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A SEARCH FOR CORRELATIONS OF TeV GAMMA RAYS WITH ULTRA–HIGH-ENERGY COSMIC RAYS

C. W. Akerlof,[1] S. Biller,[2,3] P. Boyle,[4,5,6] J. Buckley,[4,7] D. A. Carter-Lewis,[8] M. Catanese,[8] M. F. Cawley,[9] V. Connaughton,[4,10] D. J. Fegan,[5] J. Finley,[11] J. Gaidos,[11] A. M. Hillas,[2] F. Krennrich,[8] R. C. Lamb,[8] R. Lessard,[5] J. McEnery,[5] G. Mohanty,[9] N. A. Porter,[2] J. Quinn,[5] A. Rodgers,[2] H. J. Rose,[2] F. Samuelson,[8] M. S. Schubnell,[1] G. Sembroski,[11] R. Srinivasan,[11] T. C. Weekes,[4] and J. Zweerink[8,12]

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ABSTRACT

A search was conducted for TeV γ-rays emitted from the direction of the ultra–high-energy cosmic ray detected by the Fly's Eye experiment with energy $E \sim 3 \times 10^{20}$ eV. No enhancement was found at a level of $10^{-10}\gamma$ cm^{-2} s^{-1} for $E > 350$ GeV. A steady source of ultra–high-energy cosmic ray protons or photons would be expected to produce a γ-ray flux above this level. An upper limit was also set for the flux of TeV γ-rays from 3C 147, the most prominent active galactic nucleus in the error box.

Subject heading: cosmic rays — galaxies: active — galaxies: individual (3C 147) — gamma rays: observations

1. INTRODUCTION

The surprising discovery of ultra–high-energy cosmic rays (UHECRs) with $E > 10^{20}$ eV poses significant questions about how such particles can reach energies substantially in excess of the Greisen-Zatsepin-Kuz'min cutoff (Greisen 1966; Zatsepin & Kuz'min 1966) imposed by interactions with the cosmic microwave background radiation. If these particles are accelerated in relativistic shock fronts in a manner similar to the standard models for lower energy cosmic rays (Blandford 1978; Legage & Cesarsky 1983; Bell 1978), the physical constraints are difficult to reconcile with what we know about possible acceleration sites on distance scales of 40 Mpc. Recent studies have suggested that the distribution of the arrival directions of UHECRs may be anisotropic (Chikawa et al. 2001; Sommers 2001), which may indicate the existence of discrete sources. A variety of possible sources have been suggested, ranging from radio galaxies (Biermann & Strittmatter 1987) to γ-ray bursts (Waxman 1995) and topological defects (Bhattacharjee 1997); these and other suggestions have been discussed in a recent comprehensive review (Nagano & Watson 2000).

Since the lifetime of UHECRs in the intergalactic medium is limited to 10^8 yr, it is likely that the position of sources of this radiation on the celestial sphere lie close to their arrival directions as measured on Earth. A steady source of UHECRs, whatever its origin, will almost inevitably produce a detectable signal at lower energies. If the UHECRs are either protons or photons, their mean free paths (interaction with the microwave background for protons, interaction with the radio background for photons) will be $\approx$1 Mpc. The secondary products of these interactions (the intergalactic shower) will cascade on the microwave background and be apparent as a steady source of lower energy photons. The detailed prediction of the secondary flux is difficult, since it will be determined by the nature of the primary as well as the intergalactic magnetic fields. The flux expected at TeV energies from such cascades has been calculated (Protheroe & Stanev 1996) and is at levels where detection techniques are sensitive. The extraordinary flux sensitivity of the atmospheric Cerenkov imaging technique (Ong 1998) prompts a search for the TeV γ-ray counterparts' sources around the arrival direction of the highest energy cosmic rays.

