FERMILAB-PUB-09-313-T

Pulsars as the Source of the WMAP Haze

Manoj Kaplinghat[a], Daniel J. Phalen[b], and Kathryn M. Zurek[b,c]

[a] *University of California, Irvine, CA, USA*

[b] *Department of Physics, University of Michigan*
Ann Arbor, Michigan 48109, USA

[c] *Particle Astrophysics Center, Fermi National Accelerator Laboratory*
Batavia, Illinois 60510, USA

May 1, 2009

Abstract

The WMAP haze is an excess in the 22 to 93 GHz frequency bands of WMAP extending about 10 degrees from the galactic center. We show that electron-positron pairs injected into the interstellar medium by the galactic population of pulsars with energies in the 1 to 100 GeV range can explain the WMAP haze. The same spectrum of high energy electron-positron pairs from pulsars, which gives rise to the haze, can also explain the observed excesses in AMS, HEAT and PAMELA.

1 Introduction

The measurements of the temperature anisotropies in the Cosmic Microwave Background (CMB) by the Wilkinson Microwave Anisotropy Probe (WMAP) has made possible an impressively precise extraction of cosmological parameters. WMAP has also been able to measure Interstellar Medium (ISM) emission of low energy photons from dust and ionized gas in the inner regions of the galaxy. However, an excess of synchrotron radiation in the WMAP bands between 22 and 93 GHz has been observed, after a subtraction of the free-free, dust and standard synchrotron emission [1]. This excess has been dubbed the WMAP "haze."

One possible explanation of the excess is in terms of annihilating dark matter [2], where the charged byproducts of the dark matter radiate synchrotron photons in the presence of the galactic magnetic field. A neutralino from supersymmetric theories annihilating to W^+W^- gives a good fit to the radial distribution of the spectrum, with a dark matter halo profile scaling with a radial dependence which is slightly steeper than NFW [3], and a magnetic field in the few μG range. Remarkably, the annihilation cross-section required to produce the haze is the annihilation cross-section one would predict from the thermal freeze-out of the WIMP, namely $\sigma v \simeq 3 \times 10^{-26}$ cm^3/s We urge caution, however, because recent work [4] has shown that the significance of the WMAP haze may be significantly reduced if the frequency dependence of the synchrotron component is allowed to vary spatially.

This signal may be even more interesting in light of the recent observations of an excess of high energy cosmic ray positrons and electrons. The excess was originally observed by the HEAT [5] and AMS [6] experiments, and was confirmed more recently by the PAMELA [7], ATIC [8] and PPB-BETs [9] experiments. The source of these positrons is unknown, however, there are several possibilities. Like the WMAP haze, they may be explained by annihilating DM (see *e.g.* [10, 11]). An explanation of the signal in terms of annihilating dark matter (DM), however, has multiple obstacles to overcome. First, it must annihilate with a cross-section much larger than that suggested by the thermal abundance, $\sigma v \simeq 3 \times 10^{-24-23}$ cm^3/s. Second, the DM candidate must be hadrophobic in order to avoid overproducing anti-protons [10, 12] and to produce a steep enough spectrum [11]. Gamma rays and radio measurements also generate significant constraints [10, 13], since the charged SM byproducts of the annihilation may emit either hard final state radiation or synchrotron emission in the galactic magnetic field. In short, if the positron excesses are to be explained in terms of annihilating Weakly Interacting Massive Particle, the WIMP must have non-standard properties. There are possible exceptions to these conclusions in the case that we happen to be nearby a dense clump of dark matter [14], or for non-standard propagation models [15].

The cosmic ray positron excess may be purely astrophysical, however. There are several possible astrophysical explanations. The excess may result from secondary production and acceleration in the cosmic ray source itself [16]. Supernova remnants may also produce highly energetic positrons to explain the PAMELA signal [17]. It has been noted many times that a single or few pulsars in the neighborhood of a kpc from us or a distribution of pulsars may contribute e^+e^- with an energy spectrum that can reproduce the steep rise over the E^{-3}

background seen in PAMELA [18, 19, 20, 21, 22, 23, 24].

In this paper we explore the possibility that the WMAP haze can also be explained by e^+e^- pair production in pulsars. Pulsars produce a significant flux of energetic electrons and positrons spread over the disk of the galaxy, which then emit synchrotron radiation as they traverse outward from the disk in the magnetic field of the galaxy. To explain the haze, the expected signal from pulsars must both reproduce angular dependence of the signal from the galactic center, as well as the frequency dependence through the WMAP bands from 22 to 93 GHz. We show that a distribution which is typical of that necessary for explaining the PAMELA data with pulsars also naturally produces the WMAP haze, given typical galactic magnetic fields and diffusion parameters.

In the next section we describe the model for the electron distribution from mature galactic pulsars, and in the following section their propagation through the ISM and the haze calculation.

2 Injection spectrum of positrons from pulsars

The mechanism by which pulsars produce electrons and positrons and details about their energy distribution are not very well understood. However, the theoretical models reproduce important characteristics like the observed distribution of spins, ages, and photon fluxes from radio to gamma-rays (e.g., [25]). Here, we wish to demonstrate that with a plausible model for pulsar e^+e^- injection spectra (that is consistent with observations), one can reproduce the WMAP haze. We begin by reviewing the model we utilize for the pulsar e^+e^- injection spectrum.

