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# Galactic parameters expected from recent cosmic-ray data

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**Abstract:** Based on our three-dimensional cosmic-ray (CR) propagation model, we estimate Galactic parameters, the gas density of ISM, the diffusion coefficient, and so on. We apply the CR propagation model for the CR elements nowadays available, stable primary ones (p, He, ...), stable secondary ones (B, sub-Fe), unstable ones ($^{10}$Be, $^{26}$Al, ...), antiprotons ($\bar{p}$'s), and the diffusive $\gamma$-rays (D$\gamma$'s). Our propagation model reproduces satisfactorily the all observed data except the enhancement of EGRET D$\gamma$-data appearing in GeV region. It is not yet clear whether the enhancement of $\bar{p}$'s around 0.2–1 GeV is significant or not, as the current data are still too poor to conclude definitely in this stage.

## Introduction

We have studied the CR propagation for stable and the unstable elements as well as the D$\gamma$'s based on our three-dimensional propagation model [7-10]. In this paper, we further study the CR antiprotons (CR-$\bar{p}$'s) in connection with our CR propagation model, combining it with the production cross-section of $\bar{p}$ in p-p collisions [11], which reproduces very well the accelerator data nowadays available. Because of the limited space, we don't touch the details of our propagation model, but present the essence of the model shortly in the next section, particularly the differences from those currently used.

## Model of cosmic-ray propagation

Three Galactic parameters, the diffusion coefficient, $D$, the gas density of the ISM, $n$, and the source density of CRs, $Q$, are the most essential for the study of the CR propagation in the Galaxy, and we assume they have following forms depending on space position $\boldsymbol{r}(r,z)$:

$$D(\boldsymbol{r}) \equiv D(r,z) = D_0 \exp[+(r/r_D + |z|/z_D)], \quad (1)$$

$$n(\boldsymbol{r}) \equiv n(r,z) = n_0 \exp[-(r/r_n + |z|/z_n)], \quad (2)$$

$$Q(\boldsymbol{r}) \equiv Q(r,z) = Q_0 \exp[-(r/r_Q + |z|/z_Q)], \quad (3)$$

where $D_0$, $n_0$ and $Q_0$ correspond to the diffusion coefficient, the gas density and the source density of CR at the Galactic center (GC), $\boldsymbol{r}(0,0)$, respectively, and no clear boundary appears in these parameters in both the longitudinal and the latitudinal directions, but instead we introduce scale heights, ($r_D$, $r_n$, $r_Q$) and ($z_D$, $z_n$, $z_Q$), for the spatial gradients for the Galactic parameters.

In the present work, we often deal with the values of these three parameters at the solar system (SS), which are simply expressed as $D_\odot = D(r_\odot, 0)$, $n_\odot = n(r_\odot, 0)$, and $Q_\odot = Q(r_\odot, 0)$, with $r_\odot$ = 8.5 kpc, respectively.

Although the actual distributions of the above three parameters must be much more complicated, we focus here our concern on the *gross features* of these three in the Galaxy, smearing the complicated structures with local irregularity in the form of the exponential-type gradient.

In the study of D$\gamma$'s, two *average* scale heights, $\bar{r}$ and $\bar{z}$, play essential roles, appearing not in the separate forms of $(r_D, r_n)$ and $(z_D, z_n)$, but always in the coupled forms defined by

$$\frac{1}{\bar{r}} = \frac{1}{2}\left(\frac{1}{r_D} + \frac{1}{r_n}\right); \quad \frac{1}{\bar{z}} = \frac{1}{2}\left(\frac{1}{z_D} + \frac{1}{z_n}\right). \quad (4)$$

We further assume the source CR density $Q$ and the diffusion coefficient $D$ have the following rigidity-

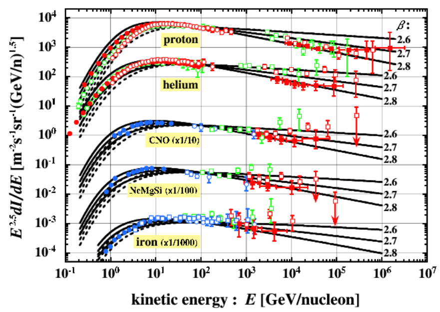


Figure 1: CR intensity for individual elements

dependences,

$$Q(\boldsymbol{r};R) = Q(\boldsymbol{r})R^{-\gamma};\quad D(\boldsymbol{r};R) = D(\boldsymbol{r})vR^{\alpha}, \quad (5)$$

where $R$ is the rigidity of the CR particle in GV, and $v$ its velocity in units of the velocity of light $c$.

