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ABSTRACT

Search for 10 TeV Gamma-Ray Emission from Active Galactic Nuclei with the Tibet Air Shower Array

The Tibet AS γ Collaboration

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A search for 10 TeV γ -ray emission from 15 active galactic nuclei (AGNs) which were detected by EGRET, was made with the Tibet air shower array installed at an elevation of 4300 m above sea level. The data set, taken in the period from 1990 June 18 through 1992 September 29, has been used to search for continuous emission as well as emission on the time scale of 1 day. No evidence for emission from any of the AGNs on any of the time scales examined was found. The 95% Confidence Level upper limit to the continuous flux is presented on each source, and in particular the result for Markarian 421 is compared with other experiments. Further observation of γ -rays at energies around 10 TeV from nearby AGNs will provide reliable information on the strength of the intergalactic background photon field.

Subject headings: cosmic rays – galaxies : active – galaxies : nuclei – gamma-rays : observations – quasars : individual (Markarian 421)

1. Introduction

Recently the Energetic Gamma-Ray Experiment Telescope (EGRET) on board the Compton GRO has reported 18 extragalactic objects as powerful γ -ray emitters above 100 MeV with high certainty (Fichtel 1994 for a general review). Some of these have also been observed to be variable on the emission of γ -rays, changing their intensities by a factor of ~ 4 within a few days (Mattox et al. 1993 ; Kniffen et al. 1993). The energy spectra of γ -rays observed are quite hard, with differential spectral indices ranging from -1.7 to -2.4, suggesting that the flux at TeV energies may be high enough to be observed. In fact, one of these objects, Markarian 421, which is the weakest and the closest AGN (redshift $z=0.031$) observed by EGRET (Lin et al. 1992), was also observed at

energies above 500 GeV by the Whipple Observatory collaboration (Punch et al. 1992 ; Mohanty et al. 1993). The apparent lack of the more distant AGNs emitting TeV γ -rays (Kerrick et al. 1993) could be attributed to scattering of TeV γ -rays by an intergalactic infrared radiation field (Gould & Schreder 1967a, b ; Stecker, De Jager, & Salamon 1992).

The EGRET results reveal to us that the emission of high-energy γ -rays is a common and dominant feature in AGNs with radio jets, and these could be the source of the extragalactic cosmic rays (Protheroe & Szabo 1992). Since there is no reason to suspect a physical cut off in the source energy spectrum at high energies, it is an obvious challenge to establish the energy spectrum at TeV energies and beyond. One model also shows that the flux of γ -rays from those objects could continue to 10 TeV or even higher (Atoyan 1992). This is further motivated by the Whipple observation of TeV γ -rays from Markarian 421 (Punch et al. 1992 ; Mohanty et al. 1993) with the flux falling well on the extrapolation of the EGRET spectrum. It is, however, pointed out that high-energy γ -rays from AGNs will be reduced by photon-photon interactions with the intergalactic infrared photon field before reaching Earth. For the nearer AGNs ($z < 0.2$), the effects of absorption are small in the energy region less than several 100 GeV, while above these energies and for more distant objects, the amount of absorption becomes significant. Its estimation, however, is inevitably attended with a large uncertainty since the intensity and energy spectrum of the intergalactic infrared photons are unknown. In other words, observations of high-energy γ -rays from AGNs will provide an estimate of the intergalactic infrared photon density which is much better than those obtained by direct measurements (Stecker & De Jager 1993).

High-energy γ -rays are also affected by the interactions with the 2.7 K microwave background radiation field. However, pair production interactions with this field will not produce a break in the spectrum from a nearby source

such as Markarian 421 below energies of ~ 100 TeV (Gould & Schreder 1966 ; 1967a, b ; Protheroe 1986).

From this point of view, search for possible γ -ray emission at VHE and UHE energies becomes a key subject for many ground-based Cerenkov mirror experiments and high-sensitivity air shower array experiments. In this paper we present results on the search for 10 TeV γ -ray emission from 15 AGNs in the northern sky, all of which have already been detected by EGRET, with the Tibet air shower array (Amenomori et al. 1992).

2. Experiment

The Tibet air shower array is located in Yangbajing at an altitude of 4300 m above sea level ($90^{\circ}.53$ E and $30^{\circ}.11$ N), corresponding to an atmospheric depth of 606 g/cm^2 . The array consists of 49 scintillation detectors of 0.5 m^2 each, which are distributed on a grid of 15 m spacing. Among them, 45 detectors (FT detectors) are equipped with fast response photomultipliers (PMTs) to measure the arrival direction of air showers with good accuracy. Since 1990 June the system has operated at a trigger rate of about 20 Hz under any 4-fold coincidence requirement in the FT detectors and recorded about 9×10^8 shower events during the period of 1990 June 18 through 1992 September 29. The effective running time for this period was 598.6 days.