We consider only pulsars older than 10^5 years as potential sources of the e^+e^- pairs that create the haze. This is because young pulsars are expected to be surrounded by a nebula created by the kinetic energy released from the supernova explosion (almost 10^{51} ergs), so that e^+e^- cannot escape from this nebula until the pulsar is sufficiently old. A typical pulsar kick at birth is around ~ 500 km/s, it would take the pulsar thousands of years to escape the nebula, which have typical sizes in the parsec range. In addition, the nebulae themselves thin out in tens of thousands of years. For the mature pulsars, we will assume that the nebulae surrounding pulsars do not play a dominant role in shaping the energy spectrum and we neglect the contributions from pairs diffusing out of younger pulsar nebulae. The younger pulsars are fewer in number but could contribute significantly to the higher energy end of the e^+e^- spectrum. However, we note that the bulk of the synchrotron radiation in the WMAP bands comes from e^+e^- with energies much less than 100 GeV, which justifies our focus on mature pulsars.

To demonstrate the feasibility of our assertion that pulsars could explain most of the visible WMAP haze, we follow the Cheng and Zhang 2001 model (CZ01 from here on) [20], which relies on the production of highly energetic radiation in the outer magnetosphere gap of a rapidly spinning pulsar [26, 27, 28]. In the CZ01 model, the mean energy of e^+e^- injected into the inter-stellar medium $\overline{E}$ is set by its period, P, which increases with time.

For a rotating magnetic dipole (in vacuum) this spin-down is given by

$$P(t) = P_0\,(1+\Delta t/\tau_0)^{1/2}\ , \tag{2.1}$$

$$\tau_0 = 1.35\times 10^4\mathrm{yr}\left(\frac{P_0}{30\mathrm{ms}}\right)^2\left(\frac{M}{1.4M_\odot}\right)\left(\frac{R}{15\mathrm{km}}\right)^4\left(\frac{B}{10^{12}\mathrm{G}}\right)^{-2}\ , \tag{2.2}$$

where Δt is time since birth of the pulsar, P_0 is the initial period, M is the mass of the pulsar, R its radius and B is the surface magnetic field. The energy injected into the pairs all comes from the spin-down and the surface magnetic field is assumed to be constant. In the CZ01 model,

$$\overline{E} \simeq 44\mathrm{GeV}\left(\frac{P}{0.1\mathrm{s}}\right)^{-3.6}\left(\frac{B}{10^{12}\mathrm{G}}\right)^{0.27} \tag{2.3}$$

where P is the period of the pulsar at the time of emission and one of the parameters of the CZ01 model, the fraction of pairs escaping from the light cylinder, is set to 0.01.

The CZ01 model converts a fraction of the available spin-down power for pulsar ages $> 10^5$yr to pairs. To set the scale we note that in this model, for $P = 0.5$ s and $B = 10^{12}$ G, the differential e^+e^- emission rate is 10^{35}/GeV/s, with mean energy 1 GeV. Only the gamma-ray pulsars are assumed to produce e^+e^- pairs in this model and this introduces a B dependent upper-limit on the period ($P < 0.25(B/10^{12}\mathrm{G})^{6/13}$s).

In order to predict the properties of the pulsar today, we need the initial period and magnetic field, and also the initial kick that the nascent neutron star received when the supernova occurred. The CZ01 study includes a Monte Carlo of these and other parameters that result in present day distributions that are broadly consistent with observations. We note that in the CZ01 model the spatial distribution of the injected e^+e^- will depend somewhat on the energy range of interest, if pulsars older than about million years contribute significantly to that energy range. To test this, we repeat the modeling of CZ01, including a description of motion of pulsars in the galactic potential, and compute the final spatial and energy distribution of positrons. Our result for the energy distribution of the positrons agrees with CZ01. In addition, we find that the mean age of the pulsars, weighted by the positron ejection rate, is of order 10^5 years for the energy range of interest. Given the birth velocities, these ages imply that typical pulsars (contributing significantly to the positron flux) have only traveled ~ 100 parsecs from their birth place. To keep the discussion simple, we take the spatial distribution of these pulsars to be the same as the initial pulsar distribution, which in turn tracks that of the young stars in the stellar disk. Specifically, we adopt [29, 30]

$$\begin{aligned}\rho(\vec{x}) &= N^{-1}e^{-r/r_0-|z|/z_0}, \quad \text{where} \\ N &= 4\pi z_0 r_0^2(1-e^{-r_{disk}/r_0}(1+r_{disk}/r_0))\,,\end{aligned} \tag{2.4}$$

where $r_{disk} = 20$ kpc, $r_0 = 4.5$ kpc and $z_0 = 80$ pc. We note that taking into account the increase in z_0 due to the proper motion of the pulsars will make it easier to fit the haze.

