Diffuse Gamma Rays from the Galactic Plane:
Probing the “GeV Excess” and Identifying the “TeV Excess”

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ABSTRACT

Pion decay gamma rays have long been recognized as a unique signature of hadronic cosmic rays and their interactions with the interstellar medium. We present a model-independent way of constraining this signal with observations of the Galactic Plane in diffuse gamma rays. We combine detections by the EGRET instrument at GeV energies and the Milagro Čerenkov detector at TeV energies with upper limits from KASCADE and CASA-MIA ground arrays at PeV energies. Such a long “lever arm”, spanning at least six orders of magnitude in energy, reveals a “TeV excess” in the diffuse Galactic Plane gamma-ray spectrum. While the origin of this excess is unknown, it likely implies also enhanced TeV neutrino fluxes, significantly improving the prospects for their detection. We show that unresolved point sources are a possible source of the TeV excess. In fact, the spectra of the unidentified EGRET sources in the Milagro region must break between \( \sim 10 \) GeV and \( \sim 1 \) TeV to avoid strongly overshooting the Milagro measurement; this may have important implications for cosmic-ray acceleration.

Finally, we use our approach to examine the recent suggestion that dark-matter annihilation may account for the observed excess in diffuse Galactic gamma-rays detected by EGRET at energies above 1 GeV. Within our model-independent approach, current data cannot rule this possibility in or out; however we point out how a long “lever arm” can be used to constrain the pionic gamma-ray component and in turn limit the “GeV excess” and its possible sources. Experiments such as HESS and MAGIC, and the upcoming VERITAS and GLAST, should be able to finally disentangle the main sources of the Galactic gamma rays.

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1. Introduction

The Milky Way Galactic Plane has long been known to be a strong source of diffuse gamma-ray emission (Kraushaar et al. 1972; Fichtel et al. 1975). The Energetic Gamma Ray Emission Telescope (EGRET) instrument on the Compton Gamma-Ray Observatory satellite measured this emission over the full sky and for energies in the range $0.03 - 10$ GeV, with reasonably high resolution in each bin (Hunter et al. 1997, where the data are reported with angular bins of width 0.5 degree and with several logarithmically-spaced bins per decade in energy). It was expected that a very significant component of the diffuse emission would arise from the decays of neutral pions ($\pi^0 \rightarrow \gamma + \gamma$), arising from the collisions of hadronic cosmic rays with the hadronic component of the interstellar medium (i.e., $p + p \rightarrow p + p + \pi^0$; Stecker 1970, 1971; Dermer 1986). We refer to these throughout the paper as “pionic” gamma rays, to distinguish them from gamma rays produced by leptonic processes, e.g., the inverse-Compton upscattering of ambient photons by very high-energy electrons.

The spatial variation of the pionic component of the diffuse Galactic gamma-ray emission should track the column density of the interstellar medium. However, since other sources of gamma rays also depend, though in more complicated ways, on the imprecisely-known distribution of interstellar matter and radiation, it is difficult to extract the pionic component by its spatial dependence alone. However, the energy spectrum of the pionic gamma rays has a characteristic shape, which follows from the kinematics of the boosted pion decays and the convolution with the hadronic cosmic ray spectrum. This shape is symmetrical (when plotted as $\log dN/dE$ vs $\log E$) about the “pion bump” peak at $m_{\pi^0}/2 \simeq 0.07$ GeV, with long power-law tails to higher and lower energies (Stecker 1971). Since no strong evidence of this bump was seen, Prodanović & Fields (2004) estimated the maximum pionic fraction of the diffuse Galactic gamma-ray emission to be $\sim 50\%$. This is supported by the very detailed and comprehensive study of the Galactic gamma-ray emission by Strong, Moskalenko & Reimer (2004). That study indicates that a key second feature of pionic gamma rays is that at high energies (certainly by $\sim 1$ TeV) they should dominate the total emission and their slope will follow that of the hadronic cosmic rays. (The emission at energies below the bump is expected to be subdominant to the leptonic components.) In the GeV energy range, a significant component of the observed EGRET data is not well explained, and this discrepancy, which is observed in all sky directions, is known as the “GeV excess” (Hunter et al. 1997).

In this paper, we consider constraints on the pionic gamma rays from experiments operating at much higher energies than EGRET. There are upper limits on the total gamma-ray emission near both TeV ($= 10^3$ GeV) and PeV ($= 10^6$ GeV) energies. Depending on assumptions about the slope of the hadronic cosmic ray spectrum, these place at least somewhat
restrictive limits on the pionic gamma-ray emission. However, the most exciting recent development is the first positive detection of diffuse gamma-ray emission from the Galactic Plane, by the Milagro Collaboration (Atkins et al. 2005). They find $\phi_\gamma (>3.5\ \text{TeV}) = (6.8\pm 1.5\pm 2.2) \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the Galactic Plane region of longitude $\ell \in (40^\circ, 100^\circ)$ and latitude $|b| < 5^\circ$. The basic question of the present paper is “What is the origin of the (apparently) diffuse flux observed by Milagro?” The Milagro Collaboration argued that their result is consistent with being purely pionic in origin, though they note that some of the flux may arise from unresolved point or extended sources (Atkins et al. 2005). As we will argue in steps of increasing detail, their result appears to be too large to be purely pionic, and thus seems to indicate a new mystery of Galactic gamma rays, which we will call the “TeV excess.” Our GeV–TeV–PeV overview perspective is shown in Fig. 1. In brief, our arguments are as follows:

1. We can simply extrapolate the last EGRET points to higher energies, and the Milagro result should not exceed this trend – and while it does not, it could not be any larger. This is shown in Fig. 1 as the solid line.$^1$ This alone indicates that a strong inverse Compton component at high energies is disfavored (Atkins et al. 2005), in agreement with considerations at lower energies (Strong, Moskalenko & Reimer 2004). In the PeV range, this extrapolation appears to be at best barely allowed, and is possibly excluded, depending on the choice of the hadronic cosmic ray spectrum.

2. A more sophisticated approach is to only extrapolate the pionic component to high energies, where it should dominate. We first consider a pionic component of maximal normalization (while this is unrealistically high, it is in fact lower than the normalization obtained if the GeV EGRET data is effectively assumed to be purely pionic, as above). We allow two choices for the hadronic cosmic ray energy spectrum slope at high energies, as shown by the dashed lines in Fig. 1. The first, with index $\alpha = 2.61$ (for $d\phi/dE \sim E^{-\alpha}$), is motivated by the slope chosen by the Milagro Collaboration, which provides a good single-parameter fit joining the highest-energy EGRET points to the Milagro point. We argue below that the physics of pionic emission suggests that this is an unrealistically shallow spectrum if the observed GeV–TeV signal is indeed pionic. When we instead choose $\alpha = 2.75$, in accordance with the locally observed cosmic rays (Asakimori et al. 1998), we find that the Milagro measurement is 5 times larger than the maximal pionic flux allowed at 3.5 TeV. The PeV limits are on the

$^1$The Milagro Collaboration extrapolated the integral energy spectrum, while we use the differential energy spectrum (though adopting the same spectral index). While these procedures are in principle equivalent, the smoothness of the integral spectrum comes at the cost of correlations between the points.
verge of ruling out (or detecting!) the pionic signal, regardless of the choice of $\alpha$. In addition, when the PeV limits are derived using local cosmic ray spectrum, this rules out the continuation of GeV-TeV $\alpha = 2.61$ gamma-ray power law to PeV energies.

