Gamma-Ray Spectra due to Cosmic-Ray Interactions with Dense Gas Clouds [1]

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Abstract. Gamma-ray spectra from cosmic-ray proton and electron interactions with dense gas clouds have been calculated using a Monte Carlo event simulation code, GEANT4. Such clouds are postulated as a possible form of baryonic dark matter in the Universe. The simulation fully tracks the cascade and transport processes which are important in a dense medium, and the resulting gamma-ray spectra are computed as a function of cloud column-density. These calculations are used for predicting the Galactic diffuse gamma-ray spectrum which may be contributed by baryonic dark matter; the results are compared with data from the EGRET instrument, and used to constrain the fraction of Galactic dark matter which may be in the form of dense gas clouds. In agreement with previous authors, we find useful constraints on the fraction of Galactic dark matter which may be in the form of low column-density clouds ($\Sigma \lesssim 10\,\mathrm{g\,cm^{-2}}$). However, this fraction rises steeply in the region $\Sigma \sim 10^2\,\mathrm{g\,cm^{-2}}$, and for $\Sigma \gtrsim 200\,\mathrm{g\,cm^{-2}}$ we find that baryonic dark matter models are virtually unconstrained by the existing gamma-ray data.

INTRODUCTION

The nature of dark matter remains one of the outstanding questions of modern astrophysics. The success of the cold dark matter cosmological model (albeit with "dark energy" now required: ΛCDM) argues strongly for a major component of the dark matter being in the form of an elementary particle. However, the inventory of baryons which we can observe locally falls far short of the total inferred from observations of the cosmic microwave background fluctuations [1], leaving open the possibility that there may be a significant baryonic component of dark matter. There have been many papers dealing with the possibility that cold, self-gravitating molecular clouds constitute a major component of the dark matter [2, 3, 4, 5, 6, 7, 8, 9]. A variety of different forms, including isolated, clustered, and fractal, have been considered for the clouds, but all proposals involve dense gas of high column-density, in contrast to the diffuse gas in the interstellar medium which is easily detected in emission and/or absorption.

One of the fundamental predictions of a model featuring dense gas clouds is the gamma-ray emission resulting from cosmic-ray interactions within the clouds [3, 10, 11, 8]. Because of the potentially large total mass of gas involved, this process may

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[1] This is an abbreviated version of the paper published in Astrophys. J. 610, 868–875 (2004).

yield a diffuse flux in the Galactic plane comparable to the flux from known sources for photon energies around 1 GeV [8].

Here we present detailed calculations of the gamma-ray spectra arising from cosmic-ray interactions with dense gas clouds. We have used a Monte Carlo simulation code, GEANT4, developed for simulating interaction events in detectors used in high-energy particle physics. Not surprisingly, we find that the predicted spectra differ substantially between high and low column-density clouds, and we discuss the interpretation of our results in the context of the observed Galactic gamma-ray emission.

GAMMA-RAY PRODUCTION IN DENSE MATTER

Previous calculations of gamma-ray spectra from cosmic-ray irradiation assumed single interactions of protons with the interstellar medium (Refs. [12, 13, 14] and references therein). In order to investigate cosmic-ray interactions with dense gas, where cascade processes and particle transport are important, we have used a Monte Carlo code, GEANT4,[2] to derive gamma-ray production spectra. This code is a general purpose Monte Carlo code of particle interactions and is widely used for simulation of high-energy particle detectors in accelerator experiments. Cross-sections and interactions of various hadronic processes, i.e., fission, capture, and elastic scattering, as well as inelastic final state production, are parametrized and extrapolated in high and low particle energy limits, respectively.

SIMULATION MODEL

Our calculations assume a spherical cloud of molecular hydrogen of uniform density and temperature (10 K). The radius of the sphere was assumed to be $R = 1.5 \times 10^{13}$ cm $\simeq$ 1 AU. Protons and electrons are injected randomly at a surface point of the cloud and particles subsequently emanating from this surface are counted as products. The adopted spectra of cosmic-ray protons and electrons were taken from Mori [15] (here we use the "median" flux; note that the units on his equation (3) should read $\mathrm{cm^{-2}s^{-1}sr^{-1}GeV^{-1}}$), and Skibo and Ramaty [16], respectively. The simulated range of kinetic energy of cosmic rays is 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} to 5×10^{-9} g cm^{-3} in factors of 10. This corresponds to the column density, $\Sigma = 2\rho R\langle\cos\theta\rangle$, of $10^{-2}, 10^{-1}, \ldots 10^{5}$ g cm^{-2}, respectively, where θ is the incident angle of a cosmic ray into a cloud and $\langle\cos\theta\rangle = 2/3$ for random injection.

