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Observation of Ultra-High-Energy Diffuse Gamma Rays from the Galactic Plane with the Tibet Air Shower Array

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We reported on the first detection of the ultra-high-energy diffuse gamma rays from the Galactic plane [1]. The highest energy of the detected gamma rays is estimated to be unprecedentedly high, nearly 1 PeV. It is reasonable to expect that the detected gamma rays are produced by the hadronic interaction between cosmic rays escaping from the most powerful Galactic sources "PeVatrons" and the interstellar gas in the Galaxy. This experimental evidence is an important milestone to solve a long-standing mystery of cosmic-ray origins.

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1. Introduction

Since the discovery of cosmic rays in 1912 [2], their energy distribution has been observed for more than 10 orders of magnitude, but many mysteries remain, such as their origin, acceleration mechanism, and propagation to Earth. In 1958, a rapid decrease in the cosmic-ray flux was observed at the energy greater than a few Peta-electron-volt (PeV), which is called "Knee" [3]. Based on this observational fact and theoretical considerations, it was thought that cosmic rays with energies below a few PeV were produced by astrophysical objects in the Galaxy, such as supernova remnant (SNR). Since then, there has been some evidence for low-energy cosmic rays around Tera-electron-volt (TeV) region being produced in the SNR [4], but in spite of exhaustive searches over the last 20 years, there is no compelling evidence for the existence of the powerful object called PeVatron in our Galaxy, which can produce cosmic rays with energies beyond PeV energies. It is known that high-energy cosmic rays interact with the interstellar gas distributed in the Galaxy and emit gamma rays with an energy of roughly 10% of cosmic rays. Therefore, the gamma-ray observations at least 100 TeV is essential to obtain evidence of the PeVatron. However, the gamma-ray flux rapidly decreases as the energy increases. In addition, the cosmic-ray background noise, which is more than 10^5 times higher than the gamma-ray flux, have to be eliminated to the utmost limit.

2. Tibet ASγ Experiment

The Tibet ASγ experiment was started in 1990 with a small AS array constructed in Tibet plateau at an altitude of 4,300 m, in China [5]. After a few extensions, the present AS array consists of 597 particle detectors which were deployed over an area of 65,000 m^2. The secondary particles in the air shower are observed by the Tibet AS array, which consists of many scintillation detectors with 7.5 m spacing in a grid pattern. The gamma-ray energy and arrival direction are determined using energy depositions and arrival timings recorded in the detectors [6]. In order to reduce the cosmic-ray background events against the gamma-ray signals, the muon component in an air shower are utilized. Since the number of muons in the air shower is much less than that of cosmic rays, the counting of the number of muons allows us to separate gamma rays from cosmic rays with high accuracy [7]. In order to measure the number of pure muons, a water-Cherenkov-type muon detector was installed underground, where most of particles except muons are absorbed. This muon detector, which is the key to this observation, has the world's largest area of 3,400 m^2, and 20 inch-in-diameter photomultiplier tubes (PMT) are installed in the pool of water 1.5 m deep. With these instruments, we successfully observed 24 gamma-ray events from the Crab Nebula above 100 TeV against 5.5 background events, which corresponds to 5.6σ statistical significance [8]. The highest energy of the detected gamma rays was estimated to be 450 TeV. This was the first detection of gamma rays beyond 100 TeV from an astrophysical source.

3. UHE Diffuse Gamma Rays from the Galactic Plane

We analyze the data collected by the Tibet AS+MD array for approximately two years between 2014 and 2017. In order to extract diffuse gamma-ray signals in the large amount of cosmic-ray background events, we adopt a tight muon cut, which is just one order magnitude tighter than that

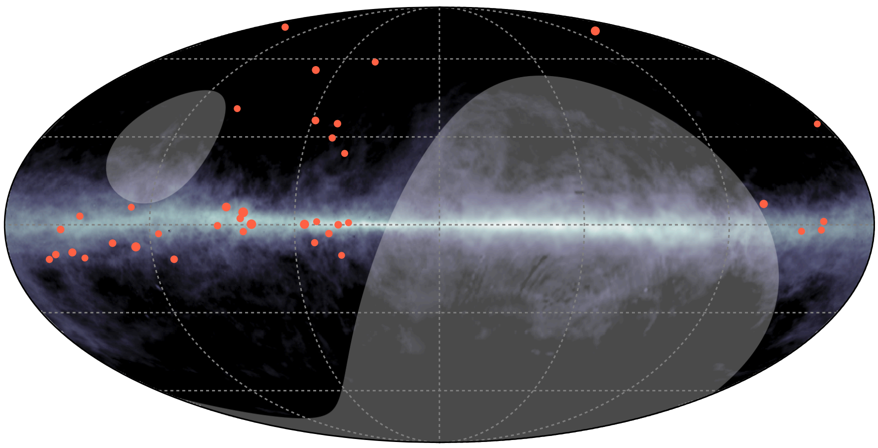

Figure 1: Distribution of gamma-ray-like events above 398 TeV (red points) in the Galactic coordinates. The circle size is proportional to the gamma-ray energy. The background contour shows the atomic hydrogen distribution [9]. The gray shaded area indicates outside of the field of view.

of our previous analysis for the point-like source. With this tight muon cut, we have succeeded in reducing the cosmic-ray background events to approximately 10^{-6} above 398 TeV. As a result, 38 gamma-ray-like events are survived after the cut above 398 TeV, and 23 events are seen along the the Galactic plane within $|b| < 10°$ with low cosmic-ray background events [1]. Figure 1 shows the distribution of gamma-ray candidates above 398 TeV in the Galactic coordinates. The coordinates of gamma-ray-like events with $398 < E < 1000$ TeV are listed in the supplemental material of [1]. The high Galactic latitude events ($|b| > 20°$) are assumed to be the cosmic-ray background events in this analysis. The highest energy is estimated to be unprecedentedly high 957 TeV, nearly 1 PeV. Surprisingly, the observed gamma rays above 398 TeV are not located at the direction of known gamma-ray objects, but are spatially spread over direction in the Galactic plane [1]. These spatially spread gamma rays are thought to have been produced by the interaction of cosmic-ray protons with the interstellar gas in the Galaxy. On the other hand, the high-energy electrons interact with low-energy photons filled in the Galaxy, and also produce ultra-high-energy (UHE) gamma rays. However, since the electrons lose their energy rapidly and cannot travel far from their object, gamma rays should be generated very close to the sources. Furthermore, the measured fluxes in the UHE region [1] are in reasonable agreement with a recent model based on the hadronic cosmic-ray interactions developed by Lipari and Vernetto [10]. These facts provide the first compelling evidence that protons, not electrons, are being accelerated to UHE regions in the Galaxy, and it is the hard evidence of the existence of the PeVatron, the origin of the cosmic-ray proton, whose existence has been the subject of controversy for decades, in the past or present. This is also the first experimental proof of the theoretical model that cosmic-ray protons up to the "Knee" energy region are trapped by the magnetic field in the Galaxy, forming a pool of cosmic rays.

In addition, 4 events out of 23 gamma rays located within $|b| < 10°$ above 398 TeV concentrate in the Cygnus Cocoon region (around $l = 80°$, $b = +1°$ in Fig. 1), which is a good candidate of the PeVatron [11–13]. This result may provide further strong evidence that the Cygnus Cocoon is a cosmic-ray source "Pevatron".

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