Spatial Dependent Diffusion of Cosmic Rays and the Excess of Primary Electrons Derived from High Precision Measurements by AMS-02

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Abstract: The precise spectra of Cosmic Ray (CR) electrons and positrons have been published by the measurement of AMS-02. It is reasonable to regard the difference between the electrons and positrons spectra ( \( \Delta \Phi = \Phi_{e^-} - \Phi_{e^+} \) ) as being dominated by primary electrons. Noticing that the resulting electron spectrum shows no sign of spectral softening above 20 GeV, which is in contrast with the prediction of standard model. In this work, we generalize the analytic one dimensional two-halo model of diffusion to a three dimensional realistic calculation by implementing a spatial variant diffusion coefficients in DRAGON package. As a result, we can reproduce the spectral hardening of protons observed by several experiments, and predict an excess of high energy primary electrons which agrees with the measurement reasonably well. Unlike the break spectrum obtained for protons, the model calculation predicts a smooth electron excess and thus slightly over predicts the flux from tens of GeV to 100 GeV. To understand this issue, further experimental and theoretical studies are necessary.

1 Introduction

With unprecedented high precision, the AMS02 collaboration has recently confirmed the excess of positron fraction previously observed by PAMELA [1, 2]. The data shows a discrepancy from the prediction of standard model of CR propagation (conventional model), where the data dramatically rises at energies \( \sim 10 - 300 \) GeV, and this is concluded as the excess of positron. Proposed explanations include dark matter annihilations/decay [3, 4], extra sources such as pulsars [3, 4], production of secondary lepton occurs around acceleration sources [5, 8], or interactions between high-energy CRs and background photons [9, 10]. The precise measurement of AMS also gives us an opportunity to study the spectrum of primary electrons. Considering that the excess components of positrons and electrons are equally produced either from dark matter annihilation/decay or nearby Pulsar acceleration, though secondary productions by cosmic rays interaction with gas are not exactly equal but orders of magnitude are smaller than primary electrons in quantity, it is reasonable to treat the difference between the flux of electrons and positrons as the flux of primary electrons ( \( \Delta \Phi = \Phi_{e^-} - \Phi_{e^+} \) ). As is pointed by [11], such obtained spectrum of primary electrons exhibits a roughly constant spectral index for energies above \( \sim 20 \) GeV, while the standard model predicts a continuously softening spectrum. This anomaly suggests an excess of primary electrons. In order to give a good fit to the data, a two-break injection spectrum was found inevitable with allowed parameter space in conventional model [11, 12].

On the other hand, a remarkable spectral hardening of primary CR nuclei and protons at several hundred GeV has been revealed by ATIC [13], CREAM [14], and PAMELA [15]. Possible explanations to this spectral hardening include the spatial dependent diffusion of cosmic rays [16, 17], dual acceleration mechanism at the shock of SNRs [18], interaction of cosmic rays with shock wave [19], or additional contribution from nearby SNRs [20] and so on.

As assumed in Conventional Model (CM), CRs undergo a uniform diffusion in the galaxy, which provides a good but oversimplified approximation to the CR propagation. The CRs diffusion is due to their random scattering on hydromagnetic waves and depends on the magnetic-field irregularities. On the Galactic disk, the irregularities are caused by SNRs explosions, while in the diffusive halo, the irregularities are generated by CRs themselves in the absence of SNRs. It has been found that the spectra of the turbulences in the far outer galaxy and in the halo should be flatter than that in local or inner galaxy [21], which implies strong spatial changes of CR diffusion properties. In this work, we study the impact of latitudinal variation of CR diffusion properties on spectrum of primary electrons, and generalize the Two-Halo Model (THM) [16] to a three dimensional realistic calculation by implementing a spatial variant diffusion coefficients in DRAGON package. For comparison, we also perform CM calculation with DRAGON, which assumes a uniform diffusion of CRs in space. First, we reproduce the spectral hardening of primary protons to determine the relevant parameters, and then we attempt to study the excess of electrons with this scenario.
2 Modeling and parameter settings

