OBSERVATION OF TeV GAMMA RAYS FROM THE FERMI BRIGHT GALACTIC SOURCES WITH THE TIBET AIR SHOWER ARRAY

M. AMENOMORI1, X. J. BI2, D. CHEN3, S. W. CUI4, DANZENGLUOBU5, L. K. DING2, X. H. DING5, C. FAN2,6, C. F. FENG6, ZHAOYANG FENG2, Z. Y. FENG7, X. Y. GAO8, Q. X. GENG8, Q. B. GOU9, H. W. GUO8, H. H. HE1, M. HEB6, K. HIBINO6, N. HOTTA10, HAIBING HU5, H. B. HU2, J. HUANG2, Q. HUANG7, H. Y. JIA7, L. JIANG2,8, F. KAJINO11, K. KASAHERA12, Y. KATAYOSE13, C. KATO14, K. KAWATA3, LABACIREN5, G. M. LE15, A. F. LU6, H. C. LI2,4, J. Y. LI6, C. LIU2, Y. Q. LOI16, H. LU2, X. R. MENG5, K. MIYUTANI12,17, J. MU8, K. MUNAKATA14, H. NAMIO1, M. NISHIZAWA18, M. OHISHI3, I. OHTA19, S. OZAWA12, T. SAITO20, T. Y. SAITO21, M. SAKATA11, T. K. SAKO3, M. SHIBATA13, A. SHIOMI22, T. SHIRAI22, H. SUGIMOTO23, M. TAKITA1, Y. H. TAN2, N. TATEYAMA9, S. TORII12, H. TSUCHIYA24, S. UDO2, B. WANG2, H. WANG24, Y. WANG2, Y. G. WANG6, H. R. WU2, L. XUE6, Y. YAMAMOTO11, C. T. YAN25, X. C. YANG5, S. YASUE26, Z. H. YE27, G. C. YU1, A. F. YUAN1, T. YUDA1, H. M. ZHANG2, J. L. ZHANG2, N. J. ZHANG9, Y. ZHANG2, YI ZHANG2, YING ZHANG2,7, ZHAXISANGZHU5, and X. X. ZHOU7

(The TIBET ASγ Collaboration)

1 Department of Physics, Hirokasi University, Hirokasi 036-8561, Japan
2 Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
3 Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan
4 Department of Physics, Hebei Normal University, Shijiazhuang 050016, China
5 Department of Mathematics and Physics, Tibet University, Lhasa 850000, China
6 Department of Physics, Shandong University, Jinan 250100, China
7 Institute of Modern Physics, SouthWest Jiaotong University, Chengdu 610031, China
8 Department of Physics, Yunnan University, Kunming 650091, China
9 Faculty of Engineering, Kanagawa University, Yokohama 221-8886, Japan
10 Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan
11 Department of Physics, Konan University, Kobe 658-8501, Japan
12 Research Institute for Science and Engineering, Waseda University, Tokyo 169-8555, Japan
13 Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan
14 Department of Physics, Shinshu University, Matsumoto 390-8621, Japan
15 National Center for Space Weather, China Meteorological Administration, Beijing 100081, China
16 Physics Department and Tsinghua Center for Astrophysics, Tsinghua University, Beijing 100084, China
17 Saitama University, Saitama 338-8570, Japan
18 National Institute of Informatics, Tokyo 101-8430, Japan
19 SakuShin Gakuen University, Utsunomiya 321-3025, Japan
20 Tokyo Metropolitan College of Industrial Technology, Tokyo 116-8523, Japan
21 Max-Planck-Institut für Physik, München D-80805, Germany
22 College of Industrial Technology, Nihon University, Narashino 275-8576, Japan
23 Shonan Institute of Technology, Fujisawa 251-8511, Japan
24 RIKEN, Wako 351-0198, Japan
25 Institute of Disaster Prevention Science and Technology, Yinan 065201, China
26 School of General Education, Shihin University, Matsumoto 390-8621, Japan
27 Center of Space Science and Application Research, Chinese Academy of Sciences, Beijing 100080, China

Received 2009 October 4; accepted 2009 December 1; published 2009 December 29

ABSTRACT

Using the Tibet-III air shower array, we search for TeV γ-rays from 27 potential Galactic sources in the early list of bright sources obtained by the Fermi Large Area Telescope at energies above 100 MeV. Among them, we observe seven sources instead of the expected 0.61 signals at a significance of 2σ or more excess. The chance probability from Poisson statistics would be estimated to be 3.8 × 10−5. If the excess distribution observed by the Tibet-III array has a density gradient toward the Galactic plane, the expected number of sources may be enhanced in chance association. Then, the chance probability rises slightly, to 1.2 × 10−5, based on a simple Monte Carlo simulation. These low chance probabilities clearly show that the Fermi bright Galactic sources have statistically significant correlations with TeV γ-ray excesses. We also find that all seven sources are associated with pulsars, and six of them are coincident with sources detected by the Milagro experiment at a significance of 3σ or more at the representative energy of 35 TeV. The significance maps observed by the Tibet-III air shower array around the Fermi sources, which are coincident with the Milagro 3σ sources, are consistent with the Milagro observations. This is the first result of the northern sky survey of the Fermi bright Galactic sources in the TeV region.

