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Observation of the Fermi pulsar catalog at TeV energies with the Tibet air shower experiment

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Abstract. Using the Tibet-III air shower array, we search for steady TeV γ-rays from 18 pulsars in the Fermi Large Area Telescope pulsar catalog. Among them, we observe 8 sources including the Crab instead of the expected

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0.41 sources at a significance of 2σ or more excess. Under the assumption of Poisson distribution, the chance probability is estimated to be 1.4×10^{-8}. When the Crab is excluded, it becomes 1.8×10^{-7}. These low chance probabilities clearly show that the Fermi pulsars have a statistically significant correlations with TeV γ-ray excesses.

1 Introduction

The Tibet air shower array has been operating at Yangbajing Cosmic Ray Observatory (90.522° E, 30.102° N; 4300 m above sea level) in Tibet, China since 1990 (Amenomori et al., 1992). We observe cosmic rays and γ-rays using the extensive air shower technique of a scintillation detector array with a duty cycle of about 24 h every day regardless of weather conditions and with a wide field of view of about 2 s. These capabilities give us an unbiased survey of the northern sky. After several upgrades, the Tibet-III array was completed and started collecting data in the late 1999s.

On the other hand, the Fermi Gamma-ray Space Telescope (Fermi) (http://fermi.gsfc.nasa.gov/) was launched in June 2008 to cover the energy range of 20 MeV to 300 GeV, with a sensitivity approximately a hundred times better than that of the Energetic Gamma Ray Experiment (EGRET). The Large Area Telescope (LAT) on board the Fermi satellite surveyed the entire sky for 3 months, after which the 205 most significant sources were published in a bright source list above 100 MeV at a significance greater than $\sim10\sigma$ (Abdo et al., 2009a). The typical 95% uncertainty radius of source position in this list is in the 10 to 20′ range; these values are greatly improved compared to those of EGRET. This provides a more accurate, unbiased search for common sources across multi wavelengths, compared with the EGRET era.

Recently, the Milagro experiment reported 14 of the 34 Fermi sources selected from the list at a false-positive significance of 3σ or more at the representative energy of 35 TeV (Abdo et al., 2009b). The Tibet AS array also found statistically significant correlation between the Fermi bright sources and TeV γ-ray excesses at 3 TeV (Amenomori et al., 2010a).

In this paper, we report on a search for TeV γ-ray sources in the first pulsar catalog of the Fermi LAT (Abdo et al., 2010) with the Tibet-III array. We also discuss simple statistical tests for our results and possible coincidences with the Milagro observations.

2 Tibet III Air Shower Array

The array consists of 533 plastic scintillation detectors of $0.5\,\mathrm{m}^2$ placed at grid point 7.5 m apart, and its coverage area is approximately $22{,}050\,\mathrm{m}^2$ (Amenomori et al., 2003). Each detector, called a fast-timing (FT) detector, has an FT photomultiplier tube to collect scintillation photons. The number of air shower particles and the arrival timing of particles at each detector are recorded, allowing us to estimate primary cosmic ray or γ-ray direction and energy for each air shower. The systematic uncertainty of the absolute energy scale observed by the Tibet-III array in the multi-TeV region is calibrated to be less than ±12% using the Moon's shadow observation (Amenomori et al., 2009). The single-event angular resolution is estimated to be 0.9° for mode energy 3 TeV, although it depends on the observed number of air shower particles. Comparing the amount of deficit caused by the Moon by the MC simulation and the data, the angular resolution is confirmed (Amenomori et al., 2000). The systematic pointing error is also estimated to be smaller than 0.011°. It is verified by the displacement of the center of the Moon's shadow in the north-south direction (Amenomori et al., 2009).

Using the Tibet-III and previous arrays, we have successfully observed TeV γ-ray sources, such as the Crab Nebula (Amenomori et al., 1999, 2009), Mrk 501 (Amenomori et al., 2000), and Mrk 421 (Amenomori et al., 2003). We have also successfully drawn a precise two-dimensional map of the large scale cosmic-ray anisotropy in the northern sky (Amenomori et al., 2006), where we first pointed out new small-area enhancements in the Cygnus arm direction at multi-TeV energies. One of the enhancements is coincident with MGRO J2019+37, which was established recently by the Milagro experiment as a TeV γ-ray source (Abdo et al., 2007). It is worth noting that the Tibet ASγ experiment has reported several times (Zhang, 2003, 2005; Zhang et al., 2005) on the marginal excesses from the direction closing (0.9° apart) to MGRO J1908+06/HESS J1908+063 before the final discovery made by the Milagro experiment.

