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# Towards a Simple Explanation for the Diffuse Galactic Center γ-Ray Spectrum Measured by EGRET

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**Abstract**

The diffuse γ-ray emission from the central part of the galaxy as measured by EGRET shows a notable excess above 1 GeV relative to that expected from cosmic ray collisions assuming an interstellar (IS) proton spectrum similar to that observed at Earth. Many explanations for this difference have appeared in the literature but none of them focus on the most obvious and simplest answer. Using calculations from a Monte Carlo diffusion program we show that the shape of the IS proton spectrum from 1-100 GeV is sensitive to the amount and the distribution of matter traversed by these protons. We can produce an IS proton spectrum that mimics that required to explain the EGRET γ-ray spectrum for line integrals of matter density perpendicular to the galactic disk ~3-4 times those believed to apply at the location of the Sun 8.5 Kpc from the center. These matter distributions are reasonable for lines of sight through the center of the galaxy. Examples of propagated proton spectra will be presented, all assuming a constant source spectrum $\sim P^{-2.25}$.

## 1. Introduction

The diffuse γ-ray emission from the central part of the galaxy as measured by EGRET shows a notable excess above 1 GeV relative to that expected from π° decay from cosmic ray collisions (Hunter, 1997, see also Strong, et al., 1997). The expected emission is calculated assuming a cosmic ray proton spectrum similar to that observed locally. Many explanations for this difference between observations and predictions of the shape of the γ-ray spectrum have appeared in the literature but none of them focus on the most obvious and simplest answer. We believe that this answer is contained in the study of this γ-ray spectrum by Mori, 1997, and also by an understanding of how the cosmic ray proton spectrum is modified during its propagation in the galaxy after an initial acceleration. In his analysis Mori notes that if the IS proton spectrum is taken to be $\sim E^{-2.45}$, which is quite different than the one he initially assumes for the local IS spectrum, then the γ-ray spectrum from ~1-10 GeV measured by EGRET can be well reproduced. The other point of interest from Mori's analysis is Figure 10, which shows the contribution of cosmic ray protons of various energies to γ-rays of specific energies. It is seen from this figure that for protons ≥5 GeV the γ-ray production probability is nearly Gaussian with a peak at ~0.16 times the proton energy. This means that the γ-ray spectrum from ~0.8-10 GeV as measured by EGRET closely maps the IS proton energy spectrum from ~5-60 GeV. It is in this energy range than that the IS proton spectrum needs to have an average index of -2.45. Above this energy the IS proton spectrum can be steeper, but within this energy range the IS proton spectrum should look much like the EGRET γ-ray spectrum only scaled up a factor ~6 in energy.

## 2. Calculation of the IS Proton Spectrum

In this calculation we use a one dimensional Monte Carlo (MC) diffusion model, cross-checked by Leaky Box Model calculations. We assume that the proton injection spectrum is given by $dj/dp \sim P^{-2.25}/\beta$ and that the diffusion coefficient at z=0 is given by $K_0=2\times10^{28}\, P^{0.50}\, cm^2$ sec above 1GV. This assures that the high energy proton spectrum will have an index that approaches -(2.25+0.50)= -2.75 above 100 GeV as is measured (Webber, 1997). The other details and parameters of the MC calculation are described in Webber and Rockstroh, 1997. A most important parameter in this calculation is the line integral, $I_m=\int n\,dz$, of the matter density perpendicular to the disk along with the distance to the boundary $z_b$ in kpc (the size of the halo). We find that we can accurately fit (±5%) the B/C and Fe sec/Fe ratios at both low (1 GeV/nuc) and high (~100 GeV/nuc) energies for several combinations of the matter density at z=0 and the z dependence of the matter density. These fits will lead to different values of $I_m$. However, only one value of $I_m$ will predict both the secondary/primary ratios and the correct radioactive decay fractions for $^{10}Be$, $^{26}Al$, etc. (Webber, 1999). This $I_m=(8.4\pm1.7) \times 10^{20}\ cm^{-2}$ and has a value of $n_0=1.2\ cm^{-3}$ at z=0 for the sum of all components of matter. This is the value of $I_m$ used in the local proton spectrum calculation shown in Figure 1. This proton spectrum is normalized to have a value $j \times E^{2.5}=(3.3 \pm0.3) \times 10^3$ at 1 GeV which fits the proton spectrum at 1 GeV and below used in solar modulation studies, and a value $jxE^{2.5}=(6.8\pm0.3) \times 10^3$ at $10^2$ GeV which fits the higher energy measurements. Between 1 and 100 GeV this spectrum also fits some magnetic spectrometer measurements if proper allowance is made for solar modulation effects (Webber, 1999). This calculated local $j \times E^{2.5}$ spectrum shown in Figure 1 lies somewhat above the Mori median spectrum and has a slightly different shape at 10 GeV and below, but will not correctly predict the γ-ray spectrum seen from the galactic center.

