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SEARCH FOR EMISSION OF ULTRA–HIGH-ENERGY RADIATION FROM ACTIVE GALACTIC NUCLEI

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ABSTRACT

The CYGNUS air-shower array has been used to search for emission of ultra–high-energy gamma radiation from 13 active galactic nuclei (AGNs) that were detected by EGRET. The data set spans the period 1986 April 2 to 1993 January 1. The data set has been searched for continuous emission, for emission on the time scale of 1 week, and for 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 90% Confidence Level (CL) upper limit to the continuous flux from Mrk 421 above 50 TeV is 7.5×10^{-14} cm^{-2} s^{-1}.

Subject headings: BL Lacertae objects: general — galaxies: active — gamma rays: observations

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 (AGNs) (Fichtel et al. 1993; Hartman et al. 1992). The detected AGNs are all blazars. Blazars are radio loud, exhibit rapid variability, and show a high degree of polarization in their optical spectra, suggesting that their emission is dominated by nonthermal processes. It is believed that the bulk of the emission from these objects originates in jets of plasma, thought to be ejected perpendicular to an accretion disk. The gamma-ray spectra of these objects 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, Mark 421, has been detected above 500 GeV by the Whipple atmospheric Čerenkov 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 AGNs (Gould & Schreder 1967a, b; Stecker, De Jager, & Salamon 1992). The presence of an IR field would severely attenuate any gamma rays above a few TeV, even from an AGN as close as Mrk 421. For example, if the IR field is given by equation (2) of Stecker et al. (1992) the CYGNUS array would have essentially no sensitivity to gamma rays from Mrk 421. The intensity and spectrum of the intergalactic IR field are unknown. In this paper it is assumed that there is no absorption due to an intergalactic IR radiation field.

The properties of the 2.7 K cosmic microwave background radiation field (CMBR) are well known. It has been pointed out by several authors (Nikishov 1961; Jelley 1966; Gould & Schreder 1966, 1967a, b) that ultra–high-energy (UHE) (~ 100 TeV) gamma rays will interact with this field and create electron-positron pairs. While these high-energy electrons may subsequently impart their energy to a low-energy photon (via inverse Compton scattering), an intergalactic magnetic field as low as $\sim 10^{-13}$ G will cause the directional information to be lost. Thus it is expected that an ultra–high-energy gamma ray that interacts enroute to Earth will not appear to come from the source.

2. THE CYGNUS EXPERIMENT

The CYGNUS air shower array located in Los Alamos, NM, has been described elsewhere (Alexandreas et al. 1992, 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 (declination = 36°) the median detected primary energy for gamma-ray–initiated events is ~ 70 TeV, assuming that gamma rays and cosmic rays have similar energy spectra. The median primary energy increases as the zenith angle increases.

The CYGNUS-I array has two muon detectors. The first muon detector, previously used by the LAMPF neutrino

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experiment E-225 (Allen et al. 1992), is a ~44 m^2 array of multiwire proportional chambers. The minimum energy required for a muon to penetrate the detector's shielding is 2 GeV. It has been in continuous operation from the beginning of data taking in 1986 April. The second muon detector was originally a 70 m^2 liquid scintillator detector used by the LAMPF neutrino experiment E-645. This detector was used for muon identification in 1987 between January 22 and May 14, and again in 1990 from May to November. In 1990 November the liquid scintillator was replaced by 20 scintillation counters (total area ~46 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; the minimum muon energy required to penetrate the shielding here 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/cos δ in right ascension. We have searched for emission from all of the AGNs detected by EGRET that are visible from our latitude (see Table 1). Given that there is both steady and episodic emission at lower energies, we have looked for emission on three different time scales: steady emission, emission on the time scale of 1 week, and emission on the time scale of 1 day. We have also searched for continuous emission in the muon-poor data sample (events with zero observed muons).

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 & Ma prescription (Li & Ma 1983). To search for emission on the time scale of 1 week, the daily results for 7 consecutive calendar days are summed, with a new (not statistically independent) 7 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 of these quantities for the weekly and daily time scales. No statistically significant excess is observed from any of the AGNs for any of the time scales examined.