The CZ01 Monte Carlo predicts that the energy spectrum of the e^+e^- pairs should be $E^{-1.6}$ above about a GeV up to tens of GeV. The spectrum drops sharply above $E_{\mathrm{cut}} \sim 100$ GeV. Both these features (the slope and cut-off energy) are model dependent and we discuss the effect of changing these later on. To keep the discussion more general, we therefore adopt an energy spectrum (number of e^+e^- pairs per unit time per unit energy) given by

$$Q(E) = \dot{N}_{100} Q_0 f_e \left(\frac{E}{\rm GeV}\right)^{-\alpha} e^{-E/E_{\rm cut}}\,, \qquad (2.5)$$

where our baseline model has $\alpha = 1.6$ and $E_{\rm cut} = 100$ GeV, and we allow it to vary later to see how it changes our results. We have separated out a factor f_e, which is the efficiency of converting the spin-down power of the pulsar into e^+e^- pairs (after an age of 10^5yr), and the factor $\dot{N}_{100}$, which is the number of pulsars created every century.

The normalization Q_0 is fixed by the spin down power of all the pulsars, that is $W_0 = N_p\langle I\Omega^2\dot{P}/P\rangle$ where N_p is the total number of pulsars and the brackets indicate averaging over the galactic population. We set $N_p = 0.01\dot{N}_{100}(T/{\rm yr} - 10^5) \simeq 1000\dot{N}_{100}T/10^5{\rm yr}$, where T is the typical age of the pulsar contributing the e^+e^- pairs. The normalization condition for Q_0 is given by,

$$\int \dot{N}_{100} Q_0 E^{-\alpha} e^{-E/E_{\rm cut}} E dE \;=\; W_0 = N_p \times 6\times 10^{38}\frac{\rm GeV}{\rm s}\langle\left(\frac{P}{0.1{\rm s}}\right)^{-4}\left(\frac{B}{10^{12}{\rm G}}\right)^2\rangle\,, \qquad (2.6)$$

$$\Rightarrow Q_0 \;\approx\; 10^{40}{\rm GeV}^{-1}{\rm s}^{-1}\frac{100^{\alpha-1.6}\Gamma(0.4)}{\Gamma(2-\alpha)}\left(\frac{100{\rm GeV}}{E_{\rm cut}}\right)^{2-\alpha}\,, \qquad (2.7)$$

where E is the electron or positron energy in GeV and we have assumed median values for the pulsar mass of $1.4M_\odot$, radius of 15 km, initial period of 30 ms, and surface magnetic field of 2×10^{12}G. For these values, Eq. 2.2 shows that $T \gg \tau_0$ and therefore $\dot{P}/P = 1/2T$ for these mature pulsars. This simple estimate for Q_0 agrees with the Monte Carlo results of CZ01, who find $Q(E) = 1.7\times 10^{39}E^{-1.6}\exp(-E/80)/{\rm GeV/s}$, if we assume $f_e \simeq 0.15$, $\dot{N}_{100} = 1$, $E_{\rm cut} = 80$GeV.

It is important to note that f_e is the fraction of spin down *power* that is injected into pairs *after* the assumed maturity age of 10^5yr. This efficiency f_e is expected to be large since e^+e^- are the lightest electromagnetically coupled fermions. The fraction of total initial energy injected into the ISM in pairs is very small, $\sim f_e\tau_0/T$. This argument shows that if a significant amount of the spin-down energy released before the assumed maturity age of 10^5yr were to be available in the form of e^+e^- pairs injected into the ISM, then the required efficiency would be very small. We see this by noting that in the approximation that some fraction of all of the spin-down energy is injected into the ISM instantaneously in the form of e^+e^- with spectrum $E^{-1.6}$ and cut-off 100 GeV, we have $W_0 = \dot{N}_{100}(1/2)I\Omega_0^2/100{\rm yr}$, which works out to $Q_0 = 2\times 10^{41}$ ${\rm GeV}^{-1}$ ${\rm s}^{-1}$ if we take (conservatively) $(1/2)I\Omega_0^2 = 10^{52}$GeV. The efficiency required then to get the same normalization as the CZ01 model is less than a 1%. We will not discuss such a contribution further.

The origin of the $E^{-1.6}$ spectrum in the CZ01 model are the scalings of $\overline{E}$ and the spin down power with period P. We note that $dn/dE \propto T/P^4/E^2 \propto 1/P^2/E^2$ where we have used the fact that the number of pulsars is proportional to the age and we have used the approximation $P^2 \propto T$. We include the $\overline{E}$ dependence on P to obtain $dn/dE \propto E^{2/3.6-2} \propto E^{-1.4}$, somewhat different from the $E^{-1.6}$ scaling because of the approximations we have made.

The cut-off in the spectrum around 100 GeV is related to our assumption that the pulsars have to be approximately 100 kyr or older to contribute significantly to the haze, and that the mean energy of pairs injected into the ISM depends on the pulsar period in the CZ01 model (see Eq. 2.3). This estimate of the cut-off is uncertain both because of our blanket assumption that pulsars younger than 100 kyr do not contribute pairs, and also because in framing the arguments above we have assumed all pulsars are born with spin period of 30 ms. We certainly expect scatter about both these parameters. Including such scatter will change the details of the cut-off significantly but not the main result of the paper. In addition, a small change in the strong dependence of the mean energy on the period would affect the cut-off significantly. This steep dependence arises from processes that accelerate the pairs into the ISM and these processes are not well-understood. We note that the energy spectrum at lower energies ($\sim$ 10GeV) is much less sensitive to the above uncertainties.

