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CONSTRAINTS ON GAMMA-RAY EMISSION FROM THE GALACTIC PLANE AT 300 TeV

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ABSTRACT

We describe a new search for diffuse ultra–high-energy gamma-ray emission associated with molecular clouds in the Galactic disk. The Chicago Air Shower Array (CASA), operating in coincidence with the Michigan muon array (MIA), has recorded over 2.2×10^9 air showers from 1990 April 4 to 1995 October 7. We search for gamma rays based upon the muon content of air showers arriving from the direction of the Galactic plane. We find no significant evidence for diffuse gamma-ray emission, and we set an upper limit on the ratio of gamma rays to normal hadronic cosmic rays at less than 2.4×10^{-5} at 310 TeV (90% confidence limit) from the Galactic plane region: ($50° < l < 200°$; $-5° < b < 5°$). This limit places a strong constraint on models for emission from molecular clouds in the Galaxy. We rule out significant spectral hardening in the outer Galaxy, and conclude that emission from the plane at these energies is likely to be dominated by the decay of neutral pions resulting from cosmic-ray interactions with passive target gas molecules.

Subject headings: cosmic rays — Galaxy: fundamental parameters — gamma rays: observations — ISM: clouds

1. INTRODUCTION

Diffuse gamma rays arriving from regions of enhanced density, such as giant molecular clouds, are powerful tracers of the interactions of cosmic rays with matter in the Galaxy. We expect diffuse emission from molecular cloud regions where the permeating flux of high-energy cosmic rays interacts with the nuclei of gas atoms (mostly hydrogen) to produce new hadronic particles, including neutral pions, that subsequently decay into gamma rays. In this manner, the gas in molecular clouds acts as a passive target, converting some fraction of impinging cosmic rays into gamma rays. Such diffuse emission has been recorded by several space-borne detectors, including the EGRET experiment aboard NASA's *Compton Gamma Ray Observatory* (*CGRO*) Indeed, the all-sky flux at 100 MeV is largely ($\sim$90%) diffuse emission from molecular clouds in the Galactic plane. Most of this emission is contained within a narrow band along the Galactic equator ($b < \pm 5°$), and is sharply concentrated toward the Galactic center. The EGRET results have been used, together with radio data, to develop a three-dimensional model of both the gas and cosmic-ray densities in the Galaxy (Bertsch et al. 1993; Hunter et al. 1997). This model, which estimates the contributions to diffuse emission from electron bremsstrahlung, nucleon-nucleon interactions, and inverse Compton (IC) processes, accurately matches the observed emission in detail as seen by EGRET for all Galactic longitudes over the energy range from 30 MeV to about 1 GeV. (The model deviates somewhat from observations at energies above 1 GeV, possibly due to a change in the cosmic-ray spectrum; see Mori 1997.) The EGRET results support a Galactic origin of cosmic rays, presumably as a result of shock acceleration in supernova remnants (SNRs).

Much less is known about the nature and distribution of cosmic rays at energies above 100 TeV (10^{14} eV). Past efforts have focused mostly on searches for point sources of gamma rays using large-area, ground-based air shower detectors. However, after many sensitive searches, no compelling evidence exists for the detection of even a single persistent gamma-ray point source at these energies (see, e.g., Alexandreas et al. 1993; Cronin, Gibbs, & Weekes 1993; Borione et al. 1997a; Borione et al. 1997b).

We can obtain a simple estimate of the expected ultra–high-energy diffuse flux from clouds in the Galaxy by disregarding gradients and approximating the cosmic-ray density and the matter density within any particular molecular cloud as uniform. In this case, the diffuse gamma-ray flux from this interaction can be expressed as

$$J_\gamma(>E) = \frac{1}{4\pi}\, q_\gamma(>E)\langle N_{\rm H}\rangle\ , \tag{1}$$

where $\langle N_{\rm H}\rangle$ is the total hydrogen column density in a given direction through the cloud and $q_\gamma(>E)$ is the source function for gamma-ray emissivity:

$$q_\gamma(>E) = 4\pi J_{\rm CR}(>E)\mathscr{F}(\sigma_{\rm inel}, \gamma, f_A)\ . \tag{2}$$

Here $J_{\rm CR}(>E)$ is the ambient integral flux of normal hadronic cosmic rays, and $\mathscr{F}$ is a function of the total inelastic cross section $\sigma_{\rm inel}$, the integral spectral index of cosmic rays γ, and a correction factor f_A that takes into account that some primaries and targets are nuclei and not protons. The function $\mathscr{F}$ varies slowly with energy, and is largely independent of the form of the cosmic-ray spectrum at ultra-high energies (see, e.g., Dermer 1986, Gaisser & Stanev 1991, Aharonian 1991, Berezinsky & Kudryavtsev 1990, for details concerning diffuse emissivity predictions).

