

Diffusive Cosmic Ray Acceleration at the Galactic Centre

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ABSTRACT

The diffuse TeV emission detected from the inner $\sim 2^\circ$ of the Galaxy appears to be strongly correlated with the distribution of molecular gas along the Galactic ridge. Although it is not yet entirely clear whether the origin of the TeV photons is due to hadronic or leptonic interactions, the tight correlation of the intensity distribution with the molecular gas strongly points to a pionic-decay process involving relativistic protons. But the spectrum of the TeV radiation—a power law with index $\alpha \approx -2.3$ —cannot be accommodated easily with the much steeper distribution of cosmic rays seen at Earth. In earlier work, we examined the possible sources of these relativistic protons and concluded that neither the supermassive black hole Sagittarius A* (identified with the HESS source J1745-290), nor several pulsar wind nebulae dispersed along the Galactic plane, could produce a TeV emission profile morphologically similar to that seen by HESS. We concluded from this earlier study that only relativistic protons accelerated throughout the inter-cloud medium could account for the observed diffuse TeV emission from this region. In this paper, we develop a model for diffusive proton acceleration driven by a turbulent Alfvénic magnetic field present throughout the gaseous medium. Though circumstantial, this appears to be the first evidence that at least some cosmic rays are accelerated diffusively within the inner ~ 300 pc of the Galaxy.

Key words: acceleration of particles, cosmic rays, Galaxy: centre, galaxies: nuclei, radiation mechanisms: nonthermal

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1 INTRODUCTION

The earliest observations of the Galactic center with the High-Energy Stereoscopic System (HESS) revealed the presence of several TeV point sources, including HESS J1745–290, coincident with the supermassive black hole Sagittarius A*, and a second type of source, such as the supernova remnant/pulsar wind nebula G0.9+0.1 (about 1° —or roughly 144 pc at that distance—toward positive longitude l of the Galactic center), distributed along the plane (Aharonian et al. 2004). An extended period of observation since then, coupled with HESS’s unprecedented sensitivity, has provided an opportunity of subtracting these point sources from the overall map of this region to search for the fainter, diffuse emission. We now know that diffuse TeV radiation is produced along the Galactic-center ridge extending over 2° , spread out roughly 0.2° in Galactic latitude b .

The diffuse TeV emission is strongly correlated with the distribution of interstellar gas (Aharonian et al. 2006). Along with the energy range accessible to HESS (> 200 GeV), this morphology points to the decay of neutral pions produced in hadronic cascades as the dominant source of diffuse radiation, and is therefore quite likely due to the scattering of relativistic cosmic rays with protons in the ambient medium (see, e.g., Crocker et al. 2005; Ballantyne et al. 2007). The TeV gamma rays are apparently produced within a scale height of roughly 30 pc, similar to that of giant molecular cloud (GMC) material in this region, as traced by its CO and CS line emission (see, e.g., Tsuboi et al. 1999). The $\sim 10^8 M_\odot$ of molecular gas provides a rich target of overlapping clouds for the incoming cosmic rays.

In their paper, Wommer et al. (2008) explored several possible source(s) of energetic hadrons at the Galactic center, and their propagation through a turbulent medium. The survey included Sagittarius A* itself, which may be where the cosmic rays producing HESS J1745-290 originate, and the pulsar wind nebulae dispersed along the Galactic ridge. They also considered the possibility that the relativistic protons may be accelerated throughout the inter-cloud medium.

The origin of these energetic hadrons is an intriguing puzzle because a simple cosmic-ray interpretation for the diffuse TeV emission is problematic for several reasons. For example, the observed gamma-ray spectrum does not appear to be consistent with the distribution seen at Earth. The gamma-ray spectrum measured by HESS in the region $|l| < 0.8^\circ$ and $|b| < 0.3^\circ$ (with point-source emission subtracted) can reasonably be fit with a power law with photon index $\Gamma = 2.29 \pm 0.27$. And since the spectral index of the gamma rays tracks the spectral index of the cosmic rays themselves, the implied cosmic ray index (~ 2.3) is much harder than that (~ 2.75) measured locally.