It has been long considered that the SNRs are the origin of primary Galactic Cosmic Rays, and the diffusive shock acceleration is regard as the main acceleration mechanism. CRs are accelerated at SNRs and then diffuse in the Galaxy, suffering from fragmentation and energy losses in the ISM and interstellar radiation field (ISRF) and magnetic field, decay and possible reacceleration or convection. Considering those processes, the CRs propagation equation can be written as

\[
\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = Q(\vec{r}, p, t) + \nabla \cdot (D_{xx} \nabla \psi - V_c \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} [\dot{p} \psi - \frac{p}{3} (\nabla \cdot V_c \psi)] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r},
\]

where \(\psi(\vec{r}, p, t)\) is the density of CR particles per unit momentum \(p\) at position \(\vec{r}\), \(Q(\vec{r}, p, t)\) is the source distribution, \(D_{xx}\) is the spatial diffusion coefficient, \(V_c\) is the convection velocity, \(D_{pp}\) is the diffusive reacceleration coefficient in momentum space, \(\dot{p} \equiv \frac{dM}{dt}\) is momentum loss rate, \(\tau_f\) and \(\tau_r\) are the characteristic time scales for fragmentation and radioactive decay respectively. In CM, the CRs diffusion is assumed to be uniform in space and only energy-dependent, and the diffusion coefficient is parametrized as \(D_{xx} = \beta D_0 (\rho/\rho_0)^\delta\), a function where \(\rho\) is the rigidity and \(\delta\) reflects the property of the ISM turbulence. The reacceleration can be described by the diffusion in momentum space and the momentum diffusion coefficient \(D_{pp}\) is coupled with the spatial diffusion coefficient \(D_{xx}\) as

\[
D_{pp}D_{xx} = \frac{4p^2v_A^2}{3\delta(4-\delta)(4-\delta)\omega},
\]

where \(v_A\) is the Alfven speed, \(\omega\) is the ratio of magneto-hydrodynamic wave energy density to the magnetic field energy density, which can be fixed to 1. In this work, we consider a space-dependent diffusion process, and take the parameter \(\delta\) of diffusion coefficient as a variation along \(z\) axis with \(\delta(z)\).

To illustrate the effect of spatial change of CR diffusion properties, we first consider a simplified situation. If we only consider the diffusion process during CRs propagating in the galaxy and neglect other processes, as is described in [12], it can be solved using 1D analytical calculations. Proposed THM considers the latitudinal changes of CR diffusion properties, and it divides the diffusive halo with a typical half-thickness \(L \sim 5\ \text{kpc}\) into two regions, where the inner halo is influenced mainly by SNRs with a half-thickness \(\xi L\ (\xi \sim 0.1)\), and the outer halo dominates the rest wide region driven by CRs themselves. The diffusion coefficient is expressed as

\[
D(z, \rho) = \begin{cases} 
D_0 \beta (\frac{\rho}{\rho_0})^\delta, & \text{for } |z| < \xi L \ (\text{inner halo}) \\
D_0 \beta (\frac{\rho}{\rho_0})^{\delta+\Delta}, & \text{for } |z| > \xi L \ (\text{outer halo})
\end{cases}
\]

where \(\rho\) is rigidity and \(D_0\) specifies its normalization at the reference rigidity \(\rho_0\). This model behaves like a reservoir, where CRs leak out rapidly in the outer halo and can re-enter the inner halo. As the result, the spectrum of CR primary species is read as

\[
N_0 \equiv N(z = 0) \sim \frac{L}{D_0} \{\xi \rho^{-\nu-\delta} + (1-\xi) \rho^{-\nu-\delta-\Delta}\},
\]

which obviously indicates two components of the spectrum. We can derive from Eq. (4) that the inner halo dominates high-energy part with the factor \(\xi\), and the outer halo mainly contributes CRs at low energies with the factor \((1-\xi)\). Because of relative larger diffusion coefficient in the outer halo, CRs possess a higher escape velocity, which causes fast leakage and only the low-energy CRs re-enter the observer on the Galactic disk. In the meanwhile, the inner halo with smaller diffusion coefficient can detain more CRs at high energies. As the consequence, we can derive the spectral hardening of primary protons from the spatial change of CR diffusion properties.