Since the column density of hydrogen gas in molecular clouds is well established from radio observations, the

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uncertainty in estimating the flux of diffuse gamma rays is dominated by the uncertainty in the flux of hadronic cosmic rays within the cloud. We can reduce the effect of this uncertainty by considering the *ratio* of gamma-ray to cosmic-ray fluxes. In the case of a uniform flux of cosmic rays, this ratio will simply be proportional to the average column density. For example, using the value of $\mathscr{F}$ from Aharonian (1991), the expected diffuse emission is given as

$$\frac{J_\gamma}{J_{\rm CR}} \simeq 2 \times 10^{-5} \langle N_{\rm H} \rangle_{22} , \tag{3}$$

where $\langle N_{\rm H} \rangle_{22} \equiv \langle N_{\rm H} \rangle/(10^{22}\ {\rm cm}^{-2})$ is the average column density of gas in any direction. In the plane of the outer Galaxy visible by CASA-MIA ($40° \leq l \leq 200°$), $\langle N_{\rm H} \rangle_{22}$ varies between 0.8 and 1.2 for $|b| \leq 5°$ (e.g., Bloemen et al. 1984). In this case, the flux ratio, $J_\gamma/J_{\rm CR}$, depends only weakly on the exact form of the cosmic-ray spectrum, and is expected to be constant as a function of energy to within a factor of 2 over the range from 100 to 400 TeV. A realistic estimate of the emission, based upon a three-dimensional model of both Galactic gas and cosmic-ray densities, yields a similar result (Berezinsky et al. 1993). We note that if the ambient flux of cosmic rays within a particular cloud is stronger than the average flux measured at Earth (e.g., because the cloud is in close proximity to a source of cosmic rays), then we would expect the diffuse gamma-ray flux to be stronger than predicted.

2. OBSERVATIONS AND ANALYSIS METHOD

When ultra–high-energy cosmic rays and gamma rays strike the upper atmosphere of the Earth, they produce large cascades of electromagnetic and hadronic particles. For primary particle energies around 100 TeV, these particle cascades, called extensive air showers, reach the ground and can be detected readily by surface scintillation counters. At ground level, the showers consist largely of electrons, photons, and muons. A vertically incident 100 TeV proton primary produces a shower at ground level of roughly 30,000 electrons and 2000 muons. The shower consists of a thin "pancake" of relativistic particles, whose orientation preserves the direction of the incident primary particle. A sparse array of detectors, sampling a small fraction of the shower particles, can thereby determine the total number of particles in the shower and the arrival direction of the primary particle with reasonable precision. The combination of the CASA and the MIA comprises the largest and most sensitive such array built to date.

The CASA experiment consists of 1089 scintillation detectors laid out on a square grid of 15 m spacing. The experiment is located at Dugway, Utah (40°.2 N, 112°.8 W), at an atmospheric depth of 870 g cm^{-2}. The total collection area of CASA is roughly 230,000 m^2, of which 0.7% is actually covered by scintillator. The detectors have local analog and digital electronics to record the number of particles and the shower arrival time at each scintillator. The number of particles detected can be used to estimate the energy of the primary particle (cosmic ray or gamma ray). By comparing the observed shower rate to the known cosmic-ray flux, we find that the median energy of gamma rays creating showers detectable by CASA is approximately 120 TeV (Borione et al. 1997b).

At the Dugway site, beneath CASA, we have constructed a very large array of muon counters—the MIA. This array consists of 1024 scintillation counters buried three 3 m below ground level. The counters are grouped into 16 "patches" and have a total scintillator area of 2500 m^2. The amount of earth overburden above MIA results in a muon energy threshold of $\sim$0.8 GeV; electromagnetic punch-through is negligible for all but the very largest showers. A complete description of the CASA-MIA instrument can be found elsewhere (Borione et al. 1994).