It is interesting to speculate that we may be seeing the first (albeit indirect) evidence of propagation effects as the cosmic rays diffuse outwards from the center. These energetic protons would escape from the Galaxy on an energy-dependent time scale $t_{\text{esc}} \propto E^{-\delta}$, with $\delta \sim 0.4-0.6$ (Bhattacharjee 2000). So the injected spectrum would be flatter (by a change in index of $\sim \delta$) than that observed here if most of the cosmic rays detected at Earth originate at the Galactic center. The very interesting possibility that the two distributions may still be consistent with each other deserves further investigation as a follow-up to the work reported here.

The principal purpose of this paper is to develop a self-consistent model for cosmic-ray acceleration within the inner $\sim 2^\circ-4^\circ$ of the Galaxy. Wommer et al. (2008) concluded that the conditions at the Galactic center preclude a point-source origin for these particles. The supermassive black hole Sagittarius A* may be responsible for producing HESS J1745-290, but its hadronic efflux cannot extend out beyond a latitude $\sim \pm 1^\circ$ because the protons lose their energy or scatter with the ambient medium on much smaller scales. Other point sources, such as the known pulsar wind nebulae, also produce a morphology with centrally peaked emission regions not consistent with the HESS map. It appears that only cosmic rays accelerated throughout the inter-cloud medium can produce a diffuse TeV glow consistent with the observations.

But are the particles accelerated diffusively, or do they emerge from a (presumably large) population of sources distributed along the Galactic ridge? Wommer et al.'s simulations indicate that the gamma-ray emissivity associated with any given object drops by a factor ~ 2 within a distance of roughly 0.1° . This is effectively the contour range of the HESS maps, so individual sources would not stand out as long as their angular separation were less than this value. In a projected area $\sim 2^\circ \times 1^\circ$, this proximity would require about 50 individual sources. Unfortunately, the total number of TeV sources detected by HESS (many of them presumably pulsar wind nebulae) is far smaller than this. Other possibilities include low-mass X-ray binaries, but only ~ 5 of them have been identified in this region (Bird et al. 2007). Other classes of object with a volume density greater than this apparently do not produce relativistic hadrons.

Our working assumption here will therefore be that the cosmic rays observed along the Galactic-center ridge are accelerated diffusively throughout the inter-cloud medium. In the next section, we will summarize the available data pertaining to the gas and magnetic field distributions at the Galactic center, and then describe a scenario in which protons may be accelerated to TeV energies (and beyond) due to the presence of a turbulent Alfvénic magnetic field. We will follow their evolution in energy space, and calculate the spectrum of hadrons impacting the molecular gas. And

from the pp -induced pion decays, we will calculate the TeV spectrum for direct comparison with the data.

2 THE PHYSICAL CONDITIONS

The large concentration (up to $\sim 10^8 M_\odot$) of dense molecular gas at the Galactic center is largely confined to GMC's with a size $\sim 50\text{--}70$ pc (Güsten and Philipp 2004). These clouds appear to be clumpy with high-density ($\sim 10^5 \text{ cm}^{-3}$) regions embedded within less dense ($\sim 10^{3.7} \text{ cm}^{-3}$) envelopes (e.g., Walmsley et al. 1986). The average cloud density is therefore roughly 10^4 cm^{-3} .

The GMC's at the Galactic center are threaded by a pervasive magnetic field, whose strength is revealed by the presence of non-thermal filaments (NTFs) in the diffuse interstellar medium (Morris 2007). The strongly polarized synchrotron emission from the NTFs indicates that the magnetic field points along the filaments, whose apparent rigidity when they interact with molecular clouds and the turbulent interstellar medium suggests field strengths on the order of a few milligauss (see, e.g., Yusef-Zadeh and Morris 1987).

