Galactic Diffuse Gamma-ray Spectrum from Cosmic-ray Interactions with Gas Clouds

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Abstract

Gamma-ray spectra from cosmic-ray proton and electron interactions with gas clouds have been calculated using a Monte Carlo simulation code, Geant4. Such clouds are postulated as a possible form of baryonic dark matter in the Universe. The simulation results are used for evaluating the galactic diffuse gamma-ray emission and compared with observational data.

1. Introduction

The great mystery of missing mass (or, positively speaking, dark matter) in our Galaxy remains as a serious challenge to astrophysics. Lacking observational evidences, among many speculations various authors have proposed models of baryonic dark matter. Along this line some authors proposed a possible model in which dark matter consists of a population of self-gravitating clouds of mainly molecular hydrogen (Pfenniger et al. 1994). A favored set of parameters for these cloud is: masss $M \sim 10^{-4} M_{\odot}$, raidus $R \sim 10^{13}$cm, temperature $T \sim 10$K, velocity dispersion $\bar{v} \sim 150$km s^{-1}, for a halo distribution with a covering factor $f \sim 5 \times 10^{-4}$ (Draine 1998). These clouds can survive for billions of years (Wardle and Walker 1999). One of the predictions of such model is the pionic gamma-rays emitted by the clouds after cosmic-ray interactions with the clouds may have a diffuse flux in the Galactic plane comparable to the flux from known sources for photon energies above 1 GeV (Sciama 2000). Considering the observed GeV excess of diffuse emission by the EGRET detector aboard the Compton Gamma Ray Observatory (Hunter et al. 1997), it is worth considering this new emission mechanism more seriously.

Here we present a realistic spectrum of such diffuse gamma-rays from cosmic-ray interactions with the clouds using a Monte Carlo simulation code, Geant4, developed for simulating particle interaction in detectors used in high-

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energy physics (Geant4). The resulting spectrum shows different features compared with spectra assuming thin materials. We also discuss the possible impact of our results on the Galactic diffuse emission.

2. Calculation

Previous calculations of gamma-ray spectrum from cosmic-ray proton interactions assumed single interactions of protons with interstellar medium. In order to take account of finite density effect, a Monte Carlo code, Geant4, has been used to derive gamma-ray spectra from cosmic-ray proton interactions with dense medium. The π^0 production in this code has been tested comparing with accelerator data (Dannheim 1999). We assume a spherical cloud of molecular hydrogen with uniform density at temperature 10K. The radius of the sphere was assumed to be $R = 1\text{AU} = 1.5 \times 10^{13}$cm. Protons and electrons are injected randomly at a surface point of the cloud and particles emanating from the sphere surface were counted as products. Assumed spectrum of cosmic-ray protons and electrons were taken from Mori ("median", 1997) and Skibo and Ramaty (1993), respectively. The simulated range of kinetic energy of cosmic-rays are from 10 MeV to 10 TeV. We divided this energy range into four and superposed the resulting spectra with appropriate weight factors in order to increase the simulation statistics at higher energies, considering the rapidly falling spectrum of cosmic rays. The density of molecular hydrogen, ρ, was varied from 5×10^{-16} g/cm^3 to 5×10^{-9} g/cm^{-3} in step of factor 10.

3. Results

Figure 1 shows the resulting gamma-ray spectra obtained in Geant4 simulation for proton injection to a cloud with density $\rho = 5 \times 10^{-12}$g cm^{-3}. The dashed, dotted and dot-dashed histograms shows spectrum components classified by the parent processes producing gamma-rays, i.e., π^0 dacay, bremsstrahlung and positron-electron annihilation. Latter two components do not show up when we assume single interactions with thin material. The error bars are calculated from Monte Carlo statistics. Although the π^0 decay component shows a broad peak around 70 MeV and dominates above about 200 MeV, electron bremsstrahlung component broadens the π^0 peak.

The resulting gamma-ray spectra for various density of clouds are shown in Figure 2 (proton injection) and Figure 3 (electron injection). Note that for high densities Monte Carlo statistics is rather low, since the yield itself is poor.

