The Fermi haze from Dark Matter and Anisotropic Diffusion

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Abstract

THE FERMI HAZE is a diffuse component of gamma-ray emission centered towards the galactic center, extending up to approximately ± 50 degrees in latitude, recently revealed after analysis of full-sky map data from the Fermi LAT instrument[1] (see also[2]). The Fermi "haze" is the gamma-ray counterpart generated by inverse Compton emission from the same population of electrons which generate the microwave synchrotron haze observed at WMAP wavelengths[3, 4]. Its two distinct characteristics, are its significantly harder spectrum than the emission elsewhere in the Galaxy and its morphology that is elongated along the latitude with respect to the longitude with an axis ratio 2. If these electrons are generated by dark matter annihilation, in the Galactic halo, the standard spherical halo and isotropic diffusion of cosmic rays in the Galaxy can not explain the elongated morphology of the signal. However, the existence of ordered magnetic field towards the center of the Galaxy can cause cosmic rays to diffuse anisotropically along the ordered field lines. Also dark matter halos have been shown to be generically triaxial by cosmological simulations. The combination of a prolate dark matter halo and anisotropic diffusion can easily yield the required morphology of the signal without making unrealistic assumptions about the galactic magnetic field while also being consistent with local cosmic-ray measurements as well as CMB constraints. A Sommerfeld enhancement to the annihilation cross-section of $\sim$30 yields a good fit to the morphology, amplitude, and spectrum of both the gamma-ray and microwave haze.

1. Fermi Gamma-ray haze

[3] and [4] have proposed the WMAP microwave haze which suggests the existence of a population of electrons with a spectrum harder than the SNe accelerated electrons. Such a population of hard electrons should also give an ICS signal as well. The *Fermi* data clearly show that the haze is in fact elongated in latitude b extending to $|b| \sim 50$ degrees(see Figure 1).