Confirming evidence for such field strengths in and around the GMC's is provided by their apparent stability, which does not appear to be due to the confining pressure of the surrounding medium. The observed pressure $P_{\text{plasma}} \sim 10^{-9.2} \text{ erg cm}^{-3}$ due to the hot plasma between the clouds is an order of magnitude smaller than that required since the turbulent pressure within them is $P_{\text{turb}} \sim 10^{-8} \text{ erg cm}^{-3}$ (Güsten and Philipp 2004). Clouds may instead be bound by their own magnetic fields. Equating the turbulent and magnetic ($B^2/8\pi$) energy densities gives field strengths of ~ 0.5 mG within the clouds, not too different from the typical value measured in the NTFs.

We are now also reasonably sure of the magnetic field strength between the clouds. In the past, the field intensity near the Galactic center had been uncertain by two orders of magnitude. We've just seen how on a scale of ~ 100 pc the NTFs contain field strengths as high as ~ 1 mG (see also Yusef-Zadeh and Morris 1987, and Morris and Yusef-Zadeh 1989), implying a magnetic energy density more than 10,000 times greater than elsewhere in the Galaxy. At the other extreme, equipartition arguments based on radio observations favor fields of only $\sim 6 \mu\text{G}$ on ~ 400 pc scales (LaRosa et al. 2005). But a more careful analysis of the diffuse emission from the central bulge has revealed a down-break in its non-thermal radio spectrum, attributable to a transition from bremsstrahlung to synchrotron cooling of the in situ cosmic-ray electron population. Crocker et al. (2010) have shown recently that this spectral break requires a field of $\sim 50 \mu\text{G}$ extending over

several hundred parsecs, lest the synchrotron-emitting electrons produce too much γ -ray emission given existing constraints (Hunter et al. 1997).

For the purposes of this paper, we will therefore assume an average inter-cloud magnetic field strength $B \sim 30\text{--}50\mu\text{G}$ throughout the inner several degrees of the Galaxy, with a corresponding inter-cloud density $n = 10\text{ cm}^{-3}$ (again consistent with the limits placed by Crocker et al. 2010 on the diffuse bremsstrahlung and synchrotron emissivities), and an associated temperature $T_{\text{plasma}} \sim 5 \times 10^5 - 5 \times 10^6\text{ K}$ (see, e.g., Belanger et al. 2004, 2006). The conditions much closer to Sagittarius A* are somewhat different and appear to be controlled primarily by ongoing stellar wind activity (Rockefeller et al. 2004). But this is a very small region compared to the rest of the TeV emitting gas, so we do not expect it to significantly influence our results.

3 CALCULATIONAL PROCEDURE

If purely turbulent, the magnetic field that permeates the inter-cloud environment can be treated as a superposition of many randomly polarized transverse waves which span a large range of wavelengths

$$\delta\mathbf{B} = \sum_{\lambda} \delta\mathbf{B}'_{\lambda} \exp\left[i\frac{2\pi}{\lambda}(x' - v_A t)\right], \quad (1)$$

where the primed frame is unique to each wave and $\delta\mathbf{B}'_{\lambda} \cdot \hat{x}' = 0$ (e.g., Giacalone & Jokipii 1994; Fraschetti & Melia 2008). While the exact nature of this turbulence is not well-constrained, waves are typically assumed to have energy densities which follow a power-law spectrum, so that $(\delta B_{\lambda})^2 \sim \lambda^{\Gamma}$. As such, a purely turbulent magnetic field is dominated by the longest wavelength fluctuations. Assuming that these fluctuations propagate at an Alfvén speed $v_A \approx \delta B / \sqrt{4\pi m_p n}$, a turbulent electric field $\delta\epsilon \sim (v_A/c) \delta B$ must also be present as required by Faraday’s law (Fraschetti & Melia 2008). Under the most ideal conditions, the turbulent electric field can energize protons over a time Δt by an amount

$$\Delta E_p \approx e \delta\epsilon c \Delta t \approx e \delta B v_A \Delta t. \quad (2)$$

However, such an ideal acceleration can only occur over a length-scale λ_{max} (and hence, a time $\Delta t = \lambda_{\text{max}}/c$), beyond which the process becomes stochastic.

