Search for Diffuse Gamma Rays from the Galactic Plane in Multi-TeV Region with the Tibet Air Shower Array

The Tibet ASγ Collaboration
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Abstract

Diffuse gamma rays from the Galactic plane were searched combining the Tibet II data with energies more than 4 TeV and III data obtained during 1999-2002 with energies more than 1.5 TeV. The Tibet III increased available data by a factor ~1.8 than the Tibet II only. The sky regions searched are the inner Galaxy, $20^\circ < l < 55^\circ$, and outer Galaxy, $140^\circ < l < 225^\circ$ with the plane thickness $|b| \leq 2^\circ$, and the Cygnus region, $67^\circ < l < 92^\circ$ with $|b| \leq 5^\circ$. Although no significant excess was observed, the intensity upper limits are given with 99% confidence level at mode energies 3~20 TeV, assuming a differential spectral index of -2.4. The present results give the most stringent upper limits on the inverse Compton model with a source electron spectral index of -2.0.

1. Introduction

EGRET observations (Hunter et al. 1997) gave a detailed intensity distribution of high-energy gamma rays coming from the Galactic plane. The gamma-ray intensity above 1 GeV from the inner Galaxy is higher than the COS B data by a factor of about 3. It is also higher than the conventional model predictions (e.g., Bertsch et al. 1993) by a factor of 1.7, assuming the proton's inverse power law index of α=2.75. Mori

pp. 1–4

(1997) showed that the EGRET excess can be interpreted by adopting a harder proton index of α=2.45 within a plane thickness of $|b| \leq 10°$. Webber (1999) also showed that the excess in $|b| \leq 5°$ can be reproduced by α=2.25.

Porter & Protheroe (1997) indicated that in such a high-energy region, cosmic-ray electrons may create a significant part of the diffuse gamma rays. Pohl & Esposito (1998) argued that if the injection electron's inverse power index of β=2.0 is employed, the EGRET excess above 1 GeV can be well explained by the inverse Compton (IC) scattering. At the TeV-PeV region, the diffuse gamma rays was calculated by Berezinsky et al. (1993) in terms of cosmic-ray interaction with the interstellar matter (ISM).

In the previous paper (Amenomori et al. 2002) we analyzed the Tibet II data at 10 TeV and the Tibet III data at 3 TeV. In the present paper we analyze the increased Tibet III data at 3 TeV and the combined Tibet II and III data at 10 TeV and 20 TeV.

2. Experiment and data analysis

The Tibet II array with 221 scintillation counters of 0.5 m^2 each, was constructed at Yangbajing in 1994, keeping the same lattice interval of 15 m as the Tibet I. The performance of the Tibet II is almost same as the Tibet I (Amenomori et al. 1992, 1993). The mode energy is 10 TeV for air showers with $\Sigma\rho_{\rm FT} \geq 15$ m^{-2}, where $\Sigma\rho_{\rm FT}/2$ is the sum of the detected number of particles. The angular resolution is about 0.9° at 10 TeV, calibrated by the Moon shadow (Amenomori et al. 1993, 1996). The Tibet III array, enlarged in 1999, consists of 533 counters with a 7.5 m lattice interval. The additional detectors are excluded in the analysis at 10 and 20 TeV so as to keep a same performance as the Tibet II, although all of them are used for the analysis at 3 TeV.

Figure 1 shows an exposure map in the galactic coordinates for air showers obtained with the Tibet III array with zenith angles $\theta \leq 50°$. The shower event density increases from light gray to dark gray. Shower events are used in the sky regions of $20° < l < 55°$ for the inner Galaxy (IG) and of $140° < l < 225°$ for the outer Galaxy (OG), in $|b| \leq 2°$, and of $67° < l < 92°$ for the Cygnus (Cyg) region with $|b| \leq 5°$.

