THE \textit{FERMI} GAMMA-RAY HAZE FROM DARK MATTER ANNIHILATIONS AND ANISOTROPIC DIFFUSION

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\textbf{ABSTRACT}

Recent full-sky maps of the Galaxy from the \textit{Fermi Gamma-Ray Space Telescope} have revealed a diffuse component of emission toward the Galactic center and extending up to roughly $\pm 50^\circ$ in latitude. This \textit{Fermi} “haze” is the inverse Compton emission generated by the same electrons that generate the microwave synchrotron haze at \textit{Wilkinson Microwave Anisotropy Probe} wavelengths. The gamma-ray haze has two distinct characteristics: the spectrum is significantly harder than emission elsewhere in the Galaxy and the morphology is elongated in latitude with respect to longitude with an axis ratio of $\approx 2$. If these electrons are generated through annihilations of dark matter (DM) particles in the Galactic halo, this morphology is difficult to realize with a standard spherical halo and isotropic cosmic-ray (CR) diffusion. However, we show that anisotropic diffusion along ordered magnetic field lines toward the center of the Galaxy coupled with a prolate DM halo can easily yield the required morphology without making unrealistic assumptions about diffusion parameters. Furthermore, a Sommerfeld enhancement to the self-annihilation cross-section of $\sim 30$ yields a good fit to the morphology, amplitude, and spectrum of both the gamma-ray and microwave haze. The model is also consistent with local CR measurements as well as cosmic microwave background constraints.

\textit{Key words:} astroparticle physics – dark matter – diffusion – Galaxy: halo – gamma rays: ISM

1. \textbf{INTRODUCTION}

With the first year data release, the \textit{Fermi Gamma-Ray Space Telescope} provided a wealth of new insights and detail of the gamma-ray sky. The energy range and angular resolution of the Large Area Telescope on board \textit{Fermi} has significantly advanced the understanding of many areas of gamma-ray astronomy, from point source studies like pulsars (Abdo et al. 2009a, 2010f; Saz Parkinson et al. 2010) and blazars (Abdo et al. 2009b, 2010e, 2010a, 2010c), to diffuse emissions from the extragalactic gamma-ray background (Abdo et al. 2010d; Ackermann et al. 2010a; Abdo et al. 2010b) and the interstellar medium (ISM; Abdo et al. 2009c; Porter et al. 2009; Strong et al. 2010).

Recently, Dobler et al. (2010) have assembled full-sky maps of the Galaxy using the published raw photon data from \textit{Fermi} from several hundred MeV up to several hundred GeV. These maps of gamma-ray emission from the diffuse ISM are produced primarily through three processes: cosmic-ray (CR) protons collide with the ISM producing $\pi^0$ particles that decay to gammas, bremsstrahlung from CR electrons (and positrons) colliding with ions, and inverse Compton (IC) scattering of starlight, infrared, and cosmic microwave background (CMB) photons by CR electrons. Because bremsstrahlung and $\pi^0$ emission are due to collisions of CRs with the ISM, these emissions are highly spatially correlated with other maps of the ISM like the dust column density map of Schlegel et al. (1998). Since the IC emission is generated by interactions of CR electrons with the interstellar radiation field (ISRF), there is not a good morphological tracer of this emission at other energies. However, CR electrons are primarily accelerated in supernova (SN) remnants and so their injection morphology should be very disk-like. Although diffusion effects are important, for isotropic diffusion through the Galaxy the resultant IC emission should also be very disk-like.

Using template fitting techniques to morphologically regress out the emission from $\pi^0$s, bremsstrahlung, and IC from disk electrons from the \textit{Fermi} maps, Dobler et al. (2010) found an excess “haze” of IC emission toward the Galactic center (GC) extending $\pm 50^\circ$ in latitude with an axis ratio of roughly 2.0. This \textit{Fermi} haze is the gamma-ray counterpart to the microwave haze observed by the \textit{Wilkinson Microwave Anisotropy Probe} (WMAP) as described in Finkbeiner (2004a) and Dobler & Finkbeiner (2008a). At WMAP wavelengths, the same electrons that generate the \textit{Fermi} IC haze interact with the Galactic magnetic field to produce synchrotron microwaves. Recently, Su et al. (2010) have reconsidered the morphology, arguing for a “bubble”–like structure. Nonetheless, for reasons outlined in Section 2 we use the “haze” moniker throughout this paper, although we are effectively considering the same gamma-ray signal.

In both the gamma-ray and synchrotron cases, the haze emission is significantly harder than elsewhere in the Galaxy, implying that the electrons which produce the haze have a harder spectrum than the electrons accelerated and diffused through the Galactic disk. In fact, the electron spectrum (number density per unit energy) needed to produce IC gamma rays with the observed haze spectrum is roughly $dN/dE \propto E^{-1}$ at high energies. This is significantly harder than electrons generated by SN shock acceleration after taking into account diffusion effects. For shock acceleration, the injection spectrum is $dn/dE \propto E^{-2}$ leading to a diffused spectrum of roughly $dn/dE \propto E^{-2}$, two powers of $E$ softer than the data require.