In principle, the kinematics of protons injected in the inter-cloud environment can be determined by numerically solving the governing equations of motion (e.g., Wommer et al. 2008). For the present work, however, the large difference between the radii of gyration ($\sim 10^{-5}\text{ pc}$) of TeV protons in a $50\mu\text{G}$ field and the size ($\sim 300\text{ pc}$) of the inter-cloud region makes such an approach

computationally taxing. However, the results of such numerical investigations into the kinematics of $> 10^2$ TeV protons (which require less computational time) indicate that a simple, random-walk model can adequately capture the essential features of particle diffusion and acceleration within the inter-cloud medium. Specifically, the spatial motion of particles is well approximated by a simple 3-D random walk with a step-size $R_s \sim \lambda_{max}$. In turn, the evolution of a particle's energy is well-approximated by a 1-D random-walk in which the particle gains/loses energy

$$E_s = \chi \Delta E_p = 5.3 \text{ TeV } \chi \left(\frac{\delta B}{50 \mu\text{G}} \right)^2 \left(\frac{R_s}{1 \text{ pc}} \right), \quad (3)$$

at each spatial step, with χ randomly selected between -0.5 and 0.5 .

We therefore adopt a Monte Carlo scheme in which N_p particles are injected randomly (but with uniform probability) within a radius R_{acc} of the Galactic Center, excluding the regions occupied by the 14 dominant GMCs in the GC region. The positions along the plane of the sky of these GMCs are taken from Oka et al. (1998), with the unknown line-of-sight positions determined via a randomization process constrained by the requirement that the line-of sight distribution of these clouds matches the Galactic plane distribution (see Fig.1 and Table 1 in Wommer et al. 1998). Particles random-walk through the inter-cloud medium with a specified step-size R_s until they either move beyond an escape radius R_{esc} or they encounter one of the GMCs. Particles that encounter a GMC are assumed to pp scatter in the high-density medium, resulting in the production of neutral pions and subsequent decay photons. Each particle's contribution to the ensuing gamma-ray emissivity is calculated using the expression

$$Q_\gamma(E_\gamma) = 2 c n \sigma_0 \int_{E_{\pi_0}^{min}} dE_{\pi_0} \frac{[0.67(1 - E_{\pi_0}/E_p)^{3.5} + 0.5e^{-18E_{\pi_0}/E_p}]}{E_{\pi_0} \sqrt{E_{\pi_0}^2 - m_{\pi_0}^2 c^4}} \quad (4)$$

(e.g., Fatuzzo & Melia 2003), where $\sigma_0 = 32$ mbarns, $E_{\pi_0}^{min} = E_\gamma + m_{\pi_0}^2 c^4 / [4E_\gamma]$, and E_p is calculated for each particle using the 1-D random walk scheme detailed above. The total emissivity is then found by summing over the full ensemble of N_p protons.

We begin our investigation by calculating the kinematics and resulting emissivity for $N_p = 10^5$ protons for the model parameters $R_s = 1$ pc, $R_{acc} = 250$ pc, $R_{esc} = 500$ pc, and $\delta B = 50 \mu\text{G}$. A comparison between the (normalized) emissivity (dotted curve) and the HESS data is presented in Figure 1. Clearly, this scenario cannot account for the observations. We note, however, that the curvature exhibited by the dotted curve at > 1 TeV energy suggests that such a scenario could work if particles are energized to smaller values when they interact with the molecular clouds. We therefore consider the possibility that particles can only be energized in small, compact regions within the inter-coud medium, and thereby add an ‘‘efficiency’’ parameter η that represents the