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[2] Available at http://wwwinfo.cern.ch/asd/geant4/geant4.html

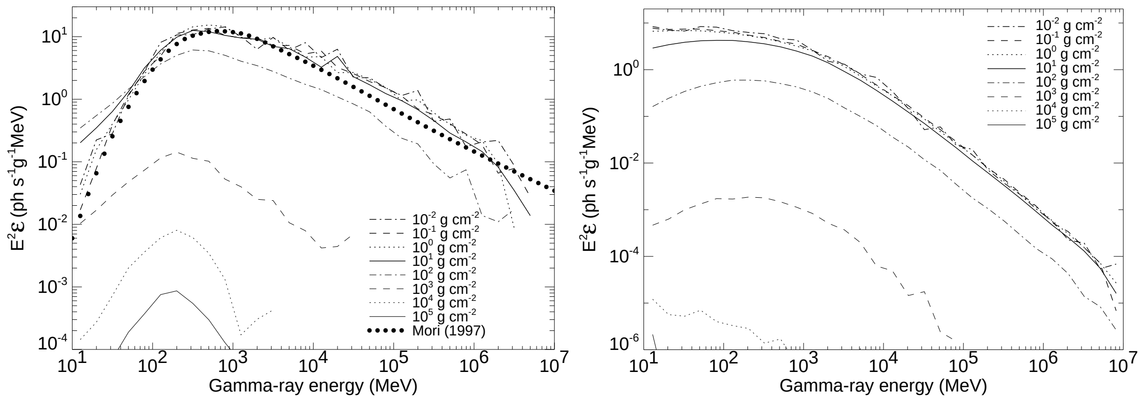

FIGURE 1. Gamma-ray emissivities for dense clouds irradiated by cosmic-ray protons (left panel), with a spectrum appropriate to the solar neighbourhood. The results have been multiplied by a nuclear enhancement factor of 1.52 [15] to account for the presence of heavier nuclei in the cosmic-rays. Also plotted is the emissivity from Mori [15], which corresponds to the "thin material" limit (filled circles); this limit offers a good approximation for $\Sigma \lesssim 10\,\mathrm{g\,cm^{-2}}$. The right panel shows the similar plot for cosmic-ray electrons.

RESULTS OF SIMULATION

The resulting gamma-ray emissivities for clouds of various column densities are shown in figure 1 (left panel: proton injection, right panel: electron injection). Here the emissivities are defined for irradiation by cosmic-rays of all species (see §2.3, equation (3)); to take account of the contribution of heavier nuclei than helium, the emissivity due to proton irradiation (figure 4) has been multiplied by a nuclear enhancement factor [17, 12, 13, 18] of 1.52 [15]. Note that for high densities the Monte Carlo statistics are rather poor, since the yield itself is low. Figure 1 includes a comparison of our calculated gamma-ray production functions with that of Mori [15] (corresponding to the "thin material" limit). The results are consistent with those of Mori [15] for column densities less than about 10 g cm^{-2}, except in the energy range $E > 10^6$ MeV where the effect of the maximum energy assumed in the Monte Carlo simulation is evident. We note the very low values of the emissivity at energies $\gtrsim$100 MeV, for column densities $\Sigma \gtrsim 10^3\,\mathrm{g\,cm^{-2}}$. A slightly steeper spectrum in the 10^4–10^6 MeV region comes from our omission of the contribution of heavy nuclei, which were taken into account in Mori [15]. A somewhat surprising feature of these curves is that the power-law index above 1 GeV is almost the same as the input cosmic-ray proton flux for column densities less than about 1000 g cm^{-2} (for higher column densities the statistics of the simulations are not good enough to decide whether this result still holds).

CALCULATION OF DIFFUSE GAMMA-RAYS

Using the gamma-ray production spectra obtained in the previous section, we have calculated the diffuse gamma-ray emission from the Galaxy as follows. The predicted gamma-ray spectrum for each case is

$$I_D = \frac{1}{\Sigma}\int_0^\infty \mathrm{d}s\,\rho(s)J_{\mathrm{cr}}(s)\frac{\mathrm{d}N}{\mathrm{d}E} \tag{1}$$

where $\mathrm{d}N/\mathrm{d}E$ is the spectrum returned by the simulation in units of photons/MeV/primary, for an individual cloud, appropriate to the incident cosmic-ray spectrum. The quantity $J_{\mathrm{cr}}(s)$ is the intensity of cosmic rays at a distance s along the line of sight, in units of primaries cm^{-2} s^{-1} sr^{-1}, and $\rho(s)$ is the mean density in gas clouds of column density Σ.