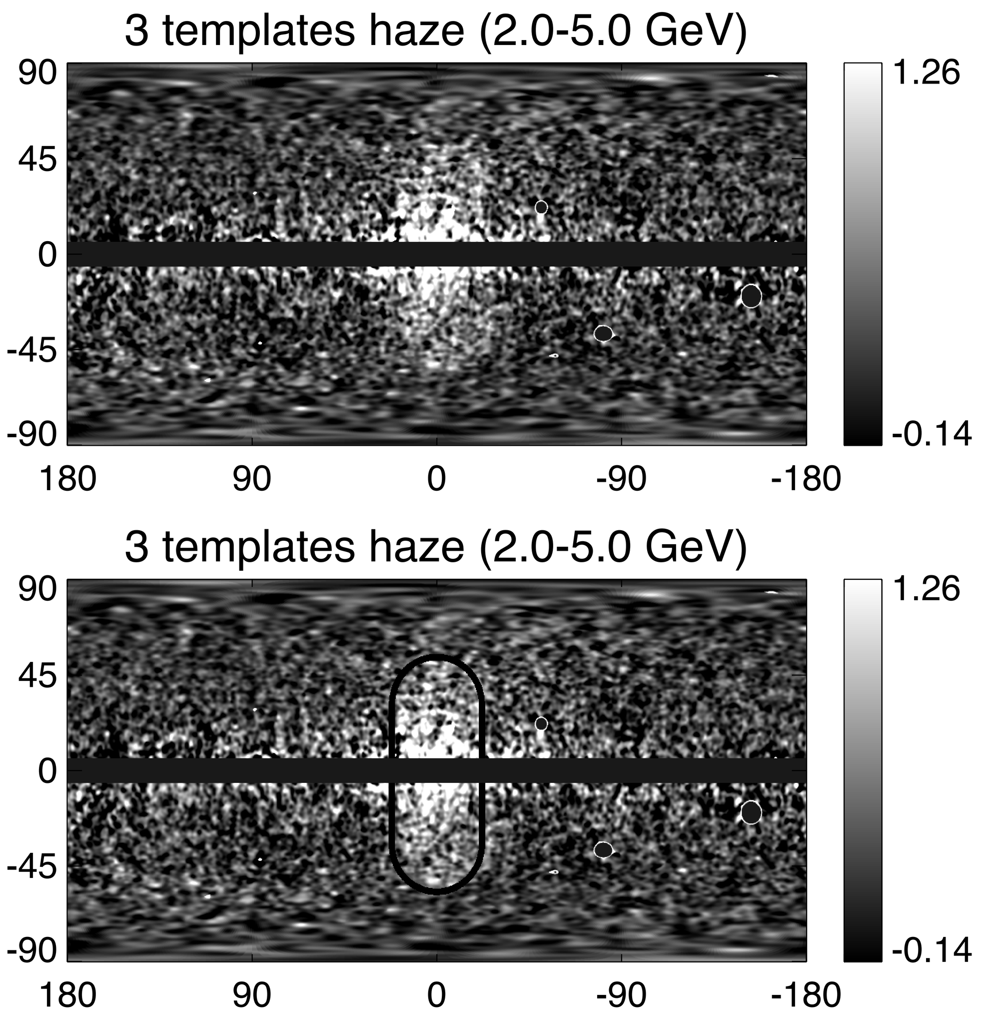

Figure 1: *The Fermi haze residual using 3 templates fit ($E_{0.5-1.0}$, isotropic, GALPROP)*

2. Anisotropic Diffusion

The propagation of CRs through the ISM is governed by the diffusion equation,

$$\frac{\partial \psi}{\partial t} = \frac{\partial (b\psi)}{\partial E} + \vec{\nabla}(D\vec{\nabla}\psi) + Q,$$

where ψ is the number density per unit particle momentum of CRs at time t and position $\vec{x}$, b is an energy loss coefficient. Typically, isotropic diffusion is assumed so that D is not a function of $\vec{x} = (r, z)$. However in our case the diffusion term generalizes to:

$$\vec{\nabla}(D\vec{\nabla}\psi) = \frac{1}{r}\frac{\partial}{\partial r}(rD_{rr}\frac{\partial \psi}{\partial r} + rD_{rz}\frac{\partial \psi}{\partial z}) + \frac{\partial}{\partial z}(D_{zz}\frac{\partial \psi}{\partial z} + D_{zr}\frac{\partial \psi}{\partial r}),$$

where D_{rr}, D_{zz}, D_{rz} and D_{zr} are functions of $\vec{x} = (r, z)$. We modified the GALPROP propagation code to calculate the gamma-ray and microwave maps as well as the CR fluxes. For more details see [6].

In the generic case where, an electron travels in a magnetic field with both an irregular $B_{\rm irr}$ and ordered $B_{\rm ord}$ component, the electron spirals around the ordered field lines with cyclotron frequency Ω, while there is a characteristic frequency ν at which the electron is scattered from its path by the irregular component. This behavior can written in the diffusion tensor as [5]:

$$D_{ij} = D_0 \left(\frac{\nu^2 \delta_{ij} + \Omega_i \Omega_j}{\nu^2 + \Omega^2} \right),$$

where D_0 is the diffusion constant for the isotropic case, δ_{ij} is the delta function, Ω_i is the cyclotron frequency due to the field pointed along the i-direction ($\Omega_i \propto B_i$ and $\Omega^2 = \Omega_i^2 + \Omega_j^2$), and $\nu \propto B_{\rm irr}$. In our case, we assume for simplicity that the ordered field is oriented perpendicular to the Galactic plane, $B_r = 0$ and $B_z = B_{\rm ord}$, so that $D_{rz} = D_{zr} = 0$. In this case, the diffusion tensor becomes,

$$D_{ij} = D_0 \times \begin{pmatrix} (1 + B_{\rm rat}^2)^{-1} & 0 \\ 0 & 1 \end{pmatrix},$$