A database was made by imposing the following conditions: 1. Each of any four FT detectors produces a signal with more than 1.25 particles. 2. Among the four detectors recording the highest particle densities, two or more are in the innermost 5×5 detectors. 3. The mean lateral spread of each shower $\langle r \rangle$ is less than 25 meters, where $\langle r \rangle = \sum r_i \rho_i / \sum \rho_i$ and r_i is the distance of the i th detector from the estimated shower center and ρ_i is its particle density. We call these the 'contained' events, and in total about 2.2×10^8 contained events are obtained.

Monte Carlo simulations were done to examine the performance of the array. It is found there (1) the mode energy of primary particles detected by this array is about 7 TeV for protons and 8 TeV for γ -rays and (2) detection efficiencies of the contained events at 10 TeV are about 18 % for proton-induced showers and 31 % for gamma-induced ones, respectively. Furthermore, the observation of the moon shadow, with a sufficiently high significance, has confirmed that the angular resolution of the array is better than 1° for all the contained events (Amenomori et al. 1993a, b).

3. Results and Discussions

A right ascension (RA) scan technique was used to search for a DC excess from an object concerned, that is, a circle of apparent radius of 1° was taken to calculate the number of events coming from the source region (Amenomori et al. 1992). This size, which contains about 50% of the signals, is optimized in order to have the best signal-to-noise ratio. The background was evaluated from events falling into the five windows adjacent to the source window on both the right and left sides at the same declination. A comparison of the source and background events was made to examine an excess of signals from the source direction. Among the 18 detected AGNs by EGRET (Fichtel 1994), 15 can be investigated in our sky survey. The target AGNs and the results of the search for continuous emission are listed in Table 1. In this observation, however, no evidence is found for steady emission of 10 TeV γ -rays from any object.

Upper limits on the excess number of events at the 95% confidence level were obtained for these AGNs by assuming that the background and signal obey the Poissonian distribution using the Protheroe procedure (Protheroe 1984), and the results are summarized in Table.1. Flux upper limits were calculated by the Monte Carlo simulation. Showers from γ -rays were generated

from a differential power-law spectrum of the form of $E^{-\beta}$ with $E_{\min} = 1$ TeV. The power index β was assumed to be 2.0 for each of AGNs. The results are presented in Table 1 and Fig.1.

Special attention should be paid to one of the AGNs, Markarian 421, because this is the most promising AGN for detection at energies around 10 TeV. The observed integral fluxes from EGRET (Lin et al. 1992) and the Whipple Observatory (Mohanty et al. 1993), and the flux upper limits obtained by our experiment, CYGNUS (Alexandreas et al. 1993) and CASA-MIA (Borione et al. 1993) are shown in Fig. 2. The straight line is a direct extrapolation from the EGRET data to the Whipple data (Mohanty et al. 1993), with the integral power index of -1.06. Our results almost fall on this line, giving an upper bound for the integral spectral index to this source.

Absorption of VHE γ -rays by photon-photon interactions depends strongly on the strength of the infrared photon field as well as the cosmological distance to the source. For γ -rays in the TeV energy range, the pair creation cross section is maximized when the soft photon energy is in the infrared range of $\epsilon_{\text{ph}} \sim 2(mc^2)^2/E \sim 0.5(1\text{TeV}/E)$ eV, corresponding to a wavelength of $\sim 2.5(E/1\text{TeV}) \mu\text{m}$ (Stecker et al. 1992). For Markarian 421, the TeV γ -ray differential spectrum with roughly E^{-2} power-law observed by the Whipple Observatory (Mohanty et al. 1993) shows no absorption at least up to an energy of several TeV. Stecker & De Jager (1993) have estimated new upper limits on the intergalactic infrared energy density in the 1-5 μm range, based on this Whipple result. Their 2σ upper limits are much lower than the direct observational upper limits by Matsumoto, Akiba, & Murakami (1988) and are consistent with radiation produced by stars in normal galaxies (Stecker Puget, & Fazio 1977). However, observational determinations of the intergalactic infrared and optical energy density are very difficult and generally give only upper limits which lie above theoretical estimates. So this always

involves many uncertainties. A theoretical upper limit for the infrared energy density was first estimated from starlight in normal galaxies by Stecker et al. (1977). On the other hand, somewhat lower estimates were made by Yoshii & Takahara (1988) and Tyson (1990) in the optical region, based on galaxy counts and some model calculations. For γ -rays from Markarian 421, this (“Stecker”) higher infrared background limit predicts a break in the spectrum at several TeV, while the spectrum seems to extend up to 10 TeV or more for the (“Tyson”) lower infrared background (Aharonian, Coppi, & Völk 1993). Thus, observations of Markarian 421 at energies around 10 TeV are urgently needed to confirm this.

We also searched for possible daily DC excesses from all these AGNs because the time scale of flux variability, if any, is closely related to the size of the emission region. Short time scale variations will indicate the existence of a very compact object, presumably a supermassive black hole which is fed by accretion. EGRET (Mattox et al. 1993 ; Kniffen et al. 1993 ; Fichtel 1993) has observed at least four AGNs having flux variations with a factor of 2 - 8 during several day observations. In the present case, the daily DC excess from each of the AGNs was calculated by the Li & Ma formula (Li & Ma 1983). It is found that there is no significant daily DC excess from any object. As an example, in Fig.3 are presented the distributions of Li & Ma sigma for three of the AGNs which were found to have somewhat large flux variations by EGRET. The solid curves in the figures are standard normal distribution. It can be seen that most of points fall on the expected curves although one or two points deviate somewhat with a slightly high significance. The maximum daily excess is observed to be 4.2σ (probability is 2×10^{-5}) for the source 1633+382. This significance, however, is obtained during 600 day observations, so that the probability times a trial factor as large as 600 is 1.2×10^{-2} . Hence the observed maximum excess is not statistically significant.