The Galactic variation of the spectrum $J_{cr}(s)$ is not well constrained by existing data, and consequently we adopt the simplifying assumption that the shape of the cosmic-ray spectra (both electrons and protons) is the same everywhere in the Galaxy, with variations only in the normalisation. With this assumption it is convenient to recast the calculation as

$$I_D = \frac{1}{4\pi}\mathscr{E}Q, \tag{2}$$

(ph cm^{-2}s^{-1}sr^{-1}MeV^{-1}), where the emissivity is $\mathscr{E} = 4\pi/\Sigma J_{\mathrm{cr}}(\odot)\mathrm{d}N/\mathrm{d}E$ (ph s^{-1} MeV^{-1} g^{-1}) with $J_{cr}(\odot)$ the cosmic-ray mean intensity in the Solar neighbourhood and $Q \equiv \int_0^\infty \mathrm{d}s\,\rho(s)J_{\mathrm{cr}}(s)/J_{\mathrm{cr}}(\odot)$ is the weighted column density (g cm^{-2}) of the cloud population along the line-of-sight under consideration. This formulation is convenient because the emissivity, $\mathscr{E}$, describes the properties of the gas clouds themselves and is independent of the Galactic variations in mean dark matter density and cosmic-ray density; conversely the quantity Q characterises these properties of the Galaxy, and is independent of the properties of the gas clouds themselves. The emissivity shown in figures 4 and 5 is the quantity $E^2\mathscr{E}$, whereas figures 6 and 7 show $\int_E^\infty \mathrm{d}E'\,\mathscr{E}$. For the inner Galactic disk, where we are interested in $\langle I_D\rangle$, we need to average over the whole solid angle, Ω, under consideration: $\langle Q\rangle = \int \mathrm{d}\Omega\, Q/\Omega$. In order to calculate Q we need to adopt models for both the Galactic cosmic-ray distribution and the Galactic distribution of the clouds.

The quantity $\rho(s)$, the density in cold, dense gas clouds, is only weakly constrained by direct observation, because the hypothetical clouds constitute a form of *dark* matter. We therefore proceed by adopting a conventional dark matter density distribution for the Galaxy, namely a cored isothermal sphere, as our model cloud density distribution, with a fiducial normalisation which is equivalent to the assumption that all of the dark matter is in the form of dense gas clouds. This corresponds to the model $\rho = \sigma^2/[2\pi G(R^2+z^2+r_c^2)]$, in terms of cylindrical coordinates (R,z), with $\sigma = 155\,\mathrm{km\,s^{-1}}$. We have adopted a core radius of $r_c = 6.2$ kpc based on the preferred model of Walker (1999). (This choice corresponds to Walker's preferred value of cloud column density $\Sigma = 140\,\mathrm{g\,cm^{-2}}$.) Walker's model exhibits a core radius which is a function of cloud column density, but we have fixed the core radius at 6.2 kpc for all of our computations. This choice permits more straightforward consideration of the observational constraints because Q is independent of Σ in this case.

It then remains to specify the cosmic-ray energy-density as a function of position in the Galaxy. Webber et al. [19] (hereafter WLG92) constructed numerical models of cosmic-ray propagation in the Galaxy. We adopt the model cosmic-ray mean intensity distribution $J_{cr}(R,z)$ (see the published paper for the model selection):

$$\frac{J_{cr}(R,z)}{J_{cr}(\odot)} = \left(\frac{R}{R_0}\right)^{0.6} \exp[(R_0 - R)/L - |z|/h], \tag{3}$$

in terms of cylindrical coordinates (R,z). Here $R_0 \simeq 8.5$ kpc is the radius of the solar circle, while $L = 7$ kpc, $h = 1.5$ kpc and $J_{cr}(\odot) = J_{cr}(R_0, 0)$. This distribution has the character of a disk with a central hole.

These models for $\rho(s)$ and J_{cr} allow us to compute the quantity Q, as per equation 4, and the resulting variation over the sky is plotted in figure 8. For reference we give the values of $Q(l,b)$ evaluated at the cardinal points, as follows: $Q(0,0) = 6.47 \times 10^{-2}\,\mathrm{g\,cm^{-2}}$, $Q(\pm 90°, 0) = 1.54 \times 10^{-2}\,\mathrm{g\,cm^{-2}}$, $Q(180°, 0) = 7.70 \times 10^{-3}\,\mathrm{g\,cm^{-2}}$, and $Q(b = \pm 90°) = 2.44 \times 10^{-3}\,\mathrm{g\,cm^{-2}}$. In order to compare with the EGRET results of Ref. [20], we have also evaluated the average of Q over the inner Galactic disk: $\langle Q(|l| \leq 60°, |b| \leq 10°)\rangle = 3.28 \times 10^{-2}\,\mathrm{g\,cm^{-2}}$.