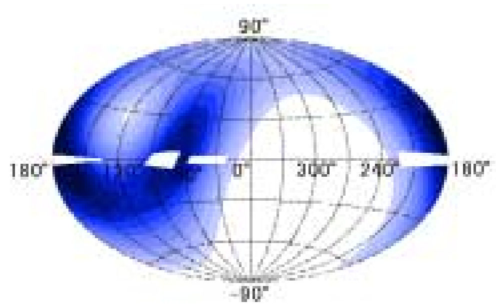

Fig. 1. Exposure map for the Tibet III

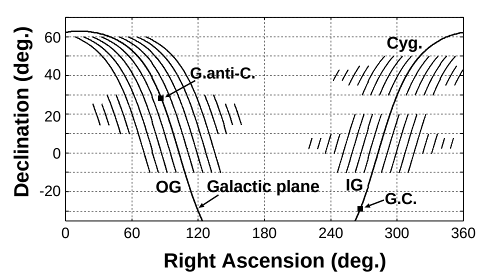

Fig. 2. Binning of the warped belts

The experimental data are analyzed in the basically same method as the previous paper (Amenomori et al. 2002), except for binning width of warped belts in the right ascension. In the present case, air shower events are assigned to the sky regions from which they arrived, of 4.5° (5.625°) bin 80 (64) belts along the Galactic plane of the IG (OG) in the equatorial coordinates, and 16° bin 20 belts for Cyg, as shown in Fig. 2.

This figure shows 8° bin warped belts, for example, for IG (OG) with the declination range of $-10° \leq \delta \leq 20°$ ($-10° \leq \delta \leq 60°$), and for Cyg with $30° \leq \delta \leq 50°$. These declination ranges of the on-plane belts in the equatorial coordinates correspond to parts of convex lens shape zones, shown in Fig. 1, with an average thickness of 4° for IG (OG), and 10° for Cyg in the galactic coordinates.

We make the distribution of the number of events in 4.5° (5.625°) bin warped belts for IG (OG) and 16° bin belts for Cyg, respectively. The background curves are fitted to the experimental data, ignoring the on-plane belt and some belts besides it. An excess of the on-plane data over the fitted curve is measured by a standard deviation of the number of showers by the formula $(E - B)/\sqrt{B}$, in two 2.25° (IG), three 1.875° (OG) and eight 2° (Cyg) bin belts, where E is the number of on-plane events and B is the estimated number of background events in the on-plane region, which is obtained by fitting of many off-plane belts, ignoring the above described several central belts.

The deviation distributions of the number of off-plane events from the fitted background curves are represented by best-fit Gaussians with standard deviations of almost equal to unity for IG, OG and Cyg, respectively. So the background curves are excellently fitted to the experimental data. Thus, we can accurately estimate the number of on-plane background events.

3. Results

The significance of an on-plane excess is given in Table 1. No significant excess is found. We calculate the gamma-ray flux ratio, $J_\gamma/J_{\rm CR}$, for 99% CL upper limits, to the galactic cosmic rays at energies of 3, 10 and 20 TeV. The differential intensity multiplied by E^2 with these upper limits are also given for IG, OG and Cyg, assuming gamma-ray spectral index of -2.4. Thus, we can calculate the intensity upper limits in 99% CL at respective mode energies for IG, OG and Cyg, using the all-particle cosmic-ray energy spectrum compiled by Apanasenko et al. (2001).

Figure 3 shows the present 99% CL upper limits, (a) for IG and Cyg (labeled by C) and (b) for OG, at mode energies of 3 TeV (fat T3), 10 and 20 TeV (T2+3), together with our previous data (Amenomori et al. 2002) at 3 TeV (thin T3) and 10 TeV (T2). Also are shown the EGRET data (Hunter et al. 1997) and Cherenkov upper