Both indices, $\gamma$ and $\alpha$, are critical parameters in understanding CR acceleration at the source and the subsequent propagation, with $\gamma = 2.1$–$2.4$, and $\alpha = 1/3 - 1/2$, where the index 1/3 is predicted for a Kolmogorov-type spectrum of hydromagnetic turbulence, and 1/2 for a Kraichnan-type.

We further take the stochastic reacceleration by hydromagnetic turbulence into account, introducing a parameter $\zeta_0$, corresponding to the the *effective* cross-section for the occurrence of collision of CR's with the magnetic turbulence. The magnitude of $\zeta_0$ is as large as 50–60 millibarn (mb), indicating that the *effective* latitudinal scale height, $z_a$, of the reacceleration occurrence is as large as (2-3)$\times z_n$ $\approx$ 500-800 pc [8,9].

## Comparison with the experimental data

In our model, there are twelve Galactic parameters; (i) ($\gamma$, $\alpha$), the index of the CR source spectrum in rigidity, $R^{-\gamma}$, and the index of the rigidity-dependent diffusion coefficient, $R^{\alpha}$, respectively (see Eq. [5]); (ii) ($D_0$, $n_0$, $Q_0$), the diffusion coefficient, the gas density, and the source density of CRs at the GC respectively (see Eqs. [1-3]); (iii) ($r_D, r_n, r_Q$), the longitudinal scale heights corresponding to ($D_0$, $n_0$, $Q_0$) respectively (see Eqs. [1-3]); (iv) ($z_D, z_n, z_Q$), the latitudinal scale heights corresponding to ($D_0$, $n_0$, $Q_0$) respectively (see Eqs. [1-3]); and (v) $\zeta_0$, the reacceleration efficiency (see Refs. [7,8]). Practically, however, they are condensed into seven kinds of parameters in the analyses of the observational data, with each playing an effective role for each data. Namely, 1) the index of the asymptotic energy spectrum of the primary components, $\beta \equiv \gamma + \alpha$, 2) the index of the rigidity dependence of the diffusion coefficient, $\alpha$, 3) the ratio of the scale height of the gas density to that of the diffusion coefficient, $\nu = z_n/z_D$, 4) the cross-section for the occurrence of collision with the magnetic turbulence, $\zeta_0$, 5) the gas density at the SS, $n_\odot$, 6) the inverse of the average path length (or the cross-section for the leakage from the Galaxy at the SS, $\bar{\sigma}_\odot \simeq D_\odot/[n_\odot c z_n z_D]$, and 7) the ratio of the halo thickness to the latitudinal spread of unstable nuclei with the life time of $\bar{\tau}_0$ ($= 10^6$ yr) at the SS, $\bar{\eta}_\odot = 2z_D/\sqrt{\bar{\tau}_0 D_\odot}$.

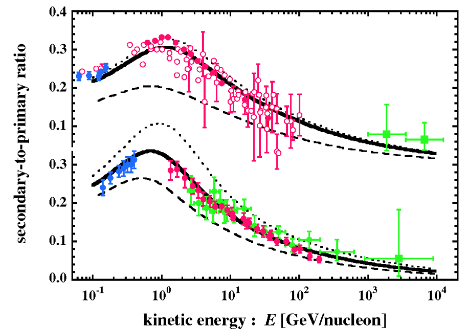


Figure 2: secondary-to-primary ratio

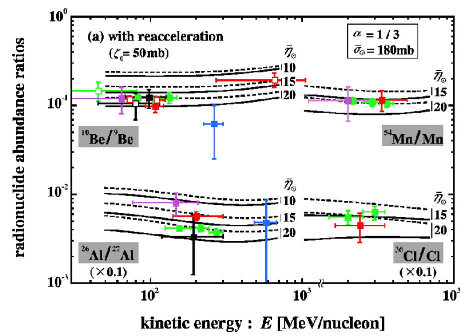


Figure 3: Abundance ratio of radionuclide

First, we present the stable primary components (p, He, ... Fe) summarized by RUNJOB group [4] in Fig. 1, where we find the all elements are consistent with the index $\beta = 2.7$-$2.8$ (see Refs. [7,8] and references therein for the experimental data).