The estimates in this section assuming a vacuum dipole rotator model for the mature pulsars have provided us with the basic features of the positron injection spectrum. We find that the spatial distribution should track that of the young stars in the disk, with an energy spectrum that is less steep than E^{-2} – specifically $E^{-1.6}$ for the model of CZ01 – and a total normalization that requires about 10% of the spin-down power of $\mathcal{O}(10^5\text{yr})$ pulsars to be injected into positrons.

3 Pulsars as a Source for the Haze

The positrons pumped into the ISM will lose energy and diffuse outwards and as they do so, they will produce the synchrotron background. To model this we use the standard diffusion equation that describes the propagation and energy loss for a charged particle.

$$\frac{\partial}{\partial t}\frac{dn}{dE_e}(\vec{x},t,E) = K(E)\nabla^2\frac{dn}{dE_e} + \frac{\partial}{\partial E}B(\vec{x},E)\frac{dn}{dE_e} + Q(\vec{x},t,E)\,, \tag{3.1}$$

where $Q(\vec{x},t,E)$ is the source function, i.e., rate of production of positrons per unit energy with energy E at time t and location $\vec{x}$. It is a sum over all the pulsars in the galaxy. We have assumed that the diffusion coefficient $K(E)$ is spatially constant, as there is no evidence in the cosmic ray or diffuse galactic gamma-ray data to the contrary. In addition, we note that very little is known about the diffusion constant at the center of the galaxy.

The synchrotron emission from the positrons along the line of sight receives contributions from a large number of pulsars. Since pulsars are being created on time scales of 100 years in the galaxy and this is much shorter than the diffusion time scale and the assumed 10^5 year time lag, we expect a steady state calculation to work well. In the limit that the diffusion equation can be solved in a steady state, the source function reduces to

$$Q(\vec{x},E) = \rho(\vec{x})Q(E), \tag{3.2}$$

with $Q(E)$ given by Eq. 2.5 and $\rho(\vec{x})$ given by Eq. 2.4. This gives us explicitly

$$
\begin{aligned}
Q(E,\vec{x}) &= 3\times 10^{-27}\left(\frac{\dot{N}_{100}}{1\ \mathrm{century}^{-1}}\right)\left(\frac{f_e}{0.15}\right)\left(\frac{100\ \mathrm{GeV}}{E_{\rm cut}}\right)^{2-\alpha} \\
&\quad \times\left(\Gamma(0.4)/\Gamma(2-\alpha)\right)100^{\alpha-1.6}\left(E/\mathrm{GeV}\right)^{-\alpha} e^{-E/E_{cut}} \\
&\quad \times e^{-r/(4.5\ \mathrm{kpc})-|z|/(80\ \mathrm{pc})}\ \mathrm{GeV}^{-1}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-3}.
\end{aligned} \tag{3.3}
$$

We use GALPROP [31, 32] to compute the diffusion, and check the results with an ordinary partial differential equation solver. The diffusion coefficient is

$$
K(E) = K_0\left(\frac{E}{4\ \mathrm{GeV}}\right)^{\delta}, \tag{3.4}
$$

where we take $K_0 = 5.88\times 10^{28}\ \mathrm{cm}^2/\mathrm{s}$ and the index $\delta = 0.33$. The energy loss coefficient $B(E,\vec{x})$ is calculated in GALPROP. It is dominated by inverse Compton scattering and synchrotron radiation for electrons and positrons in the energy range of interest. The energy loss due to inverse Compton scattering is calculated using the Klein-Nishina cross section with an interstellar radiation field that comes with the GALPROP package, discussed in [33, 34]. Energy loss due to synchrotron radiation is calculated using an exponential form of the galactic magnetic field,

$$
B(r,z) = B_0 e^{-r/r_b-|z|/z_b}, \tag{3.5}
$$

where B_0 is chosen such that the the magnetic field at the galactic center is 10 μG, consistent with [35], and the characteristic length $r_b = 7$ kpc is chosen such that the magnetic field at the solar radius is 3 μG. We note here that the magnetic field close to the center of the galaxy is observationally hard to constrain. The values chosen here reproduce the haze and are consistent with cosmic ray data. These assumptions about energy losses differ relative to earlier work done exploring constraints with the haze by Hooper [36] by the assumption of the ratio of energy density of starlight to the magnetic field, as discussed in [37].

We plot in Fig. 1 the electron flux spectrum at various positions with respect to the galactic center. The diffusion softens the spectrum considerably, implying a larger flux in the lower frequency bands of the WMAP haze. The question is then whether the spectrum remains sufficiently hard to explain the WMAP haze in the all frequency bands, from 22 to 93 GHz. We examine this next.

After propagation, at any given point in space, the flux in synchrotron radiation (in erg/s/Hz) in the presence of the magnetic field is computed according to the relation [38]

$$
\epsilon(\nu,\gamma) = \frac{4\pi\sqrt{3}e^2\nu_B}{c}x^2\left(K_{4/3}(x)K_{1/3}(x) - \frac{3}{5}x[K^2_{4/3}(x) - K^2_{1/3}(x)]\right) \tag{3.6}
$$

with $x = \nu/(3\gamma^2\nu_B)$, $\nu_B = eB/(2\pi m_e)$, and $\gamma(E)$ the electron's boost.