where $B_{\rm rat}$ is the ratio of the ordered to irregular field and we have used the fact that $\Omega/\nu \propto B_{\rm ord}/B_{\rm irr}$. The normalization of D_0 is fixed by fitting to the local CR measurements. For the irregular component of the B-field we assume:

$$B_{\rm irr} = B_0 e^{(R_\odot - r)/r_1 - |z|/z_1},$$

while the ordered component is parametrized as:

$$B_{\rm ord} = B_1 e^{-r/r_2 - |z|/z_2} \times \left(1 + K e^{-r/r_3 - |z|/z_3}\right).$$

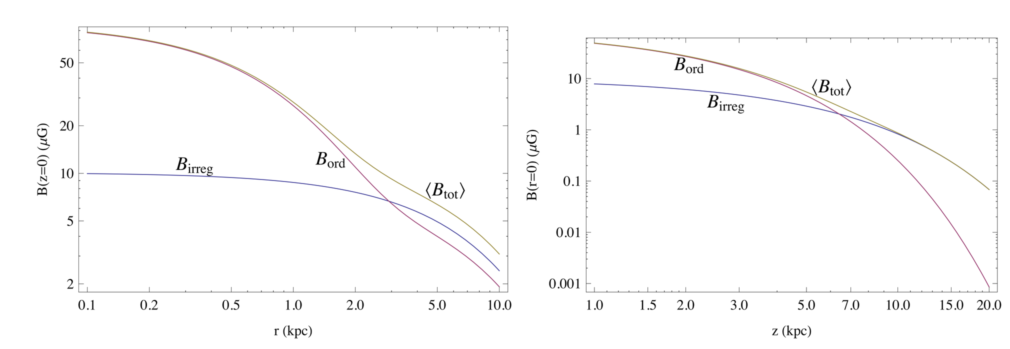

Figure 2: *Amplitude profiles for the ordered, irregular components and total B-field vs r (*left*) and z (*right*).*

[7] have suggested magnetic fields up to few mG in large non-thermal radio filaments (with widths of pc and lengths $\sim$ 50 kpc). In updated work of [8] the values suggested are $\sim$0.5 mG. Those non-thermal filaments seen by VLA are directed perpendicular to the disk plane and are probes of the general B-field properties, suggesting a bipolar field. The parameters B_0, B_1, K, $r_{1,2,3}$, and $z_{1,2,3}$ that we use are set by hand to reproduce the appropriate IC geometry and agree with measured values of the Galactic magnetic field at distances greater than ~ 1 kpc from the GC while also giving a local value for the total magnetic field of 5.4 μG and an ordered-to-total amplitude ratio of $\approx$0.62 which agrees well with measured values.

3. Results

In Figure 3 we show the GALPROP IC map at $E = 3.0$ GeV for various assumptions about the dark halo prolateness and anisotropic diffusion. For the case of a spherical halo with isotropic diffusion (completely tangled magnetic field), the resultant IC signal is largely spherical. A prolate halo with isotropic diffusion is overly concentrated towards the center of the Galaxy, while anisotropic diffusion gives the best morphological match to the data.