DISUCSSION

For our purposes it is not actually necessary to quantify the uncertainties on the model input parameters; it suffices to use the discrepancy between model and data as a measure of the uncertainty in our understanding of the observed emission. In turn this measure determines the constraints which we can apply to any putative unmodeled emission, such as the contribution from dense gas which we are concerned with here. At photon energies $E > 1$ GeV the fractional discrepancy is roughly 60% [20], in the sense that the observed emission is 1.6 times larger than the model, and we henceforth adopt $0.6/1.6 \simeq 40\%$ of the total observed intensity as our estimate of the unmodeled emission. Although this estimate is derived from data at high energies, the effects of the various contributing processes are all very widely spread, and *the estimate therefore applies independent of photon energy.* The constraints appropriate to high/low Galactic latitudes can now be re-evaluated.

At high Galactic latitudes the observed intensity is $I \simeq 1.5 \times 10^{-5}\,\mathrm{ph\,cm^{-2}s^{-1}sr^{-1}}$ for $E \geq 100$ MeV [21], implying that any unmodeled emission should be $\lesssim 6 \times 10^{-6}\,\mathrm{ph\,cm^{-2}s^{-1}sr^{-1}}$ in this band. This result is actually slightly stricter than the criterion used by Ref. [22] and thus leads us to tighten our high-latitude constraints, relative to those quoted in §3.2: the observed high-latitude gamma-ray intensity constrains the amount of low column-density gas to $\lesssim 20\%$ of the total density of the Galactic dark halo, with this fraction rising to 100% for gas clouds of column density $\Sigma \gtrsim 200\,\mathrm{g\,cm^{-2}}$.

At low Galactic latitudes we can make use of the mean intensity of the inner Galactic disk, which has been accurately determined by Hunter et al. [20]. For example at 1 GeV the mean intensity ($|l| \leq 60°$, $|b| \leq 10°$) is $\langle I\rangle \simeq 3 \times 10^{-8}\,\mathrm{ph\,cm^{-2}s^{-1}sr^{-1}MeV^{-1}}$, and our calculation of $\langle Q\rangle$ for this region yields (§2.3) $3.28 \times 10^{-2}\,\mathrm{g\,cm^{-2}}$, implying that the emissivity of the Galactic dark halo material must be, on average, $\mathscr{E} \leq 4.6 \times 10^{-6}\,\mathrm{ph\,s^{-1}g^{-1}MeV^{-1}}$. By comparison, the actual emissivity of low column-density gas is computed to be (§2.3, table 2) $\mathscr{E}(1\ \mathrm{GeV}) \simeq 1.4 \times 10^{-5}\,\mathrm{ph\,s^{-1}g^{-1}MeV^{-1}}$, implying that $\lesssim$30% of the Galaxy's dark halo may be comprised of low column density gas. For higher column densities the emissivity falls, and table 2 shows that for $\Sigma = 100\,\mathrm{g\,cm^{-2}}$ the emissivity is only $5.5 \times 10^{-6}\,\mathrm{ph\,s^{-1}g^{-1}MeV^{-1}}$. The gamma-ray data on the inner Galactic disk thus indicate all of the Galaxy's dark halo to be made of dense clouds of column-density $\Sigma \gtrsim 100\,\mathrm{g\,cm^{-2}}$.

SUMMARY

The gamma-ray spectra arising from cosmic-ray interactions with gas clouds of various column-densities have been calculated using a Monte Carlo event simulator, GEANT4. Our calculations reproduce the analytic result in the low column-density limit, where only single particle interactions need to be considered, but exhibit significant differences for clouds of column-density $\Sigma \gtrsim 10^2\,\mathrm{g\,cm^{-2}}$ where the emissivity declines substantially for photon energies $E \gtrsim 100$ MeV. The low emissivity of dense gas means that the baryonic content of the Galaxy's dark halo is not so tightly constrained by the gamma-ray data as had previously been thought. For $\Sigma \gtrsim 200\,\mathrm{g\,cm^{-2}}$ we find that the existing gamma-ray data, taken in isolation, do not exclude purely baryonic models for the Galactic dark halo.

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