Search for multi-TeV gamma-rays from nearby SNRs with the Tibet air shower array

The Tibet ASγ Collaboration

M. Amenomori[1], S. Ayabe[2], S.W. Cui[3], L.K. Ding[3], X.Y. Ding[4], C.F. Feng[5], Z.Y. Feng[6], Y. Fu[5], X.Y. Gao[7], Q.X. Geng[7], H.W. Guo[4], M. He[5], K. Hibino[8], N. Hotta[9], J. Huang[9], Q. Huang[6], A.X. Huo[3], K. Izu[10], H.Y. Jia[6], F. Kajino[11], K. Kasahara[12], Y. Katayose[13], K. Kawata[11], Labaciren[4], G.M. Le[14], J.Y. Li[5], H. Lu[3], S.L. Lu[3], G.X. Luo[3], X.R. Meng[4], K. Mizutani[2], J. Mu[7], H. Nanjo[1], M. Nishizawa[15], M. Ohnishi[10], I. Ohta[9], T. Ouchi[10], S. Ozawa[9], J.R. Ren[3], T. Saito[16], M. Sakata[11], T. Sasaki[8], M. Shibata[13], A. Shiomi[10], T. Shirai[8], H. Sugimoto[17], K. Taira[17], M. Takita[10], Y.H. Tan[3], N. Tateyama[8], S. Torii[8], H. Tsuchiya[10], S. Udo[2], T. Utsugi[2], C.R. Wang[5], H. Wang[3], X. Wang[5], X.W. Xu[3,10], L. Xue[5], X.C. Yang[7], Y. Yamamoto[11], Z.H. Ye[14], G.C. Yu[6], A.F. Yuan[4], T. Yuda[18], H.M. Zhang[3], J.L. Zhang[3], N.J. Zhang[5], X.Y. Zhang[5], Zhaxiciren[4], and Zhaxisangzhu[4]

[1]Department of Physics, Hirosaki University, Hirosaki, Japan
[2]Department of Physics, Saitama University, Saitama, Japan
[3]Laboratory of Cosmic Ray and High Energy Astrophysics, Institute of High Energy Physics, CAS, Beijing, China
[4]Department of Mathematics and Physics, Tibet University, Lhasa, China
[5]Department of Physics, Shangdong University, Jinan, China
[6]Institute of Modern Physics, South West Jiaotong University, Chengdu, China
[7]Department of Physics, Yunnan University, Kunming, China
[8]Faculty of Engineering, Kanagawa University, Yokohama, Japan
[9]Faculty of Education, Utsunomiya University, Utsunomiya, Japan
[10]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Japan
[11]Department of Physics, Konan University, Kobe, Japan
[12]Faculty of Systems Engineering, Shibaura Institute of Technology, Saitama, Japan
[13]Department of Physics, Yokohama National University, Yokohama, Japan
[14]Center of Space Science and Application Research, CAS, Beijing, China
[15]National Institute for Informatics, Tokyo, Japan
[16]Tokyo Metropolitan College of Aeronautical Engineering, Tokyo, Japan
[17]Shonan Institute of Technology, Fujisawa, Japan
[18]Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya Japan

Abstract. It has been generally believed that galactic cosmic rays with the energy of less than at least 100 TeV are accelerated in shell-type supernova remnants (SNRs). If SNRs are the site of cosmic-ray acceleration, the associated nuclear interactions should result in a detectable flux of gamma-rays for nearby SNRs. The Tibet air-shower array has been much improved because the detectors have increased in number by sixty percent in 1999. A search for continuous multi-TeV gamma-ray emission from nearby sixteen shell-type SNRs has been performed with the improved air-shower array (the Tibet III array). These SNRs are located within 5 kpc distance in the declination band of 0° to +60°. No significant emission has been detected and flux upper limits are set for each of these SNRs. The results piled up the data of six nearby SNRs located within 2 kpc distance impose restrictions on the model of shock acceleration of cosmic rays.

