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Search for Emission of Ultra High Energy Radiation from Active Galactic Nuclei

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Abstract

A search for emission of ultra-high energy gamma radiation from 13 active galactic nuclei that were detected by EGRET, using the CYGNUS extensive air-shower array, is described. The data set spans the period 1986 April 2 to 1993 January 1. The data set has been searched for continuous emission, emission on the time scale of one week, and for emission on the time scale of one day. No evidence for emission from any of the AGN on any of the time scales examined was found. The 90% C.L. upper limit to the continuous flux from Mrk 421 above 50 TeV is $7.5 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$.

1. INTRODUCTION The Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Observatory has observed high-energy gamma-ray emission from 16 active galactic nuclei (AGN) (Fichtel *et al.* 1993, Hartman *et al.* 1992). The gamma-ray spectra of these AGN are quite hard, with differential spectral indices ranging from -1.7 to -2.4 (Fichtel *et al.* 1993). The high energy emission from some of these objects has been observed to be variable, with measured intensities changing by a factor of ~ 4 within a few days (Fichtel *et al.* 1993).

One of the sources detected by EGRET, Mrk 421, has been detected above 500 GeV by the Whipple atmospheric Cerenkov telescope (Punch *et al.* 1992). Assuming that a simple power law energy spectrum connects these two observations, the integral gamma-ray flux from Mrk 421 can be represented as

$$\phi(> E) = 7.14 \times 10^{-12} E^{-1.07} \text{ cm}^{-2} \text{ s}^{-1} \quad (1)$$

with E measured in TeV.

Mrk 421 is the weakest and the closest AGN observed by EGRET. No other AGN has been observed to emit TeV gamma radiation. Scattering of TeV photons by an intergalactic infrared (IR) radiation field could be responsible for the apparent lack of TeV emission from the more distant AGN (Gould and Schreder 1987a,b, Stecker, De Jager, and Salamon 1992). Since the intensity and spectrum of the intergalactic IR field are unknown, in the following analysis it is assumed that there is no absorption due to an intergalactic IR radiation field.

The properties of the 2.7K cosmic microwave background radiation field (CMBR) are well known. It has been pointed out by several authors (Nikishov 1961, Jelley 1966, Gould and Schreder 1966, 1967a,b) that ultra-high energy (UHE) (~ 100 TeV) gamma rays will interact with this field and create electron-positron pairs, leading to a cutoff in the spectrum observed at earth. The calculation of flux upper limits presented here accounts for this effect.

2. THE CYGNUS EXPERIMENT The CYGNUS air shower array located in Los Alamos, NM, has been described elsewhere (Alexandreas *et al.* 1991, and Alexandreas *et al.* 1993). This paper describes the analysis of 350 million events taken with the CYGNUS-I array from 1986 April to 1993 January.

For a source passing through zenith ($\delta = 36^\circ$) the median primary energy for gamma-ray-initiated events is ~ 70 TeV, assuming that cosmic gamma rays and cosmic rays have similar energy spectra. The median detected primary energy increases with zenith angle.

The CYGNUS-I array has two muon detectors. The first muon detector (Allen *et al.* 1992) is a $\sim 44 \text{ m}^2$ array of multiwire proportional chambers. The minimum energy required for a muon to penetrate the detector's shielding is 2 GeV. The second muon detector was originally a 70 m^2 liquid scintillator detector. This detector was used for muon identification in 1987 between January 22 and May 14, and again in 1990 from May to November. In November of 1990 the liquid scintillator was replaced by 26 scintillation counters (total area $\sim 46 \text{ m}^2$). The minimum energy required for a muon to penetrate the shielding was 5 GeV. In 1991 October the scintillation counters were moved to a shielded room, a minimum muon energy required to penetrate the shielding is 0.7 GeV.

3. SEARCH STRATEGY AND RESULTS The search method has been described elsewhere (Alexandreas *et al.* 1993). The source bin spans 2.0° in declination (δ) and $2.0^\circ/\cos\delta$ in right ascension. We have searched for emission from all of the AGN detected by EGRET that are visible from our latitude (see Table 1). Given the presence of both steady and variable components to the emission at lower energies, we have looked for emission on three different time scales: steady emission, emission on the time scale of one week, and emission on the time scale of one day. We have also searched for continuous emission in the muon-poor (events with zero observed muons) data sample.

For each day, the observed number of events and the expected number of background events in each source bin are found. This is expressed as the number of standard deviations (positive or negative) calculated according to the Li and Ma prescription (Li and Ma 1983). To search for emission on the time scale of one week, we have summed the daily results for seven consecutive calendar days, with a new (not statistically independent) seven day period beginning on each day.