A search for a steady TeV γ-ray source in the error boxes of UHECRs might offer some chance of detection. The optical depth for TeV photons (Nikishov 1962; Gould & Schreder 1966; Stecker 1992; Biller 1995) is considerably greater than the range of UHECRs, so the attenuation of the γ-ray signal is negligible. Thus, such gamma radiation should be an excellent probe of higher energy phenomena, which might otherwise be opaque. The starting point for guessing the γ-ray flux is the cosmic ray spectrum measured by the Fly's Eye experiment (Bird et al. 1994),

$$J(E) = 5.13 \times 10^{21} (E/1\ \mathrm{eV})^{-3.07}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}\ eV^{-1}} \quad (E > 10^{17}\ \mathrm{eV}) .$$

For energies greater than 3×10^{20} eV, the extrapolated integral flux is 1×10^{-21} particles cm^{-2} s^{-1} sr^{-1}. For the one

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[1] Department of Physics, University of Michigan, 2477 Randall Laboratory, 500 East University Avenue, Ann Arbor, MI 48109-1120.

[2] Department of Physics, University of Leeds, Leeds LS2 9JT, UK.

[3] Current address: Department of Physics, University of Oxford, OX1 3RH, UK.

[4] Whipple Observatory, Harvard-Smithsonian Center for Astrophysics, P.O. Box 97, Amado, AZ 85645-0097; tweekes@cfa.harvard.edu.

[5] Physics Department, University College Dublin, Belfield, Dublin 4, Ireland.

[6] Current address: Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637-1433.

[7] Current address: Department of Physics, Washington University, One Brookings Drive, St. Louis, MO 63130.

[8] Department of Physics and Astronomy, Iowa State University, Osborn Drive, Ames, IA 50011.

[9] Department of Experimental Physics, St. Patrick's College, Maynooth, County Kildare, Ireland.

[10] Current address: NASA Marshall Space Flight Center, ES 84, Huntsville, AL 35812.

[11] Department of Physics, Purdue University, 1396 Physics Building, West Lafayette, IN 47907.

[12] Current address: Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA, 90024.

extreme event measured at the end of the spectrum, the corresponding flux from a point source is 6×10^{-20} particles cm^{-2} s^{-1}. A plausible assumption, based on the behavior of active galactic nuclei (AGNs), is that the source has a constant νF_ν distribution extending downward in energy to the TeV range. If the total available energy is partitioned roughly equally between γ-rays and cosmic rays, the anticipated γ-ray flux would be in the neighborhood of $6 \times 10^{-11} \gamma$ cm^{-2} s^{-1} at 3×10^{11} eV. This value is in the range of sensitivities achievable with the Whipple γ-ray telescope at Mt. Hopkins, Arizona (Reynolds et al. 1993), which can detect the flux from the Crab Nebula ($\approx 10^{-10} \gamma$ cm^{-2} s^{-1}) with a significance of 7 σ in 1 hr.

These considerations led us to conduct an exploratory experiment to see if an enhancement of γ-rays could be detected from the direction of the Fly's Eye UHECR event (Bird et al. 1995). Although there is some uncertainty in the energies of UHECRs (Sommers 2001), this event is better determined than most because its impact parameter, relative to the Fly's Eye detector, was small (Kieda 2002, private communication); this is still one of the highest energy UHECR events detected to date (Nagano & Watson 2000). This particular event was selected because the error box was small and the position on the sky was convenient for observations at a small zenith angle from the Whipple Observatory where the atmospheric Cerenkov technique is most sensitive. The celestial coordinates of this event are

$$\alpha(1950) = 85^{\circ}.2 \pm 0^{\circ}.5 \ , \ \delta(1950) = 48^{\circ}.0 \pm 6^{\circ}.0 \ .$$

2. OBSERVATIONS

The object of this experiment was to locate a possible point source of TeV radiation correlated with the direction of the Fly's Eye event. Normally, TeV observations at Whipple are conducted with accurate a priori knowledge of source locations. However, it is possible, using techniques akin to computer tomography, to reconstruct an unknown point source location from statistical analysis of the data, as was first shown in a paper by Akerlof et al. (1991). This technique has been refined further and used to search for TeV photons from γ-ray bursts (Connaughton et al. 1997), supernova remnants (Buckley et al. 1998), and unidentified EGRET sources (Fegan et al. 2001).

