Observations of TeV Gamma Rays with the Tibet Air Shower Array and Future Prospects

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***Abstract*— Since 1990, the Tibet air shower array has been successfully operated at Yangbajing in Tibet, China. We have continuously observed very high energy cosmic rays and gamma rays by the Tibet air shower array having 2 steradian field-of-view. In this paper, we introduce our brief history of gamma-ray observations, future plan and its status. We are now proposing to build the 10,000 m^2 water-Cherenkov-type muon detector array under the Tibet air shower array. In late fall of 2007, a first prototype water Cherenkov muon detector of approximately 100 m^2 was successfully constructed.**

I. INTRODUCTION

In 1989-1990, a small-scall air shower array was constructed at Yangbajing in Tibet, China (90.522°E, 30.102°N) at altitude of 4,300 m above sea level, which corresponds to an atmospheric depth of 606 g/cm^2 [1]. It is called the Tibet I array. This array consists of only 49 scintillation detectors of 0.5 m^2 each, which were placed at a lattice with 15 m spacing. The Tibet I array was originally designed to investigate mainly two scientific objects. One is measurement of the primary cosmic-ray energy spectrum and its chemical composition at energies from 10^{14} to 10^{17} eV to study a broken power-law structure in the cosmic-ray spectrum at about 4×10^{15} eV, generally called as the "knee" [2] [3]. This prominent feature is thought to be very important and deeply related with galactic cosmic-ray origin, acceleration and propagation. Another is to search for very high energy gamma-ray sources above 10 TeV. This might be stimulated by a detection of PeV gamma rays from Cygnus X-3 by the Kiel group in 1983 [4], although there is no clear confirmation yet. Since gamma rays from the cosmic-ray accelerator are traveling straight towards the Earth unaffected by the magnetic field, They can to be an useful tool to identify the origin of cosmic rays. We searched for 10 TeV and 30 TeV gamma rays from the Crab Nebula, Cygnus X-3 and Hercules X-1 with the Tibet I array, and then we obtained stringent flux upper limits from these three sources [1]. As for extragalactic sources, we also searched for 10 TeV and 30 TeV gamma rays from 15 active galactic nuclei (AGN) [5] and 10 TeV burst-like events coincident with the BATSE bursts [6], respectively, by the Tibet I array.

In the TeV energy region, the first clear evidence for signals from the Crab Nebula was reported by the Whipple collaboration with an imaging air Cherenkov telescope (IACT), which detects the Cherenkov lights produced in the atmosphere by relativistic charged particles in air showers, in 1989 [7]. After the Whipple observation, a lot of IACTs have successfully detected about 70 gamma-ray sources with their excellent angular resolution and efficiency so far. On the other hand, a complementary approach, such as the extensive air shower (EAS) arrays which directly detect particles in the air shower at the ground, has surveyed for gamma rays from various gamma-ray emitters. The advantage of this technique is that it enables us to operate 24 hours every day, regardless of weather, and to observe almost half of the celestial sphere with a higher energy threshold, compared with IACTs. In such a situation, the Tibet I array was gradually updated to the Tibet II and Tibet high density (HD) array by increasing the number of detectors in 1994-1996 as shown in Figure 1. The Tibet HD array of 5,175 m^2 with dense scintillation detector spacing (7.5 m grid) has successfully detected multi-TeV gamma rays from the Crab Nebula for the first time by the EAS array technique [8]. The Tibet HD array also have detected multi-TeV gamma-ray flare from Mrk 501 in 1997. This was the only observation using a conventional air shower array. [9].

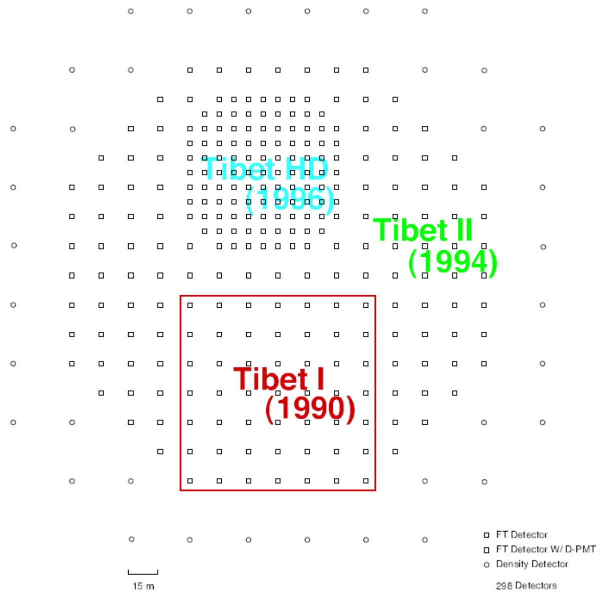

Fig. 1. Scintillation detector deployment of the Tibet I, II and HD air shower arrays.