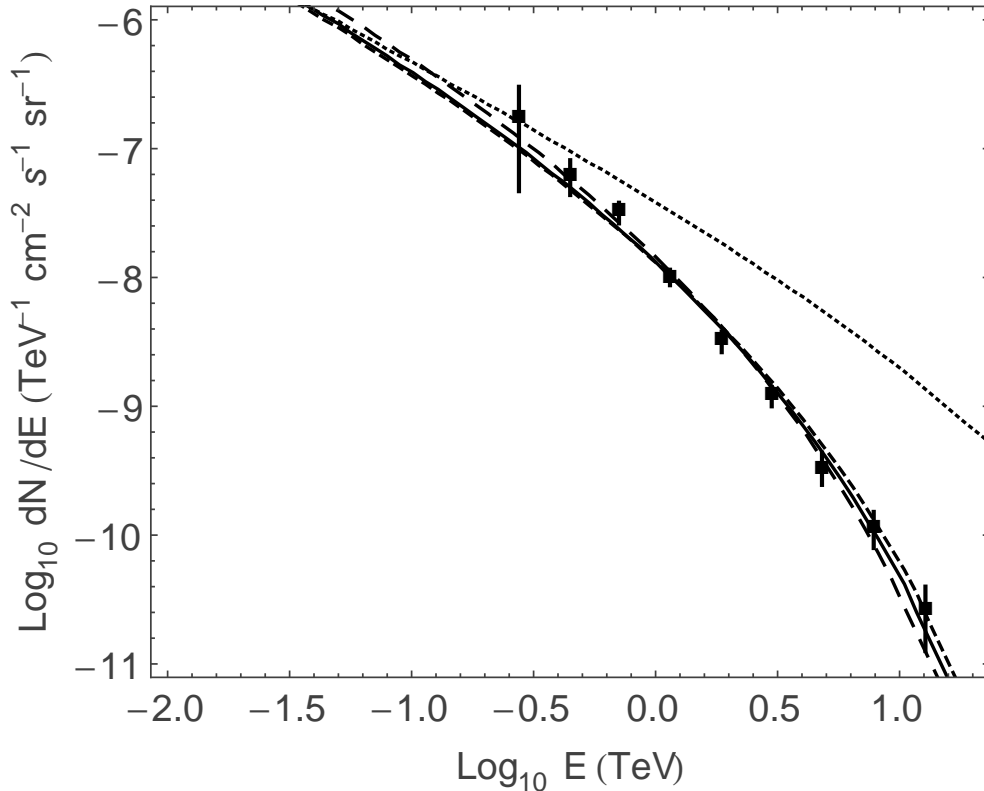


Figure 1. The γ -ray spectra resulting from the decay of neutral pions produced by the scattering of protons accelerated diffusively within the inter-cloud region of the GC and the dense molecular gas contained within the 14 large GMCs occupying this region. The curves show the results of our simple random-walk model of this process for a purely turbulent inter-cloud magnetic field and four scenarios as defined by the following parameters: dotted – $R_{acc} = 250$ pc, $R_{esc} = 500$ pc, $\delta B = 50 \mu\text{G}$, $\eta = 1$; solid – $R_{acc} = 250$ pc, $R_{esc} = 500$ pc, $\delta B = 50 \mu\text{G}$, $\eta = 0.001$; long-dashed – $R_{acc} = 150$ pc, $R_{esc} = 250$ pc, $\delta B = 50 \mu\text{G}$, $\eta = 0.002$; short-dashed – $R_{acc} = 250$ pc, $R_{esc} = 500$ pc, $\delta B = 30 \mu\text{G}$, $\eta = 0.01$. The step-size R_s and inter-cloud density were set to 1 pc and 10 cm^{-3} , respectively, for each scenario. The HESS data are taken from Aharonian et al. (2006).

fractional volume of the inter-cloud region within which particles can gain/lose energy. For the model parameters adopted above, a good fit to the data can be obtained with an efficiency of $\eta = 0.001$, as shown by the solid curve in Figure 1. While the resulting fit to the data is quite good, it may be hard to reconcile such a low value of efficiency. As such, we consider next an inter-cloud medium with the same values of $\delta B = 50 \mu\text{G}$ and $R_s = 1$ pc, but assume $R_{acc} = 150$ pc and $R_{esc} = 250$ pc, since a smaller region results in less particle acceleration. Indeed, we find that for these model parameters, good fits to the HESS data can be obtained with an efficiency of $\eta = 0.002$, as shown by the long-dashed curve in Figure 1. This efficiency is still lower than may be reasonably expected. We next consider an inter-cloud medium with a magnetic field strength $\delta B = 30 \mu\text{G}$ (but keeping the values of R_s , R_{acc} and R_{esc} unchanged from our initial case). The efficiency required to obtain a good fit to the data, as shown by the short-dashed curve in Figure 1, is now $\eta = 0.01$.