TABLE 2

NUMBER OF OBSERVED AND EXPECTED EVENTS FOR EACH SOURCE EXAMINED FOR A TYPICAL DAY AND A TYPICAL WEEK[a]

Source	Daily Results			Weekly Results		
	N_{on}	N_{off}	f_{90}	N_{on}	N_{off}	f_{90}
0202+149	41	41.0	0.30	280	278.0	0.11
PKS 0235	47	42.5	0.38	298	296.8	0.11
PKS 0420	8	9.8	0.55	65	62.0	0.28
PKS 0528	35	35.2	0.32	271	259.9	0.14
0716+714	20	23.1	0.33	143	150.0	0.13
4C +71.07	28	23.3	0.58	183	150.9	0.34
Mrk 421	94	90.8	0.22	515	547.4	0.05
3C 273	11	14.4	0.39	96	99.6	0.17
3C 279	6	5.5	1.06	48	34.4	0.71
PKS 1606	31	34.4	0.27	182	212.7	0.07
4C +38.41	79	79.1	0.21	499	522.2	0.06
4C +11.69	35	33.8	0.36	247	215.5	0.25
3C 454.3	50	42.5	0.44	286	295.5	0.09

[a] Also given are the 90% confidence level upper limits on the fraction of excess events in the source bin.

The observed number of on-source events and the expected number of background events can be used to derive a 90% CL 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):

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

where $\Omega(=1.2 \times 10^{-3}$ 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 that survive the muon cut. For the data set without muon cuts $\epsilon_\mu = 1.0$. If the muon content of a gamma-ray–induced shower is 1/30 that of a proton shower of the same energy (Stanev, Gaisser, & Halzen

TABLE 1

RESULTS OF THE SEARCH FOR CONTINUOUS EMISSION WITH AND WITHOUT MUON CUTS[a]

Source	Decl.	z	N_{on}	N_{off}	f_{90}	ϕ_γ	N^μ_{on}	N^μ_{off}	f^μ_{90}	ϕ^μ_γ	E_m
0202+149	14.8	...	56022	55826	0.010	...	26515	26253	0.009	...	...
PKS 0235	16.4	0.94	60686	60307	0.012	2.18	29056	28686	0.010	2.0	20
PKS 0420	−1.5	0.92	13530	13205	0.037	59.3	5034	4932	0.015	26.7	20
PKS 0528	13.5	2.07	52015	52209	0.006	...	24130	24032	0.006	...	...
0716+714	71.4	...	28596	28402	0.015	...	12151	12039	0.010	...	...
4C +71.07	71.1	2.17	29255	29250	0.010	...	12336	12426	0.005	...	...
Mrk 421	38.5	0.031	103832	103798	0.006	0.09	57312	57348	0.004	0.075	50
3C 273	2.3	0.158	19816	20277	0.005	0.13	7905	8136	0.003	0.09	50
3C 279	−5.5	0.538	7152	7336	0.010	9.6	2490	2550	0.008	8.1	25
PKS 1606	10.6	1.23	41699	41966	0.006	7.8	18742	18897	0.004	6.2	15
4C +38.41	38.2	1.81	101839	101804	0.006	13.6	56044	56440	0.002	5.4	10
4C +11.69	11.5	1.037	44956	44409	0.019	20.7	20434	20178	0.010	12.1	15
3C 454.3	15.9	0.859	59606	59365	0.010	2.17	28434	28098	0.010	2.3	20

[a] For each source we give the declination and redshift, the total number of observed (N_{on}) and expected (N_{off}) events, and the total number of observed (N^μ_{on}) and expected (N^μ_{off}) events with no detected muons. Also given for each source are f_{90} (f^μ_{90}) (see text for explanation) and the corresponding upper limit to the flux, ϕ_γ (ϕ^μ_γ), above the median detected energy (E_m), in TeV, for that source declination. The units for the flux limits are 10^{-12} cm^{-2} s^{-1}. For sources whose redshifts are either unavailable or too large we cannot compute a flux limit.