3. More realistically, the normalization of the pionic component should be even lower, at most $\sim 50\%$ of maximal in the “optimized” model of Strong, Moskalenko & Reimer (2004) designed to minimize the GeV excess. On the other hand, the “conventional” model of Strong, Moskalenko & Reimer (2004), which uses the locally observed cosmic-ray spectrum and normalization, comes somewhat closer to the EGRET data near the pionic maximum at $m_{\pi}/2$, but leaves the GeV excess (thus motivating the non-standard optimized model). The results from the conventional model appear as the dotted line in Fig. 1. As noted by de Boer et al. (2005), the GeV excess of the conventional model allows room for a large component of gamma rays from dark matter annihilation products (including pions, though we reserve the word “pionic” to refer to pions produced by cosmic ray collisions with the interstellar medium). These gamma rays from dark matter are claimed to help ameliorate the GeV excess (note that their spectrum abruptly ends below the dark matter mass of 50–100 GeV). We point out here that this interpretation increases the TeV excess, making the Milagro measurement about 10 times larger than the pionic component.

Thus, taking a realistic normalization and slope for the pionic component, we find that the Milagro measurement seems to indicate a TeV excess, which would be even more interesting than their conclusion that their result may be consistent with being purely pionic. Our arguments are supported by the gamma-ray flux limits at PeV energies. The diffuse gamma-ray data is summarized in §2. In §3 we analyze the consistency of the data with diffuse pionic emission, and explore the possibility of unresolved sources contributing significantly to the Milagro measurement. We go on in §4 to show how the framework of the GeV–TeV–PeV Galactic gamma-ray emission can be tested in detail. We conclude in §5 with an observational strategy which uses present and upcoming gamma-ray experiments to disentangle the nature of diffuse Galactic gamma-ray sources, both pionic and otherwise.

The resolution of the outstanding issues has important implications for more than just the pionic gamma rays, and will shed new light on Galactic cosmic rays in numerous ways: it will probably finally detect, and at least strongly constrain, the presence and interactions of hadronic cosmic rays throughout the Galactic interstellar medium; it will constrain the origin, source distribution, and spectra of both hadronic and leptonic cosmic rays; and it will thereby sharpen our account of the Galactic cosmic ray energy budget and thus the efficiency of cosmic ray accelerators. Furthermore, a detailed and quantitative understanding of astrophysical sources of diffuse Galactic gamma-rays will greatly clarify the existence and
nature of any other Galactic sources, such as dark matter. And finally, a good understanding of Galactic gamma-rays will allow for this foreground to be better subtracted to obtain the diffuse extragalactic gamma-ray background.

2. High-Energy Gamma-Ray Data

The Milagro Gamma-Ray Observatory is a ground-based water Čerenkov detector in New Mexico that collects air-shower particles created when high-energy particles interact in the atmosphere; showers initiated by gamma-rays and hadrons can be statistically distinguished by how they register in the detector (Atkins et al. 2003, 2004, 2005). The Milagro Collaboration recently reported a diffuse flux \( \phi_\gamma(> 3.5 \text{ TeV}) = (6.8 \pm 1.5 \pm 2.2) \times 10^{-11} \) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) of gamma rays from the Galactic Plane region \( \ell \in (40^\circ, 100^\circ) \) and latitude \( |b| < 5^\circ \) (Atkins et al. 2005). Note that this emission is integrated over both higher energies and also the entire angular region, where no resolved sources were detected (Atkins et al. 2005). In fact, to obtain the Galactic Plane diffuse emission Milagro did not directly measure the gamma-ray flux, but rather the ratio of electromagnetic to hadronic showers. Furthermore, their measurement was made by subtracting the off-source and on-source (Galactic Plane) fluxes, in order to cancel the isotropic cosmic-ray component; this also cancels the extragalactic gamma-ray background, which is at the otherwise relatively high level \( \sim 10^{-6} \) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) (compare in Fig. 1). An independent measurement of the hadronic cosmic-ray flux was then taken to derive the gamma-ray flux, and the result also depends on the assumed spectral indices of each species. We note that for the hadronic cosmic rays, Milagro adopts the conventional observed value \( \alpha = 2.75 \).

The Milagro Collaboration reports that their result is consistent with the diffuse emission extrapolated from EGRET, assuming a spectral index \( \alpha = 2.61 \), which is taken from the last four points of the EGRET integral spectrum (Atkins et al. 2005). This single-parameter fit provides a good description of these data. (By extrapolating from the EGRET differential spectrum, our Fig. 1 highlights the uncertainty in this procedure, that is, it demonstrates how a small change in the assumed spectral index can be important over a large energy range.) The apparent success of a single power law over this large energy baseline is very suggestive that the emission at these energies is dominated by a single source. In particular, given the understanding of how the various components of the diffuse emission change with energy from Strong, Moskalenko & Reimer (2004), one sees that this effectively assumes that all of the EGRET GeV data is pionic. However, the Milagro Collaboration is careful to note that their result could have a contribution from unresolved point or extended sources (Atkins et al. 2005; Nemethy 2005).
This first detection of diffuse emission at TeV energies invites a detailed comparison with other data. In our analysis, we will start with the assumption that Milagro detection corresponds to truly diffuse pionic emission, and then investigate the validity and consequences of this.

The EGRET data covers the range $0.03 - 10$ GeV and is publicly available from the NASA archives \(^1\) in the form of integral gamma-ray fluxes (in a given energy bin) at a given galactic coordinate where the coordinate step is $0.5^\circ$. We have taken those data points that fall into the Milagro region $\ell \in (40^\circ, 100^\circ), |b| < 5^\circ$, and averaged them for each energy bin. Finally, we have determined the EGRET gamma-ray flux at the mean energy for each bin, where the underlying assumption is that the flux is energy-independent over the width of a bin. This is presented in Fig. 1 with red data points. Following Strong, Moskalenko & Reimer (2004), we took fixed fractional uncertainties of 15% on the fluxes (since these are predominantly systematic in nature, they do not change when the field of view changes). Below, we additionally consider the EGRET sources detected in this region, taking their spectra from the Third EGRET Catalog (Hartman et al. 1999).

We also consider the upper limits on gamma-ray fluxes from other high-energy experiments. Although these experiments did not observe exactly the same region of the Galactic Plane as Milagro, we argue that their results can be put on a common footing. Especially at and above 1 TeV, it is expected that the diffuse Galactic emission is purely pionic, and hence scales with the column density (Strong, Moskalenko & Reimer 2004). Then fluxes from different regions of the Galactic Plane, if corrected for differences in column density, can be made physically equivalent, even if they are geographically distinct. This depends on the common assumption that there are no significant variations in the hadronic cosmic ray fluxes and spectra as a function of position in the Galactic Plane (e.g., Strong & Mattox 1996, but see also Strong et al. (2004)).