In showers initiated by cosmic-ray nuclei, muons are produced from charged pion and kaon decays in the central hadronic core. Showers initiated by gamma rays do not produce muons in significant quantities because the cross section for γ-air hadron production is much smaller than the cross section for electron-positron pair production (γ-air $\rightarrow e^+e^-$). In other words, in contrast to cosmic-ray nuclei, gamma rays usually interact electromagnetically, and produce air showers with fewer charged mesons, and therefore fewer muons at ground level. On average, CASA-MIA detects approximately nine muons for each cosmic-ray air shower. In contrast, we expect to detect only 0.25 muons for each gamma-ray shower, on average.

To search for diffuse concentrations of cosmic gamma rays, we employ the technique developed by Matthews et al. (1991). The number of muons resulting from a gamma-ray–initiated shower should be, on average, much less (by a factor of 30–40) than the number of muons from a hadron-initiated shower of comparable energy. We therefore search for gamma-ray emission by looking for a localized excess of cosmic rays that are muon-poor with respect to the number of muons expected from typical hadron-initiated showers (Covault et al. 1991).

We parameterize the muon content of each shower by the quantity

$$r_\mu \equiv \log_{10}\left(\frac{n_{\mu_{\rm obs}}}{n_{\mu_{\rm exp}}}\right) , \tag{4}$$

where $n_{\mu_{\rm obs}}$ and $n_{\mu_{\rm exp}}$ represent the numbers of muons actually observed and the number of muons *expected* for hadronic showers. We determine the expected number of muons on a shower-by-shower basis by parameterizing the lateral density of muons in terms of the function $\rho_\mu(R, N_e, \theta_z)$ described by Greisen (1960), where R is the distance to the shower core, N_e is the electron shower size, and θ_z is the zenith angle of the incident shower. Showers with zero observed muons are assigned a large negative value for $r_\mu = -4$, which is less than the value of r_μ obtained for any shower that has at least one observed muon.

Having parameterized the muon content in this manner, we consider the expected distribution of r_μ for both hadronic and gamma-ray primaries. For hadrons, we expect that the distribution of r_μ is characterized by the actual array data, since the vast majority of air showers (at least 99.9%) are known to be hadronic. For gamma rays, we must invoke Monte Carlo simulations to determine the expected distribution of r_μ. The distribution for gamma rays will be shifted significantly toward lower values of r_μ and will include a much larger fraction of events with zero muons detected. The r_μ distributions for both hadronic and simulated gamma-ray air showers are shown in Figure 1.

We define as *muon-poor* those events that have a value of r_μ less than a value chosen to optimize sensitivity to gamma rays. This sensitivity scales as $h_\gamma/h_{\rm CR}^{1/2}$, where h_γ and $h_{\rm CR}$ represent the fraction of gamma rays and cosmic rays

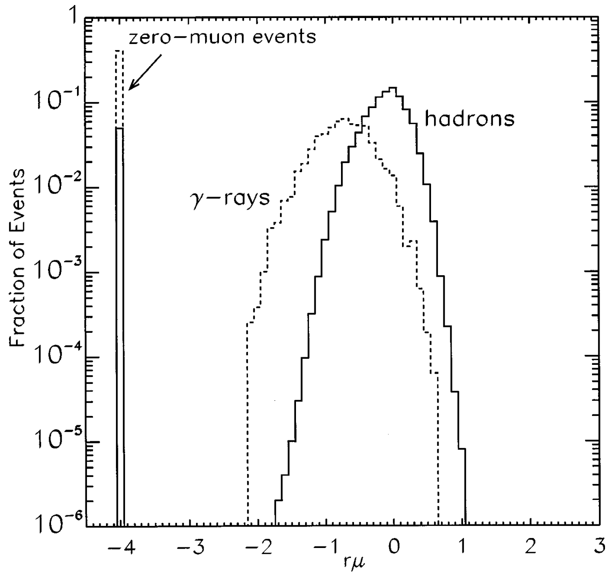

FIG. 1.—r_μ distribution of simulated gamma ray (*dashed lines*) vs. detected hadronic (*solid lines*) cosmic rays.

retained in the muon-poor sample, respectively. The optimal value of r_μ depends weakly on the source declination and the energy of the selected events (Borione et al. 1997a).