The identification of the haze in both the WMAP and \textit{Fermi} data implies that the haze is real and that the underlying electron spectrum is very hard. It is this hard spectrum and the diffuse elongated morphology that are the defining characteristics of the emission, and any proposed origin for the electrons must match both of these features. For example, several
authors have studied the connection between the haze electrons and young- and middle-aged pulsars (Zhang et al. 2009; Faucher-Giguere & Loeb 2010; McQuinn & Zaldarriaga 2011). The morphology, however, of the diffused electrons accelerated in pulsar winds would be very disk-like and would not match the morphology. Others have tried to reproduce the haze emission with a combination of increased SN rate and modified diffusion parameters (McQuinn & Zaldarriaga 2011; Gebauer & de Boer 2009), but this also cannot produce the observed morphology or the observed spectrum, even when including possible reacceleration effects. Lastly, there has been speculation that both the gamma-ray haze (Linden & Profumo 2010) and the microwave haze (Mertsch & Sarkar 2010) are due to imperfect template subtraction, however neither of these criticisms has been able to produce the morphology or the spectrum (amplitude and shape) of the observations using simulations. Furthermore, the gamma-ray haze is visible in the Fermi sky maps without performing any template fitting, demonstrating that it is a clearly real structure.

This work builds upon previous studies of the haze, which explore the possibility that the haze electrons are generated through dark matter (DM) annihilations in the Galactic halo. Finkbeiner (2004b) originally showed that the microwave haze morphology and spectrum in the WMAP one-year data were reasonably well matched by a DM model with a particle mass of $M_\chi \sim 100$ GeV and with a self-annihilation cross-section $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ which is roughly that required to yield the observed relic density of DM $\Omega_{DM} \approx 0.23$ if the DM particle is a thermal relic of the big bang.

However, initial data from Fermi of the inner Galaxy suggested that the IC emission from the haze electrons extended up to at least $\sim 200$ GeV, implying a DM particle mass of closer to $\sim 1$ TeV. Since the annihilation rate is proportional to the number density squared, this requires a $(\sigma v)$ roughly 100 times the thermal relic value in order to match the data. With light force carriers, a “boost factor” of 100 in the Galactic halo is easily obtainable (Arkani-Hamed et al. 2009; Pospelov & Ritz 2009) via the Sommerfeld mechanism (Sommerfeld 1931; Hisano et al. 2005, 2004; Cirelli et al. 2008; Lattanzi & Silk 2009), in which $(\sigma v)$ increases with decreasing relative velocity up to some saturation value, while still producing the correct relic density (Feng et al. 2010; Finkbeiner et al. 2011). Such a particle model is also consistent with local electron and positron CR anomalies observed by the Payload for Antimatter Exploration and Light-nuclei Astrophysics (Picozza et al. 2007; Adriani et al. 2009, 2010) satellite and Fermi (Abdo et al. 2009d; Ackermann et al. 2010b) as shown by Cholis et al. (2009a) and Cholis & Weiner (2009). A model independent fit to all of the data (gamma rays, microwaves, and CRs) by Lin et al. (2010) confirms that the injection spectrum must be $E^2 dN/dE \propto E^2$, which is broadly consistent with the spectrum of a Sommerfeld-enhanced DM annihilation scenario in which the main products are leptons.

These works have shown that the amplitude and spectrum of the haze are easily reproduced with a DM particle annihilation model; but here we are concerned primarily with the morphology. The morphology of the gamma-ray haze is the most difficult aspect to model since the haze is significantly elongated in latitude with respect to longitude. In fact, the geometry is impossible to realize with disk-like (or, as we show in Section 4, spherical) injection, ruling out SNe or pulsars as a possible source.

Such a geometry is also inconsistent with a spherical DM halo and isotropic diffusion. However, it is very likely that neither of these assumptions is accurate. Generically, DM N-body simulations of Milky Way sized halos imply prolate halos with an axis ratio of roughly 2 (Diemand et al. 2008; Kuhlen et al. 2008; Springel et al. 2008) and observations of the spatial distribution of Milky Way satellites imply a prolate halo oriented perpendicular to the Galactic disk (e.g., Zentner et al. 2005). In addition, the presence of any ordered magnetic field lines toward the GC implies that the electrons will not diffuse isotropically as they follow the fields. In Section 2 we discuss the morphology of the haze in more detail, and in Section 3 we outline our anisotropic diffusion model, which produces a DM IC halo that closely resembles the observed morphology. In Section 4 we compare our model to the data (the morphology, amplitude, and spectrum of the haze emission), and in Section 5 we summarize our conclusions.

2. HAZE MORPHOLOGY

Prior to the release of the gamma-ray data, the microwave haze was described by Finkbeiner (2004a) and Dobler & Finkbeiner (2008a) as being centered on the GC, roughly spherical, and decreasing in amplitude approximately as $1/r$, where $r$ is the angular distance to the GC. However, such a microwave signal is limited by the extent of the B-field off the disk. The Fermi data on the other hand clearly show that the haze is in fact elongated in latitude and extends to $|b| \sim 50^\circ$. Despite the lower angular resolution and signal to noise, the gamma-ray data give a more complete picture of the location of the haze electrons. The reason for the different morphologies is that the synchrotron amplitude is proportional to the magnetic field strength while the IC is proportional to the ISRF. Since the magnetic field falls off quickly with distance above the Galactic disk while the CMB amplitude is latitude independent, the microwave haze is confined to lower latitudes compared to the gamma-ray haze.

The detailed morphology of the gamma-ray haze close to the Galactic plane is difficult to determine. In Dobler et al. (2010), three methods of template fitting were used: (1) the actual Fermi data from 1.0–2.0 GeV was used as a full-sky template, (2) the (Schlegel et al. 1998; SFD) dust map was used alone, and (3) the SFD dust map, the Haslam 408 MHz map (Haslam et al. 1982), and a bivariate Gaussian haze template were used. Method (2) was not particularly successful at fitting the full-sky data and left significant disk-like residuals as well as the Fermi haze. Methods (1) and (3) were much more successful but gave very different haze morphologies at low latitudes ($|b| < 30^\circ$). In particular, using method (1) gives a haze that is more oval shaped while method (3) gives a haze that is more hourglass or “bubble” shaped (see Figure 1). Recently, Su et al. (2010) have explored the bubble morphology of method (3) in detail and argued that this morphology may be indicative of a significant event toward the GC (e.g., accretion onto the central black hole) in the past. However, before ascribing a physical mechanism to the generation of the haze electrons, which is dependent upon the haze morphology, it is important to determine what that morphology is and why the two methods differ.