The total flux (in kJy/sr) in a given frequency at a given angle from the galactic center is computed by folding the sychrotron power with the electron distribution at any given point.

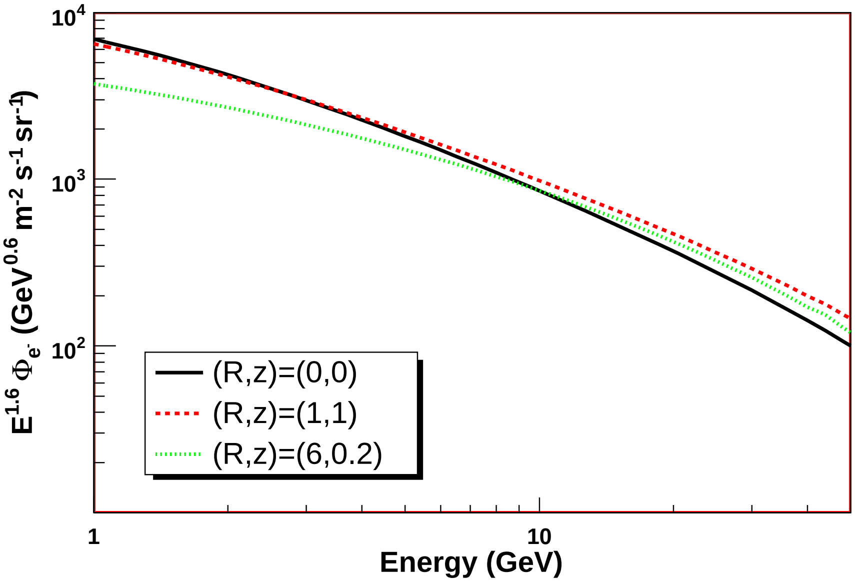

Figure 1: The curves show the e^+e^- energy spectrum at different locations in the galaxy that contribute significantly to the haze. We see that at energies below about 10 GeV, the shape of the spectrum depends on the location. For higher energies, the dominant contribution comes from more local pulsars. The energies around 10 GeV are particularly important for the haze and this figure shows that diffusion and energy-loss steepen the energy spectrum index to about -2.

The flux is then obtained by integrating along the line of sight:

$$\Phi(\nu) = \frac{1}{4\pi}\int_0^\infty d\ell \int_0^\infty dE\epsilon(\nu,\gamma(E))\frac{dn}{dE}(r(\ell),z(\ell)), \tag{3.7}$$

where $r(\ell) = |r_e - \ell\cos(\theta)|$ and $z = \ell\sin(\theta)$ if we restrict out attention to angles θ above and below the galactic center and the sun is positioned at $r = r_e = 8$kpc and $z = 0$. We now turn to presenting our results utilizing the formalism outlined above.

After propagation, we fit the haze using the flux from Eq. 3.7 in the 22 GHz WMAP band. The overall normalization of the curve depends on both the magnetic field, B_0 in Eq. 3.5, the average pulsar energy radiated W_0, and the average pulsar efficiency times pulsar production rate $f_e\dot{N}_{100}$. The range for $\dot{N}_{100}$ is 1-3 per century, following the rate of core collapse of supernovae in our galaxy. [39]. We have taken $\dot{N}_{100} = 2.8$, following [40]. In addition, owing to to uncertainties in the subtraction, we also allow a constant background at all angles to be added in the fit.

The index α in Eq. 2.5 and $E_{\rm cut}$ are important in fitting the frequency structure of the Haze observed by WMAP. The cutoff energy $E_{\rm cut}$ is required to be above a minimum value $\gtrsim$ 40 GeV such that there will be enough radiation into the 93 GHz band, however cutoff energies larger than that will only serve to decrease the required average efficiency per pulsar to reproduce the Haze. Additionally, a soft spectrum, corresponding to a large α, will not give rise to a large enough amplitude in the high frequency bands to reproduce the haze. Lastly, the fit in the angular direction results by allowing the characteristic distance over which the magnetic field is damped from the galactic center, z_b in Eq. 3.5, to vary.

As shown in Fig. 2, we find that with a natural choices of these parameters, a galactic source of pulsars can explain the WMAP haze. We find that $z_b = 1$ kpc gives a good fit to the angular distribution.

The spectral index $\alpha = 1.6$ taken from the CZ01 model [20] also fits the frequency band requirements of the haze very well. We show in Fig. 3 the results for a larger choice of α. Since the parameters W_0, f_e, and $\dot{N}_{100}$ are interchangable, to get a reasonable efficiency the most likely course is to raise the average pulsar spin down power. In general, the efficiencies noted there can be substantially and easily lowered by taking the power per pulsar W_0 and the magnetic field at the galactic center B_0 to higher, but still reasonable, values. In short, pulsars are a natural explanation of the haze.