To determine whether there is evidence for gamma-ray emission from a localized candidate source region of the sky, we examine the distribution of r_μ for showers within this region and search for an excess of muon-poor events. The excess is determined relative to a comparison region that presumably contains a background of uniform hadronic showers. To compare the r_μ distributions from source and background regions, we normalize the background so as to match the total number of events with $r_\mu > 0.0$, assuming that all such events are purely hadronic. We note that this technique has no sensitivity whatsoever to the presence of any isotropic flux of gamma rays that may be present in our data.

The distribution of events in the sky is nonuniform, since the acceptance of the array is strongly peaked toward the zenith direction. The exposure map of the CASA-MIA data set in Galactic coordinates is shown in Figure 2. To the extent that our parameterization of the muon lateral distribution applies generally to all showers, we expect that the distribution of r_μ should remain identical for all hadronic showers at a fixed overburden throughout the atmosphere. However, since the overburden changes rapidly with zenith angle to the shower, we expect that the shape of the r_μ distribution will depend upon the zenith angle. If uncompensated, these systematic changes in the shape of the r_μ distribution can have a significant impact upon our estimate of muon-poor showers.

We have developed a technique for characterizing and removing the systematics in the r_μ distribution. We divide the entire data sample into a series of coarse bins in time (about one bin per day) and horizon coordinates (8–10 bins each in elevation and azimuth). For each source event, we generate comparison background events by sampling a value of r_μ from the distribution corresponding to the appropriate horizon coordinate bin. Thus, systematic changes to the shape of the r_μ distribution that are local to the events in each sky bin will appear in both source and background distributions. This technique removes most systematic effects, provided that the bin size is chosen so that the r_μ distribution obtained from the data represents a good approximation of the r_μ distribution for the entire bin (Covault et al. 1994).

Figure 3 graphically demonstrates the application of this technique to real data. The r_μ distribution for candidate

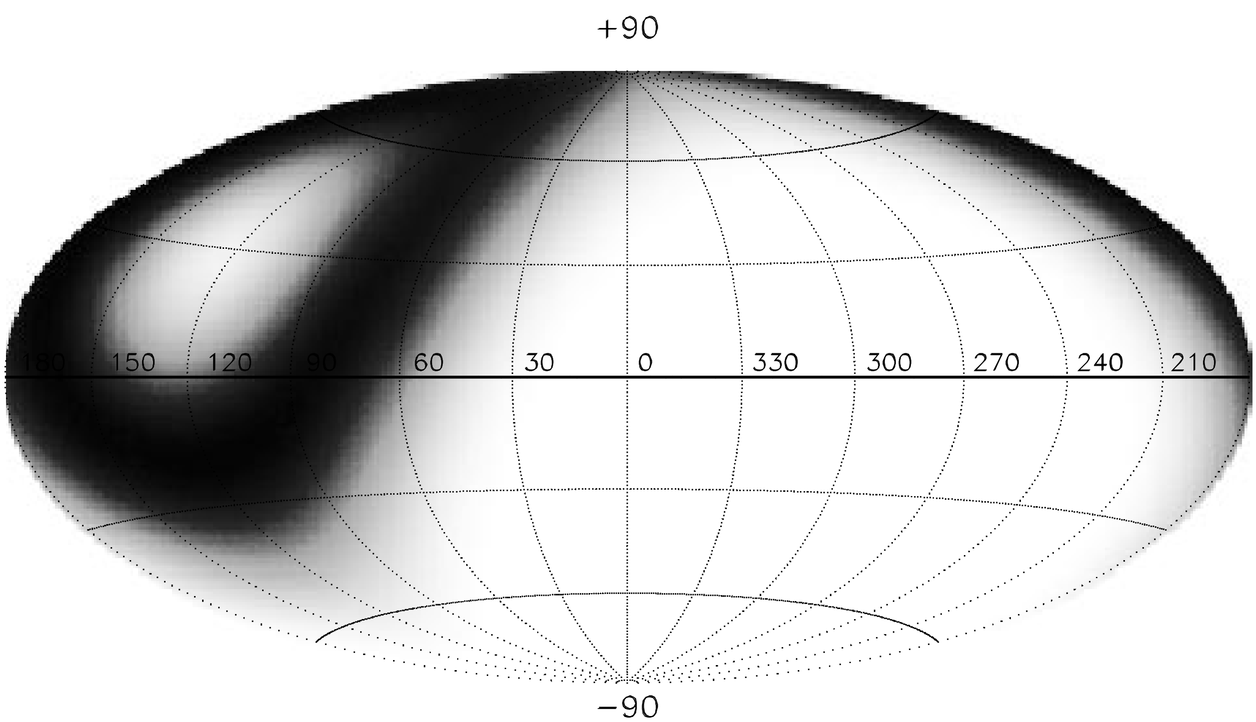

FIG. 2.—CASA-MIA exposure map in Galactic coordinates. Dark regions are visible to CASA-MIA.