Table 1 gives the observed number of events and the number of expected background events for each AGN for the entire data set and for all showers with zero observed muons. Table 2 gives typical values for these quantities for the weekly and daily time scales. No statistically significant excess is observed from any of the AGN for any of the time scales examined.

The observed number of on-source events and the expected number of background events are used to derive a 90% C.L. upper limit on the number of excess events in the source bin using the prescription of Helene (Helene 1983). These upper limits, expressed as a fraction of the cosmic-ray background in the source bin, are given in the tables (f_{90}).

The all-particle cosmic-ray flux above an energy E , $\phi_{CR}(>E)$, is used to convert f_{90} into $\phi_\gamma(>E)$, the flux of UHE photons above that energy (Alexandreas *et al.* 1993)

$$\phi_\gamma(>E) = \frac{f_{90}\phi_{CR}(>E)\Omega}{0.72R'_\gamma\epsilon_\mu}, \quad (2)$$

where $\Omega(=1.2 \times 10^{-3} \text{ sr})$ is the solid angle of the source bin and the factor of 0.72 accounts for the fraction of the signal that is expected to be contained in the source

bin. The factor ϵ_μ is the fraction of gamma ray showers which survive the muon cut. For the data set without muon cuts $\epsilon_\mu = 1.0$. For the muon poor data sample $\epsilon_\mu = 0.9$. The cosmic ray flux, ϕ_{CR} , is obtained from Burnett *et al.* 1990 in the same manner as in Alexandreas *et al.* 1993.

The factor R'_γ in equation 2 accounts for the different detection efficiencies for gamma-ray and cosmic-ray primaries of the same energy and for the different energy spectra of gamma rays and cosmic rays. To determine R'_γ an E^{-2} differential gamma ray source spectrum is propagated through the microwave background field (Nikishov 1961, Jelley 1966, Gould and Schreder 1966, 1967a,b, and Stecker, De Jager, and Salamon 1992). For a source at a given redshift this yields a spectrum at the top of the atmosphere. For a close source such as Mrk 421 ($z = 0.03$) this leads to a cutoff in the spectrum at ~ 100 TeV. For a source with a redshift of 2.2 the spectrum is cutoff at ~ 10 TeV. Equal numbers of gamma-ray showers and cosmic-ray showers are simulated, then R'_γ is the ratio of the number of gamma-ray showers that yield a trigger to the number of cosmic-ray showers that yield a trigger. Since the energy threshold of the detector increases with zenith angle R'_γ is a function of source declination. In addition, the spectrum observed at earth depends on the redshift of the source, so R'_γ depends on the redshift of the source. If the energy threshold of the array is greater than the energy of the spectral cutoff, $R'_\gamma = 0$. Thus the array has almost no sensitivity to gamma rays from sources at large redshifts and large zenith angles.

Table 1 also gives the 90% C. L. upper limit on the observed flux above the median gamma-ray energy in the source bin, E_m , for each of the examined sources. Due to the strong dependence of R'_γ on redshift we have not computed flux limits for sources whose redshift is not known. Note that because of the absorption by the CMBR these flux limits can not be simply scaled to different energies. Instead our flux limits scale like the source spectrum at the top of the atmosphere (e.g. the dotted line in Figure 1).

Figure 1 shows the measured flux from Mrk 421 together with the upper limits on the flux from these data. Two curves are drawn on the figure. The dashed curve is a direct extrapolation of the lower energy measurements of the source flux. The dotted curve is the same source spectrum after attenuation of the UHE gamma rays by the 2.7K CMBR. The upper limit to the flux at 50 TeV falls between the two curves, indicating that it is consistent with the source spectrum as measured at lower energies with attenuation by the 2.7K CMBR. Since the upper limit is above the lower curve, these results are insensitive to the intergalactic IR field.

4. SUMMARY A search for UHE emission from Mrk 421 and 12 other AGN detected by EGRET has been described. The search was performed using data from the CYGNUS experiment from 1986 April 2 through 1993 January 1. No significant excess of events is observed from any of these objects for any of the time scales examined. The upper limit on the flux of UHE gamma rays from Markarian 421 is consistent with the source spectrum measured by Whipple and EGRET with absorption by the 2.7K CMBR.

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References

- Alexandreas, D. E., *et al.* 1991, Nucl. Instr. and Meth., **A311**, 356.
- Alexandreas, D. E., *et al.* 1993, Ap. J., bf 405, 353.
- Allen, R. C., *et al.* 1992, Nucl. Instr. and Meth., **A311**, 368.
- Burnett, T. H., *et al.* 1990, Ap. J. Lett., **349**, L25.
- Fichtel, C. E., *et al.* 1993, Advances in Space Research, XXIX COSPAR Plenary Meeting, in preparation, (New York: Pergamon Press).
- Gould, R. J. and Schreder, G., 1966, Phys. Rev. Lett., **16**, 252.