To understand this strong dependence between the efficiency required to obtain a good fit to the HESS data and the adopted field strength, let us consider how \mathbf{B} and η affect the energy distribution

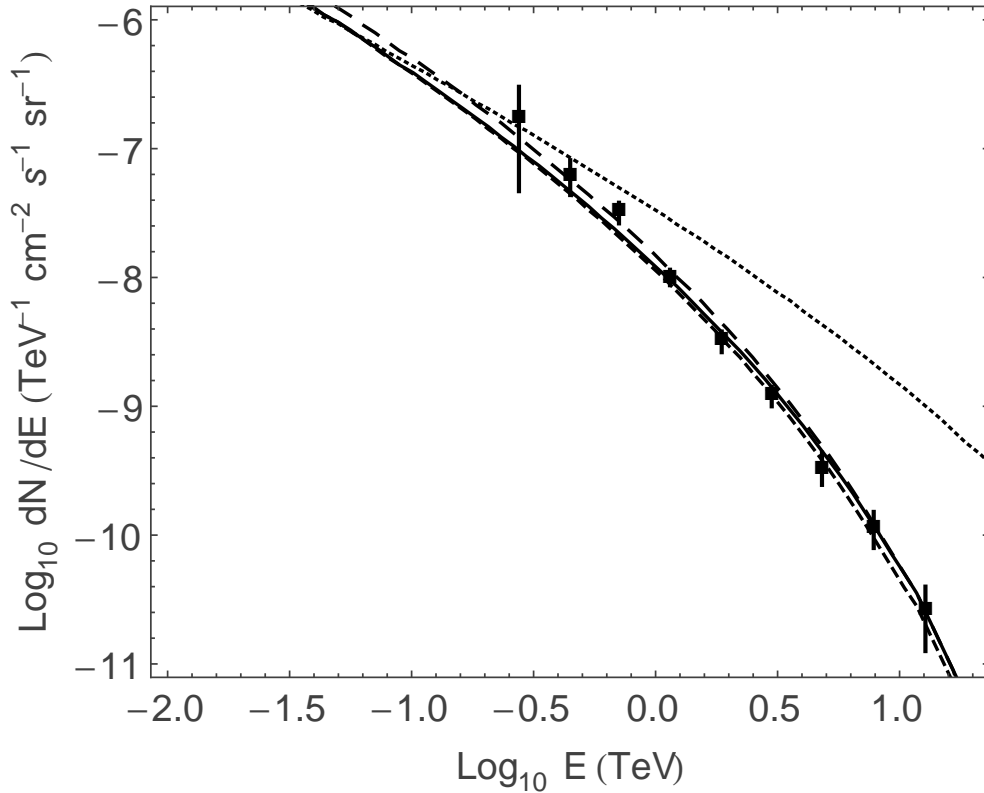


Figure 2. Same as Figure 1, but for the case of a uniform magnetic field \mathbf{B}_0 directed perpendicular to the Galactic plane superimposed with a turbulent component $\delta\mathbf{B}$. The curves represent the results of our model for four scenarios as defined by the following parameters: dotted – $B_0 = 50 \mu\text{G}$, $\delta B = 50 \mu\text{G}$, $\xi = 10$; solid – $B_0 = 50 \mu\text{G}$, $\delta B = 2 \mu\text{G}$, $\xi = 25$; short-dashed – $B_0 = 30 \mu\text{G}$, $\delta B = 3 \mu\text{G}$, $\xi = 10$; long-dashed curve – $B_0 = 30 \mu\text{G}$, $\delta B = 3 \mu\text{G}$, $\xi = 20$. The remaining parameters were set as $R_s = 1 \text{ pc}$, $R_{acc} = H_{acc} = 200 \text{ pc}$, $R_{esc} = H_{esc} = 400 \text{ pc}$ and $n = 10 \text{ cm}^{-3}$ for each scenario. The HESS data are taken from Aharonian et al. (2006).

