case of spherical symmetric geometry with specific forms of $\kappa$.

### 3.3. Mean Mass of CRs around the Knee

On inspection of Fig. 3 we also find the mean mass of the CRs around the knee should change with energy in complicated manner, because SNR component
Fig. 3. Observed all-particle spectrum and the model spectrum around the knee versus total energy of particle $E$. The observed data were adopted from Refs. 27), 30–34). The thick solid line indicates the model all-particle spectrum $F_{\text{total}}(E)$ which is the superposition of two components shown by two solid lines; SNR component $F_{\text{SNR}}(E)$ and modulated extragalactic component $F_{\text{modul}}(E)$. The SNR component is the sum of all nuclear components presented in Fig. 2 but presented here as functions of different energy scale. (a) Single component model for $F_{\text{modul}}(E)$. Modulated component is calculated for proton $f_{\text{p modul}}(E)$ with $\eta = 250$ and with the same values for $R$, $V$, and $B$ as in Fig. 1(a). Straight dotted line indicates the energy spectrum of the hypothetical CRs at the boundary $R$ as $\sim 4.3 \times 10^{20} \text{ cm}^{-2} \text{ sec}^{-1} \text{ str}^{-1} \text{ eV}^{-1}$. Notice that we can replace $f_{\text{p modul}}(E)$ with another nuclear component $f_{\text{Z modul}}(E)$ (see in the text in details). (b) Composite model for $F_{\text{modul}}(E)$. Modulated component consists of the sum of five chemical components ($f_{\text{p modul}}(E)$, $f_{\text{He modul}}(E)$, $f_{\text{CNO modul}}(E)$, $f_{\text{NeMgSi modul}}(E)$, and $f_{\text{Fe modul}}(E)$). Each components is calculated with $\eta = 250$, $R = 100$ kpc, $V = 300$ km sec$^{-1}$, and $B = 1$ $\mu$G, where each spectrum assumed at the boundary $R$ is the same (shown as straight dotted line) and is five times smaller than that for the case in Fig. 3(a). In both figures, the numerical factor in $\kappa$ was chosen so that the model spectrum reproduces best the observed spectrum.

diminishes gradually depending on its charge and the modulated component creeps in as energies go up. 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. By using the results of our model spectrum shown in Fig. 3 we calculated mean mass of the CRs. The results are shown in Fig. 4 as a function of total energy $E$ with the mean mass determined by direct measurements in regions below the knee. Dashed and solid lines indicate the case for a model with $F_{\text{modul}}(E) = f_{\text{p modul}}(E)$ and with $F_{\text{modul}}(E) = f_{\text{Fe modul}}(E)$ in Fig. 4(a), and dotted line with a composite abundance for $F_{\text{modul}}(E)$ in Fig. 4(b), respectively. Experimental determinations of the mean mass in the region above the knee are, however, scattered in rather wide range for various cause depending on the methods in ground-based measurements and also on the interaction models of hadrons in the data analysis. 35)–37) Our model predicts the mean mass above $\sim 50$ PeV would tend to that of the hypothetical extragalactic CRs as inferred from Figs. 3 and 4. Our model should be testified by future experiments in the energy range much higher than the knee.
§4. Discussion

4.1. Energetics of the hypothetical CRs

Heretofore we have simply assumed the existence of the hypothetical extragalactic CRs without any specification of their origin. We should address some comments on their origin including energetics. As an extreme case, if the hypothetical CRs pervade the intergalactic space uniformly and the spectrum is extended down to their rest mass energy as \( \sim 4.3 \times 10^{20} E^{-3} \) cm\(^{-2}\) sec\(^{-1}\) str\(^{-1}\) eV\(^{-1}\) which we have assumed in Fig. 3(a) (straight dotted line), their energy density is estimated to be as high as \( \sim 294 \) eV cm\(^{-3}\) when we assume they are protons. The density parameter corresponding to this energy density is \( \Omega h_{70}^2 \sim 0.057 \) which is much larger than that of total baryon in the universe of \( \Omega h_{70}^2 \sim 0.020 \) invoked by the Big Bang Nucleosynthesis. Therefore it is natural to consider that either the spectrum becomes harder and/or there is a cut off by other reasons in the energy region lower than the knee, and/or the hypothetical CRs are confined in local regions surrounding galaxies as well as our Galaxy and/or cluster of galaxies. Actually if we assume that the hypothetical CR spectrum becomes harder with the index of 2 in the energy range lower than \( 10^{14.5} \) eV, then the expected energy density is estimated to be as small as \( 7.9 \times 10^{-3} \) eV cm\(^{-3}\) without any influence on the resultant modulated spectrum. Yet there might remain a possibility that some portion of the density parameter comes from these invisible hypothetical CRs.

4.2. Hypothetical CRs in SMC

Measurements with the EGRET telescope show that the density of CRs inside the Small Magellanic Cloud (SMC) is several times less than in our Galaxy. This fact indicates simply that GeV CRs may originate in each galaxy, possibly in SNRs. This results seem to be incompatible with the existence of the hypothetical extragalactic CRs which we introduced here. However if SMC have the galactic wind like our galaxy, the intensity of hypothetical CRs around GeV region inside SMC should be suppressed due to the modulation effect of SMC itself. Actually the galactic wind may have collided with that of SMC, LMC, etc., and it may have the complicated structure in which the shock waves are produced on the boundary. In this paper we do not address its detail. To investigate the behaviour of the hypothetical CRs in details, we need further simulation study for complex model using three-dimensional code including a few galactic sphere (for our Galaxy, LMC, SMC, etc.).

4.3. Possible Origin of Hypothetical CRs

There are some scenarios to support the existence of the hypothetical extragalactic CRs which we introduced here. Völk & Atonyan discussed 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. Another interesting scenario is that it is possible to accelerate CR protons up to \( \sim 10^{18} \) eV by cosmic shock waves which are generated by large scale structure formation and by mergers between clusters of galaxies. Miniati et al.
have carried out a computational study of production of CR protons at cosmological shocks and pointed out that a significant fraction of the total energy associated with baryons inside a cluster could be stored in CRs as a consequence of diffusive particle acceleration at structure formation shocks. In the future, GeV–TeV γ-ray observation of the violent cluster merger event shown in the evidence for shock acceleration\(^45\), 46\) might directly lead to the existence of shock accelerated extragalactic CRs and might clear the relation between the extragalactic CRs and the CRs above the knee energy.

§5. Conclusion

We show that the galactic wind can provide a cutoff in about the right energy range lower than that around the knee. 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.

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