Because of the uncertainty in the location of the UHECRs and the small field of view of the telescope, 12 overlapping regions, each centered on the R.A. $86^{\circ}.01$ (J2000.0), were observed with the 10 m reflector. Figure 1 shows the region of sky covered by the Whipple observations. The letters in the box indicate the central point of each region. The declinations range from $42^{\circ}.51$ (position A) to $53^{\circ}.51$ (position L) in 1° increments so that, with the $3^{\circ}.5$ field of view of the camera, some overlap occurred between adjacent regions. Each position was observed for two 28 minute periods. Observations were made during four nights in 1995 December. The data rate of an air shower Cerenkov telescope is affected by telescope elevation and sky conditions, and hence the sensitivity and energy threshold of the survey varied with position.

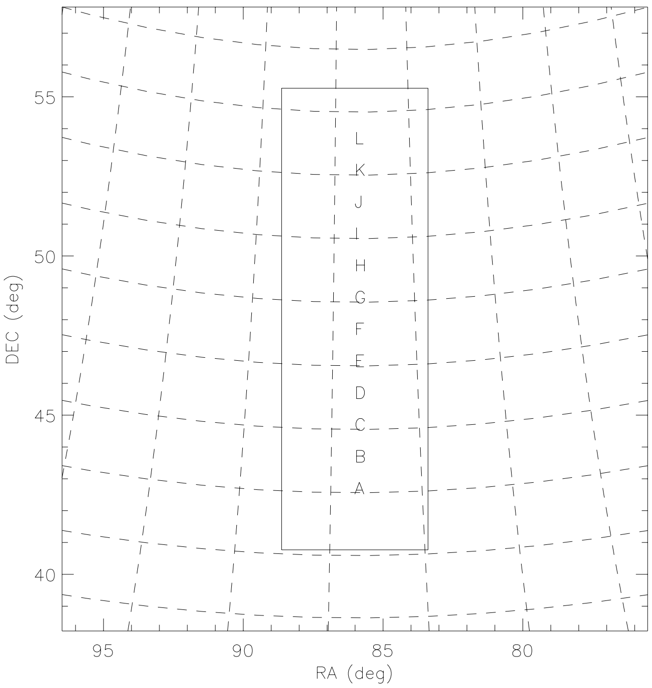

FIG. 1.—Whipple coverage of the area surrounding the Fly's Eye event. Each position is centered on R.A. = $86^{\circ}.01$ and separated from the next in declination by 1°. Since the field of view is $3^{\circ}.5$, there is some overlap between adjacent positions.

3. ANALYSIS

Generally, observations of a point source whose location is known are analyzed by searching for excess γ-ray candidates from the source direction compared to a nearby patch of sky. Control observations of a position offset in right ascension by $28^{\rm m}$ from the source location are made with the telescope at the same elevation as the source observations, and the excess of selected events from the source observations (on-source data) relative to the control (or off-source) data gives a measure of the photon flux from the source. In this analysis, the coordinates of the source are unknown and there are no control observations. One must, therefore, assume that each location on the sky is a potential source and look for an unexpectedly large number of γ-ray–like events from some point in the field of view.

Standard routines were used to flat-field and parameterize the data. Events in the data files comprise the digitized signals registered by the 109 photomultiplier tubes in the focus box of the 10 m reflector. For each shower produced, a moment-fitting analysis is used to obtain a set of image parameters characterized by *width, length, light concentration,* and *size* (total number of digital counts). These parameters represent the two angular aspects of the shower light distribution, its compactness and total energy, respectively. A combination of these image parameters has proved effective in discriminating against the hadronic background by selecting only those events with the appropriate direction for a particular source and the shape characteristic of γ-ray showers. The Supercuts technique described in Reynolds et al. (1993) rejects 99.7% of the recorded background while keeping 50% of the γ-rays. In this analysis, γ-ray–like events are selected on the basis of image shape, using *width* (semiminor axis of ellipse) and *length* (semimajor axis) cuts. The development of image-selection criteria and assessment of nonsource-centered capabilities of the 10 m reflector are given in Connaughton et al. (1998). In this analysis, γ-ray–like events are selected using the following Supercuts shape criteria:

