Observation of Sub-PeV Gamma Rays from the Galactic Plane Using the Tibet Air Shower Array with the Prototype Muon Detector

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Abstract: We are now proposing the 10,000m^2 water-Cherenkov-type muon detector (MD) array under the Tibet air shower (AS) array to find new gamma-ray sources with a wide field of view and unprecedented flux sensitivity. In the late fall of 2007, a prototype MD in area of 100m^2 was constructed under the existing Tibet AS array. In this paper, we search for sub-PeV (>200TeV) diffuse/point-like gamma rays from the Galactic plane using the muon-poor air shower events observed by the Tibet AS array and the Prototype MD.

Keywords: Tibet, PeV gamma rays, Diffuse gamma rays, Galactic plane

1 Introduction

Cosmic rays are supposed to be accelerated up to the knee energy region ($\sim$4 PeV) [1] at VHE astrophysical objects in our galaxy. Therefore, we naturally expect gamma rays in the 100 TeV region which originate in π^0 decays produced by the accelerated charged cosmic rays interacting with matter surrounding VHE gamma-ray source. However, the origin of VHE gamma rays might also be attributed to the leptonic processes, such as the inverse-Compton (IC) scattering or bremsstrahlung by accelerated electrons. One solution of this dilemma is to find a peak of π^0 decays around 70 MeV in the gamma-ray energy spectrum. The Fermi gamma-ray space telescope (FERMI) was launched on June 2008 to cover an energy range from 20 MeV to 300 GeV [2], and the Large Area Telescope instrument on the FERMI measured the diffuse gamma-ray emission from the galactic plane for energies 100 MeV to 10 GeV[3]. This important measurement informed us of our galactic signatures of physics. An alternative approach is to search for a continuous gamma-ray spectrum up to 100 TeV or more, because gamma rays of the leptonic origin rapidly diminished at higher energies due to the strong synchrotron cooling process and the Klein-Nishina effect. Although the air shower experiments have [4][5][6] searched for gamma-ray sources in the 100 TeV region, there is no compelling evidence for gamma-ray sources so far. Thus, it is interesting to observe the gamma-ray sources above 10 TeV to investigate the mechanism of gamma-ray emissions, the cosmic-ray acceleration and its origins.

2 Tibet Air Shower Experiment

The Tibet air shower experiment has been successfully operated at Yangbajing (90°31′ E, 30°06′ N; 4300 m above sea level) in Tibet, China since 1990 [7]. It has continuously made a wide field-of-view (approximately 2 steradian) observation of cosmic rays and gamma rays in the northen sky. The Tibet I array, which consisted of 45 fast-timing (FT) scintillation counters forming a matrix of 15 m span, was constructed in 1990 [7]. It was gradually upgraded to the Tibet II, and to the Tibet III, by the increasing the number of counters, and more covering area and closely matrix span from 15m to 7.5m. At present, the tibet air shower array consists of 761 FT counters placed on a 7.5 m square grid covering 36,900 m^2, and 28 denisty counters around the fast timing counter array. The mode energy of the triggered events in Tibet III is $\sim$3 TeV/$\sim$2 TeV for cosmic rays/gamma rays [1]. The absolute gamma-ray energies in multi-TeV region observed by the Tibet AS array are verified by the Moon's shadow observation [8]. 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 $\pm$12%.

Using these arrays, we already successfully detected VHE gamma rays from Crab, Mrk 501 and Mrk 421 [9][10][11] [8]. Also, we set stringent upper limits to gamma rays from Galactic plane at 3 TeV and 10 TeV [12, 13]. We also have successfully observed VHE gamma-ray sources and precise large-scale cosmic-ray anisotropy in the northern sky [14][15]. Recently, we found that Fermi bright Galactic sources have statistically significant correlations with our TeV gamma-ray excesses [16].

To positively observe gamma rays in the 100 TeV region with much better sensitivity than Tibet III, we plan to add a muon detector array to the air shower array. 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. Our current plan [17, 18, 19] relevant to gamma-ray astronomy above 10 TeV is Tibet AS (Air Shower array with 83,000m^2 in area) + MD (Muon Detector array with $\sim$10,000 m^2 in area under Tibet AS). Each muon detector is a waterproof concrete pool, 7.2 m wide $\times$ 7.2 m long $\times$ 1.5 m deep in size, equipped with two 20 inch-in-diameter photomultiplier tubes (PMTs), i.e., HAMAMATSU R3600. The Tibet MD array are made up of 192 muon detectors set up 2.5 m underground. Its total effective area amounts approximately to 10,000m^2 for muons with energies more than $\sim$1 GeV. Our current MC simulation predicts that the cosmic-ray background events will be rejected by approximately 99.99% at 100 TeV using full-scale (10,000 m^2) MD array. the full-scale MD array will improve the sensitivity to gamma-ray sources by more than an order of magnitude [20].

