A northern sky survey for ultra-high-energy gamma-ray source using the Tibet air-shower array and muon-detector array.

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The Tibet AS\gamma experiment located at 4300 m above sea level, Tibet, China, has a wide field of view and large effective area. It consists of the Tibet air-shower array (Tibet-AS), the air-shower core-detector array (YAC) and the underground water-Cherenkov muon-detector array (Tibet-MD). The Tibet-MD array significantly improves $\gamma$-ray sensitivity in the 10-1000 TeV energy region by an order of magnitude better than any other previously existing experiments in the world. In this work we will present the catalog of TeV $\gamma$-ray sources using 719 days of data from the Tibet AS\gamma experiment. The catalog represents the most sensitive survey of the northern $\gamma$-ray sky at energies above several tens of TeV. These ultra-high-energy $\gamma$-ray sources are believed to be related to pulsars and supernova remnants.
1. Introduction

The all-sky survey remains one of the major concerns for Extensive Air Shower experiments, as they have a wide field of view and a high duty cycle. The Tibet ASy experiment, have observed gamma-ray emissions from Crab, Mrk501, Mrk421 [1–3]. Since 2014, the underground water-Cherenkov muon detector (MD) array with a total area of 3400 m² started operation. We can effectively discriminate between primary gamma rays and cosmic-ray backgrounds by means of counting the number of muons in an air shower event, because a gamma-ray induced air shower has significantly less muons than a cosmic-ray induced one. Thus the gamma-ray sensitivity is significantly improved in the 10-1000 TeV energy region.

We first detect the highest energy photons beyond 100 TeV from an astrophysical source, the standard candle Crab nebula[4], and its broad-band spectra can be explained dominated by leptonic origin via the inverse Compton scattering by relativistic electrons[5]. We also detect very-high-energy gamma-ray emission around the direction of SNR G106.3+2.7, and the morphological feature of these gamma rays appears to favour a hadronic origin via the π⁰ decay caused by accelerated relativistic protons over a leptonic origin[6]. By analysising sub-PeV diffuse gamma rays destribution, We found the gamma ray distribution is extended around the Galactic plane. This is strong evidence for ubiquitous Galactic cosmic rays beyond PeV[7].

2. The Tibet ASy Experiment

The new Tibet hybrid extensive air shower experiment has been operated at Yangbajing (E 90°31’, N 30°6’, 4300 m above sea level) in Tibet, China, and data taking started from 2014. This hybrid experiment currently consists of three types of detector array, including the Tibet AS array (Tibet-AS), an underground water-Cherenkov muon-detector array (MD) and the Yangbajing AS core-detector array (YAC-II). These systems are used to observe air showers of high energy celestial gamma-ray origin and those of nuclear-component origin. The currently configuration of the Tibet AS + MD arrays are shown in Fig.1.

The Tibet-AS array consists of 597 plastic scintillation detectors, each with an area of 0.5 m², totally covering an area of 65700 m² with an inner area of 50400 m² indicated by dashed-dot line and dashed line. This array is used to detect the densities and arriving times of particles in air-shower events, and then these infomations are used to reconstruct the direction and energy of primary particles. The angle and energy resolutions of primary particles can be estimated to be approximately 0.5° and 40% at 10 TeV, 0.2° and 20% at 100 TeV for gamma rays[4].

The MD array consists of 4 pools, with 16 cells for each. Each cell has an area of 7.35 m × 7.35 m. These cell are set up underground and filled with water with 1.5 m depth. Muons in excess of 1 GeV associated with air showers are observed by detecting Cherenkov lights with 20-inch-diameter photomultiplier tubes(PMTs) mounted downward on the ceiling of each pool, while most of the electromagnetic components such as electrons, positrons and photons are blocked by the soil with depth of 2.4 m. Utilizing the fact that gamma-ray-induced air showers contain fewer muons compared with cosmic-ray-induced ones we can discriminate photon signals from cosmic-ray backgrounds by means of counting muon number detected by the MD array. Thus, the
Figure 1: Schematic view of the Tibet-AS+MD array. Red and blue filled squares denote Tibet-AS scintillation detectors and MD muon detectors. The area enclosed by the dashed-dot line indicates the total 65700 m² area. The area enclosed by the dashed line indicates the inner 50400 m² area of AS array.