3 Air Shower data analysis

We analyze the air shower data set collected by the Tibet-III array during 1915.5 days live time from November 1999 through December 2008. To extract an excess of TeV γ-ray air shower events coming from the direction of a target source in this analysis, we adopt almost the same event selections and the background estimation method published in our previous work (Amenomori et al., 2003, 2009). We use air shower events with $\sum\rho\mathrm{FT}>10^{1.25}$ as the primary energy reference, where the size $\sum\rho\mathrm{FT}$ is defined as the sum of the number of particles per m^2 for each FT detector. The modal γ-ray energy, assuming the Crab's direction and integral spectral index -1.6, is calculated to be approximately 3 TeV by the Monte Carlo simulation. The modal γ-ray energy depends on the declination and is estimated to be ~3 TeV for a declination band from 20° to 40° and ~6 TeV for declinations at 0° and 60°, respectively. The search window radius centered at the target source is expressed by $\mathrm{R}(\sum\rho\mathrm{FT})=6.9/\sqrt{\sum\rho\mathrm{FT}}$ degrees, which is shown to maximize the signal-to-noise ratio by Monte Carlo

Table 1. Summary of the Tibet III array survey on the direction of Fermi pulsars. The column "γ-ray selected" means the source discovered by searching for pulsed signals at the positions of bright gamma-ray sources seen with the Fermi LAT.
References: (1) Roberts et al. (2005); (2) Abdo et al. (2009b); (3) Djannati-Atai et al. (2007); (4) Green (2009)

Pulsar Name (Other Associations)	Period [ms]	γ-ray selected	Tibet-III Sig. [σ]	Pulsar Name (Other Associations)	Period [ms]	γ-ray selected	Tibet-III Sig. [σ]
J0030+0451	4.9		1.6	J1907+06	107	Yes	2.6
J0218+4232	2.3		-0.2	(MGRO J1908+06[2]/HESS J1908+063[3])			
J0357+32	444	Yes	-1.2	J1952+3252	39.5		-0.2
J0534+2200 (Crab)	33.1		7.1	(SNR CTB80[4])			
(SNR/PWN G184.6-5.8)				J1958+2846	290	Yes	0.1
J0631+1036	288		-0.0	J2021+3651	104		2.2
J0633+0632	297	Yes	2.4	(PWN G75.2+0.1[1])			
J0633+1746 (Geminga)	237	Yes	2.3	J2021+4026	265	Yes	2.2
(PWN G195.1+4.3[1])				(SNR γCygni[4])			
J0659+1414	385		0.7	J2032+4127	143	Yes	2.9
(SNR203.0+12.0)				(MGRO J2031+41[2])			
J0751+1807	3.5		1.3	J2043+2740	96.1		-0.1
J1836+5925	173		-0.3	J2238+59	163	Yes	2.4

study assuming a pointlike γ-ray source (Amenomori et al., 2003). Therefore, an excess might be underestimated if the target source actually extends beyond our angular resolution size.

We select 18 pulsars in the declination band between 0° and 60° from the Fermi pulsar catalog, because of the our sensitive field of view for TeV γ-ray sources.

4 Result and Discussion

The Tibet-III array observation of the selected 18 Fermi pulsars is summarized in Table 1. As a result of this excess search for these sources, we did not find statistically significant evidence for TeV γ-rays from other individual sources except for the Crab, which is recognized as the brightest standard TeV source.

Subsequently, the distribution of the observed significance is examined for statistical consistency with the normal Gaussian. Figure 1 shows the significance distribution of the 18 sources observed by the Tibet-III array. One can see that the γ-rays from the Crab are detected at a sufficiently high significance of $7.1\,\sigma$. It should be emphasized that we observe 8 sources including the Crab at a significance of $2\,\sigma$ or more in this distribution, against an expected 0.41 source (upper probability of $2\,\sigma$ multiplied by 18 sources) from the normal Gaussian. Since the expected number is small and this phenomenon should be a discrete, we can adapt Poisson statistics to these 8 sources. So the chance probability would be estimated as 1.4×10^{-8}. With the Crab excluded, the chance probability would be estimated as 1.8×10^{-7}. This low chance probability clearly shows that the Fermi pulsar have statistically significant correlations with the TeV γ-ray excesses.