Correspondence to: T.Utsugi(toshi@cr.phy.saitama−u.ac.jp)

1 Introduction

It has been generally believed that cosmic rays with the energy less than at least 100 TeV are accelerated mainly in shell-type supernova remnants (SNRs). If the kinetic energy of the SNR explosions is converted efficiently to the cosmic-ray energy, the SNRs would be able to supply with the total energy density of galactic cosmic rays. If SNRs are the site of cosmic-ray acceleration, then they should produce high energy gamma-rays induced by neutral pions as the cosmic rays interact with ambient matter in the vicinity of supernova shells. The expected gamma-ray flux has been calculated from pion production through hadronic interaction using a model of diffusive shock acceleration [1-4]. For a nearby SNR at a distance of less than 2 kpc, the expected gamma-ray luminosity should be detectable with ground-based imaging Čerenkov telescopes and air-shower arrays in the sub-TeV and supra-TeV regions. Many measurements therefore have been made with ground-based detectors so far [5,6]. The Tibet air-shower array at Yangbajing in Tibet has been much improved in 1999 because the detectors have increased in number by sixty percent. Highly unambiguous observations of multi-TeV gamma-rays has been realized by using this improved air-shower array (the Tibet III array). In the present paper are reported the results performed with the Tibet III array on a search for continuous multi-TeV gamma-ray emission from nearby sixteen shell-type SNRs, which are located within 5 kpc distance in the declination band of 0° to +60° and are younger than 10^4 years.

2 Experiment

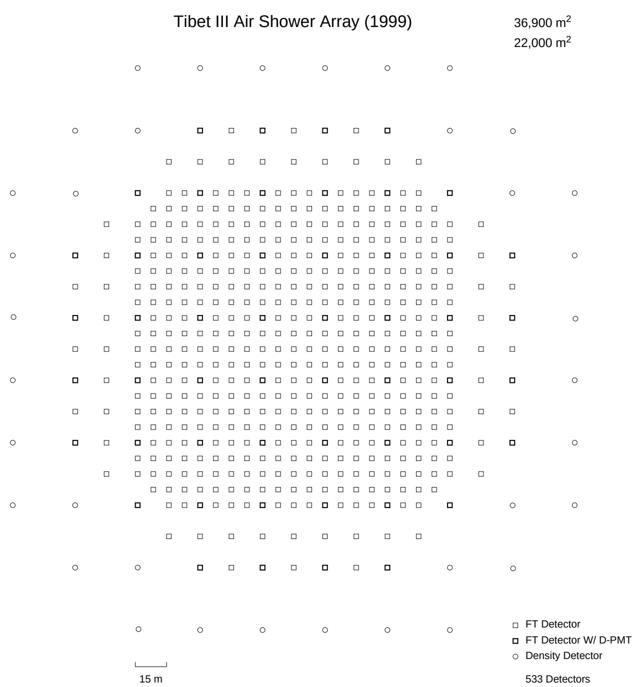


Fig. 1: Schematical view of the Tibet III array.

The Tibet air-shower array is located at Yangbajing (4,300m a.s.l., 606 g/cm^2,90.522°E, 30.112°N) in Tibet, China. The Tibet III array consists of 533 scintillation detectors of 0.5 m^2, in which 497 detectors are placed on a (7.5 m)^2 grid and 36 detectors on a (15 m)^2 grid in the total covering area of 36,900 m^2. The Tibet III array allows us to detect small air showers with the energy around 2 TeV. The shower energy determined is confirmed by observing the shift of the moon's shadow due to the geomagnetic field. The air-shower data were recorded at a triggering rate of about 680 Hz in average. The dead time of the system is estimated to be about 10 % of the total running time.

3 Analysis

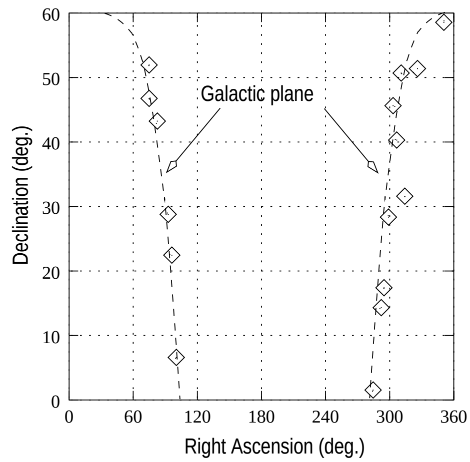


Fig. 2: Distribution of sixteen SNRs.

The analysis has been made by using the data set taken during the period from November 1999 through May 2001. The effective running time is about 273.78 days. The event selection was performed by imposing the following conditions to the recorded data: 1) Each of any four detectors out of every detectors should detect signal more than 1.25 particles; 2) the sum of the number of particles per m^2 detected in each detector $\Sigma\rho_{\rm FT}$ should be greater than 10; 3) at least two detectors of highest four signals should be in the inside of the innermost 19 $\times$ 19 detectors; and 4) the zenith angle θ of incident direction should be less than 40°. The air-shower events detected are mainly initiated by cosmic ray protons and nuclei rather than gamma-ray. Those background cosmic rays are isotropic, while the gamma-rays from each source are apparently centered on the source direction. The reduction of background is accomplished owing to the good angular resolution. The performance of the Tibet III array, such as the angular resolution and the energy determination, was confirmed by also observing the moon's shadow [7].