Both methods (1) and (3) have associated problems. Since method (1) takes differences of Fermi data at different energies, any haze that is present in the lower energy data is subtracted off of the higher energy data so that the specific spectrum of the Fermi haze cannot be uniquely determined. In addition, since the Fermi maps have somewhat low signal to noise, subtracting one
map from another (which adds the noise in weighted quadrature while removing the signal) yields difference maps that can be quite noisy.

On the other hand, method (1) has the advantage that it does not rely on external templates (like the SFD dust map for example) and so automatically takes into account systematics like line of density effects in the ISM. In other words, the lower energy \textit{Fermi} maps are a better morphological tracer of the higher energy \textit{Fermi} maps than external templates. The fact that the haze residual remains in the difference is a statement that this emission has a significantly harder spectrum than the emission elsewhere in the Galaxy.

The advantage of method (3) is that the absolute spectrum of the haze can be well determined since the haze structure is not in the external templates. However, because of line-of-sight variations in the ISM and CR proton density, there will be, for example, variations in the ratio of $\pi^0$ gamma-ray emissivity to total dust column density. Thus the dust column map will not be a perfect tracer of the gamma-ray map. This is especially true in the inner Galaxy (within about 30° of the GC) and has the potential to significantly affect the perceived haze morphology. To illustrate this point, Figure 2 shows the \textit{Fermi} data from 2.0–5.0 GeV with the Su et al. (2010) model for IC emission and varying amounts of the SFD map subtracted. When the SFD coefficient is small, the $\pi^0$ gammas are clearly undersubtracted. However, as the coefficient is increased, a clear X-shaped oversubtraction becomes visible. This structure defines the “bubble” shape of the haze in method (3), and may be the root of the discrepancy between the two morphologies. That is, if the haze were actually oval shaped, it may appear more hourglass shaped after oversubtracting this “X.”

It is important to note that this “X” is not a feature in the SFD map (with the exception of the upper right and possibly lower right edges), but rather is being oversubtracted because the projected $\pi^0$ to dust column ratio is lower in that shape.

Furthermore, it is quite possible that the environmental conditions toward the GC which give rise to this “X” in gamma rays produce similar features in X-rays and microwaves. For example, a heating source toward the center could heat the gas leading to enhanced, harder X-ray emission and such a variation in the environment would affect the estimate of column density to spinning dust emissivity used by Dobler & Finkbeiner (2008a, 2008b) and Dobler et al. (2009) to remove the spinning dust component at microwaves. This would have the effect of making both the gamma-ray and microwave haze more hourglass shaped due to the same ISM physics that generates an edge in X-rays. Without speculating further about what this “X” structure is, we note that there is significant evidence for X-shaped bulges in other galaxies, and recent evidence from the Two Micron All Sky Survey that there exist red clump populations in the Milky Way that follow this feature (McWilliam & Zoccali 2010).

In the context of comparing the gamma-ray haze spectrum and morphology to a signal generated by injecting electrons via DM annihilations, the “bubble” morphology seems difficult to obtain (or at the very least, seems more indicative of a transient event in the GC). However, we show below that an oval-shaped haze (and even an hourglass shaped haze) is possible with DM annihilation when considering anisotropic diffusion effects. Regardless, the underlying morphology of the gamma-ray haze at low latitudes is an unsettled issue. We choose to compare our results to the oval-shaped morphology and show that method (1) plus a DM contribution to the IC emission with anisotropic diffusion effects is consistent with the data.

3. DIFFUSION MODEL

Since the basis for any anisotropic diffusion scenario is that electrons travel along ordered field lines, our diffusion model must first assume a geometry for the ordered component of the Galactic magnetic field. From there, this magnetic field can be related to specific diffusion parameters, which appear in the diffusion equation. All of our calculations are done by modifying the CR propagation code GALPROP (Strong & Moskalenko et al. 2007).
where $\mathbf{B}$ is the magnetic field, $\mathbf{D}$ is the diffusion coefficient, $\mathbf{J}$ is the current density, $\mathbf{E}$ is the electric field, and $\mathbf{Q}$ is the source term.

3.2. Anisotropic Diffusion

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

$$\frac{\partial \psi}{\partial t} = \frac{\partial (b \psi)}{\partial E} + \nabla (D \nabla \psi) + Q, \quad (3)$$

where $\psi$ is the number density per unit particle momentum of CRs at time $t$ and position $\mathbf{x}$, $b$ is an energy loss coefficient (dominated by synchrotron and IC in the case of electron CRs), $Q$ is a source term due to the injection of electrons by DM annihilations, and $D$ is the diffusion constant. It is this last parameter that must be modified for the case of anisotropic diffusion, and so we are concerned with the $\nabla (D \nabla \psi)$ term above.