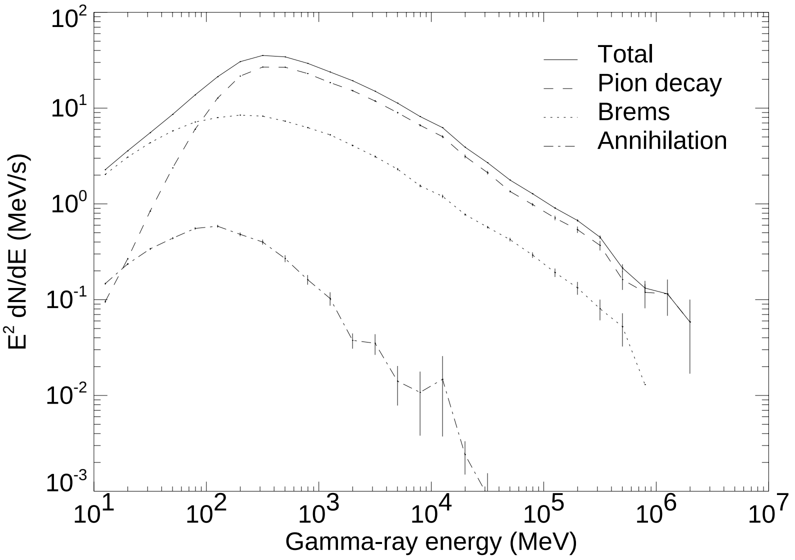

Fig. 1. Gamma-ray yield from a molecular hydrogen cloud of radius 1 AU and density 5×10^{-12}g cm^{-3}. irradiated by cosmic-ray protons.

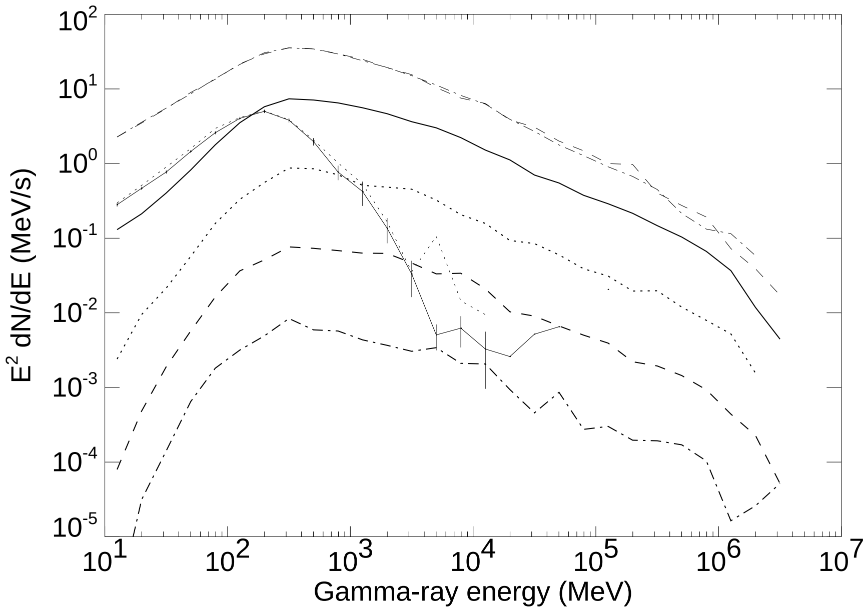

Fig. 2. Gamma-ray yield from a cloud irradiated by cosmic-ray protons. Thin curves are for densities 5×10^{-9}g cm^{-3} (solid), 5×10^{-10}g cm^{-3} (dotted), 5×10^{-11}g cm^{-3} (dashed), 5×10^{-12}g cm^{-3} (dot-dashed), and thick curves are for 5×10^{-13}g cm^{-3} (solid), 5×10^{-14}g cm^{-3} (dotted), 5×10^{-15}g cm^{-3} (dashed), 5×10^{-16}g cm^{-3} (dot-dashed), respectively.