To correct for the differences in column density in different regions of the Galactic Plane, we take a simplistic approach and scale from the EGRET diffuse flux at lower energies (even though it is not purely pionic at those energies, this should be a reasonable approach for the relative variations in expected intensity). We calculate the region correction factor by comparing the EGRET diffuse gamma-ray flux averaged over the Milagro region with the one averaged over the region observed by a given experiment. We find that our correction factors do not vary much with energy. Table 1 summarizes the input data and the region correction factors $f_{rc}$. Here, $f_{rc} = F_{\text{EG,reg}} / F_{\text{EG,Milagro}}$ where $F_{\text{EG,reg}}$ and $F_{\text{EG,Milagro}}$ are the diffuse gamma-ray flux observed by EGRET and averaged over a given Galactic region and

\(^1\)EGRET data archive: http://coss.gsfc.nasa.gov/docs/cgro/egret/
the region observed by Milagro, respectively.

For energies near 1 TeV, we show in Fig. 1 the equivalent upper limits on the diffuse Galactic gamma-ray emission from the Whipple (LeBohec et al. 2000), HEGRA (Aharonian et al. 2001) and Tibet-II/III (M. Amenomori et al. 2005) experiments. For energies near 1 PeV, we also show the similar upper limits from the CASA-MIA (Borione et al. 1998) and KASCADE (Schatz et al. 2003) experiments.

The diffuse gamma-ray limits reported have an underlying assumption of a spectral index. We present each observational limit as originally reported with their assumed spectral index. For CASA-MIA, only the ratio of gamma-ray to hadronic integrated fluxes was reported in Borione et al. (1998), and we take the spectral index given by Glasmacher et al. (1999). We have to note here that there is a strong dependence of CASA-MIA limits on the assumed spectral index. This point is emphasized in Fig. 2 where we plot the CASA-MIA limits for their measured spectral index $\alpha = 2.66$ (Glasmacher et al. 1999), and also for the steeper spectral index of $\alpha = 2.80$ reported by JACEE (Asakimori et al. 1998). On the other hand, the KASCADE limits (Schatz et al. 2003) do not depend on the assumption of the spectral index (Schatz 2006).

Table 1: Diffuse gamma-ray observations used in this paper. The flux limits quoted by the various experiments are divided by $f_{rc}$ before being shown in our Fig. 1; this compensates for the differences in expectations for different regions.

| Experiment       | Observation Region | Region | Spectral Index $\alpha$ | Confidence |
|------------------|--------------------|--------|-------------------------|------------|
| Milagro          | $\ell$ range       | $|b|$ range | Correction $f_{rc}$     | Limit      |
| Whipple          | (38.5°, 41.5°)     | < 2°   | 1.6                     | 2.4        | 99.9 %    |
| HEGRA            | (38°, 43°)         | < 2°   | 1.6                     | 2.6        | 99 %      |
| Tibet II, III    | (20°, 55°)         | < 2°   | 1.6                     | 2.5        | 99 %      |
| CASA-MIA         | (50°, 200°)        | < 5°   | 0.7                     | 2.66       | 90 %      |
| KASCADE          | R.A. ∈ (0°, 360°)  | $\delta$ ∈ (14°, 84°) | 0.2 | independent | 90 %      |
3. Analysis of the Data

3.1. Diffuse Components

The spectrum of gamma rays that originate from the decay of neutral pions created in hadronic cosmic-ray interactions with ambient protons \( (p_{cr} + p_{ISM} \rightarrow p + p + \pi^0) \), followed by \( \pi^0 \rightarrow \gamma + \gamma \) is given in a useful fit by Pfrommer & Enßlin (2004), essentially following the earlier model by Dermer (1986). The symmetry of the two-gamma emission guarantees that the photon spectrum is symmetric about a peak at \( m_{\pi}/2 \) when plotted with a log scale (e.g., Stecker 1970, 1971). Furthermore, the asymptotic logarithmic slope (i.e., the spectral index \( \alpha \)) at high energies is the same as that of the primary cosmic rays (e.g., Dermer 1986; Mori 1997; Kamae et al. 2005). Thus, the pionic spectral shape is determined by a single parameter, the cosmic-ray spectral index. However, we note that there are still uncertainties in this pionic source function; see the discussions in e.g., Blattnig et al. (2000) and Kamae et al. (2005). At the present level of analysis, the uncertainties in the astrophysical inputs, particularly the Galactic cosmic-ray spectrum, are larger.\(^2\) Prodanović & Fields (2004) have shown that the lack of a strong pionic feature at \( m_{\pi}/2 \) in the diffuse Galactic gamma-ray data can be used to place a model-independent (i.e., flux-independent) upper limit on the pionic component of \( \sim 50\% \).

For better comparison to other data, we assume a spectral index and convert the Milagro energy-integrated flux into a differential flux, also evaluated at 3.5 TeV. If we adopt the Milagro best-fit gamma-ray index of \( \alpha = 2.61 \), we find a gamma flux of \( d\phi/dE = (3.1 \pm 1.2) \times 10^{-14} \) photons cm\(^{-2}\) s\(^{-1}\) GeV\(^{-1}\) sr\(^{-1}\). This point is shown in Fig. 1 as a blue triangle. We note here that if the integral flux reported by Milagro is recalculated for a more realistic spectral index of \( \alpha = 2.75 \) then the variation of the flux is just 6\%, which is much smaller than reported uncertainty.

Even when the pionic component is maximized (Prodanović & Fields 2004), it fails to explain the Milagro result. To appreciate this mismatch, it is important to recall that the physics of the pionic signal demands that above the pion bump, the pionic spectrum is characterized by a single spectral index which is the same as that of the cosmic rays. Thus, if the high-energy EGRET and Milagro points are due to pionic emission, their spectral index must reflect the underlying cosmic ray index along the line of sight. If we adopt

\(^2\)For example, Kamae et al. (2005) finds that diffractive effects could change the gamma-ray index by about \( +0.05 \) units; this is about the level of the uncertainty in the measured local cosmic-ray spectrum, but much smaller than the index shift (\( \geq 0.2 \) units) needed to reconcile the EGRET and Milagro data with the pionic signal expected from cosmic rays.
the best-fit EGRET/Milagro index $\alpha = 2.61$ as reflecting the average Galactic cosmic ray spectrum towards the Milagro region, the resulting pionic flux at the Milagro energy is 66% of the observed result. For the locally-measured cosmic-ray spectral index of $\alpha = 2.75$, the maximal allowed pionic contribution drops to just 19% of the Milagro flux. Note however that due to large uncertainties in Milagro measurement, the maximal fraction that the pionic gamma-ray component can account for in this case, can be at most about 30%. Were we to raise the pionic prediction to meet the Milagro and high-energy EGRET signals, the result would overshoot the EGRET signal below 1 GeV.