We solve Equation (3) using GALPROP on a cylindrical grid so that

$$\nabla (D \nabla \psi) = \frac{1}{r} \frac{\partial}{\partial r} \left( r D \frac{\partial \psi}{\partial r} \right) + \frac{\partial}{\partial z} \left( D \frac{\partial \psi}{\partial z} \right). \quad (4)$$

Typically, isotropic diffusion is assumed so that $D$ is not a function of $\mathbf{x} = (r, z)$. However in our case Equation (4)

6 These parameters do give a somewhat high value of 89 $\mu$G for the total field at the very center, $r = z = 0$ kpc. However, we note that not only is this in agreement with the estimates of Crocker et al. (2010) who place a lower limit of 50 $\mu$G in the inner 400 pc from necessary synchrotron cooling to avoid violating existing diffuse $\gamma$-ray bounds, but also the very center is well outside our region of interest. Our mask of the Galactic plane extends up to $|b| = 5^\circ$ or $|z| \approx 0.75$ kpc. Inside this region, our choice of $B$-field has little impact on our results and our value at the center is only due to our specific parameterization of the field, which likely does not extend into arbitrarily small distances.
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Note. Our fiducial model is Model 1, which generates an IC signal that roughly matches the Fermi haze morphology (see Figure 6).

Table 1
Magnetic Field Morphologies and Parameters for the IC Signals Plotted in Figure 5

| Model | Bred Formula | $B_0$ (μG) | $r_1$ (kpc) | $z_1$ (kpc) | $B_l$ (μG) | $K$ | $r_2$ (kpc) | $z_2$ (kpc) | $r_3$ (kpc) | $z_3$ (kpc) |
|-------|--------------|------------|-------------|-------------|------------|-----|-------------|-------------|-------------|-------------|
| 1     | $B_l e^{-(r^2+z^2)/12} \times (1 + K \ e^{-(r^2+z^2)/12})$ | 3          | 7           | 4           | 8          | 10  | 7           | 2           | 0.8         | 10          |
| 2     | $B_l e^{-(r^2+z^2)/12} \times (1 + K e^{-r^2/3} \sqrt{\cos(z)/\sqrt{3} \times r/2})$ | 3          | 5           | 4           | 10         | 11  | 5           | 4           | 1           | 40          |
| 3     | $B_l e^{-(r^2+z^2)/12} \times (1 + K e^{-r^2/3} \sqrt{(2/r^2+z/2)})$ | 3          | 10          | 2           | 10         | 6   | 10          | 3           | 1.2         | 20          |
| 4     | $B_l e^{-(r^2+z^2)/12} \times (1 + K e^{-(r^2+z^2)/12})$ | 3.7        | 5           | 5           | 12.5       | 8   | 5           | 2.5         | 20          |
| 5     | $B_l e^{-(r^2+z^2)/12} \times (1 + K e^{-(r^2+z^2)/12})$ | 3.7        | 5           | 5           | 12.5       | 5   | 2           | 2           | 6           |

For the diffusion tensor $D_{ij}$, we have used the fact that $\Omega = \sqrt{\Omega^1 \Omega^2}$, where $\Omega^i$ is the cyclotron frequency due to the field pointed along the $i$-direction ($\Omega^i \propto B^i$ and $\Omega^2 = \Omega^1^2$), and $v$ is the characteristic frequency of deflections by the irregular component ($v \propto B_{irr}$). In our case, we assume for simplicity that the ordered field is oriented perpendicular to the Galactic plane, $B_z = 0$ and $B_r = B_{ord}$, so that $D_{rz} = D_{zx} = 0$. In this case, the diffusion tensor becomes

$$D_{ij} = D_0 \left( \frac{\Omega^1 \Omega^2}{v^2 + \Omega^2^2} \right),$$

where $D_0$ is the diffusion constant for the isotropic case, $\delta_{ij}$ is the delta function, $\Omega_0$ is the cyclotron frequency due to the field pointed along the $i$–direction ($\Omega_i \propto B_i$ and $\Omega^2 = \Omega_1^2 + \Omega^2_2$), and $v$ is the characteristic frequency of deflections by the irregular component ($v \propto B_{irr}$). In our case, we assume for simplicity that the ordered field is oriented perpendicular to the Galactic plane, $B_z = 0$ and $B_r = B_{ord}$, so that $D_{rz} = D_{zx} = 0$. In this case, the diffusion tensor becomes

$$D_{ij} = D_0 \left( \frac{1 + B_{ord}^2}{0} \right).$$

where $B_{ord}$ is the ratio of the ordered to the irregular field, and we have used the fact that $\Omega^2/v \propto B_{ord}/B_{irr}$. Note that in the limit of $B_{ord} \rightarrow 0$, $D_{rr} = D_{zz} = D_0$, and in the limit of $B_{irr} \rightarrow 0$, $D_{rr} \rightarrow 0$ as desired. The form of this diffusion tensor implies that adding an ordered field suppresses diffusion perpendicular to that field.

For the diffusion tensor coefficient, we assume $D_0 \propto E^{-0.37}$. However, in contrast to most studies involving GALPROP, we incorporate the dependence of $D_0$ on $B_{tot}$ as well. In particular, following Strong et al. (2007),

$$D_0 \propto \left( \frac{B_{irr}}{B_{tot}} \right)^{-2} \times r_{gy} = \frac{B_{tot}}{B_{irr}^2},$$

and because $B$ depends on position, $D_0 = D_0(r,z)$. We set the normalization to be the locally measured value at roughly the locally measured magnetic field amplitude if the field were completely irregular, so that our final diffusion coefficient can be written as

$$D_0 = 2.0 \times 10^{28} \, \text{cm}^2 \, \text{s}^{-1} \left( \frac{5 \, \mu \text{G}}{B_{irr}^2/B_{tot}} \right) \left( \frac{E}{4.0 \, \text{GeV}} \right)^{-0.5},$$

where the normalization is fixed by fitting to the local CR measurements.

