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DAILY SEARCH FOR EMISSION OF ULTRA–HIGH–ENERGY RADIATION FROM POINT SOURCES

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ABSTRACT

A daily search for emission of ultra–high-energy radiation from astrophysical point sources using the CYGNUS extensive air shower array is described. The data set spans the period from 1986 April 4 to 1992 June 22. Fifty-one astrophysical objects have been examined, including Cyg X-3, Her X-1, the Crab, a number of gamma-ray and X-ray sources from the *COS B* and the fourth *Uhuru* catalogs, and several cataclysmic variables, nearby galaxies, and radio pulsars. The observed daily number of events from the source directions are consistent with expected statistical fluctuations of the number of events from background cosmic rays.

Subject heading: gamma rays: observations

1. INTRODUCTION

The first reported observation of ultra–high-energy (UHE) gamma rays from the direction of Cyg X-3 (Samorski & Stamm 1983), covering the period from 1976 through 1980, was confirmed by Lloyd-Evans et al. (1983). Subsequent air shower experiments with better angular resolution, larger effective area, and lower energy threshold have not observed any significant long-term excess in the UHE range from Cyg X-3 or any other source (Alexandreas et al. 1991a; Cronin et al. 1992). On the other hand, there have been many reports of episodic emission from several possible sources. These episodes, lasting from minutes to several weeks, are too numerous to be quoted here; the subject is thoroughly covered in several recent reviews (see, e.g., Weeks 1992). In this paper we report a search for emission from astrophysical point sources on the time scale of a day using the data from the CYGNUS air shower array, which covers the period from 1986 April 4 through 1992 June 22.

2. EXPERIMENT

The CYGNUS extensive air shower experiment began operation in 1986 April with 50 scintillation counters, located around the Los Alamos Meson Physics Facility beam stop (106°.3 W, 35°.9 N). The array has been expanded since that time. This paper describes the analysis of data taken with the CYGNUS-I array, which presently has 108 counters covering an area of 22,000 m^2. The spacing of the counters of the array ranges from ~ 7 m near the center to ~ 20 m near the edges. A more detailed description of the CYGNUS experiment can be found elsewhere (Alexandreas et al. 1991b).

The sensitivity of the experiment to point-source emission has improved substantially since data taking began. A layer of lead, approximately one radiation-length thick, was placed above each counter in 1989 June to improve the angular resolution and lower the energy threshold of the array. The data can be divided into two periods. The array was augmented during Period 1 from 50 to 108 counters, none of which had lead. This growth primarily changed the collection area, with little effect on the energy reponse or relative efficiency for photon-initiated and proton-intiated showers. Period 2 data were taken with 108 counters, each having a layer of lead, and a significantly looser trigger condition.

The energy of the primary cosmic rays initiating the air showers detected by the CYGNUS array is determined with the help of detailed Monte Carlo simulations (Alexandreas et al. 1991c). For showers initiated by protons, the most probable primary energy and median primary energy detected by the CYGNUS array in its present configuration are approximately 50 and 100 TeV, respectively (Alexandreas et al. 1991b). The median primary energy for gamma-ray-initiated events is ~ 80 TeV, assuming that the gamma rays and cosmic rays have similar energy spectra. The CYGNUS-I event rate is presently ~ 3.5 events s^{-1}.