This result on the pionic normalization, supported by the more detailed work of Strong, Moskalenko & Reimer (2004), indicates that it is not realistic to simply extrapolate the EGRET data into the TeV range, where the pionic component should be dominant. At the very least, the non-pionic components of the GeV data should be subtracted first. Also, as shown by the solid line in Fig. 1, when the EGRET data are further extrapolated into the PeV range, the expectations are right on the edge of upper limits from the CASA-MIA and KASCADE experiments. The upper dashed line in Fig. 1 shows a line of the same EGRET/Milagro best-fit spectral index ($\alpha = 2.61$), with a maximal pionic normalization. Besides being ~2 times larger than favored at low energies, this curve still falls below the Milagro point (with a more realistic normalization, it would fall more significantly below).

While the spectral index fit of $\alpha = 2.61$ is quite suggestive for connecting the EGRET and Milagro observations, it is not consistent with local observations of the hadronic cosmic rays, which instead suggest $\alpha = 2.75$. Over the long lever arm of ~1 GeV to ~1 TeV, this makes a significant difference. Cosmic-ray experiments such as JACEE fit their measured cosmic-ray spectra with $\alpha = 2.80 \pm 0.04$ (Asakimori et al. 1998). In our analysis we will adopt $\alpha = 2.75$ as a more conventional, locally measured value, consistent with our previous work. In this case, we find that, even for a maximized pionic normalization, the pionic flux at 3.5 TeV is 5 times smaller than the Milagro measurement. For a pionic normalization as low as assumed by de Boer et al. (2005), the pionic flux at 3.5 TeV is about 10 times smaller than the Milagro measurement. In any case, the joint demands of using a realistic cosmic ray spectrum and not exceeding the maximal pionic normalization mean that the expectations fall well below the Milagro observation. We therefore call this problem the “TeV excess.”

Pushing beyond the TeV range to PeV energies further constrains both the TeV and GeV excesses. In Fig. 1, we see that the upper limits reported by CASA-MIA (Borione et al. 1998) and KASCADE (Schatz et al. 2003) appear to already rule out the simple single-power-law extrapolation from GeV energies upward. Indeed, the published PeV limits barely permit the maximal pionic emission allowed at an index of at the level of the EGRET/Milagro $\alpha = 2.61$ fit. Thus the PeV data already play a useful role in limiting the level of pionic emission and
thus strengthening the case for a non-pionic TeV excess seen by Milagro. Indeed, it is clear that there is no source which can have a single power law spectrum which lies beneath the GeV data and matches the TeV signal, without running afoul of the PeV constraints.

Moreover, as noted above, the PeV data from CASA-MIA were obtained from a gamma-to-hadron shower ratio in concert with an assumed cosmic-ray spectral index of $\alpha = 2.66$. In Fig. 2, we zoom into the TeV–PeV region to show the effect of choosing the steeper spectral index $\alpha = 2.80$ measured by Asakimori et al. (1998). Note that because only the ratio of integral fluxes is given, the assumption of a different spectral index also results in a different normalization need to calculate gamma-ray flux. We then see that the limits can become much stronger in absolute terms. The pionic constraints remain similar, as both the data and predictions move together. On the other hand, the tighter absolute limits now exclude a continuation of the GeV-TeV $\alpha = 2.61$ power-law fit to PeV energies.

Moskalenko et al. (2005) have recently shown that the attenuation of gamma rays by the interstellar radiation field ($\gamma + \gamma \rightarrow e^+ + e^-$) can be significant for energies $\gtrsim 10$ TeV and sightlines near the Galactic Center. This effect would be most prominent around 100 TeV. However, at few hundred TeV attenuation by the CMB takes over and dominates at PeV energies (Moskalenko et al. 2005). As the sensitivity and impact of the PeV data improves, it will be necessary to take these effects into account. In addition, the decreasing flux and heavier composition beyond the cosmic ray knee will also reduce the expected gamma fluxes.

The presence of a TeV excess must be viewed in the light of the well-known GeV excess and its possible explanations. Inverse Compton scattering makes a significant contribution at GeV energies, but in the TeV regime it declines rapidly, and is much smaller than the pionic gamma-ray flux (Strong, Moskalenko & Reimer 2004). In the de Boer et al. (2005) proposed scenario, the GeV excess originates from the annihilation of dark matter particles with mass $\approx 100$ GeV. In this case the dark-matter gamma-ray signal will have a sharp cutoff at the dark matter mass, and again cannot contribute as significantly at TeV energies. (And since we are discussing the Galactic Plane, well away from the center, the contribution of any dark matter component should be greatly reduced.) In order to explain the TeV excess, we require a component which is subdominant at GeV energies, important at TeV energies, and vanishing again at PeV energies. This might arise from unresolved sources with hard ($\alpha \approx 2$) spectra, cutting off before the PeV range, and we turn to this possibility next.
3.2. Unresolved Sources

It is possible that unresolved point or extended sources contributed to the total gamma ray flux measured by Milagro (Atkins et al. 2005; Nemethy 2005). While Milagro did not find any resolved sources in this region of the Galactic Plane, there are ten unidentified gamma-ray point sources in this region given in the Third EGRET Catalog (Hartman et al. 1999). (It is worth noting that the definition of these as point sources depends on the degree-scale angular resolution of EGRET; future experiments should be able to measure the energy spectra and angular extent of these sources much more precisely.) The spectra of these sources are described therein by single power law fits, which we extrapolate to the TeV range and consider as contributions to the Milagro diffuse measurement.

Table 2: Unidentified EGRET Point Sources in Milagro Region

| 3EG Catalog Source | Galactic Coords $\ell$ [°] | $b$ [°] | $F(>100\text{ MeV})$ [10$^{-8}$ cm$^{-2}$ s$^{-1}$] | Spectral Index $\gamma$ |
|--------------------|-----------------------------|--------|-----------------------------------|-----------------|
| J1903+0550         | 39.52                       | −0.05  | 62.1 ± 8.9                       | 2.38 ± 0.17     |
| J1928+1733         | 52.71                       | 0.07   | 157.0 ± 36.9                     | 2.23 ± 0.32     |
| J1958+2909         | 66.23                       | −0.16  | 26.9 ± 4.8                       | 1.85 ± 0.20     |
| J2016+3657         | 74.76                       | 0.98   | 34.7 ± 5.7                       | 2.09 ± 0.11     |
| J2020+4017         | 78.05                       | 2.08   | 123.7 ± 6.7                      | 2.08 ± 0.04     |
| J2021+3716         | 75.58                       | 0.33   | 59.1 ± 6.2                       | 1.86 ± 0.10     |
| J2022+4317         | 80.63                       | 3.62   | 24.7 ± 5.2                       | 2.31 ± 0.19     |
| J2027+3429         | 74.08                       | −2.36  | 25.9 ± 4.7                       | 2.28 ± 0.15     |
| J2033+4118         | 80.27                       | 0.73   | 73.0 ± 6.7                       | 1.96 ± 0.10     |
| J2035+4441         | 83.17                       | 2.50   | 29.2 ± 5.5                       | 2.8 ± 0.26      |