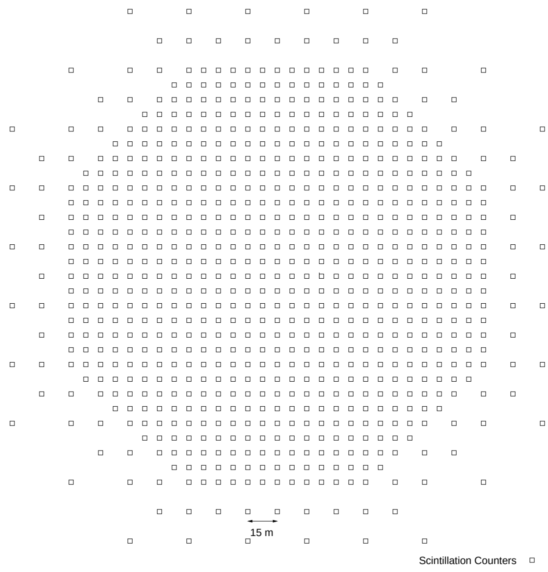

Fig. 2. Scintillation detector deployment of the Tibet III air shower array.

II. RECENT GAMMA RAY OBSERVATION

After success of gamma-ray detections by the Tibet HD array, the array was further upgraded to the Tibet III array (22,050 m^2) by expanding the high density area in 1999 [10]. In the late fall of 2003, the area of the Tibet III array was further enlarged up to 36,900 m^2 by adding 256 detectors as shown in Figure 2 and Figure 3. This new array has been successfully operating since then, triggering air shower events at a rate of 1,700 Hz.

The air shower array having wide field-of-view enables us to search for diffuse gamma rays from the Galactic plane with

Fig. 3. Picture of the Tibet III air shower array.

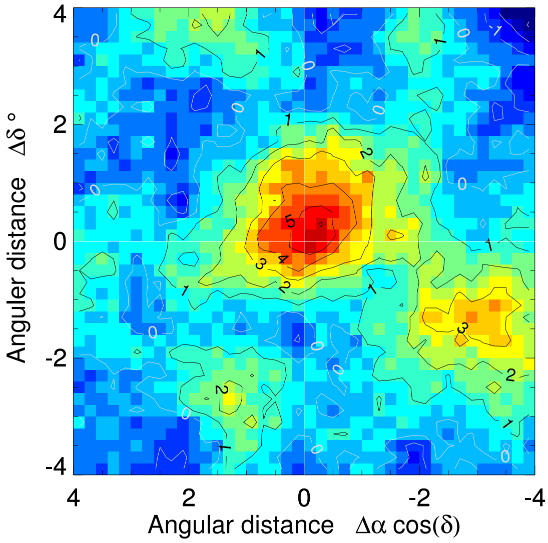

Fig. 4. Significance map around Mrk 421 observed by the Tibet III array.

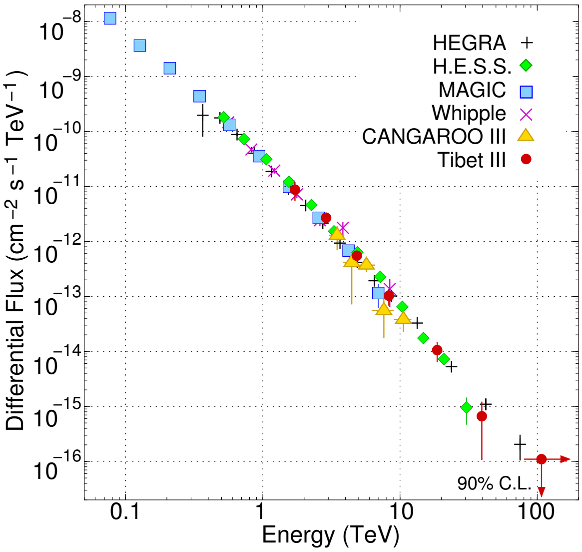

Fig. 5. Differential energy spectrum of gamma rays from the Crab Nebula observed by the Tibet III array, together with results from the IACTs, i.e., the HEGRA [20], H.E.S.S. [21], MAGIC [22], Whipple [23] and CANGAROO III [24]. The Tibet III upper limit is given at the 90% confidence level.

better sensitivity than IACTs. Data from the Tibet III array (with energies around 3 TeV) and from the Tibet II array (with energies around 10 TeV) have been analyzed for diffuse gamma rays from the Galactic plane [10]. The upper limits more were stringent in the multi-TeV region than those from IACTs in the lower energy region and other air shower arrays in the higher energy region. The latest flux upper limits on diffuse gamma rays from the Galactic plane observed by the Tibet II/III array is found in [11].

