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A Northern Sky Survey for TeV gamma-ray steady point sources using the Tibet-III air shower array

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Abstract: The Tibet III air shower array, located at 4,300 m above sea level, Tibet, China, has a wide field of view and a high duty cycle. Results on TeV gamma-ray point source search using data taken from the Tibet-III (1999 November - 2010 May) array are presented. The event statistics employed in this analysis is approximately four times more than that used in our previously published results. The result shows the directions of the Crab and Mrk421 have excess of the number of the air shower events. The shape of the significance distributions from all surveyed directions is influcenced not only by the excess of the gamma-ray events from Crab and Mrk421 but also by the excess of air shower events from the Cygnus region and the Tail-in region. In the previous survey paper, the high significance value of each prominent directions except for the Crab, Mrk 421, Tail-in region and J1908+06 can be explained by the statistical fluctuations.

Keywords: Tibet, TeV gamma rays, Survey.

1 Introduction

The all-sky survey remains one of the major concerns for ground-based observatories. Extensive Air Shower experiments, such as the Tibet air shower array experiment, have observed gamma-ray emissions from standard candle Crab nebula and from transient sources such as Mrk501 and Mrk421 [1, 2, 3]. Their characteristic abilities in high duty cycle and large field of view allow them to simultaneously monitor a larger area in space over continuous time. In 2004, Milagro updated its results in the northern sky survey in TeV energy range, and pushed the average flux upper limit down to a level between 275 and 600 mCrab that is 4.80×10^{-12} to $10.5 \times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ above 1 TeV for source declinations between 5° and 70° [4]. In 2011, ARGO-YBJ presented the northern sky survey flux upper limit above 0.1 TeV varying from 0.09 to 0.53 Crab unit for a declination of -10° and 70° [5]. In 2005, we reported on the northern sky survey for steady TeV gamma-ray point sources using the Tibet air shower data till 2001 and obtained the average flux upper limit $(1.5-3.8) \times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}(E > 3\mathrm{TeV})$ that is 0.5 - 1.2 Crab above 3 TeV for source declinations between 0° and 60°[6, 7].

We search for steady TeV gamma-ray point sources in the northern sky using the Tibet-III air shower array with the effective area of 22,050m^2 from 1999 through 2010. The number of air shower events used by this analysis is about four times as many as those used in the previous survey paper ([6]). We hereby revisit the hot spots of cosmic ray events listed as prominent directions reported in the paper.

2 Tibet Air Shower Array

The Tibet air shower experiment has been operating at Yangbajing (90°31′ E, 30°06′ N; 4300 m above sea level) in Tibet, China since 1990 [8]. The Tibet I array, which mainly consisted of 45 fast-timing (FT) scintillation counters of 0.5m^2 forming a matrix of 15 m span, was constructed in 1990 [8]. It was upgraded to the Tibet II late in 1994 occupying an area of 36,900m^2 by increasing the number of scintillation counters of 0.5m^2 with a matrix of 15 m span. The mode energy of the triggers events in Tibet I and Tibet II is 10 TeV / 7 TeV for cosmic rays / gamma rays [2, 9]. In 1996, we added 77 FT counters with a 7.5 m span inside the Tibet II to detect cosmic-ray showers lower than 10 TeV. We called this high-density array Tibet HD. Tibet HD consists of 109 scintillation counters (including 77 FT counters) covering an area of 5,175m^2 [1]. The mode energy of the triggered event$\sim$3 TeV / $\sim$2 TeV for cosmic rays / gamma rays. Using Tibet HD, we successfully detected VHE gamma rays from Crab and Mrk 501 [1, 2].

To increase the event rate, in 1999 the HD array was enlarged to cover the center part of the Tibet-II array as the Tibet-III array [10]. The area of Tibet-III has reached 22,050 m2. The mode energy of the triggered events in Tibet-III is $\sim$3 TeV / $\sim$2 TeV for cosmic rays / gamma rays same as the mode energy of Tibet-HD [11]. Using these arrays, we successfully detected VHE gamma rays from Mrk 421 [3], and we set stringent upper limits to gamma rays from Galactic plane at 3 TeV and 10 TeV [9, 12]. We also have successfully observed VHE gamma-ray sources and precise large-scale cosmic-ray anisotropy in the northern sky [6, 13, 14].

