The High Energy Gamma-Ray Background as a Probe of the Dark Matter in the Galactic Halo

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Abstract. We present constraints on the density of halo dark matter candidates within the solar circle based on the anisotropy in the high energy gamma-ray background. The known galactic components of the gamma-ray background, in particular the inverse Compton component, have been estimated more accurately. We find the spectrum of the residual emission, after subtracting the galactic component is inconsistent with emission from some of the proposed dark matter candidates. We derive upper limits of $10^8 M_\odot$ for the mass of diffuse gas and $3 \times 10^9$ pc$^{-3}$ for the number density of primordial black holes contributing to the gamma-ray background.

1. Introduction

Various observational results such as those from the Supernova Cosmology Project, estimates of the primeval deuterium abundances from primordial nucleosynthesis, microwave background anisotropies, seem to suggest a partition of the mass and energy density of the universe into $\Omega_{\text{baryon}} \approx 0.05$, $\Omega_{\text{non-baryonic}} \approx 0.3$ and $\Omega_\Lambda \approx 0.65$. Rotation curves of the Galaxy clearly indicates the existence of a large amount of unseen matter which might be either baryonic or non-baryonic. For example, the circular velocity $v=220$ km/s at the solar circle $R_\odot=8.5$ kpc implies an average density ($\rho_{\text{halo}}$) of $8.4 \times 10^{-25}$ g/cm$^3$. Of this $<10\%$ can be attributed to stars and detectable gas and dust. The nature and distribution of the remainder of this matter is as yet unknown. Gamma-rays are a unique probe of the dark matter since they are capable of tracing both baryonic and non-baryonic dark matter candidates. Baryonic candidates such as cold, diffuse gas would produce gamma-rays by interacting with cosmic ray nucleons through the $p-p$ process $p_{CR} + p_{\text{gas}} \rightarrow p + p + \pi^0 \rightarrow p + p + 2\gamma$. Non-baryonic candidates such as WIMPs which are postulated to be in the mass range 50–500 GeV would produce line and continuum gamma-rays through annihilation processes while evaporating primordial black holes (PBHs) are thought to produce an $E^{-3}$ photon spectrum with a break below 120 MeV (Halzen et al. 1991). Unfortunately, dark matter candidates are by no means the dominant source of gamma-rays in the Galaxy. Detecting them through the gamma-ray background

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requires accurate estimation of the other known galactic components of gamma-ray emission such as nucleon-nucleon (p−p), inverse Compton (IC) and electron bremsstrahlung (EB) from high energy cosmic ray electrons scattering off the Coulomb field of the gas. In addition, there is thought to be an isotropic extragalactic component from unresolved blazars, ~50 of which have been detected (Sreekumar et al. 1998, Mattox et al. 1997). The EGRET instrument on the Compton Gamma-Ray Observatory has mapped out the entire sky in the energy range 30 MeV to 10 GeV with unprecedented sensitivity. We have attempted to accurately estimate the galactic component of the gamma-ray background, especially the IC component, in light of the recent data available on the interstellar radiation field from the DIRBE instrument on COBE. We use these new results to constrain the nature and the amount of dark matter in the aforementioned forms within the solar circle.

