

Search for steady PeV gamma-ray emission from the Monogem Ring with the Tibet air shower array

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We searched for steady PeV gamma-ray emission from the Monogem Ring region with the Tibet air shower array from February 1997 to October 2004. No evidence for statistically significant gamma-ray signals was found in a region $111^\circ \leq \text{right ascension} < 114^\circ$, $12.5^\circ \leq \text{declination} < 15.5^\circ$ in the Monogem Ring where the MAKET-ANI experiment recently claimed a positive detection of PeV high energy cosmic radiation. We set a 99% confidence-level integral flux upper limit of $4.0 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ above 1 PeV on diffuse gamma-rays extended in the $3^\circ \times 3^\circ$ region, which corresponds to a 10% of the flux estimated by the result from the MAKET-ANI experiment.

1. Introduction

In a recent observation at PeV energies, the MAKET-ANI air shower experiment with an effective area 650 m^2 at Mount Aragats ($44^\circ 10' \text{ E}$, $40^\circ 30' \text{ N}$; 3,200 m above sea level) claimed a detection of significant excess (6σ) of cosmic-ray events within a $3^\circ \times 3^\circ$ search window ($111^\circ \leq \text{right ascension } (\alpha) < 114^\circ$, $12.5^\circ \leq \text{declination } (\delta) < 15.5^\circ$) in the Monogem Ring region using the air shower data recorded from 1997 to 2003 [1]. Naturally, the significant excess may be attributed to PeV gamma rays, because the Larmor radius $R_L \sim 0.4 / Z \text{ pc}$ at 10^{15} eV in the galactic magnetic field of $3 \mu\text{G}$ is too small to reach the Earth without deflection compared with the distance 300 pc between the Earth and the Monogem Ring, and the mean decay length of a neutron $\lambda \sim 10 \text{ pc}$ at 10^{15} eV is also too short.

In this paper, we report on search for diffuse/point-like PeV gamma-ray emission based on the data recorded from 1997 to 2004 around the Monogem Ring region by a large air shower array with a total area $36,900 \text{ m}^2$ constructed in Tibet.

2. Experiment

The Tibet air shower experiment has been successfully operated at Yangbajing ($90^\circ 31' \text{ E}$, $30^\circ 06' \text{ N}$; 4,300 m above sea level) in Tibet, China since 1990. The Tibet I array was constructed in 1990 [2] and it was gradually expanded to the Tibet II by 1994 which consisted of 185 fast-timing (FT) scintillation counters placed on a 15 m square grid covering $36,900 \text{ m}^2$, and 36 density (D) scintillation counters around the FT-counter array. An event trigger signal is issued when any fourfold coincidence occurs in the FT counters recording more than 0.6 particles. The mode energy of the triggered events in Tibet II is $\sim 10 \text{ TeV}$. From 1996 to 2003 we upgraded the array and at present, it consists of 761 FT counters covering $50,400 \text{ m}^2$ and 28 D counters around them. In the inner $36,900 \text{ m}^2$, FT counters are deployed with 7.5 m lattice interval. We call this upgraded array Tibet III since October 1999. The mode energy of the triggered events in Tibet III is 3 TeV.

3. Analysis

In the present paper, we employ the data obtained by the 185 FT counters and the 36 D counters corresponding to the Tibet II array configuration for the whole period in order to simplify the analysis. We collected 1.6×10^8 air shower events during 1717 detector live days from February 15, 1997 to October 10, 2004 after the quality cut and the event selection based on the following simple criteria; (1) Air shower core location: Among the 3 hottest counters in each event, 2 should be contained in the inner $36,900 \text{ m}^2$. (2) Shower Size: $\sum \rho_D$ should be more than 100 where $\sum \rho_D$ is the sum of the number of particles per m^2 counted by the 36 D counters and the 52 out of the 185 FT counters which have a wide dynamic range PMT. (3) Zenith angle: The zenith angle of the arrival direction should be less than 40° . According to the MC simulation including the quality cut and the event selection, the mode energy of gamma rays is 150 TeV, the angular resolution is less than 0.3° , and the effective area for gamma rays is nearly $2.5 \times 10^4 \text{ m}^2$ for $3^\circ \times 3^\circ$ search window in a diffuse source analysis and $1.6 \times 10^4 \text{ m}^2$ for $0.5^\circ \times 0.5^\circ$ search window in a point-like source analysis. The gamma-ray energy is estimated from $\sum \rho_D$ by the MC simulation and the energy resolution is less than 30% above 150 TeV. The systematic pointing error is estimated to be less than 0.02° by the Moon's shadow in cosmic rays [3].