In these results, we first pointed out new small anisotropies in Cygnus region at multi-TeV energies [14]. One of them is coincident with MGRO J2019+37 which the Milagro experiment recently established as a VHE gamma-ray source [15]. It is worth noting that the Tibet AS experiment has reported several times [16, 17, 18] on the marginal excesses from the direction close to MGRO J1908+06/HESS J1908+063 before the final discovery made by the Milagro experiment.

Tibet-III was gradually upgraded by increasing the number of counters and covering wider area with narrower matrix spacing from 15m to 7.5m. At present, Tibet-III consists of 761 FT counters placed on a 7.5 m square grid covering 36,900 m^2, and 28 density counters around the FT counter array. The absolute gamma-ray energies in multi-TeV region observed by the Tibet AS array are verified by the Moon's shadow observation [7]. As primary cosmic rays are shielded by the Moon, we observed a deficit in cosmic rays called the Moon's shadow, and the center of the Moon's shadow shifts westward depending on primary cosmic-ray energies due to the geomagnetic field. Using this effect, the systematic error of absolute energy scale is estimated to be less than ±12%. Also, we updated the VHE gamma-ray energy spectrum of the Crab Nebula [7]. We found no evidence for time variability of flux intensity from the Crab Nebula at multi-TeV energies. Also the VHE gamma-ray energy spectrum of the Crab Nebula is consistent with our previous results and other observations by the IACTs. Using the Tibet-III during effective running time 1915 days from 1999 through 2008, we found that Fermi bright Galactic sources have statistically significant correlations with our TeV gamma-ray excesses [19].

3 Analysis

The data used in the previous survey paper were collected from 1997 February through 2001 October by Tibet HD and Tibet-III, corresponding to effective running time of 503 days in unit of Tibet-III with effective area of 22,050m^2. The data used in this search were collected from 1999 November through 2010 May and effective running time was 2170 days by TIbet-III (the effective area of 22,050m^2). The data used in this analysis amounts to 4.31 times as much as that used in the previous paper.

Because the Tibet air shower array cannot distinguish a gamma-ray induced shower event from the overwhelming CR background shower events, when tracing and counting the number of events in an "on-source window" centered at a candidate point-source direction with a size at the level of the angular resolution, the number of background events must be estimated from the observational data recorded in the side band, which is usually referred to as the "off-source window". First, the event selection was done by the same criteria on the Tibet-III array data used in the northern sky survey paper [6] and the Method I (Short-Distance Equi-Zenith Angle Method) is used for this survey for off-source window. And we select air-shower events with $\sum\rho_{\mathrm{FT}} > 15$, which corresponds approximately to 3 TeV for primary gamma-rays. $\sum\rho_{\mathrm{FT}}$ is defined as the sum of the number of particles per m^2 for each FT counter. Similarly we select air-shower events with $\sum\rho_{\mathrm{FT}} > 100$, which corresponds approximately to 10 TeV for primary gamma rays.

The surveyed sky has been oversampled in the following way: The sky is divided into $0^{\circ}\!.1 \times 0^{\circ}\!.1$ cells, from 0° to 360° in right ascension and from 0° to 60° in declination. Pointing to the center of those cells, cones with a half-opening angle of $0^{\circ}\!.9$ (for $E > 3$ TeV) or $0^{\circ}\!.4$ (for $E >$10 TeV) are tested as on-source windows.

4 Results and Discussions

The significance distributions from all directions are shown in Figures 1a and Figure 1b for the 3 TeV and 10 TeV data set, respectively. As for the positive side in Figure 1a, a wider shoulder exists with significance values greater than 4.0 σ. The dominant contributions are due to the stable gamma-ray source Crab Nebula and the transient source

Mrk 421. After removing their contributions, in such a manner that those cells that are less than 2° in distance from the two sources are excluded, the thick histograms in Figures 1a and 1b, which show the significance distribution from the rest of the cells, agree better with a normal distribution. Though the thick histogram in Figure 1a is a little shifted from the normal distribution between 3 σ and 4 σ, it is considered to be an influence of the Cygnus region and the sidereal anisotropy (Tail-in) [20]. For the negative side, the shape of the tail is based on the existence of three local points with significance values less than -4.5σ, and the existence of such three negative significance points is well consistent with the background fluctuation.