of particles that interact with the molecular clouds. Specifically, the 1-D random walk in energy leads to a peaked energy distribution with a high-energy tail. It is this tail of the distribution that produces the curvature in the ensuing photon emissivity required to fit the HESS data. Since the energy gained/lost at each step scales as δB^2 , as shown in Equation (3), the entire distribution shifts accordingly in energy. That is, doubling the magnetic field strength shifts the energy distribution upward in energy by four times. In addition, the random walk nature of the acceleration process means that the tail of the energy distribution shifts up in energy proportionally to the square root of the number of steps during which the particle gains or loses energy, which is set by the efficiency. As such, the energy that characterizes the high-energy tail (and which is associated with the HESS data) scales as $E_{p,tail} \propto \delta B^2 \sqrt{\eta}$. In turn, the efficiency required to fit the HESS data (which requires a specific value of $E_{p,tail}$) scales as $\eta \propto \delta B^{-4}$. In contrast to this strong dependence on δB , the direct proportionality between ΔE_p and R_s means that our results are not sensitive to the value of R_s adopted, so long as $R_s \ll R_{acc}$.

In principle, good fits to the HESS data can be achieved with higher efficiencies if the inter-

cloud magnetic field has a strength significantly less than $30 \mu\text{G}$. Such a scenario for a purely turbulent field appears ruled out from observations (as noted in §2). However, it is quite reasonable to expect that the inter-cloud medium is threaded by a large-scale, static field \mathbf{B}_0 on which the turbulent magnetic field $\delta\mathbf{B}$ is superimposed. In this case, $\Delta E_p \propto v_A \delta B \propto B_0 \delta B$. To test this scenario, we have therefore also considered a model in which a uniform field \mathbf{B}_0 cuts perpendicular to the plane of the galaxy, adopting a cylindrical acceleration region defined by a radius $R_{acc} = 200$ pc and a scale height above and below the Galactic plane $H_{acc} = 200$ pc. Since particles will diffuse preferentially along the direction of the underlying magnetic field (e.g., Giacolone & Jokipii 1994), we increase the step-length along the uniform field direction by a factor ξ (expected to be of order 10 from numerical experiments with higher energy particles). As before, protons random walk until they either escape from a cylindrical boundary defined by $R_{esc} = 400$ pc and $H_{esc} = 400$ pc, or they enter one of the GMCs. For this case, particles gain/lose energy

$$E_s = \chi \Delta E_p = 0.53 \text{ TeV } \chi \left(\frac{B_0}{50 \mu\text{G}} \right) \left(\frac{\delta B}{0.5 \mu\text{G}} \right) \left(\frac{R_s}{1 \text{ pc}} \right) \quad (5)$$

during every step where, as before, χ is randomly chosen between -0.5 and 0.5 .

Our (normalized) results are illustrated by the dotted curve in Figure 2 for the case where $B_0 = \delta B = 50 \mu\text{G}$ and $\xi = 10$. As with the purely turbulent field, this scenario cannot account for the observations. We therefore explore weak-turbulence scenarios, obtaining good fits to the data for the following model parameters: 1) $B_0 = 50 \mu\text{G}$, $\delta B = 2 \mu\text{G}$, $\xi = 20$ (solid curve); 2) $B_0 = 30 \mu\text{G}$, $\delta B = 3 \mu\text{G}$, $\xi = 10$ (short-dashed curve); and 3) $B_0 = 30 \mu\text{G}$, $\delta B = 3 \mu\text{G}$, $\xi = 20$ (long-dashed curve). Clearly, a weak turbulence can account for the observations. Of course, a strong turbulence scenario could also account for the observations, but would then require a low acceleration efficiency η , as was found for the case of pure turbulence.