$$0.^{\circ}073 < \text{width} < 0.^{\circ}15 \; ,$$
$$0.^{\circ}16 < \text{length} < 0.^{\circ}30 \; ,$$

where the width and length are the semiminor and semimajor axes of the elliptical image fitted to each event. In addition, a minimum size of 400 dc (approximately 400 photo-electrons) is required, corresponding to a peak energy sensitivity around 350 GeV.

The orientation of the ellipse fitted to each image is represented by its major axis, and the most likely point of origin of the shower progenitor on the field of view lies on this axis at a distance d in degrees related to the ellipticity of the image,

$$d = 1.7[1 - (\text{width}/\text{length})] \; . \tag{1}$$

This algorithm yields two points, one on either side of the center of the image, and is considered to be accurate to about 0°.3 on either side of each point (Akerlof et al. 1991; Connaughton et al. 1997). A grid of bins 0°.1 × 0°.1 in size is constructed to cover the field of view of the camera and beyond. The grid extends 3° each side of the center so that the sensitivity of the technique outside the geometrical field of view can be exploited (Fegan et al. 2001). Each bin which lies within 0°.3 of either point of origin for an event is incremented.

The two data files taken on each position comprise the on-source data. Control, or off-source, data are obtained by averaging the grid bin occupancies of on-source files taken at similar elevations. Three groups of control data were defined: five of the 24 observations at telescope elevations below 64°, 12 between 64° and 71°, and the remaining seven at higher elevations. The excess at any grid point (i, j) in the on-source data is found relative to the corresponding point in the control observations using the equation

$$\sigma_{ij} = \frac{(N_{\rm ON} - pN_{\rm OFF})}{\sqrt{(N_{\rm ON} + pN_{\rm OFF}/N_{\rm BG})}} \; , \tag{2}$$

where $N_{\rm BG}$ is the number of observations that were averaged to make up the background contour map. A normalizing factor p is applied to account for the differences in the durations of the on-source and off-source observations. In Figure 2, the resulting contours on the grid represent the significances of the excess of photon-like events over 56 minutes from each of the positions observed.

4. RESULTS

Figure 2 shows the contour plots for positions D–I, typical of all 12 observations. The contours begin at 1 σ and increment in 1 σ steps. Given that there are no significant excesses in any of the bins in the on-source data relative to the control data, one can calculate an upper limit to the flux from each of the positions observed. The collection area above 350 GeV of the 10 m telescope for a source in the center of the camera is $5.4 \pm 0.9 \times 10^8$ cm^2 (Connaughton et al. 1998). This is larger than the collection area given in, e.g., Reynolds et al. (1993), because of the less restrictive orientation criteria applied when the source is not at the center of the field of view. Using the total number of shape-selected events in the on-source and control files, the 99.9% maximum likelihood value for emission from all positions are presented in Table 1. The errors reflect the uncertainty in the collection area of the 10 m reflector and the statistical nature of variation in selected event rates within each control data group. These limits apply to emission above 350 GeV from a source in the center of the camera. In calculating the limits from any other point in the field of view, a scaling factor must be used to account for the decreasing γ-ray efficiencies away from the center of the camera (Connaughton et al. 1998; Fegan et al. 2001). A lower flux upper limit is derived for sources that might lie at the camera's center than for those at the edge of the camera. The upper limits as a function of source offset are shown in Figure 3. The two outer lines represent the lowest and highest limits that can be set; the middle line shows the limits with the smallest error bars (the most homogeneous control group), the difference being due to the statistical variations in event rates and the diminishing efficiency of Supercuts with decreasing telescope elevation.