Taken together, Equations (7) and (9) completely define our anisotropic diffusion model and reduce to the isotropic case when $B_{ord} \rightarrow 0$ and $B_{irr} \rightarrow constant$. For more details about the dependence of diffusion on the magnetic field, see Appendix B.

Lastly we note that, in all of our models, we use a box height $L_{box} = \pm 20$ kpc. This is not directly comparable to the usual box heights (~4 kpc) discussed in the literature, because the “free escape” of electrons outside the Galactic disk is taken into account by the spatial dependence of the diffusion tensor. This is in agreement with findings by the Fermi team regarding diffuse IC away from the GC (Porter 2010) and is in fact a more appropriate box size. This also alleviates the problem of “squeashed” morphologies that are typical of smaller box heights when the CR density at the boundary is set to zero.

### 3.3. DM Annihilation Model

In Equation (3), the source term $Q$ is the rate of $e^+e^-$ injection by DM annihilations and is given by

$$Q(r,z) = \frac{1}{2} (\sigma v) \frac{dN}{dE} \left( \frac{\rho(r,z)}{M_X} \right)^2,$$

where $dN/dE$ is the injection spectrum and $\rho$ is the Galactic DM halo. We assume a prolate Einasto (Einasto 1965) halo,

$$\rho(r,z) \propto \exp \left[ -\frac{2}{\alpha} \left( \frac{r^2}{r_c^2} + \frac{z^2}{z_c^2} \right) \right],$$

with $z_c/r_c = 2.0$, $z_c = 27$ kpc, and $\alpha = 0.17$ (Merritt et al. 2005). The overall normalization is set so that the local DM density is $\rho(\odot, 0) = 0.4 \, \text{GeV} \, \text{cm}^{-3}$ (Catena & Ullio 2010, see also Salucci et al. 2010).

The injection spectrum $dN/dE$ is governed by the specific particle model. In our case, we use XDM (eXciting Dark Matter; Finkbeiner & Weiner 2007) as our fiducial model, with $M_X = 1.2$ TeV, an annihilation channel $\chi\chi \rightarrow \phi\phi$, $\phi \rightarrow e^+e^-$, and with branching ratio 1 (hereafter, XDM $e^+$; see Cholis et al. 2009c, 2009b). In this model, $\phi$ is a vector boson with $m_\phi \lesssim 2m_e$ that is the force carrier responsible for the velocity-dependent Sommerfeld enhancement (Arkani-Hamed et al. 2009; Pospelov & Ritz 2009). We do not include specific
dynamics for the host halo, but we do assume that the velocity dispersion (and hence the Sommerfeld enhancement or “boost factor”) as well as substructure contribution is flat with radius. We define this boost factor $BF$ as

$$BF = \frac{\langle \sigma v \rangle}{3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}}.$$  (12)

This model for the DM particle has $E^2 dN/dE \propto E^2$ as required by the CR, microwave, and gamma-ray data (Lin et al. 2010).

### 3.4. Fitting Procedure

We follow a similar procedure to that outlined in Appendix C of Dobler et al. (2010). Specifically, we generate a synthetic sky map,

$$S(E) = A_{\text{tot}} \times F^{E_i}_{0.5} + A_{\text{gp}} \times G(E) + A_{\text{uni}} \times U(E),$$  (13)

where we have adopted the notation $F^{E_i}_{0.5}$ to represent the Fermi map of photons with energy between $E_0$ and $E_1$. The GALPROP-generated DM map at $E = \sqrt{E_0 E_1}$ and the uniform background are denoted by $G(E)$ and $U(E)$, respectively. The parameters to be fit are the amplitudes $A_{\text{tot}}, A_{\text{gp}},$ and $A_{\text{uni}}$. We convert to a synthetic counts map $\mu(E) = S(E) \times (\text{mask}) \times (\text{exposure})$ and then minimize the log-likelihood,

$$\ln L = \sum_i [k_i \ln \mu_i - \mu_i - \ln(k_i)!],$$  (14)

where $k_i$ is the map of observed counts at pixel $i$, over the parameters $A_{\text{tot}}, A_{\text{gp}},$ and $A_{\text{uni}}$. When comparing maps at different energies, it is important to smooth the templates and data to a common beam FWHM. All of our maps use 1.6 years of data, are smoothed to $2^\circ$, and for the $F^{E_i}_{0.5}$ map, we use only “front” converting events (see Dobler et al. 2010).

### 4. RESULTS

Figure 4 shows the GALPROP IC map for $E = 3.0$ GeV and 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. The same is true for our anisotropic model with a spherical halo, implying that diffusion effects alone cannot create the observed morphology. In fact, prolate halos lead to IC morphologies that very closely resemble the haze morphology. In detail, we find that the prolate halo with isotropic diffusion is overly concentrated toward the center and that the best morphological match to the data comes from using a prolate halo with anisotropic diffusion.

The detailed assumptions on the $B$-field morphology, and thus on the spatial dependence of the diffusion, can have a strong effect on the observed morphology of the IC emission as is shown in Figure 5 where we present the IC maps at 3 GeV for four distinctively different $B_{\text{ord}}$ assumptions from those of Equation (2). The specific magnetic field model can lead to various IC morphologies from more uniform to more centrally concentrated and from more elliptical to more circular. In addition, for fields with a strong ordered component toward $r = 0$ kpc, forked morphologies (due to increased synchrotron losses toward $r = 0$ kpc) are found. Interestingly, for relatively modest changes to our magnetic field parameters, we can also reproduce an hourglass shape reminiscent of the bubble shape in Su et al. (2010). Note that all models use an identical prolate dark matter halo; the variations in shape are due exclusively to magnetic field effects on the diffusion and relative energy losses to synchrotron and IC.