Subsequently, we use the right ascension scan method to search for PeV gamma-ray sources which follows the same analysis method and parameters employed by the MAKET-ANI experiment [1]. First, each event is sorted by its arrival right ascension and declination into a $\Delta\alpha \times \Delta\delta = 3^\circ \times 3^\circ$ rectangular cell. Off-source events are taken from all the cells except the on-source cell in the same declination band as on-source cell. The

significance of the source in each cell is calculated based on the Equation (17) of Li & Ma (1983) [4]. We scanned the celestial sky in the declination band from -5.5° to 66.5° in the whole right ascension range $0^\circ - 360^\circ$. We also scanned the whole Monogem Ring region and around it in the declination band from 0° to 30° in the right ascension range $80^\circ - 130^\circ$ with $\Delta\alpha \times \Delta\delta = 0.5^\circ \times 0.5^\circ$ search window analysis for a point-like source.

4. Results and Discussions

The left panel of Figure 1 shows the distribution of the number of events in each of 120 cells in the declination band $12.5^\circ - 15.5^\circ$ by the $\Delta\alpha \times \Delta\delta = 3^\circ \times 3^\circ$ search window analysis with $\sum \rho_D > 1000$ (corresponding to > 1 PeV). The shaded histograms denote our actual result and dashed one is the expected excess from the MAKET-ANI result. The MAKET-ANI experiment detected a significant excess in the direction $111^\circ \leq \alpha < 114^\circ$, $12.5^\circ \leq \delta < 15.5^\circ$ at the 6σ statistical significance. But no significant signal was detected by the Tibet air shower array (-0.6σ). The right panel of Figure 1 demonstrates the energy dependence of the result in the region suggested by the MAKET-ANI experiment by the $3^\circ \times 3^\circ$ search window analysis, also confirming no signal detection. As the MAKET-ANI experiment detected a significant excess in the various energy threshold of >800 TeV, >1 PeV, and >2 PeV, we would have detected a significant signal at $(50 \pm 10)\sigma$ in at least one energy threshold even if relative energy scale uncertainty between the two experiments differed by a factor of 2. We set a 99% confidence-level integral flux upper limit of $1.1 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} / (2.66 \times 10^{-3} \text{ sr}) = 4.0 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ on steady diffuse gamma rays > 1 PeV extended within a rectangular region ($111^\circ \leq \alpha < 114^\circ$, $12.5^\circ \leq \delta < 15.5^\circ$) in the Monogem Ring assuming a differential spectral index -2.0 , which corresponds to a tenth of the flux estimated by Erlykin et al. [5] based on the MAKET-ANI result. One of the potential possibilities explaining the discrepancy could be transient emission which occurred out of our field of view or at occasions when we stopped data acquisition for annual maintenance, calibration, upgrading jobs, etc.

Figure 2 shows the significance map of the whole Monogem Ring region and around it ($80^\circ \leq \alpha < 130^\circ$, $0^\circ \leq \delta < 30^\circ$) based on a finer window search of $0.5^\circ \times 0.5^\circ$ cell at energies > 1 PeV. Again, no significant signal was found. There are two directions with significance $> 4\sigma$ at $(\alpha, \delta) = (108.75^\circ, 18.75^\circ)$, $(120.25^\circ, 12.75^\circ)$, which are very far from the point where MAKET-ANI experiment claimed the detection of a signal. The expected number of directions above 4σ in the normal Gaussian distribution with 6000 trials is 0.19, and the probability to get more than 2 in the Poisson distribution with mean value of 0.19 is 1.6×10^{-2} . So, the deviation may be due to statistical fluctuations. No significant deviation of significance distribution from a normal Gaussian distribution was found in the other energy thresholds (> 500 TeV, > 800 TeV, > 2 PeV). We also set 99% confidence-level flux upper limits of $2.6 \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1}$ and $5.4 \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1}$ on the steady gamma rays > 1 PeV from the PSR B0656+14 and Geminga, respectively, assuming point-like sources with differential energy spectral index -2.0 . The KASCADE group also reported that no significant sub-PeV signal was seen at the suggested location by the MAKET-ANI experiment and the PSR B0656+14 by an analysis optimized for a point-like source [6].