Table 1 lists the directions of local maximal significance points with significance values greater than 4.5 σ above 3 TeV from Method I of the previous survey paper [6] and also lists significance values of each direction measured by the Tibet-III from 2001 through 2010 and from 1999 through 2010, as $S1_{\rm measured}$ and $S2_{\rm measured}$, respectively. The significance values in the previous paper were the pretrial significance and called as $S_{\rm pretrials}$. When post-trial significance is needed, one should take account of the number of trials about 7000, which is obtained by dividing the solid angle of the surveyed sky by the solid angle of one on-source window. As an example, for the first prominent point in Table 1, the significance value is 5.3 σ from the previous paper, and multiplying the probability by 7000 to account for the number of trials, we end up with post-trial significance of 3.3 σ.

Using the Tibet-III data from 2001 through 2010 we check whether the hot spot of cosmic ray events from each prominent direction in Table 1 in the previous paper was caused by a steady gamma-ray point source. It should be noted that even if the high significance values are due to the excesses of the number of the gamma-ray induced shower events, it does not always mean these positions are the place where candidates of the TeV gamma-ray sources actually exist because of the background fluctuation. Also it shoul be noted that the excesses of prominent directions are likely to have approximately 1 sigma higher excess compared to the real flux in this survey method, when the candidate of the TeV gamma-ray point source exists near the area.

Table 1 lists the expected significance values which are calculated assuming steady gamma-ray emission from each prominent direction continues during the new dataset period with 3.31 times more independent statistics. Expected significance values $S1_{\rm expected}$ are calculated as $(S_{\rm pretrials} - 1.0) \times \sqrt{3.31}$ above 3TeV.

As seen in Table 1, except for the position near Crab Nebula, $S1_{\rm measured}$ is not in agreement with $S1_{\rm expected}$. It means the steady TeV gamma-ray point source induced by the assumed gamma-ray flux does not exist except for the Crab position. And the significance values less than 2.0 σ with four positions can be explained by the statistical fluctuation. There are two positions with a significance values greater than 2.0 σ, (70.45,18.15), (286.65,5.45), each position is located in the Tail-in region and J1908+06, respectively. The two regions are well known as regions where excesses of cosmic rays or gamma rays are expected. The significance values $S2_{\rm measured}$ are also calculated just for reference.

5 Conclusions

We surveyed the northern sky by Tibet-III with the same method as used in the previous survey paper. The result shows the directions of the Crab and Mrk421 have excess of the number of the air shower events. The shape of the significance distributions from all surveyed directions is influcenced not only by the excess of the gamma-ray events from Crab and Mrk421 but also by the excess of air shower events from the Cygnus region and the Tail-in region. In the previous survey paper, the high significance value of each prominent directions except for the Crab, Mrk 421, Tail-in region and J1908+06 can be explained by the statistical fluctuations.

To positively observe gamma rays in the 10 TeV region with much better sensitivity than Tibet-III, we plan to add a muon detector array to the air shower array (Tibet AS+MD array project). Gamma-ray induced electromagnetic air showers are muon-poor, while cosmic-ray induced hadronic ones are accompanied by many muons. This enables us to separate gamma rays from cosmic rays [21]. The sensitivity of the Tibet AS + MD array will be 5 times and 20 times better than that of the present Tibet AS array around 3 TeV and 20 − 100 TeV respectively. The Tibet AS + MD array will measure the directions of the celestial TeV gamma-ray sources and the cutoffs of their energy spectra.