This IC emission is the combination of electrons scattering CMB, IR, and starlight photons. Each of these ISRF components has a distinct morphology, and so the IC emission from each will also have a different morphology. In fact, since the starlight and IR photons are mostly confined to the plane, the high-latitude IC emission is due primarily to scattering of CMB photons. This is borne out in Figure 6, which shows the morphology of each of the IC components. The starlight and IR IC photons are concentrated much more toward the GC while the CMB IC photons extend to much higher latitudes. Furthermore, it is interesting to note the distinct bubble-like morphology of the CMB component. The implication here is that template fits like those used in Dobler et al. (2010) and Su et al. (2010), which use
can lead to various IC morphologies including forked (top left, due to increased synchrotron losses toward circular and more uniform (lower left), and also more hourglass-shaped (lower right). See Section 4 for a description.

pulling out only the CMB component would leave a bubble-like morphology. Thus, when using template regression techniques to assess the underlying morphology of the haze, care must be taken not to regress out emission from IR and starlight components while leaving only the CMB component.

potential absorb the starlight and IR morphologies, while external templates that are concentrated toward the GC, could potentially absorb the starlight and IR morphologies, while leaving the CMB morphology which appears more bubble-like. That is, if the intrinsic haze morphology is more oval shaped, pulling out only the CMB component would leave a bubble morphology.

In Figure 7 we show the residual “haze” map,

$$H_{E_0}^{E_1} = F_{E_0}^{E_1} - S_{E_0}^{E_1} + A_{gg} \times G(E),$$

as well as the residual map,

$$R_{E_0}^{E_1} = F_{E_0}^{E_1} - S_{E_0}^{E_1}.$$  

As shown in the figure, the three-component model provides a remarkably good fit to the data. There is some residual over-subtraction due to the fact that the Fermi haze appears to have an “edge” at roughly $|b| \sim 50^\circ$. This feature cannot be reproduced exactly by our models which tend to be slightly more diffuse. This lack of an edge pushes the fit to slightly oversubtract the GALPROP haze contribution. Indeed, astrophysical models such as winds (Crocker et al. 2011) or jets would also either not have an edge or, in the case of jets, likely have a shock-heated edge with a harder spectrum which is not clearly seen in the data (Su et al. 2010). Despite this, our fit removes 96%, 89%, and 69% of the variance over pixels with $|b| > 5^\circ$ at $E = 2$–$5$, $5$–$10$, and $10$–$20$ GeV, respectively (see Figure 7). Lastly, we compare the spectrum of the observed Fermi haze to that produced by the IC emission from $e^\pm$ generated by the XDM electron annihilation channel. We plot the $\mathcal{H}(E)$ emission in the window defined by $|\ell| < 20^\circ$ and $10 < |b| < 50^\circ$. This region is dominated by the Fermi haze and is relatively free of other foregrounds. When comparing the spectra, it is important to keep in mind that $\mathcal{H}(E)$ has the Fermi $F_{1.0}$ map times $A_{\text{geo}}(E)$ removed, and so in Figure 8 we show the intensity versus $E$ for $\mathcal{H}(E)$ and $G(E) - A_{\text{geo}}(E) \times G(E_{\text{lo}})$ where $E_{\text{lo}} = \sqrt{0.5 \times 1.0}$ GeV.
Performing an independent fit of the Fermi and WMAP haze profile (intensity as a function of latitude south of the GC) 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 Figure 8. In our calculations of the synchrotron radiation emission, we take into account the presence of both the ordered and the irregular B-field components. In the upper right panel of Figure 8, the predicted DM spectrum is plotted over the Fermi data assuming a BF of ∼24. It is clear from the figure that the DM spectrum with this BF provides an excellent agreement with the data, especially taking into account uncertainties in the optical and IR ISRF at latitudes far above the plane. While the cross-section in the inner galaxy is roughly a factor of three lower than that needed to explain local CR excesses, this could naturally arise from a radius-dependent velocity dispersion (Cholis & Weiner 2009), or from a depletion of substructure in the inner galaxy (Slatyer et al. 2011).

5. CONCLUSIONS

We have developed a model of Galactic CR diffusion that incorporates both an ordered and a turbulent magnetic field component. The ordered component results in anisotropic diffusion of CR electrons along field lines. Combining this model of diffusion with DM annihilations in a prolate Galactic dark halo produces an IC gamma-ray signal that matches the morphology and spectrum of the observed Fermi gamma-ray haze, namely, an oval-shaped haze with an axis ratio of ∼2:1, extending up to |b| ≈ 50°, and with a CR injection spectrum $E^2dN/dE \propto E^2$.

The detailed morphology of the haze at low latitudes is still uncertain. We have shown that the dust-column to $\pi^0$ gamma-ray ratio is higher in an X-shaped morphology toward the center of the Galaxy and that using a map of dust column like the SFD dust map as a tracer of $\pi^0$ gamma rays results in an oversubtraction of the “X.” The end result is that an oval-shaped haze may then appear more hourglass- or bubble-shaped. Using the 0.5–1.0 GeV Fermi map itself (which contains very little of the gamma-ray haze) as a tracer of disk emission at higher energies is immune to these line-of-sight effects and produces a more oval-shaped haze at the cost of noisier residuals.