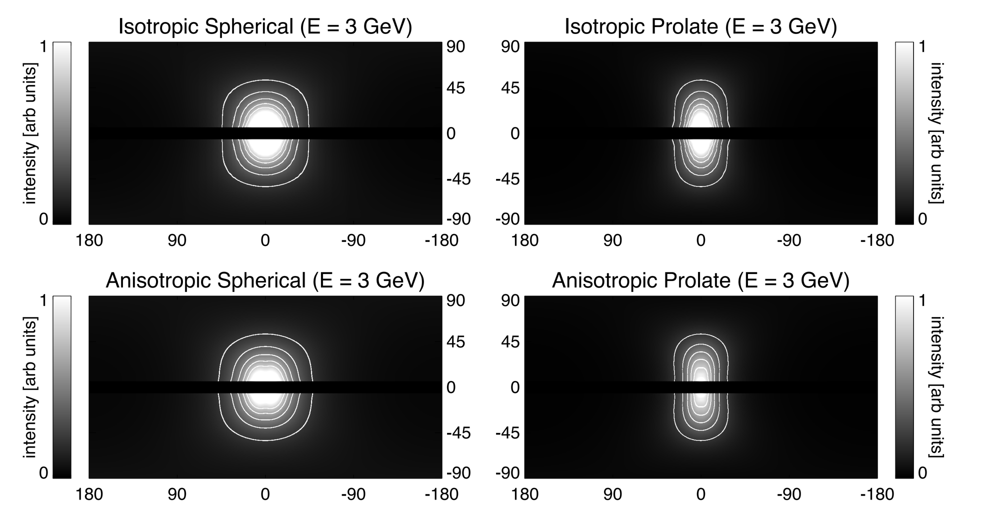

Figure 3: *GALPROP IC at 3 GeV due to $e^\pm$ production by DM annihilations with different assumptions about the diffusion model and DM halo:* upper left *spherical halo with isotropic diffusion,* upper right *prolate halo with axis ratio 2 and isotropic diffusion,* lower left *spherical halo with anisotropic diffusion,* lower right *prolate halo (axis ratio 2) and anisotropic diffusion which provides a good morphological match to the data.*

The specific assumptions on the B-field morphology, which affect the spatial dependence of the diffusion, can have a strong effect on the observed morphology of the IC emission as shown in 4 where we have used the same prolate dark halo.

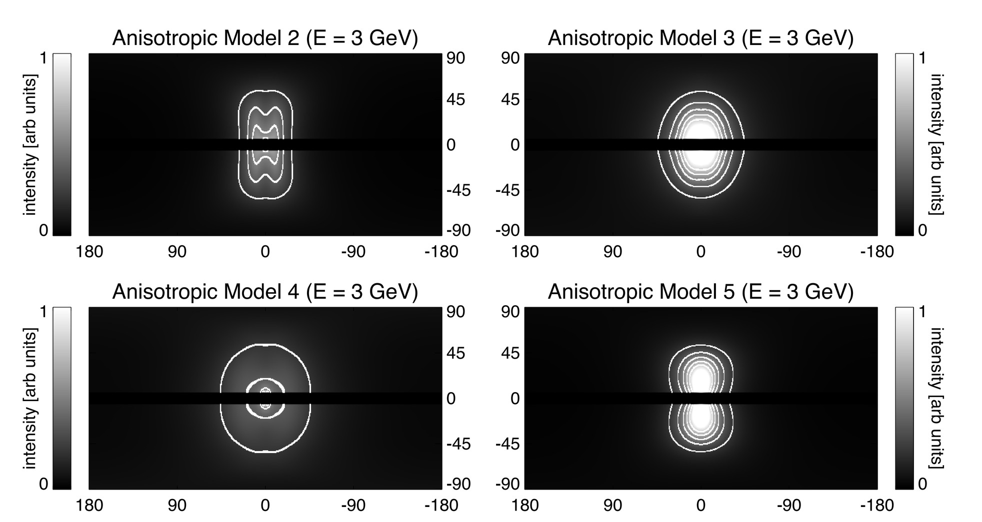

Figure 4: *The same as the bottom right panel of Fig. 3 but for different models of the ordered magnetic field, which can lead to various IC morphologies including forked (*top left*, due to increased synchrotron losses towards $r = 0$ kpc), circular and centrally concentrated (*top right*), circular and more uniform (*lower left*), and also more* hourglass-shaped *(*lower right*).*

In Figure 5, we compare the spectrum of the observed *Fermi* haze to that produced by the IC emission from $e^\pm$ generated by the XDM electrons annihilation channel: $\chi\chi \longrightarrow \phi\phi$, $\phi \longrightarrow e^+e^-$ with B.R. = 1 and DM mass $M_\chi = 1.2$ TeV[9]. In this model, ϕ is a vector boson with mass $m_\phi < 2m_\mu$ that is the force carrier responsible for the velocity dependent Sommerfeld enhancement[10]. We find that the required BF for the *Fermi* haze at 4 GeV is BF=24 while at WMAP 23 GHz it is a nearly identical BF=31, as shown in the bottom panels of 5.