Figure 1 shows the results of simulations of the response of

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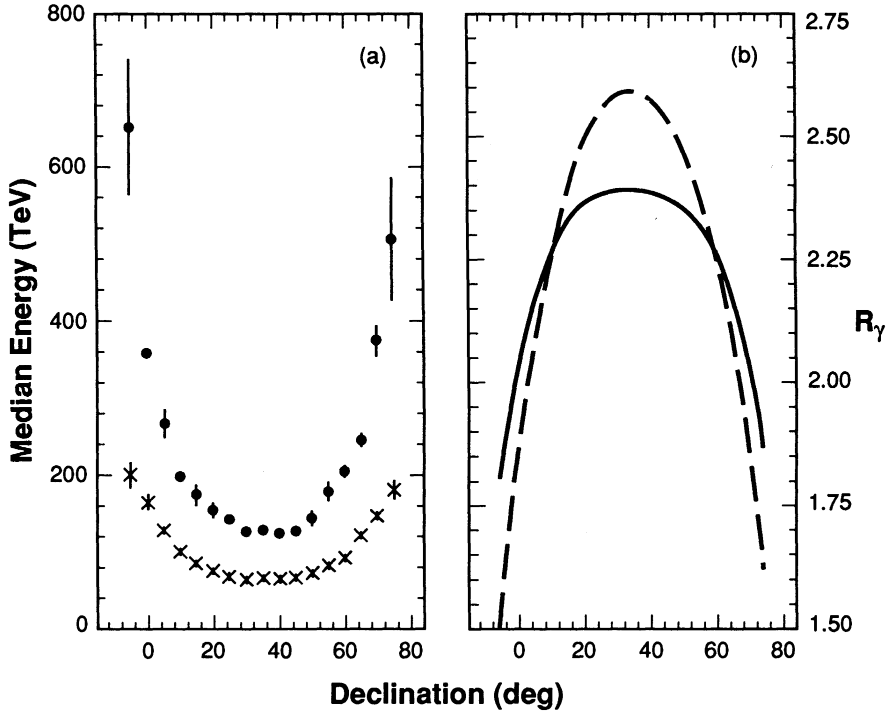

FIG. 1.—(*a*) Median detected energy of showers from a simulated photon source as a function of the source declination. The dots are for Period 1, and the crosses are for Period 2. (*b*) Ratio of the detection efficiency for photons to the detection efficiency for cosmic rays, R_γ, determined from simulations as a function of declinations. The dotted curves are for the Period 1 configuration, and the solid curves are for Period 2.

the array for the two periods. Figure 1*a* shows the median of the primary energy distribution, E_m, for detected photons from a hypothetical point source as a function of the declination of the source, assuming the photon energy spectrum has the same shape as the cosmic-ray energy spectrum. Figure 1*b* shows the ratio of the detection efficiency for photon-initiated showers to the efficiency for cosmic-ray-initiated showers, R_γ, assuming that they have the same spectral shape. Cosmic rays are assumed to consist of four parts protons, four parts He, two parts N, two parts Mg, one part Cl, and one part Fe. This composition is consistent with direct measurements (Burnett et al. 1990). Figure 2 shows the daily expected number of background events in a source bin spanning 2°.0 in declination and 2°.0/cos δ in right ascension, from several candidate sources. This figure shows the growth in sensitivity with time resulting from the upgrades described above. The higher trigger rate in Period 2 is predominantly due to the looser trigger conditions.

A few runs with hardware problems, comprising about 5% of the data sample, have been excluded from the analysis. Most of these runs have either malfunctions in the data acquisition system or noisy counters. After removal of the bad runs, the data set used for this search contains a total of about 3.04×10^8 air showers.

Studies of the solar and lunar shadows of the cosmic rays (Alexandreas et al. 1991d) have shown that the CYGNUS array has a projected rms angular resolution of $0°.75^{+0.13}_{-0.09}$, with a systematic pointing error less than 0°.6. A more recent analysis with additional data indicates an angular resolution of 0°.66 ± 0°.07.

3. SEARCH METHOD

For each air shower, the local coordinates and time of detection are transformed into celestial coordinates (α, δ); events