Mrk 421 was in an active phase during the period between the year 2000 and 2001, showing strong and frequent flares. During this flaring period, the Tibet III array successfully continued to monitor the sky region with ∼2-steradian solid angle [12]. This constant observation is beyond reach of IACTs which can observe the sky only at clear moonless nights. The stability of the array operation can be well checked by continuously observing the Moon's shadow and the event rate of air shower events. Using this array, we detected multi-TeV flaring gamma rays from Mrk 421 at a significance level of 5.1 σ as shown in Figure 4 and found a positive flux correlation between the keV and TeV energy regions.

Using dataset from 1997 to 2003, the MAKET-ANI experiment claimed a positive detection (6 σ statistical significance) of PeV cosmic radiation from the Monogem ring supernova remnant [13]. Subsequently, in order to confirm this observation, we searched for steady PeV gamma-ray emission around the Monogem ring with the Tibet II and Tibet III array from 1997 February to 2004 October [14]. However, no significant signal was found in the whole Monogem ring region, although we have 10 times better sensitivity than the MAKET-ANI.

Among the EAS array experiments, only the Tibet air shower array and Milagro experiments [15] have resulted in successful detection of gamma-ray emissions from the standard candle Crab Nebula and from transient sources such as Mrk 501 and Mrk 421 so far. Their abilities of high duty cycles and large fields of view allow them to simultaneously monitor a larger area in space over continuous time. This fact is a great advantage to search for unknown/flare-type sources and diffuse/extended sources. Using the Tibet III array, we have surveyed gamma-ray sources [16] and precise large-scale cosmic-ray anisotropy in the northern sky [17]. In these results, we first pointed out new small-scall excesses (∼2°) in Cygnus region at multi-TeV energies [17]. These excesses favor the interpretation that the extended gamma-ray emission. One of them is coincident with MGRO J2019+37 which the Milagro experiment recently established to gamma-ray source [18]. The further detailed analysis in Cygnus region have been continuing.

More recently, we have updated our results of the Crab Nebula using the Tibet III array [19]. The differential energy spectrum of the Crab Nebula is shown by filled circles in Figure 5. In the same energy range, this energy spectrum

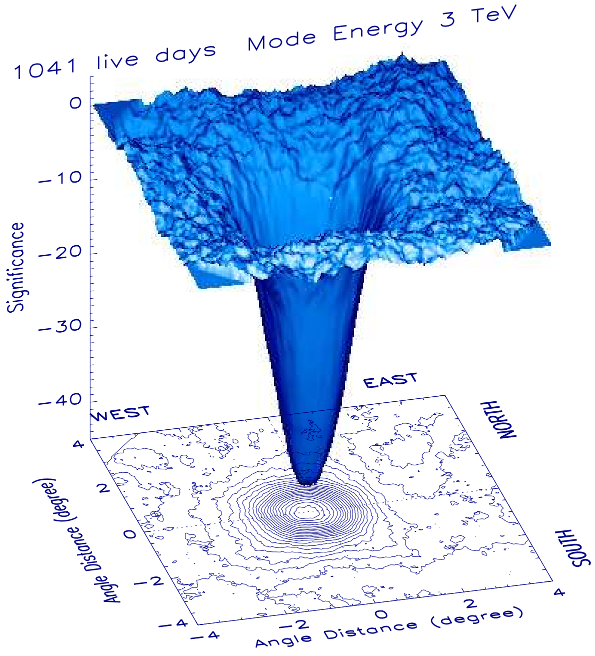

Fig. 6. 3D significance map of the Moon's shadow observed by the Tibet III array using the events in an area of 8°×8° centered on the Moon.

is statistically consistent with other observations made by IACTs. The Tibet III array was calibrated especially well by observation of the Moon's shadow as demonstrated in Figure 6. The systematic error in the absolute energy scale is estimated to be less than ±12% by the energy dependence of the Moon's shadow east-west displacement due to the geomagnetic field. The systematic pointing error is estimated to be smaller than 0.011° using the north-south displacement of the Moon's shadow uneffected by the geomagnetic field. These calibration methods are unique among the ground-based TeV gamma-ray observations, and the results will provide convincing proof for the MC simulation of our future plan. For more details, see [19].