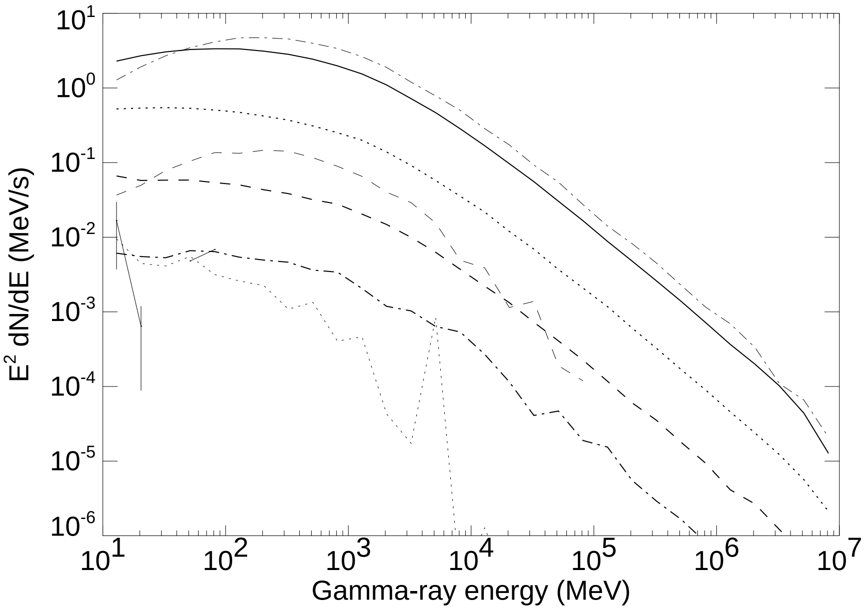

Fig. 3. Gamma-ray yield from a cloud irradiated by cosmic-ray electrons. Curves are for various densities (see previous Figure).

4. Discussion

Using the gamma-ray production spectrum obtained in the previous section, we have calculated the diffuse gamma-ray spectrum from galactic disk as follows.

The predicted gamma-ray spectrum for each case is $I = (\mathrm{d}N/\mathrm{d}E)I_{\mathrm{cr}}(0)Q$, where $\mathrm{d}N/\mathrm{d}E$ is the photon spectrum returned by Geant4 simulation in units of photons/MeV/primary, and $I_{\mathrm{cr}}(s)$ is the spectrum of cosmic-rays at distance s in units of primaries/cm^2/s/sr with s being the distance along the line-of-site. The normalisation, Q, is a mean weighted geometric optical depth of the cloud population over the inner galactic disk and is dependent on column density, for which we calculated with a collisional dark halo model (Walker 1999):

$$Q \equiv \frac{1}{\Sigma}\int_0^{\infty}\mathrm{d}s\,\rho(s)\frac{I_{\mathrm{cr}}(s)}{I_{\mathrm{cr}}(0)}$$

where Σ is the column density of the individual clouds, $\rho(s)$ is the dark matter density at distance s. We used Higdon's model of cosmic ray distribution in the Galaxy (a thin disk plus a thick disk: Higdon 1979), which is based primarily on an analysis of the distribution of synchrotron radio emission. Here we have, however, decreased the scale-height of his thick disk from 5.8 to 3 kpc, in order to bring it into line with results from cosmic-ray diffusion models. There assumed Q

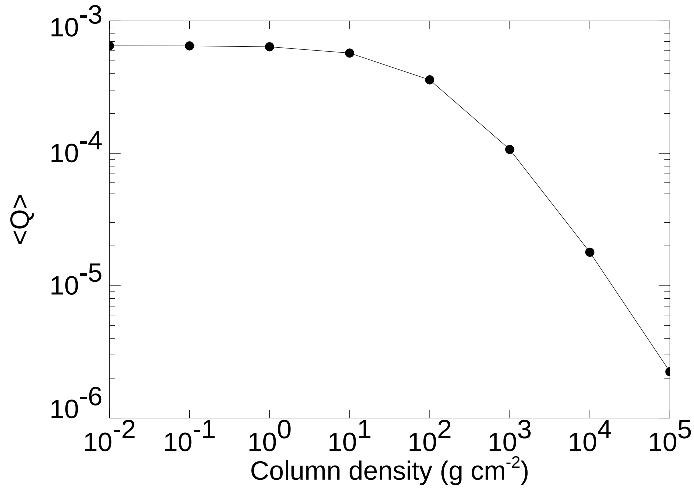

Fig. 4. Mean Gamma-ray intensity of gamma-rays over the inner galactic disk calculated by the collisional galactic disk. Here is shown averaged values over $|\ell| < 30°$ and $|b| < 10°$ to compare with the EGRET data.

to be the same for electrons and protons (i.e. the Galactic cosmic ray distribution is assumed to be the same for both).