5. INTERPRETATION

The absence of a detectable γ-ray signal from the direction of the Fly's Eye UHECR event does not lead to any clear-cut conclusion. First of all, the sky coverage was limited to the cosmic-ray error box alone, which does not include effects of possible curvature of the trajectory by intervening extragalactic magnetic fields. Such fields might bend these particles by as much as 5° or more from the original source direction. Furthermore, it was tacitly assumed that the particle acceleration process operates continuously to generate energetic particles. If instead these particles are created in short bursts, the cosmic-ray arrivals will surely lag the γ-ray photons, since they will be delayed by the additional path length due to magnetic curvature so that no follow-up observation can succeed. In the former case with small magnetic deflections and constant flux, we can make some comparisons with theoretical estimates.

We do not know if this one event comes from a particularly bright compact source or simply represents one count from an otherwise isotropic distribution. However, a second event with an energy of 1.2×10^{11} GeV measured by the Yakutsk Array (Efimov et al. 1991) was detected at coordinates less than 8° away. Similar correlations have been observed by Hayashida et al. (1996). Thus, the UHECR sky may in fact be highly anisotropic (Sommers 2001), a major focus of interest for the proposed AUGER experiment (Cronin 2001). If true, the Fly's Eye flux could be directly compared with the TeV γ-ray flux limits determined above.

6. EMISSION FROM 3C 147

The most conservative assumption of the origin of the highest energy cosmic rays is that they are accelerated in the jets of AGNs. The detection of TeV γ-ray emission from AGNs (Catanese & Weekes 1999) supports the notion of high-energy particle acceleration within some AGNs. However, within the error box of the Fly's Eye event there is no known AGN within 40 Mpc of the Galaxy.

The most interesting extragalactic object within the error box is the AGN 3C 147, one of the earliest optical quasars discovered ($z = 0.545$). It is also very bright in radio and X-rays (luminosity in both bands in excess of 8×10^{44} ergs s^{-1}). It has a strong Faraday rotation. Thus, apart from its