- Gould, R. J. and Schreder, G., 1967a, *Phys. Rev.*, **155**, 1404.
Gould, R. J. and Schreder, G., 1967b, *Phys. Rev.*, **155**, 1408.
Hartman, R. C. *et al.* 1992, *Ap. J. Lett.*, **385**, L1.
Helene, O., 1983, *Nucl. Instr. and Meth.*, **212**, 319.
Jelley, J. V., 1966, *Phys. Rev. Lett.*, **16**, 479.
Li, T. P. and Ma, Y. Q., 1983, *Ap. J.*, **272**, 317.
Nikishov, A. I., 1961, *Zh. Eksp. i Teor. Fiz.*, **41**, 549 [English Trans. *Sov. Phys. JETP*, **14**, 393 (1962)]
Punch, M., *et al.* 1992, *Nature*, **358**, 477.
Stanev, T., Gaisser, T.K., and Halse, F. 1985, *Phys. Rev. D*, **32**, 1244.
Stecker, F. W. De Jager, O. C., and Salamon, M. H., 1992, *Ap. J. Lett.*, **390**, L49.

Source	z	N_{on}	N_{off}	f_{90}	ϕ_s	N_{on}^{μ}	N_{off}^{μ}	f_{90}^{μ}	ϕ_s^{μ}	E_m
0202+1491 (1)	...	56022	55826	0.010	...	26438	26173	0.009	...	...
PKS0235 (2)	0.94	60686	60307	0.012	2.18	28966	28594	0.010	2.0	20
PKS0420 (3)	0.92	13530	13205	0.017	59.3	5024	4914	0.015	26.7	20
PKS0528 (4)	2.07	52015	52209	0.006	...	21055	21916	0.006	...	...
0716+714 (5)	...	28596	28402	0.015	...	12115	12022	0.010	...	...
4C+71.07 (6)	2.17	29255	29250	0.010	...	12300	12376	0.005	...	...
Mrk 421 (7)	0.031	103832	103798	0.006	0.09	57198	57204	0.004	0.075	50
3C273 (8)	0.158	9816	20277	0.005	0.13	7881	8075	0.003	0.09	50
3C279 (9)	0.538	7152	7336	0.010	9.6	2181	2535	0.008	8.1	25
PKS1606 (10)	1.23	41699	41966	0.006	7.8	18685	18810	0.004	6.2	15
4C+38.41 (11)	1.81	101839	101804	0.006	13.6	55863	56395	0.002	5.4	10
4C+11.69 (12)	1.037	44956	44409	0.019	20.7	20362	20117	0.010	12.1	15
3C454.3 (13)	0.859	59608	59365	0.010	2.17	28546	27988	0.010	2.3	20

Table 1. The results of the search for continuous emission with and without muon cuts. For each source we give the redshift, the total number of observed (N_{on}) and expected (N_{off}) events and the total number of observed (N_{on}^{μ}) and expected (N_{off}^{μ}) events with no detected muons. Also given are f_{90} (f_{90}^{μ}) and the corresponding upper limit to the flux, ϕ_s (ϕ_s^{μ}), for each source above the median detected energy (E_m) for that source declination. The units for the flux limits are $10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$. For sources whose redshift is either unavailable or too large we can not compute a flux limit.

S#	Daily Results			Weekly Results		
	N_{on}	N_{off}	f_{90}	N_{on}	N_{off}	f_{90}
1	41	41.0	0.30	280	278.0	0.11
2	47	42.5	0.38	298	296.8	0.11
3	8	9.8	0.55	65	62.0	0.28
4	35	35.2	0.32	271	259.9	0.14
5	20	23.1	0.33	143	139.0	0.13
6	28	23.3	0.58	183	150.9	0.14
7	94	90.8	0.22	515	547.4	0.05
8	11	14.4	0.39	98	99.6	0.17
9	6	5.5	1.08	48	34.4	0.71
10	31	34.4	0.27	182	212.7	0.07
11	79	79.1	0.21	499	522.2	0.06
12	35	33.8	0.36	247	215.5	0.25
13	50	42.5	0.44	286	295.5	0.09

Table 2. The number of observed and expected events for each source examined for a typical day and a typical week. Also given are the 90% confidence level upper limits on the fraction of excess events in the source bin. The source numbers correspond to those given in Table 1.

Figure 1: The integral gamma-ray flux from Markarian 421 measured by EGRET and the Whipple telescope together with the muon poor upper limit from the CYGNUS experiment. The dotted (dashed) curve corresponds to the expected spectrum at earth with (no) absorption by the CMBR.