Diffusive gamma-rays and antiprotons

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Abstract.

Based on our three-dimensional cosmic-ray (CR) propagation model in the Galaxy, we study the diffusive gamma-rays \((D\gamma)'s\) and antiprotons \((\bar{p}'s)\), and compare our numerical results with recent experimental data, particularly those obtained by EGRET and BESS, each for \(D\gamma\) data and \(\bar{p}\) data respectively. Galactic parameters such as the gas density and diffusion constant are determined from the most recent data for the CR energy spectra, particularly those for protons and helium nuclei from AMS and BESS with excellent accuracy over the 1—100 GeV per nucleon range, and from JACEE and RUNJOB covering the very high energy region up to 500 TeV per particle. Using these parameters, we find that the EGRET data are well reproduced in the energy region \(E_{\gamma} < \sim 2\text{ GeV}\), in both the spectral shape and the absolute value, and also that the BESS data are compatible with our propagation model in the energy region \(\gtrsim 1\text{ GeV}\).

However, there are still two open questions in these components, 1) the intensity of the \(D\gamma\)'s gives a significant enhancement, by approximately the factor 2—3, at \(\sim 2\text{ GeV}\) as compared to those expected from the CR spectrum, and 2) we could not confirm whether or not BESS data with the energies less than 1 GeV are consistent or not with those expected from other CR components.

1. Introduction

We have studied the CR propagation for stable and the unstable elements (typically \(^{10}\text{Be}\)) based on our three-dimensional propagation model [1-3], and it reproduces satisfactorily all CR observables nowadays available, assuming appropriate Galactic parameters. So it is quite interesting and important to see how such model with these parameters are in harmony with \(D\gamma\)'s and \(\bar{p}\) data. This is because both components have cosmological interests as well as the astronomical ones, for instance the pair annihilations of massive particles in dark matter, so called WIMPs, (for instance, see Edsjö & Gondolo [4]; Bergström et al. [5]; Boer [6]), might produce \(\gamma\)'s and antiparticles such as \(\bar{p}\) and/or \(e^+\), resulting in the enhancement feature in the energy spectra. In fact Egret data [7] present a clear enhancement of \(D\gamma\)'s intensity around 2—10 GeV, much higher than expected from CR data\(^1\).

Therefore this problem is quite challenging to both astrophysics and particle physics. 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.

\(^1\) Most recently Stecker, Hunter and Kniffin [8] reports that the most likely explanation of the EGRET “GeV anomaly” is an error in the estimation of the EGRET sensitivity at the energies above \(\sim 1\text{ GeV}\).
2. CR propagation model

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 $r(r, z)$:

$$D(r) \equiv D(r, z) = D_0 \exp[(r/r_D + |z|/z_D)],$$

$$n(r) \equiv n(r, z) = n_0 \exp[−(r/r_n + |z|/z_n)],$$

$$Q(r) \equiv Q(r, z) = Q_0 \exp[−(r/r_Q + |z|/z_Q)],$$

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), $r(0, 0)$, respectively. In the present work, we often deal with the values of these three parameters in the Galactic plane, which are simply expressed as $D_0 = D(r, 0)$, $n_0 = n(r, 0)$, and $Q_0 = Q(r, 0)$, and for those at the SS, we express as $D_0 = D(r, 0)$, $n_0 = n(r, 0)$, and $Q_0 = Q(r, 0)$, with $r_0 = 8.5$ kpc.

In order to study the spatial gradient of these parameters, we introduce two *average* scale heights, $\bar{r}$ and $\bar{z}$, appearing not in the separate forms of $(r_D, r_n)$ and $(z_D, z_n)$, but always in the coupled forms defined by

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

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

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

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

We further take into account the stochastic reacceleration by hydromagnetic turbulence, introducing a parameter $\zeta_0$, which corresponds 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, $z_\alpha$, of the reacceleration occurrence is as large as $(2-3) \times z_n \approx 500-800$ pc [2,3].