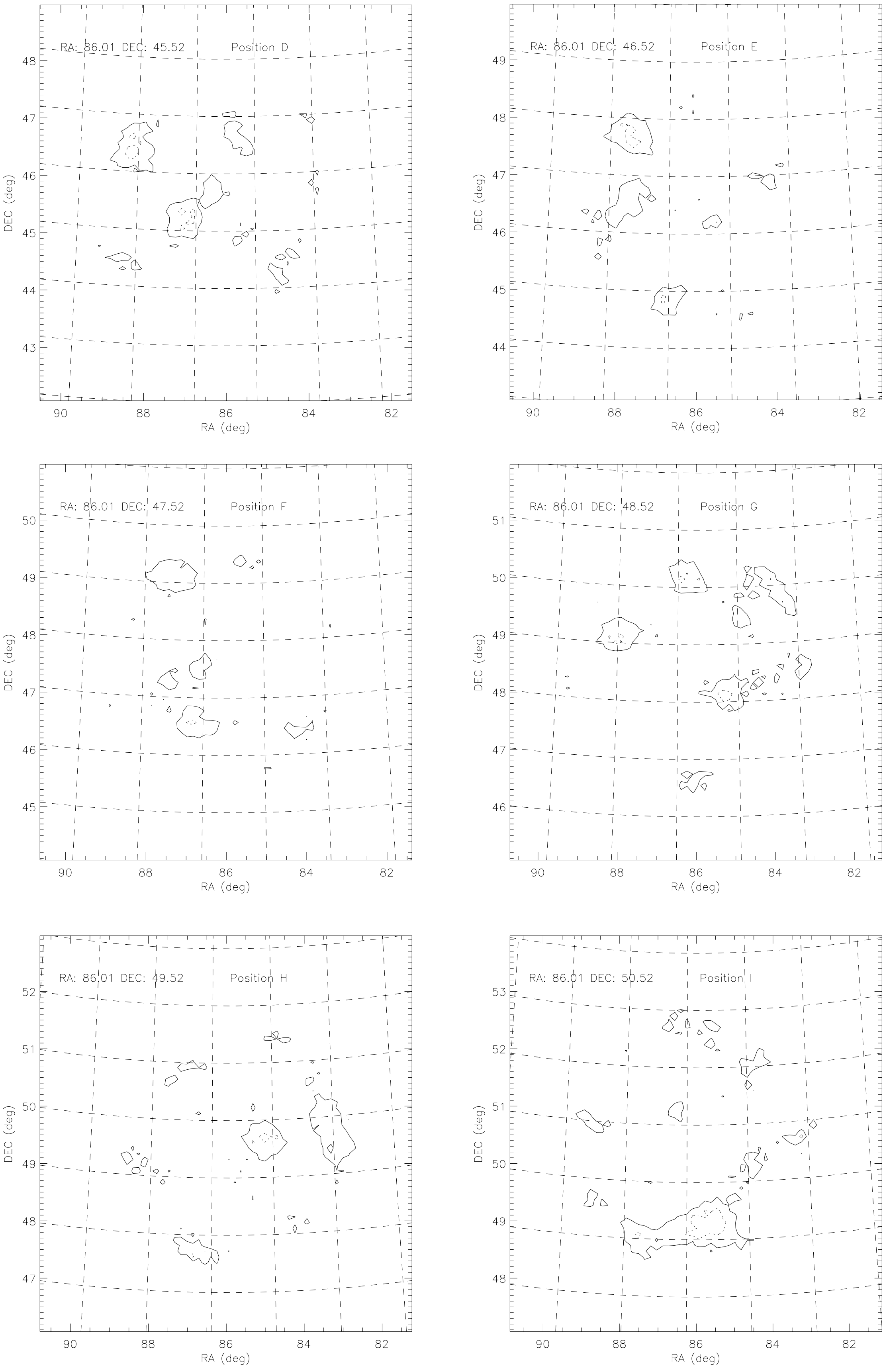

FIG. 2.—Bin excesses for positions D–I. The contours start at 1 σ and increment in 1 σ steps. With around 1000 bins per contour map, one might expect contours representing 2 or even 3 σ_{ij} deviations between the on-source and off-source data. The lack of such deviations may be explained by the fact that the off-source bin occupancy distributions are artificially smooth, each bin being an average of the equivalent bin in 6–9 different observations.

TABLE 1

Upper Limits for $E > 350$ GeV

Position	Flux ($\times 10^{-11}$ ergs cm^{-2} s^{-1})	Flux ($\times 10^{-11}\gamma$ cm^{-2} s^{-1})
A..............	3.5 ± 1.2	7.3 ± 2.5
B..............	3.6 ± 1.0	7.5 ± 2.1
C..............	4.4 ± 1.1	9.2 ± 2.3
D..............	2.7 ± 1.1	5.6 ± 2.3
E..............	5.1 ± 2.3	10.6 ± 4.8
F..............	7.7 ± 3.1	16.0 ± 6.5
G..............	3.0 ± 2.2	6.3 ± 4.6
H..............	4.9 ± 1.5	10.2 ± 3.1
I..............	3.6 ± 1.2	7.5 ± 2.5
J..............	3.9 ± 1.4	8.1 ± 2.9
K..............	1.4 ± 2.2	2.9 ± 4.6
L..............	1.5 ± 1.3	3.1 ± 2.7

redshift, this object is a prime candidate for identification as the source of the Fly's Eye event.