2. Analysis

The gamma-ray data from the individual EGRET pointings upto April 1997 were integrated to construct an all sky intensity map at 10 energy bands between 30 MeV and 10 GeV. The all sky map shown in Figure 1 has been generated by co-adding the maps in the 7 energy bands above 100 MeV and smoothing with a 5° FWHM gaussian which is approximately the resolution of EGRET at 100 MeV. Immediately noticeable is a strong component of gamma-ray emission aligned with the galactic plane which is thought to arise from the p−p process described above. Since the scale height of the neutral hydrogen gas in the Galaxy is of order 100 pc, we can eliminate most of the galactic component by restricting our analysis to high latitudes i.e. |b| > 30°. Arendt et al. (1998) performed an analysis comparing the DIRBE 100µm intensity to the column density of gas in
the Galaxy and determined a good correlation between the two. Therefore, to subtract off the high latitude \( p - p \) component, we performed a linear correlation of the form \( I_{\gamma} = B I_{100\mu m} + C \), between the DIRBE 100\( \mu \)m map and the EGRET 100–150 MeV intensity map. The constant \( B \) was determined to be \( 1.0 \times 10^{-8} \) photons \( \text{cm}^{-2} \text{s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1} \) per MJy/sr of the 100\( \mu \)m map. In comparison, Bertsch et al. (1993) adopted an analytical value of \( 5 \times 10^{-25} \) photons \( s^{-1} \text{ GeV}^{-1} \) nucleon\(^{-1} \) for the gamma-ray intensity per H atom at 125 MeV. Assuming the value of 18.6 nW \( \text{sr}^{-1} \text{cm}^{-2} \) determined by Arendt et al. (1998) for the ratio of the 100\( \mu \)m intensity to the gas column density, we derive a value of \( 6 \times 10^{-9} \) gamma-ray photons \( \text{cm}^{-2} \text{s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1} \) per MJy/sr of the DIRBE 100 \( \mu \)m map which is consistent with our fit parameters. After performing the correlation between one of the EGRET energy bands, the contribution from the gas in the Galaxy is scaled to the other EGRET energy bands using the well determined \( p - p \) and EB source function (Bertsch et al. 1993).

The IC contribution to the gamma-ray background has been rather uncertain. The process involves scattering of high energy cosmic ray electrons in the energy range 0.1 GeV to 1 TeV off starlight, dust reprocessed infrared emission and the cosmic microwave background. The only detailed modelling of this component has been by Bloemen (1985) who assumed an isotropic distribution for both the cosmic ray electrons and the interstellar radiation field (ISRF). An isotropic assumption for the ISRF is clearly inaccurate outside the galactic plane because the scale height of the stars and dust is of order 100 pc. We have reconstructed a model for the ISRF in the wavelength range 0.1\( \mu \)m to 1000\( \mu \)m based on work done by Mathis et al. (1981). The model was fit to the DIRBE all sky maps from 1.2\( \mu \)m to 240\( \mu \)m. For wavelengths shorter than 1.2\( \mu \)m, we adopt the average intensity values from the TD1 and the Pioneer 10 missions (See Chary & Wright 1998 for details about the ISRF model and the characteristics of the IC emission). The IC component is not very sensitive to the values at these shorter wavelengths since \( \nu J_{\nu} \) is lower by a factor of 5 compared to the peak at 1.2\( \mu \)m. The ISRF model is then used to calculate the intensity of radiation at each point within the Galaxy as a function of solid angle. This is convolved with a cosmic ray electron distribution which is assumed to be isotropic and the Klein-Nishina scattering cross-section to obtain the gamma-ray source function.

\[
\int_{30 \text{MeV}}^{10 \text{GeV}} j_{\nu,\gamma,r,z} d\nu = \int_{0.1 \mu m}^{1000 \mu m} \int_{0}^{4\pi} \int_{0}^{4\pi} \int_{0.1 \text{GeV}}^{1 \text{TeV}} I_{\nu,r,z}(\Omega) \frac{d\nu}{dE} \frac{d\sigma_{\text{KS}}}{d\Omega} \frac{dE d\Omega d\Omega d\nu}{c}
\]

Here \( j_{\nu,\gamma,r,z} \) is the IC gamma-ray source function as a function of galactocentric radius \( r \) and height from the plane \( z \), \( I_{\nu,r,z}(\Omega) \) is the intensity of the ISRF as a function of solid angle, \( \frac{d\nu}{dE} \) is the cosmic ray electron intensity and \( \frac{d\sigma_{\text{KS}}}{d\Omega} \) is the Klein-Nishina scattering cross section. For this paper, we adopt a cosmic ray electron distribution which has a spectral shape similar to that at the solar neighbourhood but varies spatially as:

\[
\frac{dn}{dE}(r, z) = \left( \frac{dn}{dE}\odot e^{-z/750} \right) \left( 1 + (R_{\odot} - r)/5000 \right)
\]

Chary & Wright (1998) however, report on the IC contribution from different cosmic ray electron distributions. The source function is integrated along all
lines of sight within the Galaxy to obtain an IC intensity map for high latitudes in the ten EGRET energy bands. Then, the final EGRET intensity maps have any bright point sources masked, the \( p-p \), EB and IC components subtracted and the residue analyzed for excess emission suggestive of a gamma-ray halo.