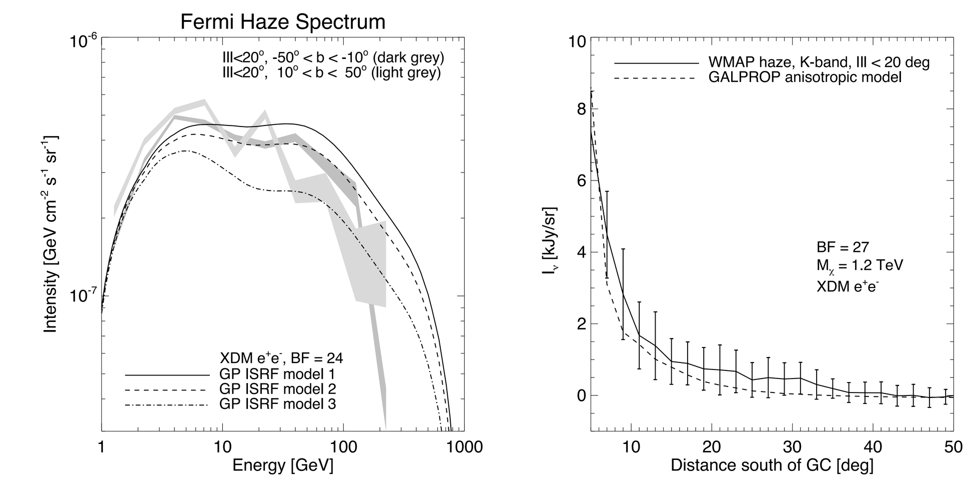

Figure 5: Left: *The spectrum of emission in north(light) and south(dark) regions from the GC. DM annihilation spectrum(solid line) is quite consistent to the data. The dashed and dot-dashed lines are for the same model reducing IR and starlight intensities by 20% and 50% respectively. The required boost factor in the annihilation rate is nearly identical to that found by fitting the radial profile south of the GC to the* Fermi *4GeV data as well as independently fitting the microwave haze profile at WMAP K-band (*right*).*

In our calculations of the synchrotron radiation emission, we take into account the presence of both the ordered and the irregular B-field components which as shown in Figure 6 has a significant effect in the averaged emissivity of the $e^\pm$ distributions as opposed to that of a completely random B-field.

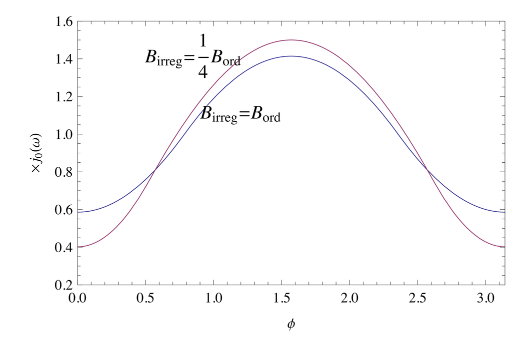

Figure 6: *Averaged emissivity from a distribution of electrons with random pitch angles vs ϕ angle from the z-axis. 1 represents the case of isotropic synchrotron emissivity $j_0(\omega)$.*

We note that the cross section in the inner galaxy is roughly a factor of three lower than that needed to explain local cosmic ray excesses, this could naturally arise from a radius dependent velocity dispersion [11], or from a depletion of substructure in the inner galaxy [12].

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2011 Fermi Symposium, 9-12 May, Rome, Italy