If 3C 147 was the source of the high-energy particles, then it is likely that it would also be a source of TeV γ-rays. However, the redshift of 3C 147 would suggest that there might be considerable absorption of TeV γ-rays by pair production on infrared photons in intergalactic space. (Nikishov 1962; Gould & Schreder1966; Stecker, DeJager, & Salamon 1992; Biller 1995). Observations of 3C 147 (and two other AGNs) were made in the 1963–1964 observing season in Glencullen, Ireland, by a combined Irish-UK team using a small atmospheric Cerenkov system with an energy threshold of 5 TeV (Long et al. 1965). A 3 σ excess was detected from the direction of 3C 147 (corresponding to a flux of 1×10^{-10} photons cm^{-2} s^{-1}). This would have indicated an incredible γ-ray luminosity of 5×10^{47} ergs s^{-1}. However, this emission was not verified and was not seen in any MeV–GeV γ-ray telescope experiment either.

3C 147 (R.A. = $05^{\rm h}39^{\rm m}$, decl. = $+49°49'$) was included in the survey with the Whipple telescope reported above (Fig. 2*g*). In addition, a series of tracking observations were made with 3C 147 in the center of the field of view for maximum sensitivity. A total of 6 hr of observation under optimum conditions gave no indication of a signal and an upper limit of 1.8×10^{-11} photons cm^{-2} s^{-1} was derived. Because of the greater sensitivity of the Whipple telescope it appears most likely that the Glencullen result was a statistical fluctuation. Hence, there is no evidence from TeV γ-ray observations to support the identification of 3C 147 as the cosmic ray source.

7. DISCUSSION

Regardless of the nature of the UHECR source and the production mechanism, it appears inevitable that if the UHECRs are hadrons or photons and if the source lies beyond a distance of a few Mpc, then a significant fraction of the UHECR energy will, on average, be converted to TeV photons as the UHECRs, and their secondary products, propagate through the radiation fields in the intergalactic medium. If the UHECR source flux is 6×10^{-20} particles cm^{-2} s^{-1}, a TeV photon flux of $6 \times 10^{-11}\gamma$ cm^{-2} s^{-1} at 3×10^{11} eV might be produced. In the exploratory experiment described above, no evidence has been found for steady emission at this flux level.

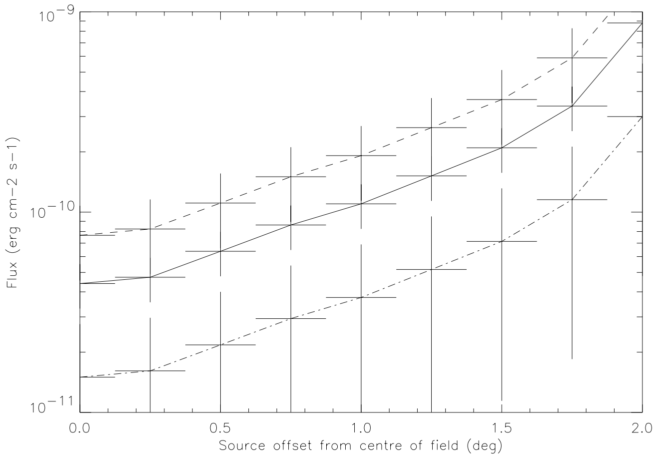

Fig. 3.—Upper limit to the flux above 350 GeV from topological defects for a point source over the field of view of the 10 m reflector: position C (*solid curve*), position F (*dashed curve*), and position L (*dot-dashed curve*).

The failure to detect a flux at TeV energies may indicate that the source is transient and would be in accordance with the hypothesis that the emission of UHECRs is associated with γ-ray bursts (Waxman 1995). Episodic emission of UHECRs makes the correlated detection of VHE γ-rays considerably more difficult, since the cosmic rays will lag the photons by intervals of the order of 100 yr (Waxman & Coppi 1996). An alternative explanation is that the UHECRs are not associated with discrete sources but are diffuse, so that the flux inferred from the detection of a single UHECR is an overestimate. This will become more apparent as more UHECRs are detected and their spatial distributions measured.