The other two curves in Figure 1 are calculated for; 1) A value of $I_m$ =4X that taken locally with $n_0=2.0\ cm^{-3}$ at z=0. This larger value of $I_m$ might be appropriate for the matter density closer to the center of the galaxy; 2) For a line of sight directly along the plane of the galaxy towards the center with $n_0=1.2\ cm^{-3}$. These different matter distributions are the only difference in the calculations. Normalized to the local proton spectrum between 1 and 3 GeV, which correctly predicts the EGRET γ-ray spectrum measured at a few hundred MeV, these calculated spectra have a large excess above a few GeV. This excess is a factor ~1.6 times the spectrum adapted by Mori at 10 GeV proton energy, increasing to 1.7 times at 30 GeV, asymptotically reaching values ~1.9-2.0 times the Mori spectrum above ~100 GeV where all of the spectra have the same slope. These spectral differences arise because of the increased matter traversed which begins to effect the shape of the IS spectrum at higher and higher energies and leads to an altogether different spectral shape in the 1-100 GeV range.

Using this modified proton spectrum we have calculated the expected γ-ray spectrum from the galactic center by simply scaling the γ-ray spectrum obtained by Mori by the factors by which our modified proton spectrum exceeds that used by Mori. This $j \times E^{2.0}$ γ-ray spectrum is shown in Figure 2. This spectrum also includes the contribution at lower energies due to electron bremsstrahlung as described in the paper by Higbie, et al., 1999. This composite spectrum provides a very good fit to the EGRET data as well as the COMPTEL γ-ray data at lower energies (note that the Strong, et al., 1997 EGRET spectrum agrees with the Hunter, et al., 1997 EGRET spectrum within a solid angle normalization factor).

## 3. Summary and Conclusions

In effect the measurement of the γ-ray spectrum from the galactic center by EGRET from a few hundred MeV to ~10 GeV (Hunter, et al., 1997, Strong, et al., 1997) is providing us with a template of the IS proton spectrum between ~1 and 100 GeV in that direction. In the direction towards the galactic center this IS proton spectrum can be quite different than that observed at Earth, not necessarily because of different source spectra, but because of the different matter distributions traversed by the cosmic ray protons. Using a Monte Carlo program to model cosmic ray propagation, we have examined the effects of different matter distributions on the cosmic ray proton spectrum. From 1-100 GeV the spectrum is found to be very sensitive to this matter distribution (see Figure 1). In Figure 2 we show a calculated γ-ray spectrum from the galactic center based on a simple scaling of the ratio of the calculated galactic center proton intensities (spectra) to those used by Mori, 1997. This γ-ray spectrum provides a good fit to the one measured by EGRET.

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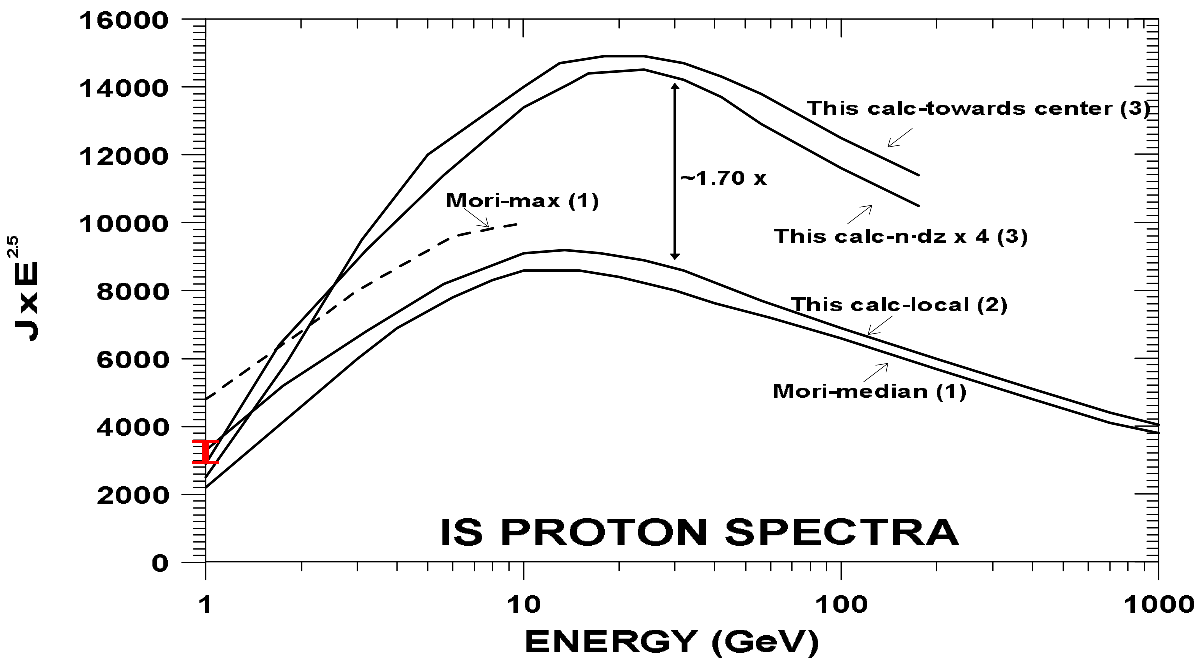