We also note that the choices of parameters we have made are consistent with those utilized in [21, 23] as a means to explain the HEAT, AMS, PAMELA, ATIC and PPB-BETs cosmic ray positron excesses with a single pulsar, or collection of local pulsars, suggesting that cosmic ray positron and dark matter anomalies may naturally have the same source.

4 Conclusions

Wd have shown that e^+e^- pairs injected into the interstellar medium by the galactic pulsars likely contributes significantly to the WMAP haze. The models of pair emission and galactic magnetic fields we investigated showed that pulsars could easily account for all of the haze and successfully reproduce both its angular and frequency distributions observed in the WMAP data. The energy spectrum of the e^+e^- pairs we used was shallow enough to reproduce the frequency dependence of the haze and the same as that required to explain the positron excess observed by HEAT, AMS and PAMELA. The parameters for the magnetic field and inverse compton energy losses that we employed to fit the haze towards the galactic center are also consistent with those that have recently been used to fit the cosmic ray positron excess from a local distribution of pulsars [21, 23]. These facts suggest that the both the haze and the positron excesses may have the same underlying explanation.

The possibility that the WMAP haze is due to annihilating dark matter is exciting and it behooves us to search for alternative astrophysical explanations. More detailed investigations are required to bracket the contribution of dark matter annihilation products to the haze. Correlating various signals of dark matter annihilation (positrons, anti-protons, anti-deutrons, gamma-rays, haze, etc) provides promise of progress in this direction.

Acknowledgements

We thank Doug Finkbeiner, Jonathan Feng and Dan Hooper for discussions. This work has been supported by the US DOE, including grant #DE-FG02-95ER40896 (KZ) and #DE-FG02-95ER40899 (DP).

References

[1] D. P. Finkbeiner, Astrophys. J. **614**, 186 (2004) [arXiv:astro-ph/0311547]. D. P. Finkbeiner, G. I. Langston and A. H. Minter, Astrophys. J. **617**, 350 (2004) [arXiv:astro-ph/0408292].

[2] D. P. Finkbeiner, arXiv:astro-ph/0409027.

[3] D. Hooper, D. P. Finkbeiner and G. Dobler, Phys. Rev. D **76**, 083012 (2007) [arXiv:0705.3655 [astro-ph]].

[4] D. T. Cumberbatch, J. Zuntz, H. K. K. Eriksen and J. Silk, arXiv:0902.0039 [astro-ph.GA].

[5] S. W. Barwick *et al.* [HEAT Collaboration], Astrophys. J. **482**, L191 (1997) [arXiv:astro-ph/9703192]. J. J. Beatty *et al.*, Phys. Rev. Lett. **93**, 241102 (2004) [arXiv:astro-ph/0412230].

[6] M. Aguilar *et al.* [AMS-01 Collaboration], Phys. Lett. B **646**, 145 (2007) [arXiv:astro-ph/0703154].

[7] O. Adriani *et al.*, arXiv:0810.4995 [astro-ph]. O. Adriani *et al.*, arXiv:0810.4994 [astro-ph].