In the GeV range, these objects have significantly harder spectra ($\alpha \approx 2$) than the pionic diffuse component, so in principle, they could become quite important at higher energies. Additionally, we found that the combined extrapolated flux at $E_{\gamma} = 3.5$ TeV of these ten point sources, spread out over the Milagro region, is $\sum_{i=1}^{10} F_{ps}^i E_{\gamma} = 3.5$ TeV $\approx 2.5 \times 10^{-13}$ photons cm$^{-2}$ s$^{-1}$ GeV$^{-1}$ sr$^{-1}$. Amazingly, this is about a factor of 10 larger than the total diffuse emission for the whole region measured by Milagro, i.e., $F_{diff} E_{\gamma} = 3.5$ TeV $\approx 3.0 \times 10^{-14}$ photons cm$^{-2}$ s$^{-1}$ GeV$^{-1}$ sr$^{-1}$. Thus it is obvious that indeed, unresolved point sources could contribute significantly to the TeV excess, even taking into account the uncertainties in the extrapolations in energy. In fact, in order to not grossly overproduce the measured flux, the spectra of these ten objects must be strongly cut off before the TeV range.
Four of these ten EGRET objects have been observed at TeV energies by the Whipple (Fegan et al. 2005; Buckley et al. 1998) and HEGRA (Aharonian et al. 2005a) experiments. In Fig. 3, we show the combined GeV and TeV spectral information on these objects. Aharonian et al. (2005a) reported a detection by HEGRA of the source TeV J2032+4130, which, if related to the J2033+4118 EGRET source, would mean a TeV signal that is more than two orders of magnitude lower than what would have been expected based on the EGRET observation. If all of the sources were like this, then these extrapolated unresolved sources would not be able to explain the TeV excess. However, in the other three cases shown, the TeV limits are not yet strong enough to decide if these sources are excluded from contributing significantly to the TeV excess. For example, even when limits for just these four sources are used, the total flux still remains about 3 times above the Milagro diffuse flux; and there are still the other six objects that we don’t have information about yet.

In addition, sources of comparable TeV intensity to those detected recently by HESS (Aharonian et al. 2005b, 2006b) could contribute significantly to the flux in the Milagro region, if present in this region of the Galactic Plane but not resolved; these sources may be bright at TeV but not GeV energies.

Consequently, it is for now impossible to determine whether the Milagro measurement arises from truly diffuse emission or unresolved sources. Even if the entire flux is due to unresolved sources, it is clear that all of these ten EGRET sources will have to be cut off before 3.5 TeV, or else the extrapolated flux could be much be too large. Direct observations of these ten EGRET sources in the TeV range are thus of very high importance for further progress.

4. Discussion

The pioneering Milagro observation (Atkins et al. 2005) above 3.5 TeV is the first positive detection of a Galactic diffuse component at very high energies. The Milagro result becomes all the more powerful when placed in the context of GeV gamma-ray observations by EGRET (Hunter et al. 1997), and PeV upper limits by CASA-MIA (Borione et al. 1998) and KASCADE (Schatz et al. 2003). In particular, the combined GeV–TeV–PeV signal is incompatible with emission from pions created by cosmic rays with the locally measured $\alpha = 2.75$ index. This result follows from the physics of pion production and decay, and is independent of any detailed Galactic model. Moreover, pionic emission is the only conventional source at TeV energies. But the pionic spectral shape and the GeV EGRET data together constrain the pionic emission to fall below the Milagro TeV signal by at least a factor of $\sim 5$ when using a pionic spectrum arising from cosmic rays as locally observed;
even without requiring consistency with the local cosmic-rays, the deficit is at least a factor of \( \sim 2 \). This mismatch constitutes the TeV excess.

The TeV excess takes its place alongside the well-established GeV excess to underscore our present state of ignorance about the sources of diffuse Galactic gamma rays. These data demand an explanation. (1) We are challenged to determine the dominant sources of diffuse Galactic gamma-rays at the highest energies, and to determine what portion of the emission is truly diffuse, and what portion is due to (as yet) unresolved point sources. (2) We are still tasked to search for a pionic signature, since the mere existence of hadronic cosmic rays and of interstellar matter together guarantee that this flux must exist at some level in the Galactic gamma-ray sky. (3) Our difficulty in explaining the diffuse Galactic gamma-ray spectrum is all the more galling given that current measurements are consistent with a very simple spectral shape: as seen in Fig. 1, the present GeV–TeV–PeV gamma-ray data are all consistent with a piecewise power law having a break at a peak around 0.8 GeV. It would be enormously instructive to determine whether improved spectral resolution and energy coverage confirm this simple form or reveal telltale features. For now, neither the low-energy or high-energy power law indices, nor the energy scale of the break, can easily be understood in terms of the observed properties of local Galactic cosmic rays.

With these broad questions at hand, we now briefly explore astrophysical consequences of some of the possible solutions, and then review the observational arsenal which can be brought to bear on these problems.

4.1. Point Source Spectral Break: Implications

To account for this TeV excess we have looked into the contribution from the unresolved sources. More precisely, in the region of the sky observed by Milagro we have noted ten unidentified EGRET sources. To estimate their gamma-ray flux at 3.5 TeV we have used their spectral information as determined by EGRET and extrapolated into the TeV energy range. We found that the total combined gamma-ray flux of these ten EGRET sources exceeds the diffuse Galactic Plane TeV gamma-ray flux observed by Milagro by about an order of magnitude. This suggests that extrapolation of the EGRET sources to TeV energies has to fail at some point. Four of these sources have been observed at TeV energies, and one has been shown to break by about two orders of magnitude. However, until all of those point sources are surveyed at TeV energies, we cannot say more about their possible contribution to the TeV excess.

The possibility of a spectral break for at least some Galactic point sources might have
important implications. If Galactic point sources (presumably, supernova remnants) are the dominant source of Galactic cosmic-ray protons at TeV energies then the shape of the diffuse pionic gamma-ray spectrum should track that of individual Galactic point sources. That is, if there is a break or a cutoff somewhere between 10 GeV and 1 TeV in gamma-ray spectra of these sources that should carry over to spectra of cosmic rays accelerated in them. In that case the break in the spectrum is a measure of maximal SNR acceleration energy. Moreover, this would imply that another cosmic-ray component (or reacceleration) is required to come in before the $\sim 1000$ TeV cosmic-ray “knee,” contrary to conventional models.

4.2. “GeV Excess” Explained by Dark Matter?

In this paper we have tested the consistency of the model proposed by de Boer et al. (2005) with the diffuse Galactic Plane TeV gamma-ray observation of Atkins et al. (2005). This model requires a conventional pionic component in order for the GeV excess to originate from WIMP annihilation. We found that such a pionic component will then be able to account for only $\sim 10\%$ of the Milagro TeV gamma-ray flux. Thus, although the GeV excess could be explained this way, there still will be a potential TeV excess. However, due to large uncertainties regarding point source contribution to Milagro TeV gamma-ray flux of EGRET sources, our model-independent analysis is unable to rule de Boer et al. (2005) model in or out, on the basis of gamma-rays alone. On the other hand, the recent analysis by Bergstrom et al. (2006) does claim to exclude the de Boer et al. (2005) model on the basis of antiproton fluxes.