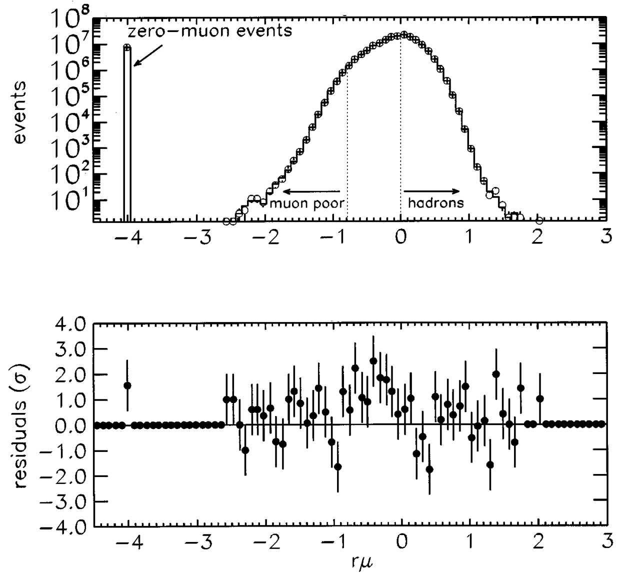

FIG. 3.—Muon content (r_μ distribution) for all CASA-MIA air-shower events arriving from the direction of the Galactic plane ($|b| < \pm 5°$) are shown in the top panel. Points with error bars represent the on-source distribution, while histogram lines represent the off-source distribution. The bottom panel indicates the on-source minus off-source residuals (sigmas per bin). Evidence for the presence of ultra–high-energy gamma rays would be indicated by an excess of muon-poor events. A statistically insignificant excess (1.63 σ) is seen.

diffuse source events within the Galactic plane ($\pm 5°$) is plotted against the r_μ distribution for the off-source background region. Analysis of residuals shows no major differences between the source and background distributions, and gives us confidence that the systematics have largely been removed. We attribute the excess in the χ^2 ($\chi^2_\nu = 1.25$, $\nu = 51$ dof) to either an unremoved systematic effect or the marginal presence of a possible signal. If there were a detectable flux of gamma rays from this region of the Galactic plane, Figure 3 would have shown an excess of signal events over background on the left-hand side of the plot. Indeed, there is an excess (1.63 standard deviations in the plot shown) that, while consistent with the expected flux, is not significant enough to claim as a detection.

3. RESULTS

We apply this analysis technique to search for evidence of gamma rays from the Galactic plane region in the energy range from 140 to 1300 TeV. No significant evidence for diffuse emission is found. Upper limits to diffuse flux from the plane of the Galaxy are calculated, taking into account the slight loss in sensitivity ($<10\%$) due to the finite angular resolution of CASA ($\sim 1°$). In Table 1, we present 90% confidence level upper limits on the flux for emission for a range of emission disk thicknesses ($|b| < 2°$, 5°, and 10°) for comparison to previous predictions and experiments. (Aglietta et al. 1992 have claimed that the band $|b| < 2°$ best matches the expected ultra–high-energy emission, based on *COS-B* results, while we believe that the EGRET results demonstrate that $|b| < 5°$ is the most appropriate search region.) The CASA-MIA flux limits are plotted in Figure 4. Also shown are upper limits from previous experiments and a theoretical prediction for the expected flux. We note that cosmic-ray rejection improves rapidly with energy, thus compensating for reduced statistics, so that the

TABLE 1

LIMITS TO DIFFUSE EMISSION

Region ($50° < l < 200°$)	Median Energy (TeV)	Significance (σ)	J_γ/J_{CR} 90% C.L. (10^{-5})
$-2° < b < 2°$	140	+1.78	7.2
	180	+1.81	3.8
	310	+2.56	5.2
	650	+1.12	3.2
	1300	+0.07	4.6
$-5° < b < 5°$	140	+1.63	3.4
	180	+0.08	2.6
	310	+0.86	2.4
	650	+1.60	2.6
	1300	+0.06	3.5
$-10° < b < 10°$......	140	+2.39	2.8
	180	+1.79	2.2
	310	+0.87	2.3
	650	+0.91	1.8
	1300	−0.56	2.3

NOTE.—Tabulated upper limits to diffuse gamma-ray emission from the plane of the Galaxy. Although positive excesses are seen, we do not view these as statistically significant enough to claim detections. Flux limits are tabulated for bands along the Galactic plane from $|b| < 2°$ to $|b| < 10°$. Median energy is quoted for integral flux limits. Selected spatial regions and energy bands are not statistically independent.

sensitivity of CASA-MIA to diffuse emission is relatively constant in the region from 200 to 1000 TeV.