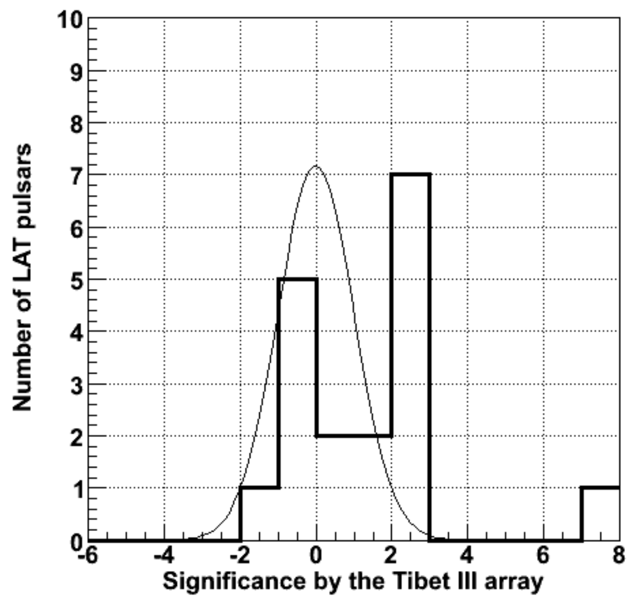

Fig. 1. Histogram shows significance distribution of 18 Fermi pulsars observed by the Tibet-III array. The largest one (which has $7\,\sigma$) shows Crab pulsar. The dashed line shows the normal Gaussian. (Amenomori et al., 2010b)

In order to check the possible bias of the data sample, spatially independent dummy sources are selected from the northern sky except for the Crab, Mrk 421, and two famous large scale cosmic-ray anisotropy regions known as the Loss-Cone and the Tail-In regions (Amenomori et al., 2006). As a result, the significance distribution of ~ 2000 dummy sources is consistent with the normal Gaussian with a mean value of $m = -0.010 \pm 0.025$ and a standard devia-

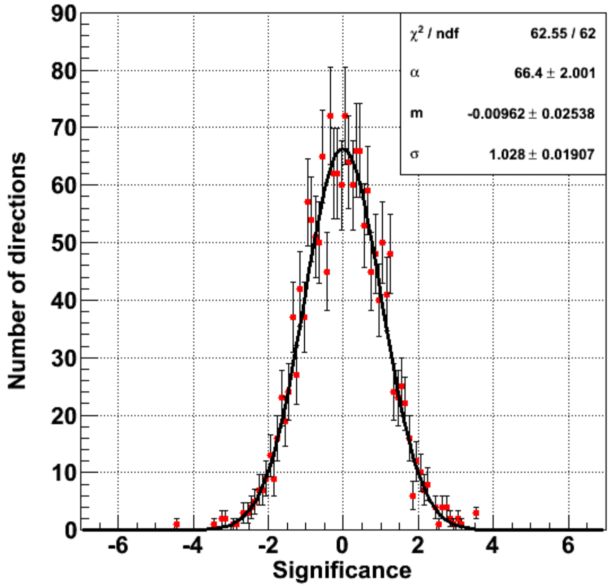

Fig. 2. Point shows the significant distribution simulated with ∼ 2000 dummy sources randomly selected from the FOV of the Tibet AS array. Line and parameters show the result of fitting by normal Gaussian. (Amenomori et al., 2010b)

tion of $\sigma = 1.028 \pm 0.019$ (Fig. 2).

If the significance distribution observed by the Tibet-III array has a density gradient toward the Galactic plane, the expected number of sources at $2\,\sigma$ or more may be enhanced in chance association. To check this, we perform a simple Monte Carlo simulation in a similar way to that implemented by Romero et al. (1999). We generate 2000 dummy-source lists of the 18 Fermi pulsars, where the Galactic latitude distributions retain the form of the actual histograms of the Fermi sources with the Galactic longitudes randomly set to new distributions within our field of view. In this case, the expected number of the source at a significance of $\geq 2\sigma$ becomes 0.49 and the corresponding chance probability would be 5.3×10^{-8}.

The Milagro observation found 14 out of 34 Fermi sources at a significance of $3\,\sigma$ or more, and its sensitivity is approximately 2 or 3 times better than that of the Tibet-III array. Hence, our threshold significance $2\,\sigma$, which corresponds to $\sim 30\%$ of the Crab flux assuming a point-like source, should be a reasonable value.

5 Conclusion

As a result of the searching of the direction of 18 pulsars in the Fermi pulsar catalog, we found a statistically significant correlation between Fermi pulsars and TeV γ-ray excesses. On the other hand, the maximum significance positions obtained by the Tibet-III array might be shifted from the pulsar positions. The same tendency is also found in the report from Milagro (Abdo et al., 2009b), so these observations would imply that the excesses are possible candidates for TeV pulsar wind nebulae. The correlation between TeV and GeV γ-rays is being realized by the wide sky survey instruments, such as the Tibet-III array and the Milagro experiment, in the early Fermi era.

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