MD array significantly improve the sensitivity of the Tibet AS array towards gamma-ray signals above 10 TeV.

3. Analysis

In this work, we use data obtained by both Tibet-AS and MD with 719 live days from 2014 February to 2017 May. The direction of primary particle was reconstructed using the same way as in the past[8]. The energy of primary particle was reconstructed using the lateral distribution of the density of secondary particles($\rho$), we use the density at distance of 50 m from the air-shower core as a better energy estimator[9]. We use the number of all muon particles($\sum \mu$) as the parameter for $P/\gamma$ separation. The gamma-like events should be muon-poor, and the energy-dependent muon-cut condition is the same as used in previous works[4].

The event selection was done by imposing the following criteria: (1) Each shower event should fire four or more Tibet-AS detectors recording more than 1.25 particles. (2) The number of available detectors for the AS reconstruction is larger than 16 (3) The estimated shower center location should be inside the array. (4) The energy larger than 10 TeV. (5) The zenith angle of the incident direction should be less than 60°. (6) The gamma-like events.

The skymap is divided base on HEALPIX framework[10] with order=10, each of which has an approximate size of $0.05^\circ \times 0.05^\circ$ we adopt the equizien angle method to estimate the background
of cosmic rays for each pix as used in previous works[3, 4, 8, 11]. The number of cosmic-ray background events is estimated from the number of events averaged over 10 off-source windows located at the same zenith angle with the on-source window. The windows size is set according to different situations.

4. Results

Fig.2 show the northern survey using the point source searching mode(with small size of searching windows depends on the energy). We totally find 12 gamma-ray sources with five-sigma significance, all of these gamma-ray sources are along the galaxy plane, including the brightest TeV γ-ray source standard candle.

Table.1 lists these gamma-ray sources, and its associated sources on TeVCat[12]. All of these regions have at least one TeV-γ-ray source within 0.5° distance, except one (RA = 279.91°, DE = −6.03°). There are two extended undefined source HESS J1841-055, HESS 1837-069 nearby[13], it can be the principal maximum of an elongated region containing multiple known extended sources.

Figure 2: Significance map of the Tibet-AS+MD northern sky gamma-ray survey using the galactic coordinate system. The white circle indicated the direction of excess with significance > 5 above 10 TeV. The grep region is outside of the field of view.

For large extend γ-ray halos, there is no significance using the same method as previous. We use large smoothing windows and “the Equi-Declination Method”. Fig.3 show the significance map around the geminga region above 10 TeV, by using 3° smoothing window. We can see the excess emission around the geminga pulsar, and there is also a excess around the south-east PSR B0656+14.
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Associated sources  Ra[deg]  De[deg]  b[deg]  D
Crab  83.65  22.02  -5.76  0.0
TeV J1825-134  276.52  -13.4  -0.58  0.05
TeV J1831-099  277.58  -9.84  0.16  0.27
TeV J1837-065  279.91  -6.03  -0.14  0.70
TeV J1840-055  280.92  -3.85  -0.03  0.26
TeV J1844-035  282.84  0.03  -0.00  0.45
TeV J1857+026  284.70  2.66  -0.42  0.40
MGRO J1908+06  287.01  6.20  -0.85  0.07
2HWC J1955+285  298.87  28.63  0.17  0.05
Cygnus OB1  305.02  36.77  0.23  0.23
Cygnus OB2  308.01  41.19  0.89  0.13
SNR G106.3+2.7  336.77  60.88  2.77  0.11

Table 1: Result by the Tibet-AS+MD for significant region above 10 TeV and its associated gamma-ray sources in TeVCat. Ra, De are the positions on J2000 coordinate system, and b is the Galactic latitude. D represent the angle distance from the TeVCat sources to the Tibet-AS+MD significant area.

Figure 3: Significance map of the γ-ray emission around Geminga. The cyan cross X indicate the position geminga pulsar, and the blue cross X indicate the position of PSR B0656+14. The white circle at the right-bottom indicate the angle resolution of the Tibet-AS array.

5. Conclusions

In this paper, we report 12 gamma-ray sources above 10 TeV. All of these gamma-ray sources are along the galaxy plane. We also shows the large extended gamma-ray emission around the geminga region. These results show the strength of the underground muon detectors for discriminating
primary gamma-ray from cosmic-ray background.

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