To confirm the hadron rejection power with this full-scale MD array, we constructed a prototype muon detector in 2007.

3 Prototype Muon Detector

In the late fall of 2007, we constructed a prototype water Cherenkov muon detector (approximately 100 m^2) at $\sim$90 m away from the center of the existing Tibet AS array, as is shown in Figure 1. The purposes of the prototype detector are to demonstrate construction feasibility, development of calibration method, confirmation of our Monte Carlo (MC) simulation and potential searching ability for sub-PeV gamma rays in the northern sky.

The muon detector is made from reinforced concrete and composed of two water pool cells located at 2.5 m under the ground. Each cell is filled up with water of 1.5 m in depth, 7.2 m $\times$ 7.2 m in area, equipped with three 20$''\phi$ downward facing PMTs (HAMAMATSU R3600). Among of the 3 PMTs, one is covered by a black sheet with $\sim$1% light transmission to effectively reduce the PMT gain (wider dynamic range), although we do not use it in this paper. The timing and charge information for each PMT is recorded by a trigger generated from surface scintillation counter array. We started the data taking in December, 2007. For a test,

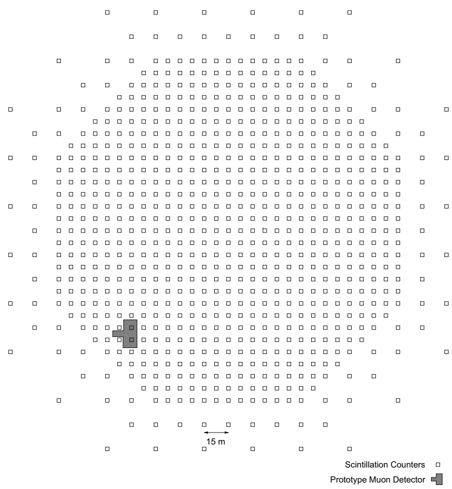

Figure 1: The Tibet airshowr array with scintillation counters (Open squares) and the 100 m^2 prototype water Cherenkov muon detector (Gray area).

we did not install any water purifier or circulation system. However, the water never freezes and bacteria do not proliferate easily, since the water temperature remains stable and cold around 5°C.

Using this prototype MD which is 1/100 scale of MD Array, we search for sub-PeV (>200TeV) diffuse/point-like gamma rays from the Galactic plan.

4 Analysis, Results and Discussions

The data used in this search were collected between 2008 March 2 and 2010 January 31 and effective running time was 429.5 days.

First, the event selection was done by the same criteria on the tibet-III array data used in the northern sky survey paper [21] using search window radius = $0.4°$, and we select air-shower events that are $\sum \rho > 2500$, which corresponds approximately to 200TeV for primary gamma-rays. Figure 2 shows the distribution of the number of muons for the Prototype MD as a function of the sum of the number of particles per m^2 detected in each FT-counter, that is, $\sum \rho$, for the Tibet III array by the MC simulation to search for gamma rays from the Crab Nebula, for reference. To maximize the detection significance of the source, a criterion based on the number of muons, shown by the solid line in figure 2, is set. By this muon-cut criterion using the prototype MD, gamma-like events are selectability survived, and the S/N ratio of the direction will be improved about 2.4 times.

4.1 Crab Nebula

Table 1 shows the numbers of events before muon-cut and survived events after muon-cut in the case of gamma rays and cosmic rays on the MC simulation respectively, and

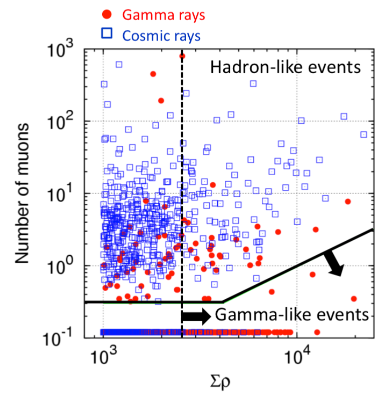

Figure 2: Distribution of the number of muons for the Proto.MD as a function of $\sum \rho$ for the Tibet III Array by MC simulation. The event-selection criteria shown by a solid line to maximize the detection significance of the source.

shows the numbers of Crab direction's events and background events by the data (429.5 days). It shows there is no significant excess of events from the Crab direction and the the survival ratio by the MC simulation is consistent with the data. Fluxes of gamma rays and cosmic rays using by the MC simulation don't reflect true fluxes. The significance are estimated based on eq. [22] of Li & Ma 1983. Figure 3 shows the 90 % CL upper limit obtained for 200TeV gamma rays from the Crab Nebula.