4 Results and Discussion

Search for continuous emission has been made for sixteen shell-type SNRs located within 5 kpc distance in the declination band of 0° to +60° and aged less than 10^4 years in referring to the Green's Catalog [8]. There is no on-source window overlapping with each other. Some of SNRs have the source region spread widely. For such spread SNRs the center of each on-source window is set at the maximum position of a X-ray emission and/or a radio emission. An equi-zenithal scan method has been used to search. The number of air-shower events coming from the on-source window is counted there. The background number of events is obtained by averaging over the events falling into eight off-source windows adjacent to the on-source one on both the east and west sides at the same zenith angle. A circular window is set with the radius of

$$0.5^\circ \times 13.67 \times \left[10^{1.44(\sec\theta-1)} \times \Sigma\rho_{\rm FT}\right]^{-0.514}$$

by considering to the angular resolution. The simulation used the COSMOS [9] and the Epics [10] codes. According to this Monte Carlo simulation with a differential power-law spectrum proportional to $E^{-2.1}$, the events with the $\Sigma\ \rho_{\rm FT} \geq 10$ and $\Sigma\ \rho_{\rm FT} \geq 100$ correspond to the showers with the energy of around 3 TeV and 10 TeV, respectively. In the table are given the statistical significance and the flux upper limit at the 90% confidence level in the energy larger than 3 TeV and 10 TeV for each SNR. No excellent excess exceeding 5 σ level has been found for steady emission of 3 TeV gamma-rays from any object of these SNRs.

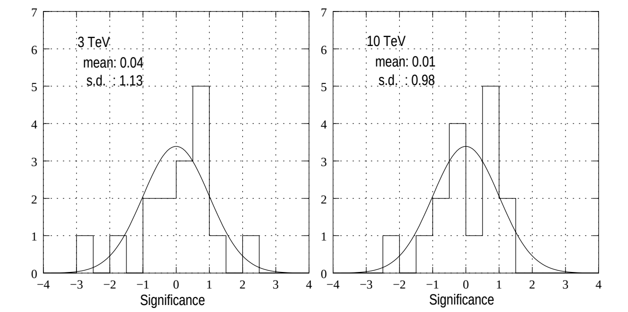
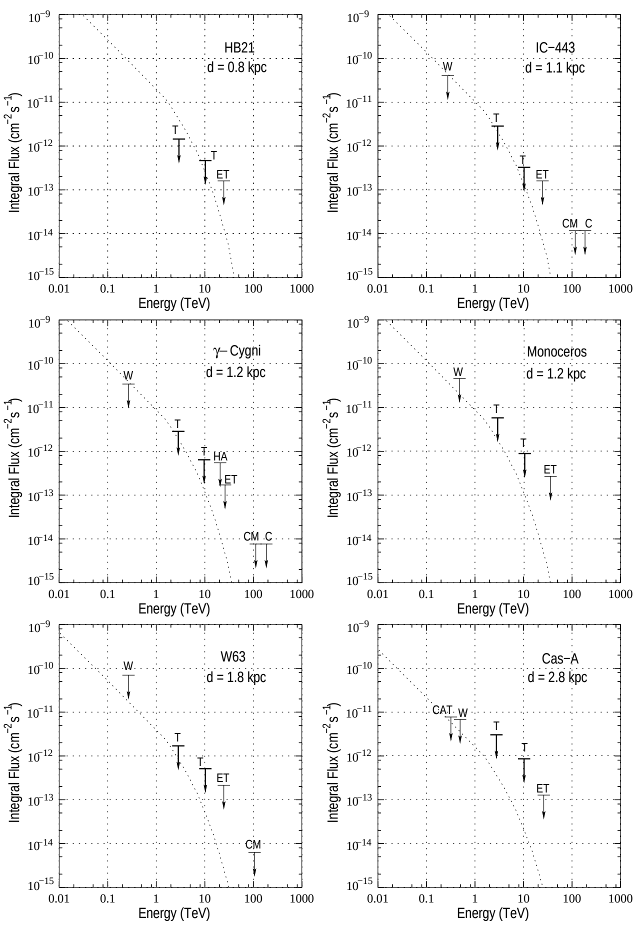


Fig. 3: Distribution of Significance.