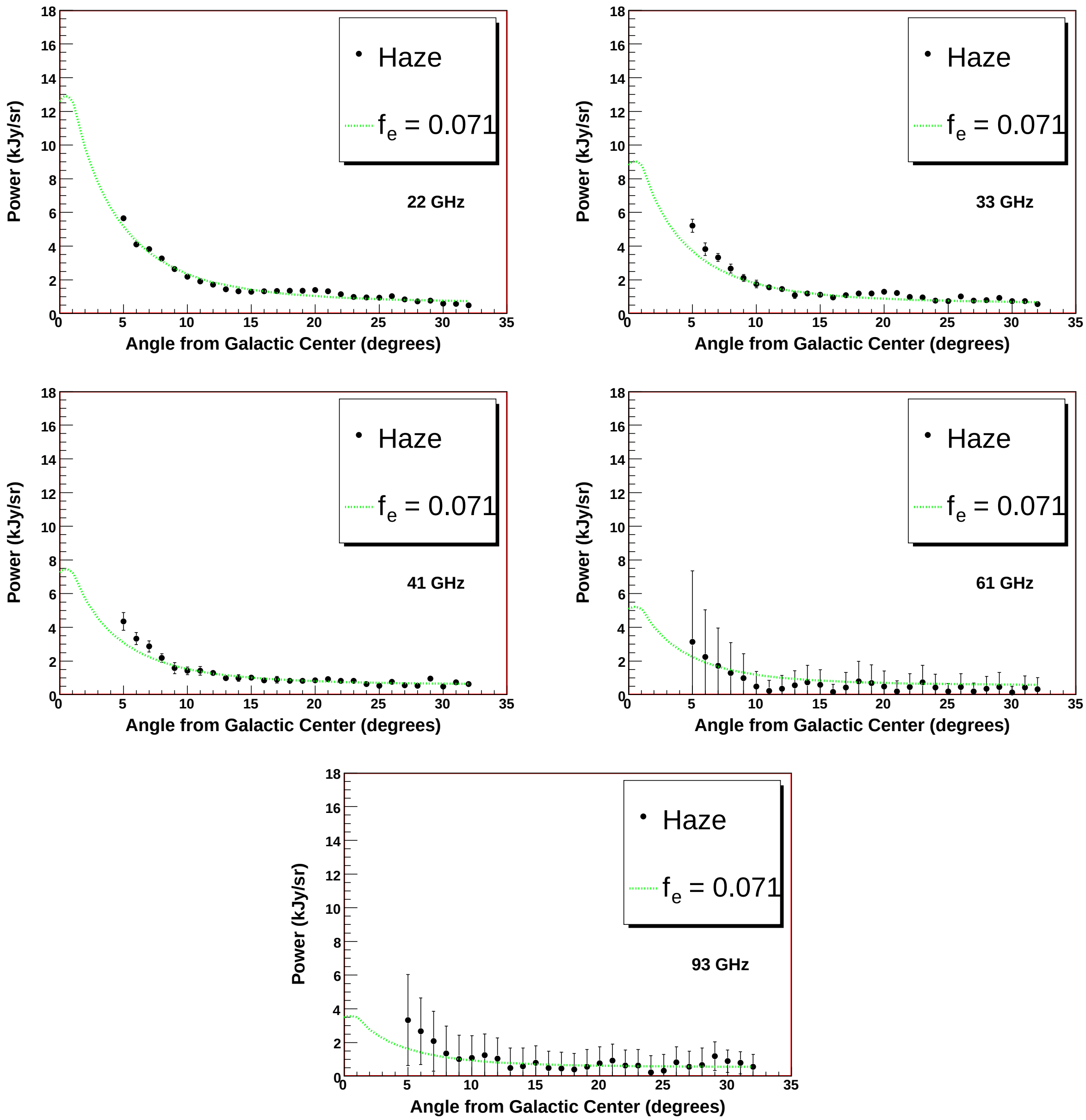

Figure 2: WMAP Haze for pulsar injection parameters $\alpha = 1.6$ and $E_{cut} = 100$ GeV and efficiency $f_e = 7\%$. This efficiency is defined as the fraction of the spin-down power converted to e^+e^- pairs after an assumed maturity age of 10^5yr. The fraction of the total initial pulsar energy required in the form of e^+e^- pairs to explain the haze is much smaller (by an order of magnitude or more).