	MC		Data(429.5days)	
	Gamma Rays	Cosmic Rays	Crab Nebula	BG $\times$ 10
Before cut	226	119	308	2975
After cut	198	16	28	338
Survival Ratio (After/Before)	0.88 ±0.02	0.134 ±0.03	0.091 ±0.02	0.114 ±0.006

Table 1: The survival ratio by the MC sumulation and data

4.2 Other point-like sources in the galactic plane

Using the same method as described in the section 4.1, we search for sub-PeV gamma rays from other point-like sources in the galactic plane within the thickness $|b| < 10°$ (Region 1: $20° < l < 90°$, Region 2: $90° < l < 155°$, Region 3: $155° < l < 225°$). The distribution of the significance in this search is examined for statistical consistency with the normal Gaussian. As a result, three significance distributions of searched sources are consistent with the normal Gaussian, respectively.

4.3 Diffuse gamma rays from the galactic plane

We search for sub-PeV diffuse gamma rays from the inner galactic plane and the outer galactic plane by the analysis method of the Amenomori et al. (2006) papar [13]. In figure 4 and 5, we plot the new flux upper limits at

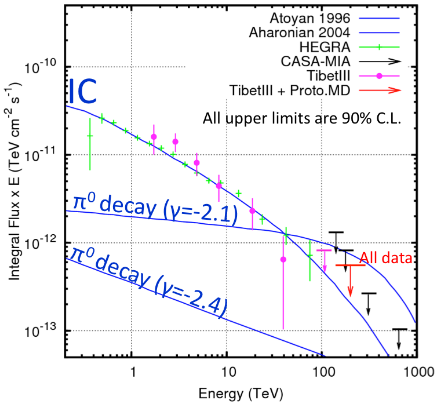

Figure 3: Flux upper limits of gamma rays for the Crab Nebula (90%C.L.).

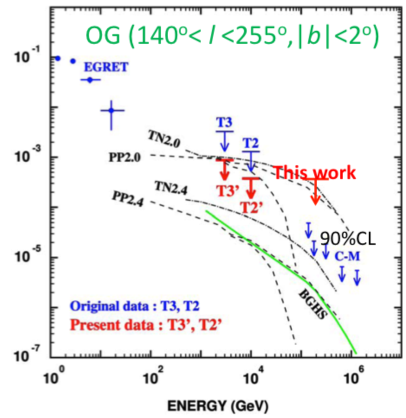

Figure 5: Diffuse gamma rays from the outer Galaxy (OG)

200TeV with the assumed differential spectral index of -2.4. Though the estimated sensitivity is estimated by the prtotype MD which is 1/100 scale of MD Array, the upper limit in the inner galactic plane is the best upper limit in this region.

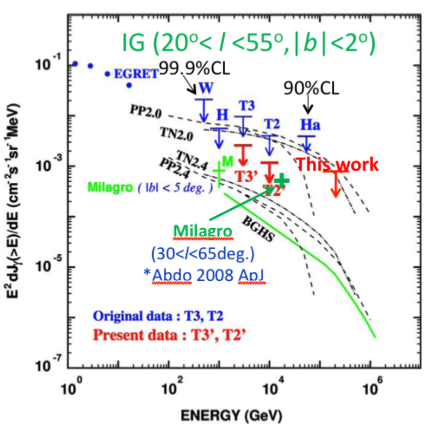

Figure 4: Diffuse gamma rays form the inner Galaxy (IG)

5 Summary

We search for sub-PeV gamma rays from the Crab Nebula, other point-like sources, and the diffuse gamma rays from the galactic plane using the Tibet AS array and Prototype muon detector. No significant excess of events is found for any gamma-ray sources. The gamma-ray sensitivity of the Tibet AS+Prot.MD for 1.2 years is comparable to that of the CASA-MIA array for 5 years above 200TeV for the point-like sources. Upper limits on the steady and transient gamma rays from the Crab Nebula are calculated. Upper limits on the diffuse gamma rays from the IG and OG regions are calculated.

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