Regardless, a three-component model of anisotropic diffusion with DM annihilations in a prolate halo plus the Fermi 0.5–1.0 GeV map plus a uniform background provides an excellent fit to the data from 1–20 GeV. The self-annihilation cross-section required for the DM-generated IC component is $\sim 9 \times 10^{-25} \text{ cm}^3 \text{s}^{-1}$ (boost factor $\sim 30$), which is easily obtainable via the Sommerfeld enhancement in our models and also

**Figure 7.** Haze (left column) and residuals (right column) of our three-template fit in energy bins from 1.0 to 20.0 GeV. The haze maps clearly show the strong haze residual with an axis ratio of $\approx 2$ that is in reasonably good morphological agreement with our anisotropic dark matter model (see Figure 6, top left panel). This is borne out in the residual maps which show a residual consistent with noise at latitudes above 20°. Close inspection reveals a slight oversubtraction toward the center due to the fact that our model does not explicitly include an “edge” at $b \approx \pm 50°$ as is seen in the data.
produces the microwave haze. Furthermore, this boost factor is well within the bounds of thermal relic and CMB constraints (Slatyer et al. 2009; Zavala et al. 2010).

The most significant outstanding issues are the sharp “edges” of the haze at high latitudes and also the morphology of the haze at low latitudes. Sharp edges are not particularly expected with either a DM annihilation or an astrophysical (such as winds or jets) mechanism, unless the spectrum at the edge is significantly hardened, which does not appear to be the case. Magnetic confinement could potentially help both explanations, though care must be taken not to significantly synchrotron brighten the edges which are not seen in the WMAP microwave data. The low-latitude morphology of the haze (oval versus bubble shape) may become more clear as more data are collected by Fermi. In particular, at high energies, the disk fades much more quickly than the haze because of the softer spectrum of the disk, and so the low-latitude haze may be revealed at high energies with 5 to 10 more years of data.

Of course, there is the possibility of a hybrid scenario in which some event evacuates a cavity toward the GC that is filled with high-energy electrons from DM annihilation that are trapped by magnetic confinement. Su et al. (2010) discount this possibility under the assumption that the DM signal would be more spherical, but we have shown here that this is not the case in general for triaxial halos. Injection from DM annihilation would also have the advantage that the hard spectrum can be obtained (as we have shown in this paper) and the injection is extended. Nevertheless, inside the edge, the haze appears to have a profile that is roughly flat in latitude above $|b| > 30^\circ$. Such a projected profile seems nearly impossible to realize (either with astrophysical or DM models) unless electrons pile up on the edges, though the naive expectation would be that the
gamma rays would be limb-brightened, which is not observed. If these features persist in future data, such hybrid scenarios are inevitable.

Lastly, we point out that introducing a significant ordered field as we have could potentially produce a significantly polarized microwave signal. By design, our model does reproduce the observed microwave haze in total temperature; comparison with the WMAP polarization data will be the subject of future work.

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APPENDIX A
ANISOTROPIC DIFFUSION IN THE GALPROP CODE

In GALPROP, the diffusion equation is solved through the Crank–Nicholson implicit method (Strong et al. 2007; Press et al. 1992):

$$\frac{\partial \psi_i}{\partial t} = \frac{\psi_i^{r+\Delta r} - \psi_i^r}{\Delta r} = \frac{\alpha_1 \psi_i^{r+\Delta r} - \alpha_2 \psi_i^{r+\Delta z} + \alpha_3 \psi_i^{r+\Delta z}}{\Delta t} + \mathcal{Q}_i,$$

where $i$ is the index of position ($r$ or $z$) or momentum and $\alpha_{1,2,3}/\Delta t$ are the Crank–Nicholson coefficients. In the case where $D$ is homogeneous in space, these coefficients are

$$\frac{\alpha_1}{\Delta t} = \frac{D}{2r_i(\Delta r)^2}, \quad \frac{\alpha_2}{\Delta t} = \frac{2D}{r_i(\Delta r)^2}, \quad \frac{\alpha_3}{\Delta t} = \frac{D}{2r_i(\Delta r)^2},$$

for diffusion along $r$ and

$$\frac{\alpha_1}{\Delta t} = \frac{D}{(\Delta z)^2}, \quad \frac{\alpha_2}{\Delta t} = \frac{2D}{(\Delta z)^2}, \quad \frac{\alpha_3}{\Delta t} = \frac{D}{(\Delta z)^2},$$

for diffusion along $z$. With the new terms from anisotropic diffusion (see Equation (5)) the Crank–Nicholson coefficients become

$$\frac{\alpha_1}{\Delta t} = D_{rr} \frac{2r_i - \Delta r}{2r_i(\Delta r)^2} + \frac{D_{rr+1} - D_{rr-1}}{4(\Delta r)^2}, \quad \frac{\alpha_2}{\Delta t} = D_{rr} \frac{2r_i - \Delta r}{r_i(\Delta r)^2},$$

$$\frac{\alpha_3}{\Delta t} = D_{rr} \frac{2r_i + \Delta r}{2r_i(\Delta r)^2} + \frac{D_{rr+1} - D_{rr-1}}{4(\Delta r)^2},$$

for diffusion along $r$ and

$$\frac{\alpha_1}{\Delta t} = \frac{D_{zz}}{(\Delta z)^2} - \frac{D_{zz+1} - D_{zz-1}}{4(\Delta z)^2}, \quad \frac{\alpha_2}{\Delta t} = \frac{2D_{zz}}{(\Delta z)^2},$$

$$\frac{\alpha_3}{\Delta t} = \frac{D_{zz}}{(\Delta z)^2} + \frac{D_{zz+1} - D_{zz-1}}{4(\Delta z)^2},$$