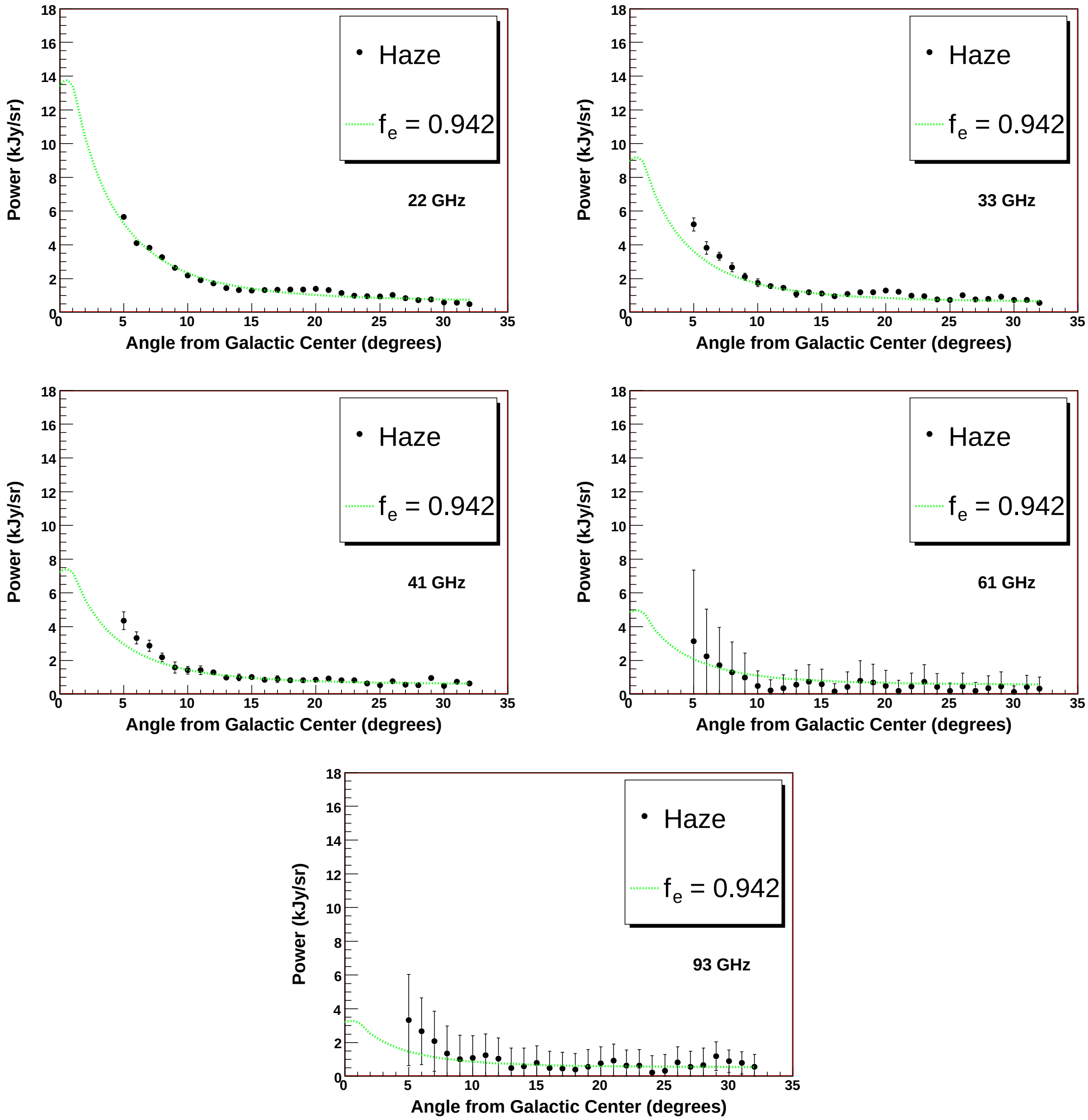

Figure 3: WMAP Haze for pulsar injection parameters $\alpha = 1.9$ and $E_{cut} = 100$ GeV. The steeper injection index results in a marginally poorer fit in the higher frequency bands. The increased efficiency can be lowered by increasing the average spin down power or magnetic field at the center of the galaxy.

[8] J. Chang *et al.*, Nature **456**, 362 (2008).

[9] S. Torii *et al.*, arXiv:0809.0760 [astro-ph].

[10] M. Cirelli, M. Kadastik, M. Raidal and A. Strumia, arXiv:0809.2409 [hep-ph].

[11] I. Cholis, L. Goodenough, D. Hooper, M. Simet and N. Weiner, arXiv:0809.1683 [hep-ph].

[12] F. Donato, D. Maurin, P. Brun, T. Delahaye and P. Salati, arXiv:0810.5292 [astro-ph].

[13] L. Bergstrom, G. Bertone, T. Bringmann, J. Edsjo and M. Taoso, arXiv:0812.3895 [astro-ph].

[14] D. Hooper, A. Stebbins and K. M. Zurek, arXiv:0812.3202 [hep-ph].

[15] P. Grajek, G. Kane, D. Phalen, A. Pierce and S. Watson, arXiv:0812.4555 [hep-ph].

[16] P. Blasi, arXiv:0903.2794 [astro-ph.HE].

[17] N. J. Shaviv, E. Nakar and T. Piran, arXiv:0902.0376 [astro-ph.HE].

[18] A. M. Atoian, F. A. Aharonian and H. J. Volk, Phys. Rev. D **52**, 3265 (1995).

[19] X. Chi, E. C. M. Young and K. S. Cheng, Astrophys. J. **459**, L83 (1995).

[20] L. Zhang and K. S. Cheng, Astron.Astrophys. **368**, 1063 (2001).

[21] D. Hooper, P. Blasi and P. D. Serpico, JCAP **0901**, 025 (2009) [arXiv:0810.1527 [astro-ph]].

[22] H. Yuksel, M. D. Kistler and T. Stanev, arXiv:0810.2784 [astro-ph].

[23] S. Profumo, arXiv:0812.4457 [astro-ph].

[24] D. Malyshev, I. Cholis and J. Gelfand, arXiv:0903.1310 [astro-ph.HE].

[25] L. Zhang, K. S. Cheng, Z. J. Jiang and P. Leung, Astrophys. J. **604**, 317 (2004) [arXiv:astro-ph/0402089].

[26] K. S. Cheng, C. Ho and M. A. Ruderman, Astrophys. J. **300**, 500 (1986).

[27] J. Chiang and R. W. Romani, Astrophys. J. **436**, 754 (1994).

[28] L. Zhang and K. S. Cheng, Astrophys. J. **487**, 370 (1997).

[29] B. Paczynski, Astrophys. J. **348**, 485 (1990)

[30] S. J. Sturner and C. D. Dermer, Astrophys. J. **461**, 872 (1996).

[31] A. W. Strong and I. V. Moskalenko, Astrophys. J. **509**, 212 (1998) [arXiv:astro-ph/9807150].

[32] I. V. Moskalenko and A. W. Strong, Astrophys. J. **493**, 694 (1998). [arXiv:astro-ph/9710124].

[33] A. W. Strong, I. V. Moskalenko and O. Reimer, Astrophys. J. **537**, 763 (2000) [Erratum-ibid. **541**, 1109 (2000)] [arXiv:astro-ph/9811296].

[34] T. A. Porter and A. W. Strong, arXiv:astro-ph/0507119.

[35] J. L. Han, arXiv:astro-ph/0603512.

[36] D. Hooper, Phys. Rev. D **77**, 123523 (2008) [arXiv:0801.4378 [hep-ph]].

[37] P. Grajek, G. Kane, D. J. Phalen, A. Pierce and S. Watson, arXiv:0807.1508 [hep-ph].

[38] G. Ghisellini, P. W. Guilbert, and R. Svensson, "The Synchrotron Boiler" Astrophys. J. **334**, L5.

[39] G. G. Raffelt, arXiv:astro-ph/0701677.

[40] C. A. Faucher-Giguere and V. M. Kaspi, Astrophys. J. **643**, 332 (2006) [arXiv:astro-ph/0512585].