1985; Drees, Halzen, & Hikasa 1989), then simulations of the array and the muon detectors (including the duty cycle of the muon detectors) show that 6.5% of the gamma-ray showers will have one or more detected muon. In addition, we assume that 5% of all gamma-ray primaries have the same muon content as proton showers (Stanev et al. 1985), so $\epsilon_\mu = 0.9$. The cosmic-ray flux, $\phi_{CR}[=1.8 \times 10^{-5}(E/\text{TeV})^{-1.76}\ \text{cm}^{-2}\ \text{s}^{-1}]$, is obtained from Burnett et al. 1990 as described 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 for a source at a given redshift (z), an E^{-2} differential gamma-ray source spectrum is propagated through the microwave background field (accounting for the cosmic expansion) (Nikishov 1961; Jelley 1966; Gould & Schreder 1966, 1967a; Stecker, De Jager, & Salamon 1992). This yields a spectrum at the top of the atmosphere. Figure 1 shows an input spectrum and the resulting spectrum at the top of the atmosphere for a close source (Mrk 421) and a distant source (4C 71). The spectrum at the top of the atmosphere is plotted for a range of values for the Hubble constant, from 50 to 100 km s^{-1} Mpc^{-1}. In what follows we adopt a value of $H_0 = 75$ km s^{-1} Mpc^{-1}. Equal numbers of gamma-ray showers and cosmic-ray showers are simulated; 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. Figure 2*a* shows R'_γ as a function of source declination for different source redshifts. Figure 2*b* shows the median-detected gamma-ray energy as a function of source declination for several source distances. Note that a source at a large redshift has a low median detected energy—near the energy threshold of the array. The array has essentially no sensitivity to gamma rays from such a source ($R'_\gamma \approx 0$). If an intergalactic IR field as given by equation (2) of Stecker et al. (1992) (with a cutoff at 0.02 eV) is present, then $R'_\gamma \approx 0.002$ for Mrk 421.

Table 1 gives the 90% CL 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

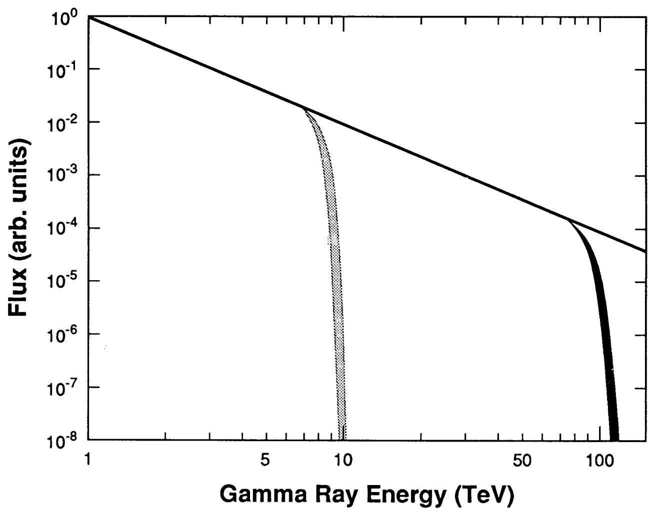

FIG. 1.—A gamma-ray source spectrum (E^{-2}) and the resulting spectra at the top of the atmosphere for sources at two redshifts. The solid line represents Mrk 421 ($z = 0.03$), and the dashed line 4C 71 ($z = 2.17$). In both cases the shaded region represents a range of values for the Hubble constant, from $H_0 = 50$ km^{-1} s^{-1} Mpc^{-1} to $H_0 = 100$ km^{-1} s^{-1} Mpc^{-1}.