For all the cases we have explored here, the γ -ray spectrum between 100 MeV and 100 GeV is well-described by a power law of the form $dN/dE \propto E^{-1}$.

We can therefore easily compare our results to the COS-B observations of the 300 MeV–5 GeV emission from the Galactic disk, which includes a possible galactic-center source. Integrating the results of our calculated spectrum normalized to the HESS data (as shown in Figures 1 and 2) over the COS-B energy range, we infer a flux of $\sim 3 \times 10^{-11}$ ph cm $^{-2}$ s $^{-1}$, coming from a region with $\Delta l = 2^0$, $\Delta b = 0.5^0$ centered on the molecular cloud distribution. This value is well below the observed total flux $\sim 10^{-7}$ ph cm $^{-2}$ s $^{-1}$ from this region (Blitz et al. 1985). It would thus appear that pionic decays produced by the stochastic acceleration of protons in a turbulent field can account for the HESS detected TeV emission while at the same time not producing a galactic

center ~ 1 GeV signal above the measured COS-B flux. We note, however, that pp scattering also produces charged pions which quickly decay into secondary leptons. Over time, this leptonic population can grow and radiate in the γ -ray band via synchrotron and Bremsstrahlung processes (see, e.g., Fatuzzo & Melia 2005). Alternatively, the electric fields associated with this turbulent magnetic field may also accelerate primary electrons. Conceivably, both primary and secondary leptons may represent viable sources of ~ 1 GeV emission and ought to be included in a more complete calculation of the resulting spectra from these particles, which would require additional model parameters (see, e.g., Rockefeller et al. 2004; Belanger et al. 2004; Liu et al. 2006; Crocker et al. 2010) and is beyond the scope of the present work. We will therefore explore this important issue elsewhere.

4 CONCLUSIONS

We have shown in this paper that diffusive acceleration of CRs by a turbulent Alfvénic magnetic field spread throughout the inner few hundred parsecs of the Galaxy can produce an effectively isotropized distribution of relativistic particles reaching the outer layers of molecular clouds, where they scatter with other protons to produce the diffuse TeV glow measured by HESS. The cosmic-ray distribution produced by this stochastic acceleration results in an excellent match to the observed TeV spectrum. Such a scenario, however, requires a low acceleration efficiency or a weak turbulent field superimposed on a stronger, large scale static field.

Interestingly, not all of the CRs remain trapped in this region. The long diffusion length (~ 1 pc) emerging from our simulations ensures that the cosmic-ray distribution produced in this fashion is isotropized throughout the molecular gas region where TeV emission occurs. But this also means that a large fraction of these energetic particles escape into the rest of the Galaxy. Calculating the evolution in their distribution as they diffuse outwards is beyond the scope of this paper. It is clear, however, that such a simulation ought to be carried out to see if these cosmic rays contribute noticeably to the distribution reaching Earth. The strength of this proposal lies in the tightly constrained cosmic-ray population within the inner bulge, which we infer from the requirements to produce the observed HESS spectrum. Thus, a detailed simulation of the cosmic-ray diffusion through the Galactic disk with the initial conditions we infer from HESS may produce the first evidence that perhaps most of the cosmic rays we see here are accelerated diffusively in the inner few hundred parsecs of the Galaxy.

It is natural to wonder whether this process can also occur elsewhere. Why should it only be

evident within the inner few degrees? The answer is rather straightforward, having to do with the unique physical conditions we see there. For example, B is much bigger—by at least a factor of 100 or maybe 1000—compared to elsewhere in the disk, so protons spend much more time in the “acceleration” zone. Secondly, both the stellar density and star formation rates are greater there compared to elsewhere, so the interstellar medium appears to be much more dynamic. The velocity and density fluctuations in the ISM are consequently much more significant in the inner bulge than elsewhere, so although this type of proton acceleration can in principle occur everywhere, it is much more effective and rapid at the Galactic center. We are continuing to develop this promising picture of cosmic-ray acceleration in the Galaxy and will report the results elsewhere.

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