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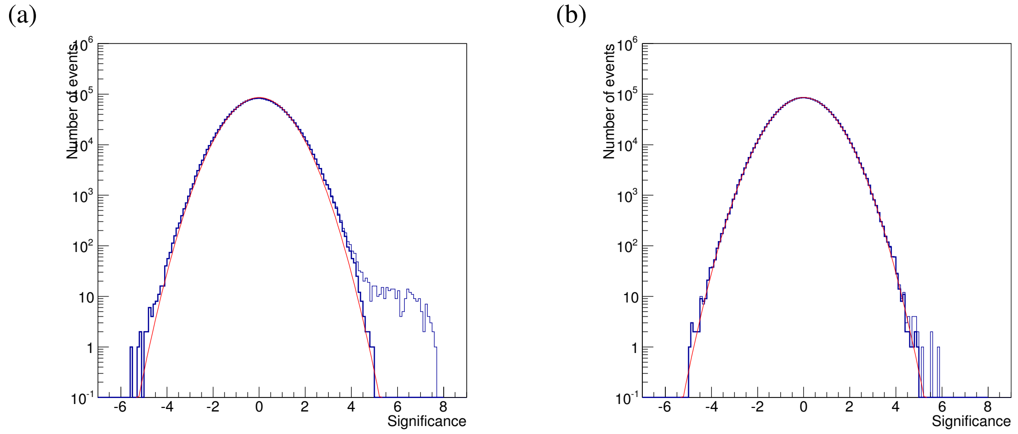

Fig. 1: Pretrials significance distribution of all directions on the sky map from (a) $\sum \rho_{\mathrm{FT}} > 15$ (∼3 TeV) and (b) $\sum \rho_{\mathrm{FT}} > 100$ (∼10 TeV) data set. It should be mentioned that not all directions are statistically independent, as the bin size is smaller than the angular resolution. The solid line is derived from all cells defined in the analyses. The thick histogram excludes those cells that have a distance to the Crab or Mrk 421 shorter than 2° . The curve represents the normal (Gaussian) distribution corresponding to the number of cells.

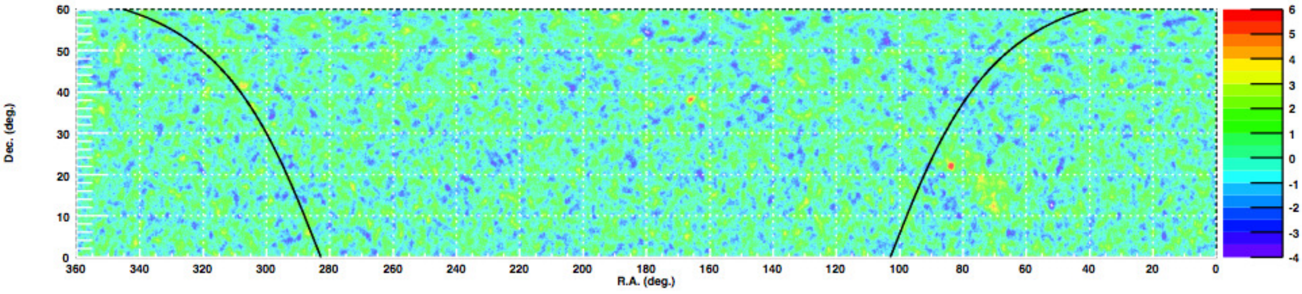

Fig. 2: Significance map in the surveyed northern sky.

R.A. (deg)	Decl. (deg)	Previous work Tibet HD + III Feb. 1997 - Oct. 2001 $S_{\mathrm{pretrials}}$ (σ)	Expected Tibet-III Dec. 2001 - May 2010 $S1_{\mathrm{expected}}$ (σ)	This work Tibet-III Dec. 2001 - May 2010 $S1_{\mathrm{measured}}$(σ)	This work Tibet-III Nov. 1999 - May 2010 $S2_{\mathrm{measured}}$(σ)	Nearby objects
69.95	12.05	5.3	7.8	2.9	4.1	Tail-in region
70.45	18.15	4.7	6.7	1.3	2.6	Tail-in region
83.55	22.25	5.2	7.6	6.4	6.9	Crab
88.85	30.25	4.5	6.4	0.7	2.2	
165.65	38.45	5.5	(8.2)	2.9	5.5	Mrk421
221.65	32.85	5.0	7.3	−0.4	1.9	
286.65	5.45	4.8	6.9	2.1	3.8	J1908+06
309.85	39.65	4.5	6.3	−0.4	1.4	Cygnus region

Table 1: Renewal results by the Tibet-III for prominent directions shown by the previous survey paper ([6]). Expected significance values $S1_{\mathrm{expected}}$ are calculated as $(S_{\mathrm{pretrials}} - 1.0) \times \sqrt{3.31}$ ($E > 3$TeV).