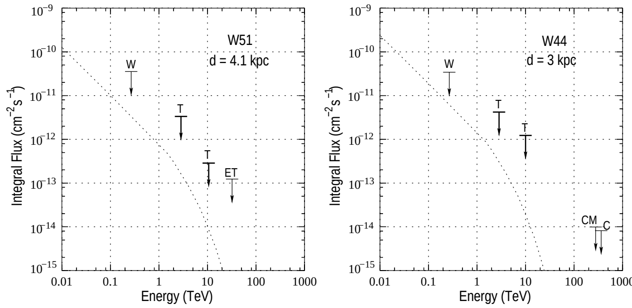


Fig. 4: Comparison with other results [1].

According to the model prediction of shock acceleration in typical SNRs [1-4], the intensity of gamma-rays is expected to be a flux level of 10^{-12} cm^{-2} s^{-1} in the energy region greater than 3 TeV from a SNRs of 1 kpc distant. The observation with the Tibet III array seems to reach such level. The Whipple group reported the upper limit on the flux of gamma-rays of about 300 GeV given from the observations with an atmospheric Čerenkov telescope. The present results on the flux upper limit for each source reach to the same level as the Whipple's one. However the present results are slightly higher than the values expected by a simple model of shock acceleration. The observation may reach to such level, if the data of some SNRs are piled up. The data of seven nearby SNRs located within 2 kpc distance are piled up and compared with a model calculation [4]. In figure 5, the observed flux upper limit at the 90 % confidence level are normalized to the one of a SNR of 1 kpc distant. The present results on the upper limits lie much below the corresponding expected values. The present results strongly constrain model predictions of shock acceleration of cosmic rays in shell-type SNRs.

[1]T: Present Result, W: Whipple [11,12], HA: HEGRA-AIROBIC [13], C: Cygnus [14], CM: CASA-MIA [15], ET: EAS-TOP [16], CAT: CAT [17]

name	R.A.	Decl.	Distance	3TeV		10 TeV	
			(kpc)	σ	Flux upper-limit	σ	Flux upper-limit
Cygnus Loop	311.517	30.684	0.44	-1.64	1.18	-2.22	0.17
G65.1+0.6	298.633	28.549	0.8	0.11	2.27	0.86	0.50
HB21	311.261	50.599	0.8	-0.19	1.37	0.02	0.53
IC443	94.256	22.581	1.1	0.22	2.80	-0.31	0.35
Monoceros	99.672	6.455	1.2	2.04	5.34	0.87	0.94
γCygni	305.197	40.410	1.2	0.66	2.70	1.48	0.64
W63	304.804	45.525	1.8	-0.53	1.73	0.83	0.55
3C400.2	294.688	17.248	2.1	0.60	2.88	-0.21	0.42
CTB 104A	321.168	50.976	2.3	-2.86	8.61	-0.44	0.40
Cassiopeia A	350.858	58.808	2.8	0.22	2.98	0.51	0.98
G156.2+5.7	73.214	52.074	3.0	-0.66	1.69	-0.20	0.44
G182.4+4.3	92.045	28.992	3.0	0.75	2.67	-0.90	0.28
W44	284.010	1.366	3.0	0.67	4.12	0.72	0.13
HB9	75.175	46.673	4.0	-0.25	1.87	-0.61	0.32
W51	290.951	14.098	4.1	1.13	3.54	-1.26	0.30
VRO 42.05.01	81.646	42.909	4.5	0.09	2.16	1.04	0.58

Table 1. The results for sixteen shell-type SNRs. Flux limits at 90 % confidence level in the unit of 10^{12} cm^{-2} s^{-1}

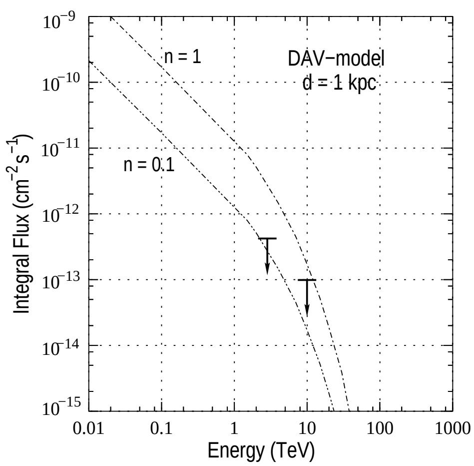


Fig. 5: Constraint on the gamma-ray flux from a SNR at 1 kpc distance. The curves are expected by assuming the ambient matter density of 1 cm^{-3} and 0.1 cm^{-3} [4].

	Σ N$_{\rm on}$	Σ N$_{\rm off}$	σ	Flux Upper limit (cm^{-2} s^{-1})
3 TeV	3565506	3566302	-0.42	$< 4.59 \times 10^{-13}$
10 TeV	166196	165941	0.62	$< 1.00 \times 10^{-13}$

Table 2: The flux upper-limit of piled up the data nearby seven SNRs located within 2 kpc.

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