4. DISCUSSION

The observed weak excess of muon-poor events in several of the selected spatial and energy ranges could be taken as evidence for the presence of diffuse emission from the Galactic plane. Indeed, if the excess is interpreted as a positive gamma-ray signal, the inferred flux is consistent with current model predictions. However, in view of the uncertainty in assessing the impact of any remaining systematics,

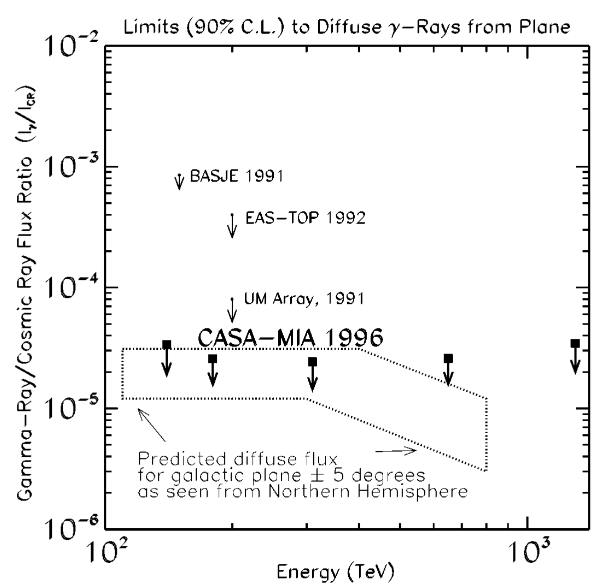

FIG. 4.—CASA-MIA sensitivity to diffuse gamma-ray emission from the central plane of the Galaxy ($|b| < \pm 5°$, $50° < l < 200°$). Sensitivities are given in terms of the fraction of gamma rays relative to the detected all-particle flux of cosmic rays at the Earth. Also shown are limits from previous experiments (BASJE—Kakimoto et al. 1991; EAS-TOP—Aglietta et al. 1992, UM—Matthews et al. 1991). Predicted flux from Aharonian (1991).

we interpret the observed excesses as not statistically significant enough to warrant a claim for detection, and we use our results to place upper limits on the predicted emission. We note that future prospects for increased sensitivity to verify or refute the presence of a possible signal at this level are not good, since this would require a much larger experiment and/or a much longer running time, neither of which is foreseen.

The CASA-MIA flux limits place strong constraints on models for diffuse emission. These limits are below the predictions of some earlier models (e.g., Berezinsky & Kudryavtsev 1990) and are approximately a factor of 2 above the minimum emission predicted by more recent models (e.g., Aharonian 1991; Berezinsky et al. 1993). These predictions are based only upon diffuse emission due to the process of normal cosmic-ray nucleon-nucleon interactions on passive gas targets. Therefore, we conclude that no other emission process is likely to dominate at ultra-high energies. Some models for cosmic-ray acceleration suggest that gamma rays from clouds in proximity to supernova remnants may be enhanced and/or spectrally hardened (e.g., Aharonian & Atoyan 1996). Others have suggested that IC scattering may be a significant component of Galactic diffuse emission at ultra-high energies (e.g., Aharonian 1995). The predictions for IC emission are very uncertain at these energies. While the CASA-MIA results allow for a significant component of diffuse emission due to IC, they suggest that IC is not the dominant component. A report by Bloemen (1991), based upon an analysis of the *COS-B* data, suggests evidence for a spectral hardening at energies above 1 GeV ($\Delta_\gamma = 0.4$) for the outer Galaxy; however, this result has not been confirmed by EGRET (Hunter et al. 1997). The CASA-MIA upper limits rule out any such spectral hardening above 200 TeV in the outer Galaxy with $\Delta_\gamma > 0.1$.

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