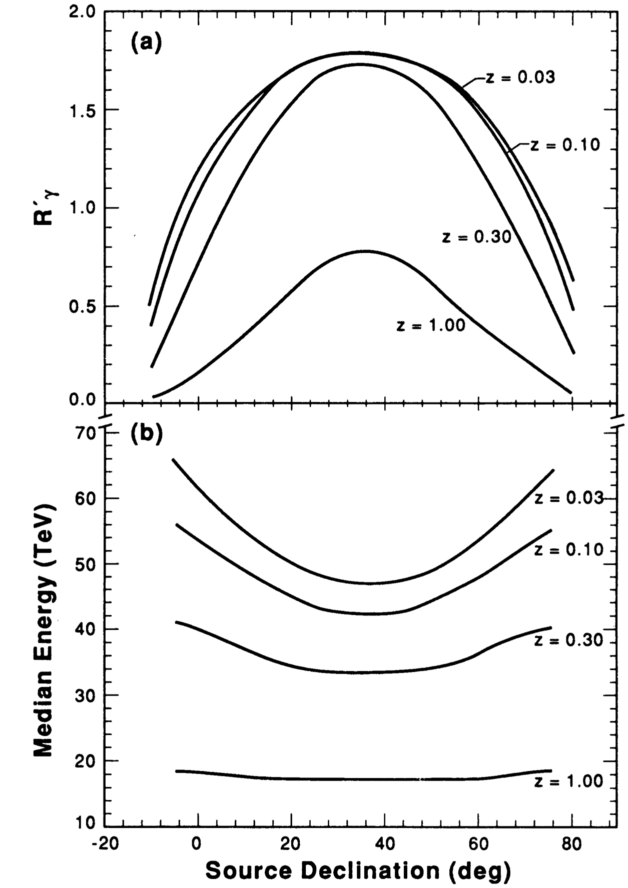

FIG. 2.—(*a*) The ratio of the number of detected photon events to the number of detected cosmic rays (R'_γ) as a function of source declination for sources at several redshifts. (*b*) The median energy of detected gamma rays as a function of source declination for sources at several redshifts.

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 cannot be simply scaled to different energies. Instead, our flux limits scale like the source spectrum at the top of the atmosphere (the dotted line in Fig. 3).

Figure 3 shows the measured flux from Mrk 421 together with the upper limit on the flux from our data. The dashed curve is an 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 2.7 K CMBR. The upper limit to the flux above 50 TeV falls between the two curves, indicating that it is consistent with an extrapolation of the source spectrum as measured at lower energies with attenuation by the 2.7 K CMBR.

In addition to Mrk 421 there are four other AGNs for which the flux upper limits given in Table 1 fall below a direct extrapolation of the spectrum as measured by EGRET (3C 279 in its high state, 4C 38 in its high state, PKS 0235, and 3C 454). In all cases, once account is taken for the absorption by the 2.7 K CMBR the upper limits lie above the extrapolated spectrum at the top of the atmosphere. For the case of 3C 279 in its high state the upper limit given in Table 1 is only 20% higher than the extrapolated spectrum with absorption by the CMBR. Since the upper limits are above the extrapolation with absorp-

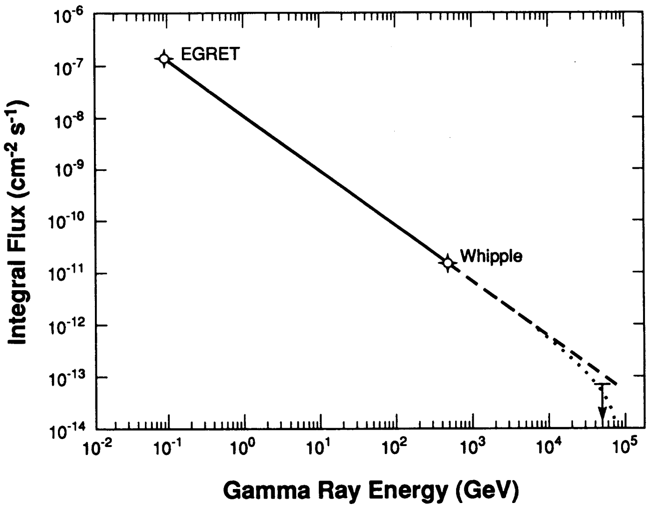

FIG. 3.—The integral gamma-ray fluxes for Mrk 421 as observed by EGRET and the Whipple telescope together with the muon-poor upper limit from the CYGNUS experiment. The dotted (dashed) curve corresponds to the expected spectrum at Earth with (without) absorption by the CMBR.

tion by the CMBR these results are insensitive to the intergalactic IR field.

A search for UHE emission from Mrk 421 and 12 other AGNs detected by EGRET has been described. The search was performed using data taken with the CYGNUS experiment between 1986 April 2 and 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 Mrk 421 is consistent with an extrapolation of the source spectrum measured by Whipple and EGRET with absorption by the 2.7 K CMBR.

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