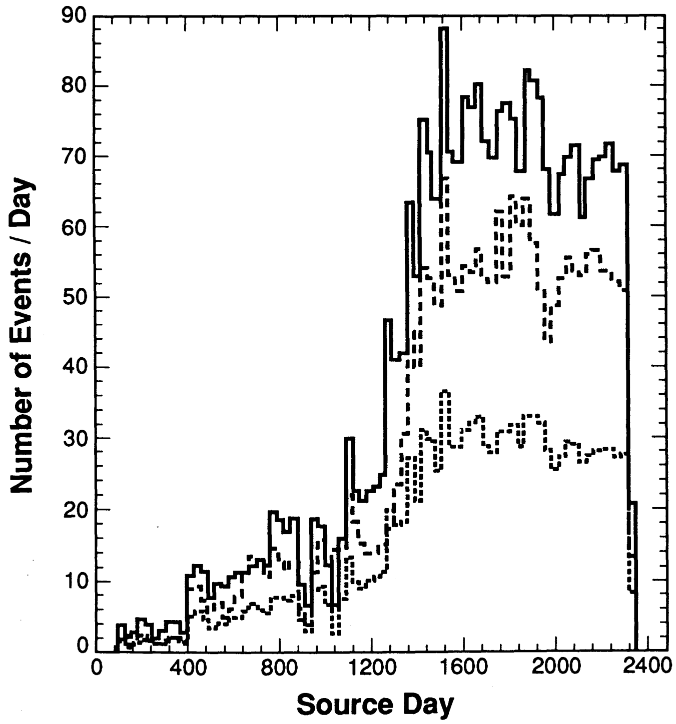

FIG. 2.—Calculated daily background counts for three sources at different declinations. *Solid curve:* Her X-1 (δ = 35°.4); *top dashed curve:* the Crab (δ = 22°.0); *bottom dashed curve:* PSR 1929+10 (δ = 10°.9). The rise in the number of background events per day is due to changes in the experimental configurations, as described in the text. The counts have been averaged over 30 day intervals to make this plot.

TABLE 1

CYGNUS SOURCE LIST[a]

	1989 FEB 1					1992 APR 1				
SOURCE	N_S	N_B	f_{90}	ϕ_γ	E_m	N_S	N_B	f_{90}	ϕ_γ	E_m
Cyg X-3	28	24.8	0.50	1.1	130	58	68.1	0.15	1.1	70
Her X-1	31	21.3	0.86	1.9	130	71	71.8	0.21	1.5	70
Crab	22	20.4	0.50	0.9	150	50	53.1	0.22	1.6	70
Cyg X-1	27	24.6	0.47	1.0	130	83	68.7	0.41	2.9	70
M31	20	20.4	0.43	1.0	130	60	65.5	0.18	1.3	70
Virgo A	7	13.1	0.31	0.4	190	35	32.8	0.39	1.9	90
AM Herc	22	23.9	0.35	0.6	150	58	65.2	0.17	1.2	70
DQ Herc	23	24.1	0.37	0.8	130	74	65.1	0.34	2.4	70
U Gem	20	19.9	0.45	0.8	150	66	52.6	0.49	3.5	70
SS Cygni	23	25.2	0.33	0.7	130	74	75.3	0.20	1.6	70
HZ 43	22	25.7	0.30	0.7	130	44	59.1	0.13	0.9	70
GK Per	26	21.1	0.63	1.4	130	68	59.4	0.36	2.6	70
V404 Cygni	28	24.6	0.51	1.1	130	73	65.8	0.31	2.2	70
Geminga	17	16.4	0.53	0.8	170	38	41.5	0.24	1.4	80
1E 2259+58	22	13.6	1.16	1.3	200	54	46.7	0.41	2.0	90
SS 433	11	6.0	1.77	1.4	270	28	17.7	1.05	2.8	130
4U 0042+32	24	18.4	0.74	1.6	130	51	65.5	0.13	0.9	70
4U 0115+63	9	12.4	0.42	0.4	230	32	31.4	0.36	1.1	120
4U 0316+41	19	18.8	0.47	1.0	130	70	65.6	0.28	2.0	70
4U 0352+30	25	23.7	0.45	1.0	130	66	61.8	0.29	2.1	70
4U 0614+09	5	10.3	0.36	0.4	210	24	24.9	0.37	1.3	110
4U 1257+28	24	25.3	0.36	0.8	130	50	60.1	0.15	1.1	70
4U 1651+39	26	24.0	0.47	1.0	130	71	72.2	0.21	1.5	70
4U 1837+04	8	8.1	0.76	0.6	270	19	17.9	0.53	1.4	130
4U 1901+03	6	6.5	0.82	0.5	300	17	14.9	0.65	1.6	140
4U 1907+09	8	8.4	0.71	0.9	200	26	26.9	0.36	1.5	100
4U 1918+15	10	13.2	0.41	0.6	180	44	33.2	0.63	3.0	90
4U 1957+40	33	24.9	0.69	1.5	130	66	69.5	0.19	1.3	70
4U 1954+31	18	25.2	0.23	0.5	130	74	63.8	0.37	2.6	70
4U 2142+38	18	23.3	0.28	0.6	130	76	60.7	0.47	3.3	70
4U 2321+58	18	12.2	1.04	1.2	200	44	43.9	0.29	1.4	90
4U 2358+21	17	12.8	0.88	1.6	150	44	45.7	0.26	1.5	80
2CG 065+00	23	24.6	0.35	0.8	130	71	66.3	0.28	2.0	70
2CG 075+00	23	23.0	0.41	0.9	130	80	68.9	0.36	2.6	70
2CG 078+01	14	25.1	0.18	0.4	130	66	66.6	0.22	1.6	70
2CG 095+04	17	19.6	0.37	0.5	180	54	52.0	0.29	1.7	80
2CG 135+01	11	13.1	0.46	0.5	220	31	33.9	0.28	1.1	100
2CG 121+04	8	9.7	0.56	0.4	290	22	25.4	0.31	0.8	130
PSR 0355+54	15	22.3	0.24	0.4	170	41	50.1	0.17	1.0	80
PSR 0950+08	4	10.5	0.32	0.3	220	17	22.3	0.28	1.0	110
PSR 1929+10	10	11.5	0.53	0.6	200	23	27.7	0.27	1.1	100
PSR 1937+21	16	20.4	0.31	0.6	150	42	47.8	0.20	1.1	80
PSR 1951+32	24	25.9	0.34	0.8	130	70	66.3	0.27	1.9	70
PSR 1953+29	19	23.5	0.29	0.6	130	67	68.2	0.22	1.6	70
PSR 1957+20	19	19.8	0.42	0.7	160	45	46.6	0.26	1.5	80
3C 279	1	2.9	0.99	0.2	680	4	3.1	1.71	2.6	200
K1	19	19.1	0.46	1.0	130	56	63.8	0.17	1.2	70
K3	24	26.0	0.33	0.7	130	77	67.8	0.34	2.4	70
K4	11	12.7	0.49	0.5	220	30	33.6	0.27	1.1	100
K5	4	7.4	0.51	0.3	310	33	27.2	0.56	1.3	140
K6	22	16.8	0.77	1.5	140	53	52.9	0.26	1.9	70