Finkbeiner (2004) has proposed that dark matter annihilations may account for both the EGRET GeV excess and the WMAP Galactic haze, through the inverse-Compton and synchrotron energy losses of electrons and positrons produced in the annihilations. Though the mechanism of producing the GeV gamma rays is different from that of de Boer et al. (2005), in both cases the gamma-ray spectrum is cut off at energies above the dark matter mass, presumably $\sim 100$ GeV.

4.3. Answering the Questions: Observations

Some of the existing and upcoming gamma-ray experiments will be able to answer the questions we have raised. Namely, the Gamma-ray Large Area Space Telescope (GLAST; Michelson 2001) will make observations in the 10 MeV – 300 GeV energy band, which means that it will go about an order of magnitude higher in energy than EGRET, and
will thus have the first view into this “unopened window” in energy. This will give new understanding of how GeV and TeV diffuse Galactic Plane gamma-ray observations connect. It will tell us more about the nature of the GeV excess and how high it extends in energy. In particular, GLAST observations of diffuse emission could find a break in the diffuse gamma-ray spectrum, which would point to the nature of the GeV excess. Though a potential break could be due to high inverse Compton component (Strong, Moskalenko & Reimer 2004), it could also have a dark matter origin; the shapes of two spectra may differ enough to make separation possible.

GLAST observations of point sources at such high energies should uncover the break in their spectra implied by the overproduction of TeV gamma-rays when GeV data are extrapolated without a break (Fig. 3). A possible break, along with in general a better determination of point source spectra, could place strong constraints and possibly give a definite answer about the existence of the diffuse TeV excess. Discovering a break in the spectra of supernova remnants in particular would immediately have important consequences for the nature of Galactic cosmic rays and thus hadronic gamma-rays. This feature would indicate a maximum cosmic ray energy which then should also limit Galactic cosmic rays accelerated by supernovae. Any cosmic rays above such energies must be accelerated from other sources, Galactic or otherwise.

The Very Energetic Radiation Imaging Telescope Array System (VERITAS; Weekes et al. 2002) will complement and partially overlap with GLAST by observing in the energy range of 50 GeV – 50 TeV. VERITAS enjoys greater flux sensitivity compared to Milagro. Consequently, VERITAS should better determine the intensity of diffuse Galactic Plane gamma-ray emission. At least as important, VERITAS has far better point source sensitivity, which results in far lower contamination by unresolved point sources. All of this will allow VERITAS to place strong constraint on the possible diffuse nature of the TeV excess and in turn constrain the pionic gamma-ray component.

The High-Energy Stereoscopic System (HESS) is already surveying point sources (Aharonian et al. 2005c). Its sensitivity is similar to VERITAS, and thus it is in the position to already answer some of these questions. Although it is located in the southern hemisphere, and does not observe the same region of the Galactic Plane as Milagro, an independent measurement of the diffuse gamma-ray flux would help resolve some of the issues we have presented in this paper. A possible diffuse Galactic Plane gamma-ray measurement made by HESS could be used to check for consistency with EGRET observations, in a similar way as presented in this paper. The much better angular resolution of HESS compared to Milagro would give a result far less dependent on the unresolved point sources. Thus, a potential discovery of a diffuse TeV excess even in this case would then tell us a lot about the nature
of this excess. We also note that the MAGIC telescope, a very large atmospheric imaging Čerenkov telescope, has a very low energy threshold, down to 30 GeV (Baixeras 2003), and will thus also be a powerful probe.

Moreover, very recently, the HESS Collaboration has reported the discovery of an apparently diffuse flux from a very small region at the Galactic Center (Aharonian et al. 2006a). While near 200 GeV, this flux is similar to expectations, it falls off less steeply ($\alpha = 2.3$ instead of 2.75), reaching an excess of at least a factor 10 near 10 TeV. While the spectrum here is falling less steeply than that which would be required to explain the Milagro TeV excess, the remarkable similarity of the excess suggests that a common origin is possible, e.g., perhaps due to source cosmic rays (Berezhko & Völk 2000, 2004). Note that Milagro has only measured a single point – the flux above 3.5 TeV – and hence cannot yet distinguish between possible new spectra emerging near that energy.

If the enhanced gamma ray flux seen by Milagro indeed arises from neutral pion decays, as in the model of Berezhko & Völk (2000, 2004) with enhanced high-energy cosmic ray fluxes near sources, then it must be accompanied by an equally enhanced flux of neutrinos from charged pion decays. (In proton-proton collisions at high energies, neutral and charged pions are produced in comparable numbers; the neutral pions decay to two gamma rays, and the charged pions ultimately decay to three neutrinos and an electron or positron.) The same conclusion would hold if the TeV flux excess is due to dark matter annihilations (Finkbeiner 2004; de Boer et al. 2005) or unresolved sources in which the gamma rays are produced by pion decays. If the excess gamma rays are produced leptonically, by inverse Compton scattering, there will not be accompanying enhanced neutrino fluxes. These considerations may allow new tests of the TeV excess in IceCube and other large neutrino detectors (Beacom & Candia 2004; Candia 2005; Kelley 2005), for which the detection prospects would be enhanced by a factor approaching 10, and more if the excess persists to higher energies.

Finally, as we have emphasized, gamma-ray energy spectra provide the most direct and model-independent probe of pionic production and hence hadronic cosmic rays. However, the sky distribution of course also provides important clues (Strong, Moskalenko & Reimer 2004), and the warp in the Galactic Plane may be helpful for separating the pionic gamma-ray component. Since the cosmic rays are believed to be isotropic within the Galaxy, the pionic component of the gamma ray flux should be proportional to the column density of gas along the line of sight, whereas the inverse Compton component depends on the radiation density. Three-dimensional models of the Galactic neutral hydrogen density, revealed by the Doppler-shifted 21-cm line emission, show that the Galactic Plane is strongly warped at radii $\gtrsim 10$ kpc (Levine et al. 2006). Some evidence of this warp can be seen in neutral hydrogen column density maps (Kalberla et al. 2005), showing up as an excursion to positive latitudes.
near Galactic longitude $\ell \sim 100$ and an excursion to negative latitudes near $\ell \sim 260$. In the energy range corresponding to pionic gamma rays, these same features should be seen. While some evidence of this effect was noted earlier (Hunter et al. 1997), it appears to be easiest to see in the new EGRET maps of Cillis & Hartman (2005), which are shown for several energy ranges (note the high-resolution figures are only available online). Here the warp effect can be quite easily seen in several of the maps, which probably implies that the distribution of all gas is similar to that of neutral hydrogen alone. Besides offering some hope to separate the pionic component with spatial information, the non-trivial geometry would allow for the first time some information about distances along the line of sight. While our comments here are only qualitative, we are unaware of any published correlation of the EGRET and 21-cm maps. The future GLAST mission, with significantly better sensitivity and angular resolution, should allow much more detailed studies.