Key words: gamma rays: general – pulsars: general – ISM: supernova remnants

1. INTRODUCTION

The Fermi Gamma-ray Space Telescope (Fermi), succeeding the Energetic Gamma Ray Experiment (EGRET), 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 EGRET. The Large Area Telescope (LAT) on board the Fermi 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 ~10σ (Abdo et al. 2009a). Remarkably, this survey detected many new γ-ray pulsars. A typical 95% uncertainty radius of source position in this list is approximately 10′ and the maximum is 20′; these values are greatly improved compared to those of
the EGRET. This provides a more accurate, unbiased search for common sources across multi wavelengths, compared with the EGRET era. Recently, the Milagro experiment observed 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).

In this Letter, we report on a search for TeV γ-ray sources in the Fermi bright source list with the Tibet-III air shower array (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 Tibet air shower array has been operating at Yangbajing Cosmic Ray Observatory (90°:522 east, 30°:102 north; 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 hr every day regardless of weather conditions and with a wide field of view of about 2 sr. 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. This array consists of 533 plastic scintillation detectors of 0.5 m² placed at grid point 7.5 m apart, and its coverage area is approximately 22,050 m² (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 modal energy 3 TeV, although it depends on the observed number of air shower particles. The systematic pointing error is also estimated to be smaller than 0:011. These are verified by the Moon’s shadow observation (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 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 live days 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 \( \sum \rho_{FT} > 10^{1.25} \) as the primary energy reference, where the size \( \sum \rho_{FT} \) is defined as the sum of the number of particles per m² for each FT detector. The modal γ-ray energy, assuming the Crab’s orbit 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 \( R(\sum \rho_{FT}) = 6.9 / \sqrt{\sum \rho_{FT}} \) degrees, which is shown to maximize the signal-to-noise ratio by Monte Carlo study assuming a point-like γ-ray source (Amenomori et al. 2003). Therefore, an excess might be underestimated if the target source actually extends beyond our angular resolution size.

The target sources in the Fermi bright source list are chosen as confirmed or potential Galactic sources in a similar way to that employed by the Milagro observation (Abdo et al. 2009b). Out of the 205 most significant sources in the Fermi bright source list, 83 are not identified as extragalactic sources (Abdo et al. 2009a). Among these 83, we select 27 sources in the declination band between 0° and 60°, corresponding to our sensitive field of view for TeV γ-ray sources.

4. RESULTS AND DISCUSSION

The Tibet-III array observation of the selected 27 Fermi bright Galactic sources is summarized in Table 1, where 13 of the selected sources are classified as pulsars (PSRs), five are supernova remnants (SNRs), and nine remain unidentified but are potential Galactic sources, as they are mostly concentrated in the Galactic plane (|b| < ~20°; Abdo et al. 2009a). As a result of this excess search for these sources, we find no 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 27 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 6.9σ. It should be emphasized that we observe seven sources including the Crab at a significance of 2σ or more in this distribution, against an expected 0.61 source (upper probability of 2σ multiplied by 27 sources) from the normal Gaussian. The chance probability from Poisson statistics would be estimated as 3.8 × 10^{-6}. With the Crab excluded, the chance probability would be estimated as 3.6 × 10^{-3}. This low chance probability clearly shows that the Fermi bright Galactic sources have statistically significant correlations with the TeV γ-ray excesses. 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). The Loss-Cone and the Tail-In regions are separated from the selected 27 Fermi sources. 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 deviation of \( \sigma = 1.027 \pm 0.019 \). If the significance distribution observed by the Tibet-III array has a density gradient toward the Galactic plane, the expected number of sources at 2σ 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 27 Fermi bright Galactic sources, 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. We count the number of ≥2σ sources in the Tibet-III data according to each dummy-source list and calculate that the average expected number of sources at 2σ or more is 0.73±0.02 in the chance association. In this case, the chance probability associated with seven sources or more goes up slightly, to 1.2×10^{-5}, while it becomes 9.7×10^{-5} with the Crab excluded.

The Milagro observation found 14 out of 34 Fermi sources at a significance of 3σ or more, and its sensitivity is approximately 2 or 3 times better than that of the Tibet-III array. Hence, our threshold significance 2σ, which corresponds to ∼30% of the Crab flux assuming a point-like source, should be a reasonable value. We note that the flux of 0FGL J2020.8+3649 seems to be quite low compared with the Milagro’s, since the flux measurement of 0FGL J2020.8+3649 with the Milagro experiment is (67±7)% of the Crab flux above 35 TeV, while our flux is (30±14)% of the Crab flux above 3 TeV. The statistical difference between them is calculated to be 2.3σ. This.