III. FUTURE PROSPECTS

A problem in very high energy gamma-ray astronomy with the ground-based experiment is dominant cosmic-ray background events against gamma-ray signals. In order to significantly discriminate between gamma rays and background cosmic rays, we are now planning to build a water-Cherenkov-type muon detector array (Tibet MD array) under the Tibet air shower (AS) array [25] [26] [27] [28]. Because gamma-ray induced air shower have much less muons than cosmic-ray induced one. Each muon detector is a waterproof concrete cell, 7.2 m wide × 7.2 m long × 1.5 m deep in size, equipped with two 20 inch-in-diameter PMT (HAMAMATSU R3600) as shown in Figure 7. The Tibet MD array consists of 192 muon detectors set up 2.5 m underground as shown by gray areas in Figure 8. Its total effective area amounts approximately to 10,000 m^2 for muon detection with an energy threshold of 1 GeV.

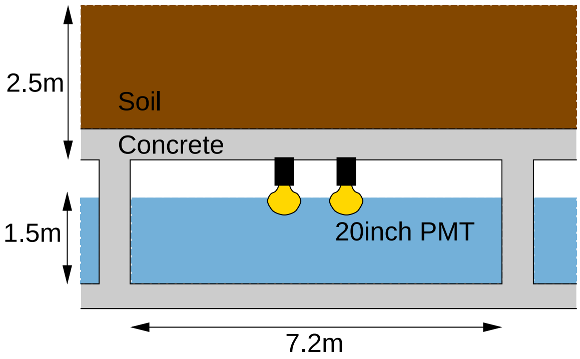

Fig. 7. Schematic sideview of each MD detector.

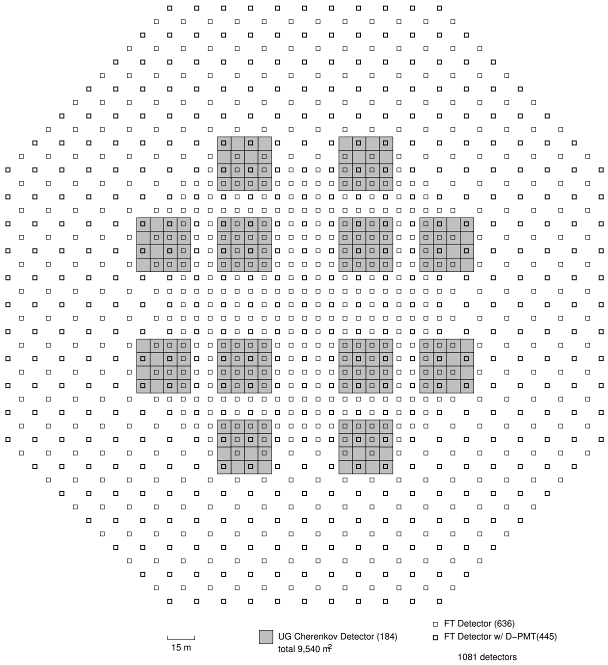

Fig. 8. Schematic view of the Tibet AS+MD array in the future. Open squares show future Tibet air shower array which consists of ∼1,000 scintillation detectors (83,000 m^2). Grey area shows water-Cherenkov-type MD array which consists of 192 water cells (10,000 m^2).

The Monte Carlo simulation including the air shower generation and responses of the Tibet AS+MD array was done to estimate the discrimination power between gamma rays and cosmic-ray background events based on counting the number of muons accompanying an air shower [26]. As a result, cosmic-ray induced air showers are suppressed by 99.99% around 100 TeV, while gamma-ray-induced air showers remain by more than 95%. Finally, we calculate the integral flux sensitivity of the Tibet AS+MD array to point-like gamma rays as shown by the thick solid curve in Figure 9. Note that our sensitivity above 200 TeV is defined as a flux corresponding to 10 gamma-ray events, since the background events are fully suppressed to less than one event.