From generic physics considerations, the coproduction of γ-rays and UHECRs seems almost inevitable, so an extension of these experimental efforts is highly warranted. By increasing the extent of the search fields and the observation time, one could probe more deeply, while providing a greater margin for the unknown magnetic deflection of the UHECR primary on its trajectory to the Earth. New γ-ray detectors such as VERITAS (Very Energetic Radiation Imaging Telescope Array System; Weekes et al. 2002), HESS (High-Energy Stereoscopic System; Hofmann et al. 2000), and *GLAST* (*Gamma-Ray Large Area Telescope*; Gehrels & Michelson 1999) will conduct sensitive sky surveys that will be suited for correlation with the position of anomalies in the UHECR distribution.

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REFERENCES

Akerlof, C. W., et al. 1991, ApJ, 377, L97
Bell, A. R. 1978, MNRAS, 182, 147
Bhattacharjee, P. 1997, A&A, 18, 263
Biermann, P. L., & Strittmatter, P. A., 1987, ApJ, 322, 643
Biller, S. 1995, Astropart. Phys., 3, 385
Bird, D. J., et al. 1994, ApJ, 424, 491
———. 1995, ApJ, 441, 144
Blandford, R. D., & Ostriker, J. P. 1978, ApJ, 221, L29
Buckley, J., et al. 1998, A&A, 329, 639
Catanese, M., & Weekes, T. C. 1999, PASP, 111, 1193
Chikawa, M., et al. 2001, in Proc. 27th Int. Cosmic Ray Conf. (Hamburg), 337
Connaughton, V., et al. 1997, ApJ, 479, 859
———. 1998, Astropart. Phys., 8, 179
Cronin, J. W. 2001, in Proc. 27th Int. Cosmic Ray Conf. (Hamburg), 234
Efimov, N. N., et al. 1991, in Proc. ICRR Int. Symp., Astrophysical Aspects of the Most Energetic Cosmic Rays, ed. M. Nagano & F. Takahara (Singapore: World Scientific), 20
Fegan, S., et al. 2001, in Proc. 27th Int. Cosmic Ray Conf. (Hamburg), 2575
Gehrels, N., & Michelson, P. 1999, Astropart. Phys., 11, 277
Gould, R. J., & Schreder, G. P. E. 1966, Phys. Rev. Lett., 16, 252
Greisen, K. 1966, Phys. Rev. Lett., 16, 748
Hayashida, N., et al. 1996, Phys. Rev. Lett., 77, 1000
Hofmann, W. 2000, in AIP Conf. Proc. 515, GeV-TeV Gamma-Ray Astrophysics Workshop: Towards a Major Atmospheric Cherenkov Detector: IV, ed. B. L. Dingus, M. H. Salamon, & D. B. Kieda (New York: AIP), 500
Legage, P. O., & Cesarsky, C. J. 1983, A&A, 118, 223
Long, C. D., Porter, N. A., Weekes, T. C., Fruin, J. F., & Jelley, J. V. 1965, Proc. IAU Symp. 23, Astonomical Observations from Space Vehicles, ed. J.-L. Steinberg (Liege: Ann. d'Astrophys., 6), 251
Nagano, M., & Watson, A. A. 2000, Rev. Mod. Phys., 72, 689
Nikishov, A. I. 1962, Soviet Phys.-JETP, 14, 393
Ong, R. 1998, Phys. Rep., 305, 93
Protheroe, R. J., & Stanev, T. 1996, Phys. Rev. Lett., 77, 3708
Reynolds, P. T., et al. 1993, ApJ, 404, L206
Sommers, P. 2001, in Proc. 27th Int. Cosmic Ray Conf. (Hamburg), 170
Stecker, F. W., DeJager, O. C., & Salamon, M. H. 1992, ApJ, 390, L49
Waxman, E. 1995, Phys. Rev. Lett., 75, 386
Waxman, E., & Coppi, P. 1996, ApJ, 464, L75
Weekes, T. C., et al. 2002, Astropart. Phys. 17, 221
Zatsepin, G. T. & Kuz'min, V. A. 1966, Soviet Phys.-JETP Lett., 4, 78