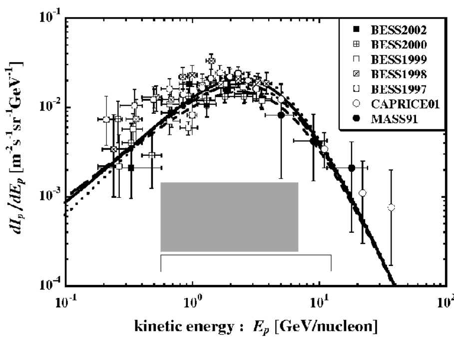


Figure 4: $\bar{p}$-flux with reacceleration curves

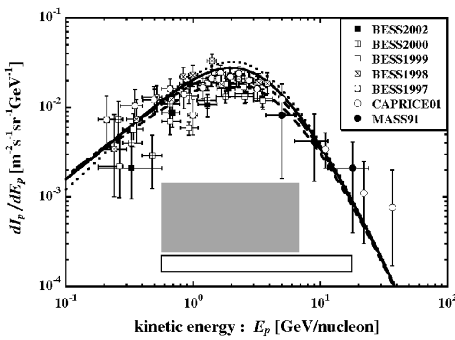


Figure 5: Same as Fig. 4, but no reacceleration

Second, we show two kinds of the secondary-to-primary ratio, B/C and sub-Fe/Fe, in Fig. 2, where heavy solid curves are the best fit curves, with $\bar{\sigma}_\odot = 176$ and 203 mb for B/C and sub-Fe/Fe, respectively, assuming $\alpha = 1/3$ (Kolmogorov-type), $\beta = 2.75$, and $\zeta_0 = 50$ mb. The small difference in $\bar{\sigma}_\odot$ between B/C and sub-Fe/Fe might possibly come from the 15%-25% uncertainty in the fragmentation cross section. Another choice with $\alpha = 1/2$ (Kraichnan-type) is not in agreement with the ACE data covering the energy region 0.5–5 GeV/n (see Refs. [8,9] and references therein for the experimental data). In the following discussions we set $\alpha$ =1/3, $\zeta_0 = 50$ mb, and $\bar{\sigma}_\odot = 180$ mb.

Third, we present four kinds of radionuclide abundance ratios, $^{10}$Be/$^{9}$Be, $^{26}$Al/$^{27}$Al, $^{54}$Mn/Mn, and $^{36}$Cl/Cl, in Fig. 3, together with the curves expected from our model, where we demonstrate three sets, $\bar{\eta}_\odot = 10,\ 15,\ 20$ with $\nu = 0.05$ (dotted curves) and 0.10 (solid ones), assuming $\beta = 2.75$ (see Ref. [9] and references therein for the experimental data). We find the curve with $\bar{\eta}_\odot \approx 15$ with $\nu = 0.1$ reproduces nicely all abundanace ratios. These results lead to $n_\odot = 0.832$ H atoms cm$^{-3}$, $\bar{n} = 0.17$ H atoms cm$^{-3}$, where $\bar{n}$ is the average gas density *effective* for CRs (observed at the SS) during their passage through the Galaxy.

Fourth, in Figs. 4 and 5 we show the most recent data on the intensity of $\bar{p}$ obtained by BESS [12], MASS [2], and CAPRICE [3] for several period of the solar activity. We give also several curves expected from our propagation model, assuming $\beta = 2.75$ with four modulation parameters $\phi = 0.3$, 0.5, 0.7, 1.0 GV, where we compare two models, one with $(\alpha,\ \zeta_0) = (1/3,\ 50\text{mb})$, namely with the reacceleration (Fig. 4), and another with (1/2, 0), namely without the reacceleration (Fig. 5). Taking the modulation effect into account, the reacceleration model is in nice agreement with the BESS data, while the enhancement of $\bar{p}$ in the low energy region, 0.2–1 GeV, is not yet clear in this stage. But BESS program will make clear this challenging problem in the near future. Details of the numerical calculations will be reported in the conference, together with those performed by other authors in the past.