Table 1

| Fermi LAT Source (0FGL) | Class | R.A. (deg) | Decl. (deg) | Tibet-III Signi. (σ) | Milagro* Signi. (σ) | Source Associations |
|-------------------------|-------|------------|-------------|----------------------|---------------------|-------------------|
| J0030.3+0450            | PSR   | 7.600      | 4.848       | 1.7                  | -1.7                |                   |
| J0357.5+3205            | PSR   | 59.388     | 32.084      | -1.7                 | -0.1                |                   |
| J0534.6+2201            | PSR   | 83.653     | 22.027      | 6.9                  | 17.2                | Crab              |
| J0617.4+2234            | SNR   | 94.356     | 22.568      | 0.2                  | 3.0                 | IC 443            |
| J0631.8+1034            | PSR   | 97.955     | 10.570      | 0.3                  | 3.7                 |                   |
| J0633.5+0634            | PSR   | 98.387     | 6.578       | 2.4                  | 1.4                 |                   |
| J0634.0+1745            | PSR   | 98.503     | 17.760      | 2.2                  | 3.5                 | Geminga           |
| J0643.2+0858            |       | 100.823    | 8.983       | -1.2                 | 0.3                 |                   |
| J1813.3+067             |       | 277.583    | 6.287       | -0.2                 | 0.2                 |                   |
| J1836.2+5924            | PSR   | 279.056    | 59.406      | -0.3                 | -0.9                |                   |
| J1855.9+0126            | SNR   | 283.985    | 1.435       | 0.7                  | 2.2                 | W44               |
| J1900.0+0356            |       | 285.009    | 3.946       | 1.0                  | 3.6                 |                   |
| J1907.5+0602            | PSR   | 286.894    | 6.034       | 2.4                  | 7.4                 | MGRO J1908+068   |
| J1911.0+0905            | SNR   | 287.761    | 9.087       | 1.7                  | 1.5                 | G43.3 - 0.2      |
| J1923.0+1411            | SNR   | 290.768    | 14.191      | -0.3                 | 3.4                 | W51               |
| J1953.2+3249            | PSR   | 298.325    | 32.818      | -0.0                 | 0.0                 |                   |
| J1954.4+2838            | SNR   | 298.614    | 28.649      | 0.6                  | 4.3                 | G65.1+0.6        |
| J1958.1+2848            | PSR   | 299.531    | 28.803      | 0.1                  | 4.0                 |                   |
| J2001.0+4352            |       | 300.272    | 43.871      | -0.5                 | -0.9                |                   |
| J2020.8+3649            | PSR   | 305.223    | 36.830      | 2.2                  | 12.4                | MGRO J2019+37    |
| J2021.5+4026            | PSR   | 305.398    | 40.439      | 2.2                  | 4.2                 |                   |
| J2027.5+3334            |       | 306.882    | 33.574      | -0.3                 | -0.2                |                   |
| J2032.2+4122            | PSR   | 308.058    | 41.376      | 2.4                  | 7.6                 | TeV J2032+4130   |
| J2055.5+2540            |       | 313.895    | 25.673      | -0.0                 | -0.0                |                   |
| J2110.8+6608            |       | 317.702    | 46.137      | 0.3                  | 1.1                 |                   |
| J2214.8+3002            |       | 333.705    | 30.049      | -1.0                 | 0.6                 |                   |
| J2302.9+4443            |       | 345.746    | 44.723      | -0.0                 | -0.6                |                   |
| LAT PSR J2238+59        | PSR   | 339.561    | 59.080      | 2.5                  | 4.7                 |                   |

Notes.

* Significance of the Milagro observations. Taken from Abdo et al. (2009b).

b These pulsars are newly discovered by the Fermi LAT observations (Abdo et al. 2009a, 2009c).

c This pulsar is not in the Fermi bright source list, but it is detected by the latest Fermi LAT observation (Abdo et al. 2009c).

Figure 1. Histograms show significance distribution of the Fermi bright sources observed by the Tibet-III array. The dashed curve is the expected normal Gaussian distribution.
difference may be explained by either statistical fluctuations, a harder energy spectrum than that of the Crab, or an extended source instead of the assumed point-like source in this analysis.