for diffusion along $z$, and where, as in the main text, we have taken $D_{rr} = D_{zz} = 0$ (since $B_r = B_z = 0$) for simplicity. When iterating recursively for a steady-state $\psi$, GALPROP utilizes the fact that the $r$- and $z$-directions are separable, whereas if we take $D_{zz} = D_{rr} \neq 0$, these directions are not separable. So while we use Equations (A4) and (A5) in practice, the general quantization of Equation (5) is (superscripts are spatial indices for clarity)

$$\nabla \left( \nabla \psi \right) = \left( \frac{D_{rr+1} - D_{rr-1}}{2\Delta r} + \frac{2D_{rr}}{2\Delta r} \right) \psi^{r+1} - \psi^{r-1} + \frac{D_{zz+1} - D_{zz-1}}{2\Delta z} \psi^{z+1} - \psi^{z-1}$$

and since $B_{tot} = \sqrt{B_{ord}^2 + B_{irr}^2}$,

$$\frac{\lambda_{zz}}{\lambda_{rr}} \sim \phi^{-2} \sim \left(1 + B_{ord}^2/B_{irr}^2\right),$$

as desired.

APPENDIX B
DIFFUSION DEPENDENCE ON MAGNETIC FIELD

Let us consider the generic case of an electron traveling in a magnetic field with both an irregular $B_{irr}$ and an ordered $B_{ord}$ component. As the electron spirals around the ordered field lines with cyclotron frequency $\Omega$, there is a characteristic frequency $\nu$ at which the electron is scattered from its path by the irregular component. In the case of a strong ordered component $B_{ord} \gg B_{irr}, \Omega \gg \nu$, while for $B_{ord} \ll B_{irr}, \Omega \ll \nu$. In other words, for strong ordered fields, the electron spirals around the field line many times before it is deflected by the irregular component. As noted in Section 3.2, this behavior is written in the diffusion tensor as (Parker 1965)

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

which, for the case of an ordered field completely along the $z$-direction, leads to the relation

$$D_{zz} \propto \frac{1}{1 + B_{ord}^2/B_{irr}^2}. \tag{B2}$$

We wish to motivate Equation (B2) from the perspective of diffusion lengths $\lambda$ since that it is the most direct measure of the diffusion coefficient, $D_{ij} = \lambda_{ij} c/3$ (where $c$ is the speed of light). In our scenario then

$$\frac{\lambda_{zz}}{\lambda_{rr}} \sim \frac{r_{gyr} N}{r_{gyr}} \sim N, \tag{B3}$$

where $r_{gyr}$ is the gyroradius and $N$ is the number of scatterings of the particle by angle $\phi \sim B_{irr}/B_{tot}$, which is the inclination angle of the field lines from the direction of the mean field due to irregularities (see Longair 2002). Note that, in the case of $B_{irr} \gg B_{ord}$, $\phi$ is large and particles are deflected significantly from their initial direction within one gyroradius while for $B_{irr} \ll B_{ord}$, $\phi \ll 1$ and particles follow the field lines of the local ordered field. For the particle to scatter by $\sim 1$ radian, we need $\sqrt{N} \phi \sim 1$ which implies

$$\frac{\lambda_{zz}}{\lambda_{rr}} \sim \phi^{-2} \sim B_{tot}^2/B_{irr}^2, \tag{B4}$$

and since $B_{tot} = \sqrt{B_{ord}^2 + B_{irr}^2}$,

$$\frac{\lambda_{zz}}{\lambda_{rr}} \sim \phi^{-2} \sim \left(1 + B_{ord}^2/B_{irr}^2\right), \tag{B5}$$

as desired.
Figure 9. Upper left: the full-sky Haslam 408 MHz map. Upper right: the latitudinal profile of Haslam and our 408 MHz synchrotron GALPROP maps for primary electrons injected via SN shocks using our anisotropic diffusion model (both with and without the ordered field component). Middle left: Haslam minus our 408 MHz GALPROP map. While the agreement is in general quite good, the map is slightly too concentrated toward the center. This is alleviated by removing the ordered field (middle right) indicating that even more complex ordered field morphologies than our simple parameterization allows can provide a good fit to the data. In addition to being a good fit to Haslam, the model without an ordered field is a reasonable match to the Fermi haze, though it is a bit centrally concentrated (bottom panels).

APPENDIX C

LOW-FREQUENCY RADIO EMISSION

Dominated by synchrotron emission from electrons with energies \( \sim \text{few GeV} \), the Haslam 408 MHz map (Haslam et al. 1982) provides an excellent constraint on both the injection morphology of the primary electrons via SN shock acceleration and also the magnetic field morphology. Thus, it is important to check that our anisotropic diffusion model maintains the “disk-like” shape of synchrotron from primary electrons at 408 MHz. Figure 9 shows the Haslam map, and the Haslam map and the predicted 408 MHz synchrotron emission due to SN injection using our full anisotropic model. As in Lin et al. (2010), we normalize the model to Haslam by setting the total emission in the region \( |\ell| \leq 10^{\circ} \) and \( -90^{\circ} \leq b \leq -5^{\circ} \) equal.

As shown in the radial profile panel (upper right), the agreement is very good, though the map difference (middle left panel) indicates that the stronger magnetic field in the center (due to the ordered component) may make the emission somewhat steeper in the region \( \sim 1-2 \text{kpc} \). However, we point out that, not only is the gamma-ray signal dominated by emission at higher latitudes, but we have used a very simple parameterization for the ordered field and additional field parameters (to lower the field within the inner 2 kpc) can remove the discrepancy. In fact, we can remove the ordered component altogether and the model comes into close agreement with both Haslam (middle right panel) and the Fermi data (bottom panels; also cf. Figure 4).

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