3. Results and discussions

First we present the CR spectra for protons and helium nuclei [9] in figure 1(a), which are the most effective ones for the study of $D\gamma$ and $\bar{p}$ components, and the secondary-to-primary ratio in figure 1(b). Here and in what follows, we assume $\beta = \gamma + \alpha = 2.75$, $\alpha = 1/3$ (Kormogorov-type spectrum of hydromagnetic turbulence), $\zeta_0 = 50$ mb, $z_n/z_D = 0.1$, and $\sigma_\odot = D_0/[n_0 c z_n z_D] = 180$ mb with $n_\odot = 0.832$ H atoms cm$^{-3}$. See references [1–4] for the parameter determination. One finds our curves reproduce very well the experimental data. We further confirmed that four kinds of [unstable-nucleus]/[stable-nucleus], $^{10}$Be/$^{9}$Be, $^{26}$Al/$^{27}$Al, $^{54}$Mn/Mn, and $^{36}$Cl/Cl in the energy range, 0.05-0.5 GeV/n, are in good agreement with our parameterization [3], while we don’t present the result here because of limited space.

Now based on these results obtained by the CR data nowadays available, we extend the numerical results to the $\bar{p}$’s and $D\gamma$’s data which are shown in figures 2(a) and 2(b) respectively. In order to perform numerical calculations for these components, we need the production cross-sections of $\bar{p}$ and $D\gamma$ in nuclear interactions, particularly in proton-proton interaction. See references [10] and [11] respectively for the detail of them.

It is remarkable that our curves for $\bar{p}$ reproduce nicely in the energy region, $\gtrsim 1$ GeV, and those for $D\gamma$ in the region, $\lesssim 2$ GeV, where the numerical curves for EB (electron bremsstrahlung) and IC (inverse Compton) appearing in figure 2(b) are based on the simulational results by Hunter et
Figure 1. CR intensity for individual elements summarized by RUNJOB group (a) and the secondary-to-primary ratio (b). See reference [9] and the references therein for the data.

Figure 2. (a) $\bar{p}$-flux obtained by BESS [15], MASS [16], and CAPRICE [17], and (b) $D\gamma$-flux obtained by EGRET [7].

al. [7]. In figure 2(a), we present several curves corresponding to different modulation parameter $\phi$, based on the force field approximation [12].

We checked further two spatial distributions of $D\gamma$’s, longitudinal and latitudinal ones, in the energy interval, $E_\gamma = 1–2$ GeV, as shown in figures 3(a) and 3(b) respectively. We find that EGRET data are again in good agreement with those expected from our model with $(\bar{r}, \bar{z}) = (40\text{kpc}, 0.6\text{kpc})$ (see equation [2]), both in shape and absolute intensity, physical meaning of which is discussed in reference [13].

On the other hand, it is somewhat difficult in figure 1(a) to conclude if the numerical results in the low energy region, $\lesssim 1$ GeV, are compatible or not with the BESS data. We need more statistics to discuss a possibility of the novel origin such as the evaporation of primordial black holes and/or the annihilation of supersymmetric dark matter particle. However we may say safely that our model with the reacceleration effect matches well the data, contrary to the previous understanding (for instance Ptuskin [14]) that the reacceleration process doesn’t favour the $\bar{p}$ spectrum.
About the Dγ’s as presented in figure 2(b), we find again a significant discrepancy between the EGRET data for Eγ ≥ 2 GeV and the curves expected from CRs intensities, which has been pointed out by many authors. However, this “GeV anomaly” is recently reexamined by EGRET team [8] as mentioned in the footnote in the introduction, and it might be due to the systematic error in the sensitivity determination of the EGRET detector. Anyway, we need better statistics to answer the above questions, and await for the future experiment mentioned above, particularly BESS-PolarII [19], AMS [20], and PAMELA [21] for ¯p, and GLAST [18] for Dγ data. With reliable Galactic parameters as well as progress in the quality of the experimental data, we might detect a signal of novel sources for ¯p’s and Dγ’s other than the secondary products in the near future.

4. References

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