Finally we present the D$\gamma$'s obtained by EGRET [6], together with the curves expected from our propagation model, where the intensities of individual CRs are normalized to those at 100 GeV/n in Fig. 1, where reliable data are now available from AMS [1] and BESS [5], and solar modulation is negligibly small. In Fig. 6 we demonstrate the intensity of D$\gamma$'s obtained by EGRET, where we assume $n_\odot = 0.832$ H atoms cm$^{-3}$ in our curves. We find again a significant discrepancy between the EGRET data for $\gtrsim 2$ GeV and the curves expected from CRs intensities, which has been pointed out by many authors. In Figs. 7, 8, we give the longitudinal and the latitudinal distributions of D$\gamma$'s in the energy interval $E_\gamma$ = 1-2 GeV near the Galactic plane. We find both are satisfactorily in agreement with the experimental data, where the scale heights in longitudinal and the latitudinal directions, $\bar{r}$ and $\bar{z}$ (see Eq. [4]) are explicitly written in figures.

## Discussions

We have presented various kinds of experimental data nowadays available, and compared with numerical results based on our three-dimensional CR propagation model. We find they are in good agreement with the expeirmental data by assuming appropriate Galactic parameters, except the

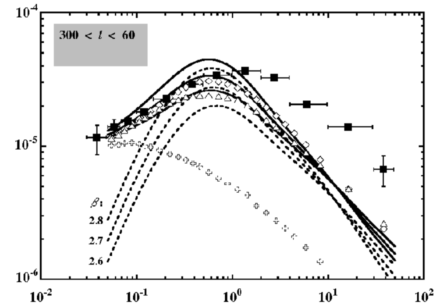


Figure 6: Intensity of D$\gamma$'s multiplied by $E_\gamma^2$

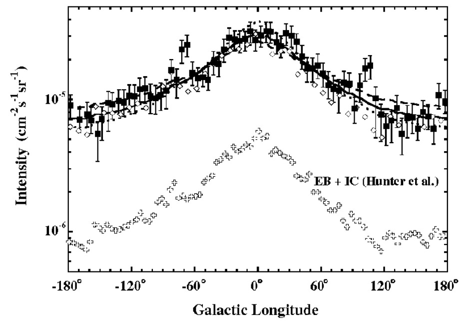


Figure 7: Longitudinal distribution of D$\gamma$'s

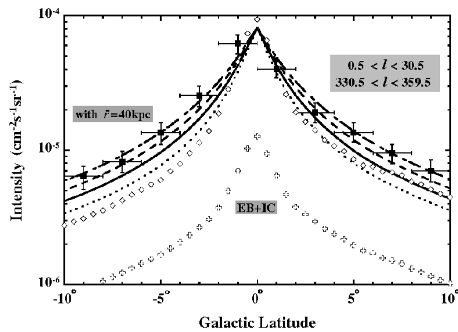


Figure 8: Latitudinal distribution of D$\gamma$'s

enhancement of D$\gamma$'s data observed by EGRET, while it is not yet clear whether the BESS $\bar{p}$ data around 0.2–1 GeV are in harmony with the numerical results, or enhanced from them. Apart from the enhancement problem in D$\gamma$'s, our model reproduces very well any kind of experimental data nowadays available. The Galactic parameters consistent with the data are 1) $\gamma + \alpha = 2.75$, 2) $\alpha = 1/3$ (Kolmogorov-type), leading to $\gamma = 2.42$, the index of the source spectrum, 3) $\nu = z_n/z_D = 0.1$, namely the halo thickness is ten times larger than the disk thickness, 4) $\bar{z} = 500$ pc, leading to $z_n = 250$ pc, and $z_D = 2.5$ kpc, 5) $\bar{r} = 40$ kpc, leading to $r_n = 20$ kpc with $r_D \gg r_n$, 6) $\zeta_0 = 50$ mb, leading to $z_a \approx 2z_n = 500$ pc, namely the effective (latitudinal) scale height of the reacceleration occurrence is as large as twice the disk thickness, 7) $n_\odot = 0.83$ H atoms cm$^{-3}$ (gas density at the SS), 8) $\bar{n} = 0.17$ H atoms cm$^{-3}$, average effective gas density for CRs during their passage through the Galaxy, 9) $D_\odot = [0.35, 1.17] \times 10^{28}$ cm$^2$s$^{-1}$ at $E = [0.1, 1]$ GeV nucleon$^{-1}$, respectively, (see Eq. [5] for the energy dependence of the diffusion coefficient), 10) $\bar{T}_\odot = [1.14, 0.38] \times 10^8$ years at $E = [0.1, 1]$ GeV nucleon$^{-1}$, respectively, for the residence time of CRs in the Galaxy.

In the present paper, we don't touch statistical analysis for the uncertainty in each value in the Galactic parameters, and more detailed studies and the discussions on the present results will be reported separately in the near future.

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