In this work, we use the released DRAGON code to solve the CR propagation equation described in Eq. (1). DRAGON allows us to perform a numerical calculation with a space-dependent coefficient. Without loss of generality, we take the diffusion coefficient index \(\delta(z)\) as the form

\[
\delta(z) = \begin{cases} 
\delta_0 + \Delta (\frac{z}{\xi L})^n, & \text{for } |z| < \xi L \ (\text{inner halo}) \\
\delta_0 + \Delta, & \text{for } |z| > \xi L \ (\text{outer halo})
\end{cases}
\]

where we use a pow-law function to describe the gradual transition from inner halo to outer halo and the index \(n\) is fixed at 5 representing the extent of how sharply \(\delta_0\) changes to \(\delta_0 + \Delta\). We extend the size of inner halo to \(\xi L\) with \(\xi \sim 0.16\) to contain most amount of SNRs. For comparison, we carry out both THM and CM using DRAGON, and the CM is set with a uniform diffusion coefficient in space. Detailed information for parameters of CRs propagation equation is shown in Table 1.

| Parameters | THM | CM |
|------------|-----|----|
| \(D_0 \ \text{(cm}^2 \ \text{s}^{-1})\) | \(5.5 \times 10^{28}\) | \(5.5 \times 10^{28}\) |
| \(v_A \ \text{(km/s)}\) | 25 | 25 |
| \(V_c \ \text{(km/s)}\) | 0 | 0 |
| \(\delta\) | 0.19 | 0.5 |
| \(\Delta\) | 0.39 | |
The injection spectrum of primary CRs at sources region is taken as a broken power-law form

$$Q_i(E_k, r, z) = f_i(r, z)q_i^0 \times \begin{cases} \left(\frac{E}{\rho_{br}}\right)^{-\alpha_0} \exp\left(-\frac{\rho}{\rho_{cut}}\right) & \text{if } (\rho < \rho_{br}) \\ \left(\frac{E}{\rho_{br}}\right)^{-\alpha_1} \exp\left(-\frac{\rho}{\rho_{cut}}\right) & \text{if } (\rho > \rho_{br}) \end{cases}$$

(6)

where $\rho_{br}$ is the break position of rigidity, and $\rho_{cut}$ represents cutoff rigidity. The normalization condition $f_i(r_0, z_0) = 1$ is imposed, where $r_0 = 8.5$ kpc is the distance from the Sun to the Galactic center. The spatial distribution of SNRs $f_i(r, z)$ is modeled as in [28]. Detailed information for injection spectrum of primary protons and electrons is listed in Table 2.

### Table 2. Injection spectrum of primary CRs

| Parameters | Proton | Electron |
|------------|--------|----------|
| $\rho_{0}(GV)$ | 9.0    | 5.7      |
| $\alpha_0$    | 2.1    | 1.7      |
| $\alpha_1$    | 2.31   | 2.7      |
| $\rho_{cut}(GV)$ | 2.5e6  | 20000    |

Following the parameters fixed above, we obtain the spectrum of primary protons. The result is shown in Fig. 1.

![Fig. 1. The proton spectra from measurements and two model calculations. The experiment data of proton come from: AMS02[24], ATIC[25], PAMELA[15], CREAM[26], KASCADE[27].](image)

The red solid line represents THM prediction, and the black solid line represents CM calculation. In both calculations, parameters are tuned to fit well with the AMS data from $10 \rightarrow 10^3$ GeV. At energies above $\sim 10^3$ GeV, THM exhibits a pronounced spectral upturn above $\sim 10^5$ GeV, and is in good agreement with the data within uncertainties. It should be noted that although spectral hardening above $\sim 10^3$ GeV can be recovered, the sharply transition of spectral slope at $\sim 200$ GeV pronounced by PAMELA[15] can’t be reproduced. As a matter of fact, when energy is below $\sim 10$ GeV, the solar modulation comes to play a major role of the spectrum. The effect of solar modulation is taken care by a so called force-field approximation [28], with the modulation potential being 550MV.

As described above, the effect of spatial change of CRs diffusion properties is confirmed to produce the spectral hardening of primary protons by a realistic 3 dimensional model. Observed data above $10^3$ GeV supports this assumption of THM. In next section, we will show the result of primary electrons with same set of diffusion parameters.