To compare our calculation with the EGRET diffuse gamma-ray data, we modified the diffuse model used in Hunter et al.:

$$I = (q_{pp\to\pi^0} + q_{\rm brems})(N_{\rm HI} + N_{\rm HII} + N_{\rm H_2}) + I_{\rm IC} + I_{\rm EG},$$

where q is a gamma-ray source function (Bertsch et al. 1993), $N_{\rm HI}$, $N_{\rm HII}$, $N_{\rm H_2}$ are densities of neutral hydrogen, ionized hydrogen and molecular hydrogen, respectively, $I_{\rm IC}$ is the gamma-ray flux by inverse Compton emission, and I_{EG} is the isotropic extragalactic background flux. Assuming all H_2 are in the form of clouds, this equation is modified as follows:

$$I = I_{\rm clouds} + (q_{pp\to\pi^0} + q_{\rm brems})(N_{\rm HI} + N_{\rm HII}) + I_{\rm IC} + I_{\rm EG},$$

where $I_{\rm clouds}$ is the flux from clouds calculated here. If we assume the cloud density as $\sim 8 \times 10^{-12}$ g cm^{-3}, we obtain a good fit to the EGRET data as shown in Figure 5.

5. Summary

Gamma-ray spectrum from cosmic-ray interactions with dense gas has been calculated using a Monte Carlo simulator, Geant4. Within reasonable range of

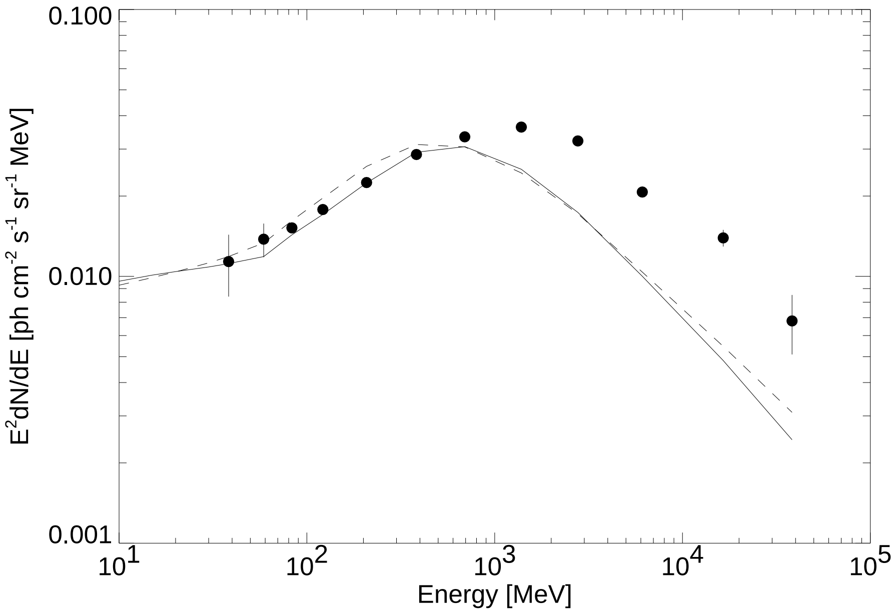

Fig. 5. Comparison of calculated galactic diffuse gamma-ray fluxes with the EGRET data (shown by points). Solid line shows the calculation by Hunter et al. (1997) and dashed line shows the best fit of the present calculation.

parameters of gas cloud as a dark matter candidate, galactic diffuse gamma-ray spectrum can be reproduced, except the "GeV excess" reported by EGRET.

6. References

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7. Title of the Paper

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