Table 1

IG (OG) or Cygnus Region (Regions of l)	Region of b	Mode Energy (TeV)	Significance (σ)	$1/\sqrt{B}$ at 1σ (10^{-4})	$\frac{J_\gamma(>E)}{J_{\rm CR}(>E)}$ 99% CL (10^{-4})	$E^2\frac{dJ_\gamma(>E)}{dE}$ (*) 99% CL (10^{-3})
I G	$\lvert b\rvert \leq 2°$	3	+2.27	1.52	7.01	7.2
($20° < l < 55°$)	$\lvert b\rvert \leq 2°$	10	+1.24	1.74	6.27	2.6
	$\lvert b\rvert \leq 2°$	20	+1.68	2.86	11.5	2.8
O G	$\lvert b\rvert \leq 2°$	3	-0.88	0.82	1.65	1.7
($140° < l < 225°$)	$\lvert b\rvert \leq 2°$	10	+1.15	0.94	3.32	1.4
	$\lvert b\rvert \leq 2°$	20	+0.41	1.54	4.44	10.7
Cyg	$\lvert b\rvert \leq 5°$	10	-0.76	0.95	1.96	0.81
($67° < l < 92°$)	$\lvert b\rvert \leq 5°$	20	+1.55	1.59	6.19	1.5

(*): in unit of $\rm cm^{-2}s^{-1}sr^{-1}MeV$

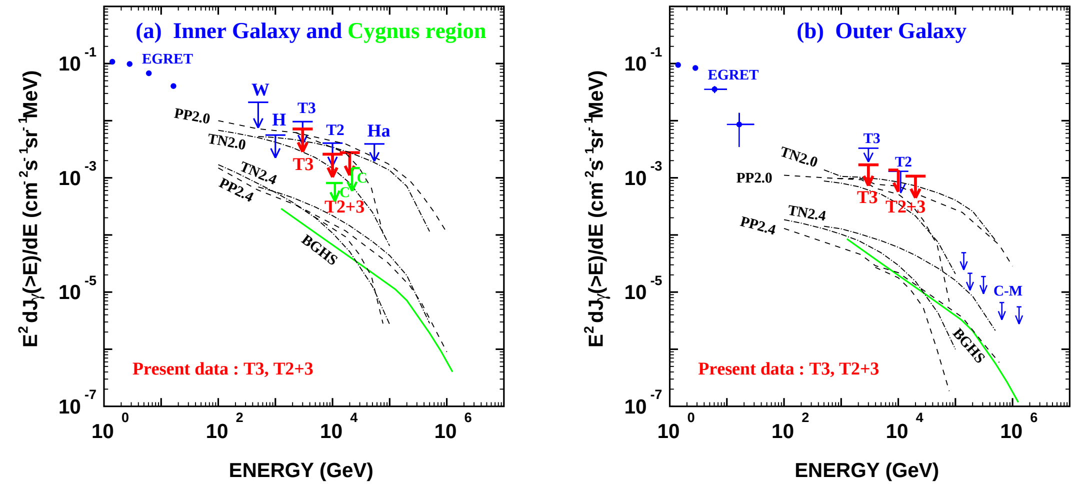

Fig. 3. Diffuse gamma rays from the Galactic planes (a) IG and Cyg, and (b) OG

limits of Whipple (W) 99.9% CL (LeBohec et al. 2000), HEGRA (H) 99% CL (Aharonian et al. 2001) and HEGRA-AIROBICC (Ha) 90% CL (Aharonian et al. 2002) and air shower results of CASA-MIA (C-M) 90% CL (Borione et al. 1998). The theoretical curves are drawn for $\pi^\circ \rightarrow 2\gamma$ by Berezinsky et al. (1993) (BGHS), and for the inverse Compton gamma rays by Porter & Protheroe (1997) (PP2.0, PP2.4) and Tateyama & Nishimura (2001) (TN2.0, TN2.4), where β=2.0 and 2.4 indicate the source electron spectral indices. The present results for IG at 10 TeV give the most stringent upper limits for the IC model with a source electron spectral index of β=2.0, at least for the model without energy-cutoff.

This work is supported in part by Grants-in-Aid for Scientific Research and also for International Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology in Japan and from the Committee of the Natural Science Foundation and the Academy of Sciences in China.

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