**Figure 1:** Examples of interstellar proton spectra used to calculate γ-ray spectra. (1)Mori, 1997, median and maximum spectra. (2)Local spectrum from Monte Carlo propagation calculation-source dj/dp ~ $P^{-2.25}$. (3)Examples of Monte Carlo calculation for different matter distributions towards the galactic center as indicated in the text.

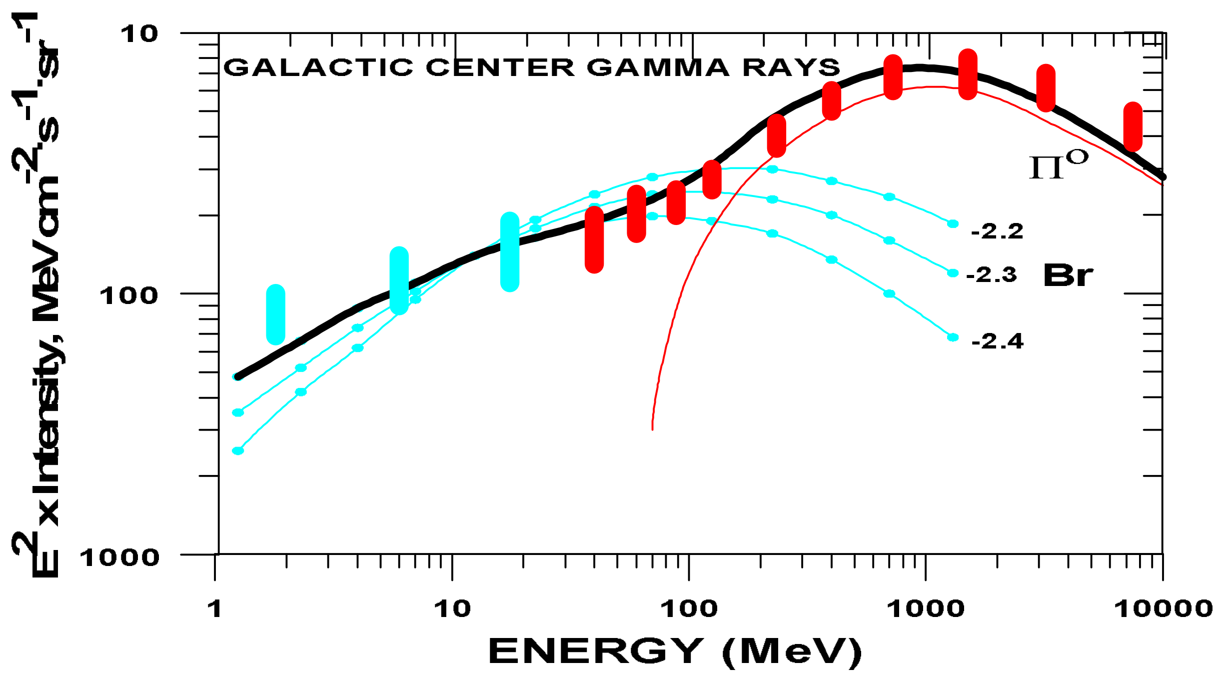


**Figure 2:** Galactic center γ-ray spectrum from COMPTEL & EGRET for –5° <b<+5° from Strong, et al., 1997. Predictions are: Blue curves-Bremsstrahlung spectra from electron source spectra with indices = -2.2, -2.3, -2.4 from Higbie, et al., 1999 paper. Red curve-∏° spectrum from proton spectrum towards the galactic center derived in Webber, 1999. Solid curve-combined ∏° spectrum and –2.40 bremsstrahlung spectrum.