[a] Together with data for each of the sources on two typical days, 1989 February 1 and 1992 April 1. The data given are N_S, the number of events in the source bin, N_B, the number of expected background events, f_{90}, the 90% confidence level upper limit for the number of excess source events relative to the number of detected cosmic-ray events in the source bin, and ϕ_γ, the 90% confidence level upper limit for the gamma-ray flux above E_m, the median gamma-ray energy for the source bin. The units for E_m are TeV and for the flux are $(\text{cm}^{-2}\ \text{s}^{-1}) \times 10^{-12}$.

that fall within a source bin are counted as on-source. The 2°0 bin size, which is somewhat smaller than was used in previous analyses (Alexandreas et al. 1991a), is more appropriate for the angular resolution determined from the solar and lunar shadows.

For each source, the data are segmented into source days; a source day consists of 24 sidereal hours centered at the source meridian transit. The expected number of background events for each source day is compared to the corresponding number of on-source events. The background is calculated as described below.

For each recorded event, 10 fake events are generated by associating the hour angle of the event with the times of 10 other events, randomly chosen from a buffer that typically spans about 5 hr of data and brackets in time the event being processed. The fake events that fall within a source bin are counted as background events for that source.

The advantage of this method is that it automatically compensates for all event rate variations, because the background events have the same time distribution as the real ones. It also compensates for changes in sensitivity that would alter the local-angle distribution of showers, because the background events are generated from the observed distribution of local coordinates.

Potential systematic effects are closely monitored. For each source and each day, events are counted in 54 control bins surrounding the source bin (5 bins in declination × 11 bins in right ascension, excluding the source bin), and backgrounds for these bins are calculated in the same way as for the source bin. Systematic errors in the background estimate have been studied by comparing the distribution of the daily excess number of events in each of the 54 bins with expectations based on Poisson fluctuations of the calculated background event rate. After removing data with detector malfunctions, no systematic effects have been found.

4. SEARCH RESULTS

The method described above has been applied to the entire CYGNUS data set. The objects examined are listed in Table 1. Cyg X-3, Her X-1, and the Crab, three of the most studied objects in the UHE range, head the list. In addition, the list includes six *COS B* sources (Swanenburg et al. 1981), seven radio pulsars, 16 *Uhuru* X-ray sources (Forman et al. 1978), six cataclysmic variables, a few nearby galaxies, and other unusual objects. The six spots in the sky (K1, K3, K4, K5, and K6, with K2 being Cyg X-3) that had the largest excesses in the air shower data of the Kiel group (Stamm & Samorski 1983) have also been examined.