4. Summary

We have made a search for 10 TeV γ -rays from 15 AGNs which were detected by EGRET in the northern sky, using the data taken during the period of 1990 June 18 through 1992 September 29 with the Tibet air shower array. No evidence is found for steady and daily emission from any of the AGNs.

While γ -rays from nearby AGNs are significantly reduced by photon-photon interactions at TeV energies, there is still an opportunity to detect γ -rays from the nearest AGN, Markarian 421, at 10 TeV energies. The present Tibet air shower array will be scaled up by a factor of 4 (The effective area will be more than 8 times larger) in the very near future. Our several year observations of γ -rays from the nearest AGNs in the 10 TeV energy range could eventually lead to the actual measurement of the intergalactic infrared or far infrared background field and also yield exciting results on the acceleration of particles near or at these astrophysical objects.

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Table 1

Extragalactic EGRET sources and the results of the search for continuous emission.

Source	Energy	N_b^a	Excess	N_s^b	F^c (10^{-12} cm $^{-2}$ s $^{-1}$)
0202+149	≥ 10 TeV	32791	0.30σ	≤ 434	0.96
(4C+15.05)	≥ 30 TeV	1562	-0.02σ	≤ 84	0.16
0235+164	≥ 10 TeV	33572	-0.24σ	≤ 348	0.75
(OD+160)	≥ 30 TeV	1576	1.12σ	≤ 123	0.23
0420-014	≥ 10 TeV	15400	1.78σ	≤ 459	1.89
(OA+129)	≥ 30 TeV	742	0.40σ	≤ 63	0.23
0528+134	≥ 10 TeV	31230	-0.09σ	≤ 353	0.82
(PKS)	≥ 30 TeV	1473	1.28σ	≤ 123	0.24
0804+499	≥ 10 TeV	34302	1.00σ	≤ 519	1.08
	≥ 30 TeV	1617	-0.37σ	≤ 72	0.13
1101+384	≥ 10 TeV	41737	0.48σ	≤ 501	0.86
(Mrk 421)	≥ 30 TeV	1930	0.41σ	≤ 105	0.17
1226+023	≥ 10 TeV	19483	1.74σ	≤ 489	1.80
(3C 273)	≥ 30 TeV	931	1.07σ	≤ 87	0.26
1253-055	≥ 10 TeV	11190	1.89σ	≤ 386	2.20
(3C 279)	≥ 30 TeV	538	0.14σ	≤ 50	0.23
1406-076	≥ 10 TeV	8521	-0.58σ	≤ 166	1.17
	≥ 30 TeV	418	0.41σ	≤ 51	0.28
1510-089	≥ 10 TeV	7472	1.15σ	≤ 251	2.03
	≥ 30 TeV	376	0.70σ	≤ 49	0.29
1606+106	≥ 10 TeV	27937	-0.24σ	≤ 331	0.83
(4C+10.45)	≥ 30 TeV	1348	-1.30σ	≤ 51	0.11
1633+382	≥ 10 TeV	40668	-0.13σ	≤ 403	0.71
(4C+38.41)	≥ 30 TeV	1889	1.59σ	≤ 147	0.24
2230+114	≥ 10 TeV	29122	0.04σ	≤ 365	0.90
(CTA 102)	≥ 30 TeV	1365	-0.61σ	≤ 66	0.14
2251+158	≥ 10 TeV	33443	-1.66σ	≤ 238	0.52
(3C 454.3)	≥ 30 TeV	1561	-0.37σ	≤ 75	0.14
2356+196	≥ 10 TeV	36261	-1.37σ	≤ 267	0.54
	≥ 30 TeV	1680	0.64σ	≤ 102	0.18

^a Number of background events from source direction.

^b Number of signals from source direction (upper limit at 95 % confidence level).

^c Flux upper limits at 95 % confidence level.

Figure Captions

Fig. 1 Flux upper limits above 10 TeV and 30 TeV at the 95% confidence level for each AGN source. The solid curves show the cases of no excess events from the source directions.

Fig. 2 Observed γ -ray fluxes for Markarian 421 and flux upper limits obtained from this experiment (T), CYGNUS (C : Alexandreas et al. 1993) and CASA-MIA (CM : Borione et al. 1993). The flux extrapolation is based on a simple power-law assumption with the index -1.06 in the integral form.

Fig. 3 Distribution of daily excesses from three variable sources for comparison with a normalized Gaussian distribution centered on zero. The x-axis shows standard deviations, and the y-axis shows the frequency of observed days normalized to the total.

Fig. 1

Fig. 2

Fig. 3