We also find that all seven sources at 2σ or more are associated with pulsars, and six of them are coincident with sources detected by the Milagro experiment at a significance of 3σ or more at the representative energy of 35 TeV. The remaining source still has a positive significance of 1.4σ measured by the Milagro experiment. Furthermore, the latest Fermi LAT observations detected 16 γ-ray pulsars in the blind frequency searches (Abdo et al. 2009c), among which only LAT PSR J2238+59 is a new pulsar not included in the Fermi bright source list. We also find a 2.5σ excess associated with LAT PSR J2238+59, as listed in Table 1. The location of this pulsar is observed at a significance of 4.7σ by the Milagro experiment (Abdo et al. 2009b). In this connection, the first Fermi LAT catalog including 46 γ-ray pulsars has been published using the first 6 months of data (Abdo et al. 2009d). We remark that no pulsed emission has ever been detected from γ-ray pulsars above a few tens of GeV (Aliu et al. 2008).

Around the Fermi Galactic bright sources with ≥2σ significance by the Tibet-III data and ≥3σ by the Milagro data except for the Crab, we compare significance maps between the Tibet-III array (a)–(d) and the Milagro experiment (a′)–(d′) taken from Abdo et al. (2009c). Selected are Fermi sources with ≥2σ significance by the Tibet-III array and ≥3σ by the Milagro experiment except for the Crab. White points in each image show the Fermi source positions: (a and a′) J1907.5+0602/J1900.0+0356; (b and b′) J0634.0+1745 (Geminga); (c and c′) J2021.5+4026/J2032.2+4122; (d and d′) J2020.8+3649. The horizontal axis, vertical axis, and color contours indicate the right ascension, declination, and significance, respectively.
Abdo et al. (2009b) in Figure 2. Each image has a 5° × 5° region including one or two Fermi sources. It is remarkable that the Tibet-III array obtains images consistent with those observed in the Milagro experiment. Besides, the maximum significance positions obtained by both the Tibet-III array and the Milagro experiment might be shifted from the pulsar positions. In fact, recent imaging air Cherenkov telescopes also discovered many candidates for TeV pulsar wind nebulae (PWNe), which are displaced within a few tenths of degree from the pulsars in the southern sky (Aharonian et al. 2006, 2007). Thus, these observations would imply that the excesses are possible candidates for TeV PWNe. 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.

Note added in proof. In this catalog, 18 pulsars are located in the Tibet-III field of view. Among them, 14 pulsars are listed in Table 1 including LAT PSR J2238+59. We find no significant excess at 2σ or more from the other four pulsar locations not listed in Table 1. Using the first Fermi LAT pulsar catalog, we find that 8 out of 18 pulsar locations have a significance of 2σ or more. In this case, the chance probability falls to 1.4 × 10^{-8}, while it becomes 1.8 × 10^{-7} with the Crab excluded.

The collaborative experiment of the Tibet Air Shower Arrays has been performed under the auspices of the Ministry of Science and Technology of China and the Ministry of Foreign Affairs of Japan. This work was supported in part by a Grant-in-Aid for Scientific Research on Priority Areas from the Ministry of Education, Culture, Sports, Science and Technology, by Grants-in-Aid for Science Research from the Japan Society for the Promotion of Science (JSPS) in Japan, and by the grants from the National Natural Science Foundation of China, the Chinese Academy of Sciences, and the Ministry of Education of China. K.K. is supported by Grant-in-Aid for JSPS Fellows 21-9437.

REFERENCES

Abdo, A. A., et al. 2007, ApJ, 664, L91
Abdo, A. A., et al. 2009a, ApJS, 183, 46
Abdo, A. A., et al. 2009b, ApJ, 700, L127
Abdo, A. A., et al. 2009c, Science, 325, 840
Abdo, A. A., et al. 2009d, ApJS, in press (arXiv:0910.1608)
Aharonian, F., et al. 2006, ApJ, 636, 777
Aharonian, F., et al. 2007, A&A, 472, 489
Aliu, E., et al. 2008, Science, 322, 1221
Amenomori, M., et al. 1992, Phys. Rev. Lett., 69, 2468
Amenomori, M., et al. 1999, ApJ, 525, L93
Amenomori, M., et al. 2000, ApJ, 532, 302
Amenomori, M., et al. 2003, ApJ, 598, 242
Amenomori, M., et al. 2006, Science, 314, 439
Amenomori, M., et al. 2009, ApJ, 692, 61
Romero, G. E., Benaglia, P., & Torres, D. F. 1999, A&A, 348, 868
Zhang, J. L. 2003, in Proc. 28th Int. Cosmic Ray Conference, Vol. 4, ed. T. Kajita et al. (Tokyo: Universal Academy Press, Inc.), 2405
Zhang, J. L. 2005, in Proc. 29th Int. Cosmic Ray Conference, Vol. 4, ed. B. Sripathi Acharya et al. (Mumbai: Tata Institute of Fundamental Research), 93
Zhang, J. L., Tan, Y. H., Lu, H., & Wang, H. 2005, Chin. Phys. Lett., 22, 1560