3. **Results and Dark Matter Constraints**

Many authors (e.g. Dixon et al. 1998) have suggested the existence of a halo of gamma-ray emission surrounding the Galactic center with intensity \( \sim 10^{-6} - 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) above 1 GeV. This could be attributed either to:

1. a halo dark matter component or
2. the inverse-Compton component or
3. a population of unresolved sources such as pulsars, in the direction of the galactic center.

We find that the magnitude of this halo intensity is similar to the difference in the IC intensity between \( l\sim0^\circ \) and \( l\sim180^\circ \) which is of order \( 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) above 1 GeV. The anisotropy in the gamma-ray background before and after subtraction of the IC component is shown in Figure 2.

![Figure 2](image-url)

**Figure 2.** The latitude averaged (\( |b| = 30^\circ - 60^\circ \)) profile of the gamma-ray intensity in the energy range 70 MeV–4 GeV as a function of \( \theta \). \( \theta \) is the angle between \( l=0^\circ \) and the line of sight. The line indicates the profile with only the \( p-p \) and EB components subtracted while the symbols represent the profile after the IC component has been subtracted.
Clearly, some of the anisotropy in the gamma-ray maps after the $p-p$ and EB components are subtracted, can be attributed to the IC component. However, there still appears to be an enhancement of order 15% in the gamma-ray intensity towards $l\sim 0^\circ$ after subtraction of the IC component. The differential photon spectrum of this residual emission above 100 MeV is $E^{-1.8}$ with an intensity of $2\times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, an order of magnitude less than the isotropic background. This spectrum is inconsistent with emission from the $p-p$ process, PBHs or annihilating WIMPs (Gondolo 1998).

A fit to the residual spectrum provides an upper limit of $3\times 10^9$ pc$^{-3}$ ($H_0=65$ km s$^{-1}$ Mpc$^{-1}$) to the number density of PBHs in the Galactic halo within the solar circle. However, since the PBHs that dominate the diffuse gamma-ray emission have mass of order $10^{14}$ g, it is not possible to constrain $\rho_{PBH,\text{halo}}$ without knowing the mass spectrum of the PBHs at the time of formation. For example, if PBHs formed in the radiation dominated era resulting in a $dn/dM \propto M^{-2.5}$ spectrum, the derived average halo mass density from PBHs would be $\rho_{PBH,\text{halo}} < 2\times 10^{-7} \rho_{\text{halo}}$ within the solar circle.

Alternatively, if the excess gamma-ray emission is attributed to the $p-p$ component from diffuse high latitude gas, the derived maximum column density is $\sim 5\times 10^{19}$ cm$^{-2}$. This is assuming a gamma-ray emissivity per H atom similar to that used to subtract the Galactic $p-p$ component earlier. The upper limit to the total mass of diffuse halo gas within the solar circle is then $\lesssim 10^8$ M$_\odot$.

Based on the spectrum of the residual emission, we conclude that the enhancement is more likely to be due to an underestimation of the inverse Compton component which in our simulations has a photon index of $-2.0$. This implies a cosmic ray electron density which is steeper than the adopted distribution, in the direction of the galactic center and at high latitudes. Another possible interpretation is a population of unresolved point sources such as pulsars. We estimate that the residual emission can be produced by about 100 pulsars with Crab like gamma-ray intensities. Better spatial resolution data which will be provided in the future by the GLAST gamma-ray mission is required to test this hypothesis.

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