The Tibet AS+MD array will have the sensitivity to gamma

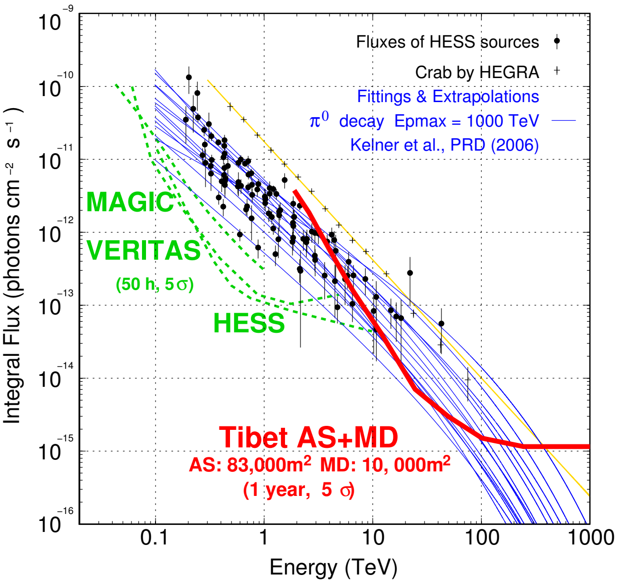

Fig. 9. Integral flux sensitivities to point-like gamma-ray sources. Dashed curves show sensitivities of Cherenkov telescopes at 5 σ for 50 hours (MAGIC, VERITAS and HESS from the upper curve). The thick solid curve demonstrates the sensitivity of the Tibet AS+MD array at 5 σ for 1 calendar year. Closed circles show the integral fluxes converted from observed differential fluxes of “HESS J” sources point by point assuming their spectral indices [29]. Thin lines show fittings and extrapolations to HESS data points assuming gamma-ray production model at proton-proton interaction by Kelner et al. [30]. The maxmum energy of protons is set to 1000 TeV.

rays in the 100 TeV region by an order of magnitude better than any other previous existing detectors in the world. The sensitivity of the full-scall Tibet AS+MD array is shown in Figure 9, together with gamma-ray fluxes of unidentified “HESS J” sources [29]. If the “HESS J”-like sources also exist in the northern hemisphere, we will discover gamma-ray signals and cutoff energy from 10 TeV to 1000 TeV at high significance level. In the whole of northen sky, we can expect to detect a dozen known/unknown point-like/extended sources and diffuse gamma rays from Galactic plane with extremely low background level (~1 event / degree^2). In the near future, the MAGIC and VERITAS experiments, together with the Tibet AS+MD array will contribute to a deeper understanding of the origin and acceleration mechanism of cosmic rays.

In the late fall of 2007, a prototype muon detector of approximately 100 m^2 in total was constructed at ~90 m away from the center of the existing Tibet air shower array. The prototype detector's goals are to check construction feasibility, development of calibration method, confirmation of our Monte Carlo (MC) simulation and searching for sub-PeV gamma rays in the northern sky. Outside and inside view of a prototype muon detector are shown in Figure 10 and Figure 11, respectively. The preliminary data analysis is in good agreement with our MC simulation results [31].

Fig. 10. Outside view of the prototype muon detector, which consists of two water cells, made of the reinforced concrete.

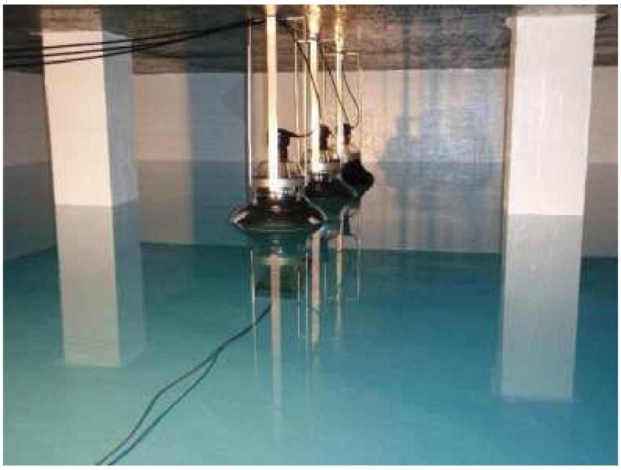

Fig. 11. Inside of a water cell of the prototype muon detector equipped with three 20 inch PMTs in an area of 52 m^2.

IV. SUMMARY

With the Tibet HD and Tibet III arrays, we have successfully detected gamma rays from the Crab Nebula, Mrk 501 and Mrk 421. In Cygnus region observed by the Tibet III array, the large-scale excess consists of a few spatially separated enhancements of smaller scale superposed onto a large-scale anisotropy. This small-scale (~2°) excess favors the interpretation that the extended gamma-ray emission from the Cygnus region. The Tibet III array was especially tuned by observation of the Moon's shadow, thanks to its very high statistics. Therefore, the Tibet III array will provide reliable results in the future. However, we will surely need drastic improvement of gamma-ray sensitivity. We are now proposing to construct a 10,000 m^2 water-Cherenkov-type muon detector (MD) array under the Tibet air shower array. The Tibet MD array will enable us to improve gamma-ray sensitivity in 100 TeV energy region by an order of magnitude better than any other previous existing experiments in the world. In late fall of 2007, a prototype water Cherenkov muon detector of approximately 100 m^2 was successfully constructed under the Tibet air shower array. The preliminary data analysis is in good agreement with our MC simulation. This prototype detector will be the first step to pioneer the 100 TeV gamma-ray astronomy.

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