5. Conclusion: An Observational Strategy to Determine the Sources of Diffuse Galactic Gamma-Rays

The nature and origin of the diffuse gamma-ray emission from our Galaxy at GeV energies (Hunter et al. 1997) has become an increasingly pressing problem, with the GeV excess (Strong, Moskalenko & Reimer 2004) seeming to demand new astrophysics (e.g., high-energy cosmic-ray populations) or new physics (annihilating dark matter). The Milagro detection (Atkins et al. 2005) of a TeV Galactic signal, possibly of diffuse origin, invites us to place the GeV emission in a larger context. In this paper, we show that TeV and PeV gamma-ray observations provide a long “lever arm” on the GeV excess and its origin.

In particular, the combined GeV–TeV–PeV observations shed new light on emission due to hadronic cosmic-ray interactions. These hadronic gamma-rays must exist at some level, and appear with a characteristic spectrum fixed by pion decay and the primary cosmic-ray spectrum. Since the “pion bump” at $E_\gamma = m_\pi/2$ is not seen, the evidence for pionic emission must come from the high-energy tail, which should dominate over any leptonic (i.e., inverse Compton) signal at high energies ($\gtrsim 1$ TeV). For this reason, TeV–PeV data offer key new constraints on pionic gamma-rays, which can allow us to determine the hadronic gamma component and thus isolate the residual contribution(s).

Can we arrive at a consistent picture of high-energy Galactic gamma-ray emission? Yes, though present data are insufficient to single out a unique combination of sources. However, some conclusions are already clear: (a) The simplest picture, in which pions are created from cosmic-rays with energy spectra as measured locally, is inconsistent with published EGRET and Milagro data. (b) Besides the “GeV excess” identified by EGRET, a “TeV
excess” is likely to be present as well. We have shown that one of the main uncertainties in accounting for the Atkins et al. (2005) diffuse TeV gamma-ray observation comes from unresolved sources. (c) As we have pointed out, indications of a possible break in spectra of some point sources can have important consequences for cosmic-ray acceleration. (d) The true picture of Galactic gamma-rays, which might follow several scenarios, can be revealed with further observations.

1. One possibility is that the TeV excess is indeed is truly diffuse and due to pionic emission (Atkins et al. 2005). In the simplest picture, this would be a scenario where no break in the diffuse gamma-ray spectrum is observed between the GeV and TeV regimes. This would in turn require a spectral index $\alpha = 2.61$, as pointed out by the Milagro Collaboration, which would indicate that measured local cosmic-ray spectrum is different from, and harder than, the Galactic average. This would also mean that the pionic component is very close to maximal, if not larger, as shown in Fig. 1. In this case, the spectrum should follow the same power law out to the PeV region. This PeV signal would lie just below the current limits, awaiting discovery (or falsification!) with modest improvements in sensitivity.

Such a hard pionic spectrum would greatly reduce the GeV excess, lessening the motivation for a large inverse Compton or dark matter component. For a more realistic pionic spectrum, there is the well-known problem of the GeV excess. We are noting here that models which explain the GeV excess with a low pionic normalization and new component at GeV energies must now be confronted with the TeV excess that they create.

2. Another possibility is that the TeV excess is truly diffuse, but not due to interstellar pionic emission. This would be the case if there is a “hard electron component,” i.e., with a spectrum not observed locally (see e.g., Aharonian & Atoyan 2000; Pohl & Esposito 1998). Such an anomalous component could create an inverse Compton signal which composes the GeV excess, but also extends to TeV energies where it dominates over the pionic component. This scenario would result in a gamma-ray spectral break at a few tens of GeV. Having a definite handle on the inverse Compton component would in turn determine the pionic gamma-ray component. Moreover, because the hard electron spectrum model explains a large fraction of the GeV excess, it thus excludes dark matter explanation. However, if the TeV excess cannot be explained with the inverse Compton component, then this would indicate a more exotic solution.

3. Just as the GeV excess raises the exciting prospect of a dark matter signal (de Boer et al. 2005), so too does the TeV excess. This scenario is testable. If the TeV excess
is due to annihilations, one expects a strict cutoff above the mass of the dark matter particle (which necessarily must be rather heavy, \( m_{DM} \gtrsim E_{\gamma,\text{Milagro}} \geq 3.5 \text{ TeV} \)); this should appear as a break or perhaps even a peak in the gamma-ray spectrum. Also, the evidence for the TeV excess comes from the Milagro region which lies \( \ell > 40^\circ \) from the Galactic center, and thus probes rather peripheral Galactocentric radii \( R > R_\odot \sin\ell \simeq 5 \text{ kpc} \). Given that dark matter densities (and the resulting annihilation rate \( \propto n_{DM}^2 \)) are expected to peak at the center, one would expect a rapid increase in the diffuse signal as one scans from the Milagro region to the Galactic center. And a dark matter interpretation of either or both gamma-ray signals faces similar challenges from other high-energy particle observations (e.g., Bergstrom et al. 2006).

4. Finally, the TeV excess could result from unresolved isolated sources such as supernova remnants. This scenario could easily be checked by surveying for TeV point sources in the Galactic region observed by Milagro. Indeed, the EGRET sources in the Milagro region appear as “hot spots” on the Milagro map, though it is unclear how significant this may be. Also, another observation of the diffuse Galactic Plane TeV gamma-rays could yield a flux that does not require a TeV excess, but is instead consistent with a diffuse pionic emission with a more conventional spectral index. Thus it is crucial that VERITAS TeV telescope surveys the EGRET sources, especially the ones in the region observed by Milagro.

A measurement of the diffuse Galactic Plane TeV gamma-ray flux with better resolution telescopes like VERITAS and HESS would not only confirm the Milagro detection, but also would provide much sharper angular resolution of the signal. These additional data could significantly tighten the constraints based on gamma-ray spectra, and open up the possibility of distinguishing the diffuse TeV sources based on the sky distribution.

Thus, existing diffuse gamma-ray observations of the Galactic plane are consistent with an energy spectrum that is at once empirically simple (a broken power law) yet stubbornly resistant to theoretical explanation. Fortunately, upcoming observations across the GeV-TeV-PeV range will add qualitative and quantitative detail that will distinguish among and/or exclude the possible sources of the highest energy photons in our Galaxy.