### 3 Results of primary electrons

Contrary to primary protons, primary electrons behave more complicated. Propagating electrons suffer severe energy loss by processes such as Synchrotron Radiation and Inverse Compton Scattering, which will rapidly steepen the spectrum of electrons with increasing energies. The power of energy loss is almost proportional to $E^2$, so higher energy electrons lose energy rapidly. TeV electrons lose most of their energies on a timescale of $\sim 10^5$ yr, and they are limited in several hundred parsecs to reach the solar system. Comparing with the power-law or upturn spectra for primary proton in Fig.1, primary electron spectra are heavily attenuated for both THM and CM. Correspondent spectra are shown in Fig.2, together with the subtraction between electron and positron flux $(\Delta \Phi = \Phi_{e^-} - \Phi_{e^+})$ measured by AMS-02.

![Fig. 2. The electron spectrum in two models. $\phi_+\text{ and } \phi_{e^-}$ data are from AMS02[29, 30].](image)

In Fig.2, observed spectrum seems to have a slightly upturned at $\sim 100$ GeV, but there is no sign of spectral break by THM(red solid line). The standard model(black solid line) can well reproduce the data below $\sim 40$ GeV, but becomes insufficient as energy increases.
The spectrum of primary electrons predicted by THM reveals a integral hardening above $\sim 10$ GeV, which make it successfully recover the data within error bars. However, it can be seen that the THM overestimates the flux of primary electrons slightly with respect to the data $\Delta \phi$ between 30 GeV and 100 GeV.

Due to rapid energy losses, primary electrons is strongly affected by the cooling time, while the influence of cooling time on primary protons can be neglected above 10 GeV. The cooling timescale of electrons can be estimated by $\tau_e \sim 17 \ Myr \ (\epsilon_e/10 \ GeV)^{-1}$, and electrons can diffuse a distance of $R = (2D\tau_e)^{1/2}$ in this time, where $D$ is the diffusion coefficient. At 10 GeV, the distances can be calculated as $\sim 3.1 \ kpc$ in CM, $\sim 2.7 \ kpc$ in inner halo and $\sim 3.2 \ kpc$ in outer halo both predicted by THM. It can be seen that the effect of rapid energy losses narrows the effective halo size with respect to the fixed half-thickness 5 kpc of the halo. The effective halo size will continuously shrink with increased energy, so the contribution of inner halo to the total spectrum will increase. As described in former simplified 1D analysis, the inner halo dominates the high energy components with a factor $\xi$ coupled with the contribution of inner halo in steady state. When the factor $\xi$ rises, relatively more high-energy CRs remain in the inner halo and harden the final spectrum. In this scenario, primary electrons predicted by THM will exhibit a integral hardening spectrum above $\sim 10$ GeV.

4 Discussion and conclusion

In this work, we focus on the latitudinal changes of CRs diffusion properties and we can reproduce the spectral hardening of primary protons above $\sim 10^3$ GeV in this scenario. However, obtained spectrum of primary electrons exhibits a integral hardening with no visible upturned break, which gives a good fit with the data above $\sim 100$ GeV and overestimates a little between 30 GeV and 100 GeV. It should be noted, although the THM produces a non-break spectrum similar to the CM prediction, the additional flux obtained with THM can not be reached by only adjusting the global parameters used in CM. The rapid energy losses of CR electrons are responsible for the difference between the spectrum of primary protons and electrons.

In addition, it has been pointed out that a continuous source distribution model is not valid for electrons in energy region above 100 GeV [31], while we still consider a continuous distribution in numerical calculation. The spectrum of electrons at high energies should depend on the age and distance of a few nearby sources, and some nearby discrete sources have been considered to explain the spectrum of electrons [32, 33]. In the meanwhile, the space-dependent effect of CRs diffusion properties has been used to explain the excess spectra widely observed for secondaries [34], the longitude profile of the diffuse $\gamma$-ray emission [17, 35], and the significant fraction of the IceCube neutrino flux [17]. It is worth taking both the effect of spatial change of CRs propagation and nearby discrete sources into account in the future.

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