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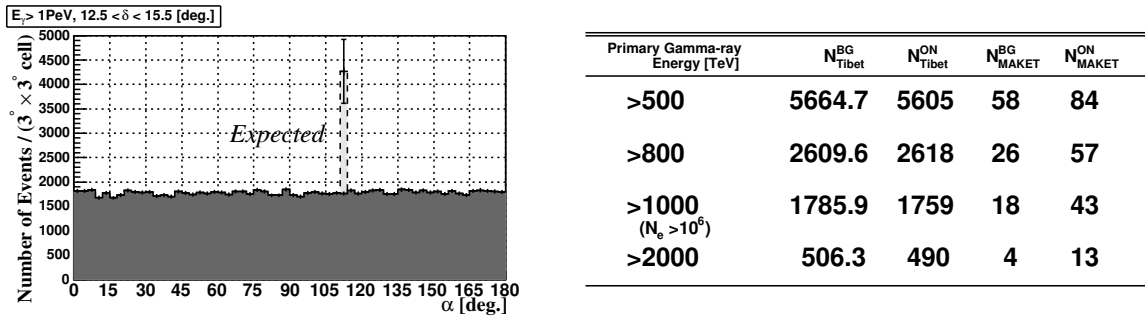


Figure 1. Left: Number of events above 1 PeV in the declination band of 12.5° – 15.5° observed by the Tibet air shower array. The shaded histograms represent our actual result, while the dashed histogram denotes the number of events expected from the MAKET-ANI result. Right: Energy dependence of the number of events in the cell $111^\circ \leq \alpha < 114^\circ$, $12.5^\circ \leq \delta \leq 15.5^\circ$ (N^{ON}) and the background (N^{BG}). The primary gamma-ray energy of the MAKET-ANI experiment was estimated by the air shower size reported in Chilingarian et al. [1], where $N_e > 10^6$ at MAKET-ANI altitude corresponds to >1 PeV [5] and we scaled the other energies. N^{BG} is a mean value of the background cells in the declination band $12.5^\circ \leq \delta \leq 15.5^\circ$.

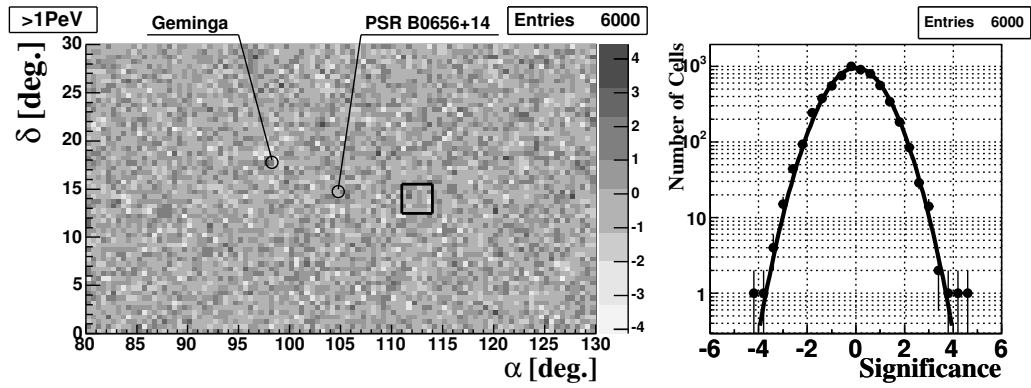


Figure 2. Left: Significance map in the Monogem Ring region and around it above 1 PeV. The rectangular region indicates the area where the MAKET-ANI experiment claimed a positive detection of a signal. Right: Significance distribution in the region shown in the map. The solid line indicates a normal Gaussian fit to the data.

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