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REFERENCES

Aharonian, F., *et al.* [HESS Collaboration] 2006a, Nature, 439, 695
Aharonian, F., *et al.* [HESS Collaboration], 2006b, ApJ, 636, 777
Aharonian, F., *et al.* [HESS Collaboration] 2005a, A&A, 431, 197
Aharonian, F., *et al.* [HESS Collaboration] 2005b, A&A, 437, L7
Aharonian, F., *et al.* [HESS Collaboration] 2005c, astro-ph/0510397
Aharonian, F. A., *et al.* [HEGRA Collaboration] 2001, A&A, 375, 1008
Aharonian, F. A., & Atoyan, A. M. 2000, A&A, 362, 937
Amenomori, M., *et al.* [Tibet AS Gamma Collaboration] 2005, astro-ph/0511514
Asakimori, K., *et al.* [JACEE Collaboration] 1998, ApJ, 502, 278
Atkins, R. W., *et al.* [Milagro Collaboration] 2005, Phys. Rev. Lett., 95, 251103
Atkins, R., *et al.* [Milagro Collaboration] 2004, ApJ, 608, 680
Atkins, R., *et al.* [Milagro Collaboration] 2003, ApJ, 595, 803
Baixeras, C. [MAGIC Collaboration] 2003, Nuclear Physics B Proceedings Supplements, 114, 247
Beacom, J. F., & Candia, J. 2004, Journal of Cosmology and Astro-Particle Physics, 11, 9
Berezhko, E. G., & Völk, H. J. 2004, ApJ, 611, 12
Berezhko, E. G., & Völk, H. J. 2000, ApJ, 540, 923
Bergstrom, L., Edsjo, J., Gustafsson, M., & Salati, P. 2006, astro-ph/0602632
Blattner, S. R., Swaminathan, S. R., Kruger, A. T., Ngom, M., & Norbury, J. W. 2000, Phys. Rev. D, 62, 094030
de Boer, W., Sander, C., Zhukov, V., Gladyshev, A. V., & Kazakov, D. I. 2005, A&A, 444, 51
Borione, A., *et al.* [CASA-MIA Collaboration] 1998, ApJ, 493, 175
Buckley, J. H., *et al.* [Whipple Collaboration] 1998, A&A, 329, 639
Candia, J. 2005, Journal of Cosmology and Astro-Particle Physics, 11, 2
Cillis, A. N., & Hartman, R. C. 2005, ApJ, 621, 291
Dermer, C. D. 1986, A&A, 157, 223
Fegan, S. J., et al. [Whipple Collaboration] 2005, ApJ, 624, 638
Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Ogelman, H., Ozel, M. E., Tumer, T., & Bignami, G. F. 1975, ApJ, 198, 163
Finkbeiner, D. P. 2004, astro-ph/0409027
Glasmacher, M. A. K., et al. [CASA-MIA Collaboration] 1999, Astroparticle Physics, 10, 291
Hartman, R. C., et al. [EGRET Collaboration] 1999, ApJS, 123, 79
Hunter, S. D., et al. [EGRET Collaboration] 1997, ApJ, 481, 205
Kalberla, P. M. W., Burton, W. B., Hartmann, D., Arnal, E. M., Bajaja, E., Morras, R., Pöppel, W. G. L. 2005, A&A, 440, 775
Kamae, T., Abe, T., & Koi, T. 2005, ApJ, 620, 244
Kelley, J. L. [IceCube Collaboration] 2005, astro-ph/0509546
Kraushaar, W. L., Clark, G. W., Garmire, G. P., Borken, R., Higbie, P., Leong, V., & Thorsos, T. 1972, ApJ, 177, 341
LeBohec, S., et al. [Whipple Collaboration] 2000, ApJ, 539, 209
Levine, E. S., Blitz, L., & Heiles, C. 2006, astro-ph/0601697
Michelson, P. F. [GLAST Collaboration] 2001, AIP Conf. Proc. 587: Gamma 2001: Gamma-Ray Astrophysics, 587, 713
Mori, M. 1997, ApJ, 478, 225
Moskalenko, I. V., Porter, T. A., & Strong, A. W. 2005, astro-ph/0511149
Nemethy, P. 2005, private communication
Pfrommer, C. & Enßlin, T. A. 2004, A&A, 413, 17
Pohl, M., & Esposito, J. A. 1998, ApJ, 507, 327
Prodanović, T., & Fields, B. D. 2004, Astroparticle Physics, 21, 627

Schatz, G. 2006, private communication

Schatz, G., et al. [KASCADE Collaboration] 2003, International Cosmic Ray Conference, 4, 2293

Stecker, F. W. 1970, Ap&SS, R6, 377

Stecker, F. W. 1971, Cosmic Gamma Rays, NASA Pub. SP-249

Strong, A. W., & Mattox, J. R. 1996, A&A, 308, L21

Strong, A. W., Moskalenko, I. V., & Reimer, O. 2004, ApJ, 613, 962

Strong, A. W., Moskalenko, I. V., Reimer, O., Digel, S., & Diehl, R. 2004, A&A, 422, L47

Weekes, T. C., et al. [VERITAS Collaboration] 2002, Astroparticle Physics, 17, 221
Fig. 1.— The diffuse gamma-ray GeV-TeV-PeV spectrum of the Galactic plane in the region visible to Milagro. The EGRET data points and the Milagro signal are empirically well-fit (solid line) with a spectral index $\alpha = 2.61$. The maximized pionic spectrum appears in the dashed lines; we see that pionic emission having the empirical $\alpha = 2.61$ index (dark blue line) signal comes close to (but somewhat undershoots) the Milagro result; on the other hand, the maximal pionic signal generated by cosmic rays with the locally measured $\alpha = 2.75$ spectrum (magenta lines) falls far short of Milagro, leaving a TeV excess. The dotted line represents a pionic spectrum normalized to the one plotted in de Boer et al. (2005) (their Fig. 5, region B) at $E = 1$ GeV. The PeV limits of CASA-MIA and KASCADE are on the verge of being constraining (see also Fig. 2). Finally, fluxes of the ten EGRET sources that we have identified were smoothed over the Milagro field of view and then summed, which is plotted with red dash-dotted line; the Milagro result falls below the extrapolation of this trend and thus demands a significant break in some or all of the EGRET source spectra (see also Fig. 3).
Fig. 2.— In this figure, we zoom in the PeV region of Fig. 1 to emphasize the strong dependence of the CASA-MIA limits on the assumed spectral index. The value adopted in this paper $\alpha = 2.66$ (Glasmacher et al. 1999) results in limits plotted as green stars. On the other hand, if a steeper spectrum is assumed $\alpha = 2.80$ (i.e., adopting the JACEE cosmic-ray flux; Asakimori et al. 1998) this results in stronger CASA-MIA limits plotted as red stars. As in Fig. 1, dashed lines represent the maximal pionic spectrum for $\alpha = 2.61$ (blue) and $\alpha = 2.75$ (magenta), while the pionic spectrum adopted by de Boer et al. (2005) is presented as a dotted magenta line.
Fig. 3.— In this figure we plot four of the EGRET sources from the Milagro $\ell \in (40^\circ, 100^\circ)$, $|b| < 5^\circ$ region that were observed in TeV range as well; we see here (but also from Fig. 1) that the power-law trends at GeV energies must not continue to TeV energies. The EGRET data points (blue) were plotted using publicly available data. The extrapolation slope used for each source is given in Table 2 (Hartman et al. 1999). Limits at $E = 3.5$ TeV plotted in red were derived from observations: J2016+3657 and J2021+3716 Whipple (Fegan et al. 2005), J2020+4017 Whipple (Buckley et al. 1998), J2033+4118 HEGRA (Aharonian et al. 2005a).