Searching for a signal in a large candidate source population poses the difficulty that a signal from a particular source, that may appear significant in isolation, may not be so when considering the statistics from all candidates. This difficulty is handled in the following manner. The potential sources are separated into a primary list, comprised of Cyg X-3, Her X-1, and the Crab, and a secondary list, consisting of the 48 remaining objects. A separate hypothesis is tested for each object on the primary list (namely, that the object emitted UHE radiation on 1 day), while a fourth hypothesis is tested for the set of 48 other objects (i.e., that any of the other objects emitted UHE radiation on 1 day).

For each source day, the deviation from background is expressed as the number of standard deviations (positive or negative) calculated according to the Li and Ma prescription (Li & Ma 1983). The distribution of daily deviations is histogrammed in Figure 3 for each of the three primary candidates and for the ensemble of 48 remaining candidates; the curves are best fits to a Gaussian with the parameters shown in the figure.

No significant single-day excess is observed from Cyg X-3, Her X-1, or the Crab; note that the burst of UHE emission from Her X-1 previously observed by this experiment in 1986 (Dingus et al. 1988) is significant primarily because of the combination of periodicity and excess on the day of the burst. The largest excess from any of these three objects is 4.09 σ. Considering the $\sim$1950 days observed for each source and the four hypotheses tested, the probability of observing an excess as large or larger than 4.09 σ is about 20%. The remaining 48 objects, with a total of 93,436 source days, also do not show any significant single-day excess, as can be seen by the excellent fit to a Gaussian. We note here that the small but significant negative deviation of the centroid of the Gaussian from zero is intrinsic to the Li & Ma prescription (Alexandreas et al. 1992). A simulated exposure with our source bin statistics and backgrounds produces precisely the observed deviation of the centroid from zero. We conclude that there is no statistically significant excess observed from any of the candidate sources in the primary or secondary list, on any day from 1986 April 4 to 1992 June 22.

The observed number of on-source events and the expected number of background events can be used to derive an upper limit for the number of signal events (Helene 1983; Protheroe 1984). The calculation of the upper limit must include effects due to the uncertain knowledge of the background. To illustrate the sensitivity to point-source emission, Table 1 shows the 90% confidence level limit for f_{90}, the number of excess source events relative to the number of detected cosmic-ray events in the source bin, for each source for a representative day in each data-taking period.

5. FLUX LIMITS

The all-particle cosmic-ray flux, ϕ_{CR}, is used to convert f_{90} into ϕ_γ, the flux of UHE emission:

$$\phi_\gamma = \frac{f_{90}\,\phi_{CR}\,\Omega}{0.72R_\gamma}\,, \qquad (1)$$

where Ω ($=1.2 \times 10^{-3}$ 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. R_γ is the ratio of the detection efficiency for photons to the detection efficiency for cosmic rays. R_γ has been determined from simulations for various source declinations (Fig. 1*b*). The flux limit for any particular source on a given day will depend on the exposure to the source on that day and the declination of the source. The exposure is reflected in the number of expected background events calculated for the source on the given day. The flux limit for a source is given as the upper limit on the integral flux above the median gamma-ray energy in the source bin, E_m, to minimize the dependence of the limit on the unknown spectral index for emission from the source (Gaisser et al. 1989).

The cosmic-ray proton flux above energy E in TeV, measured by Burnett et al. (1990), is

$$\phi_p = (5.1 \pm 1.4) \times 10^{-6} E^{-1.76\pm0.09}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}\,. \qquad (2)$$

Using the measured ratio of the all-particle flux to the proton flux of $\sim$3.5, from Figure 4 in their paper, the all-particle flux is

$$\phi_{CR} = (1.8 \pm 0.5) \times 10^{-5} E^{-1.76\pm0.09}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}\,. \qquad (3)$$

Another estimate of the total cosmic-ray flux can be obtained from the parameterization given in Nagle et al. (1988), which is

$$\phi_{CR} = 1.3 \times 10^{-5} E^{-1.55}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}\,. \qquad (4)$$

We use equation (3) to obtain flux limits from our data, because this is the most accurate direct measure of the cosmic-ray flux in this energy range. Note that the fluxes in equations (3) and (4) differ by nearly a factor of 2 for $E = 100$ TeV.

Table 1 also shows the 90% confidence level upper limit on the flux above the median gamma-ray energy in the source bin emitted by each of the examined sources on 1989 February 1

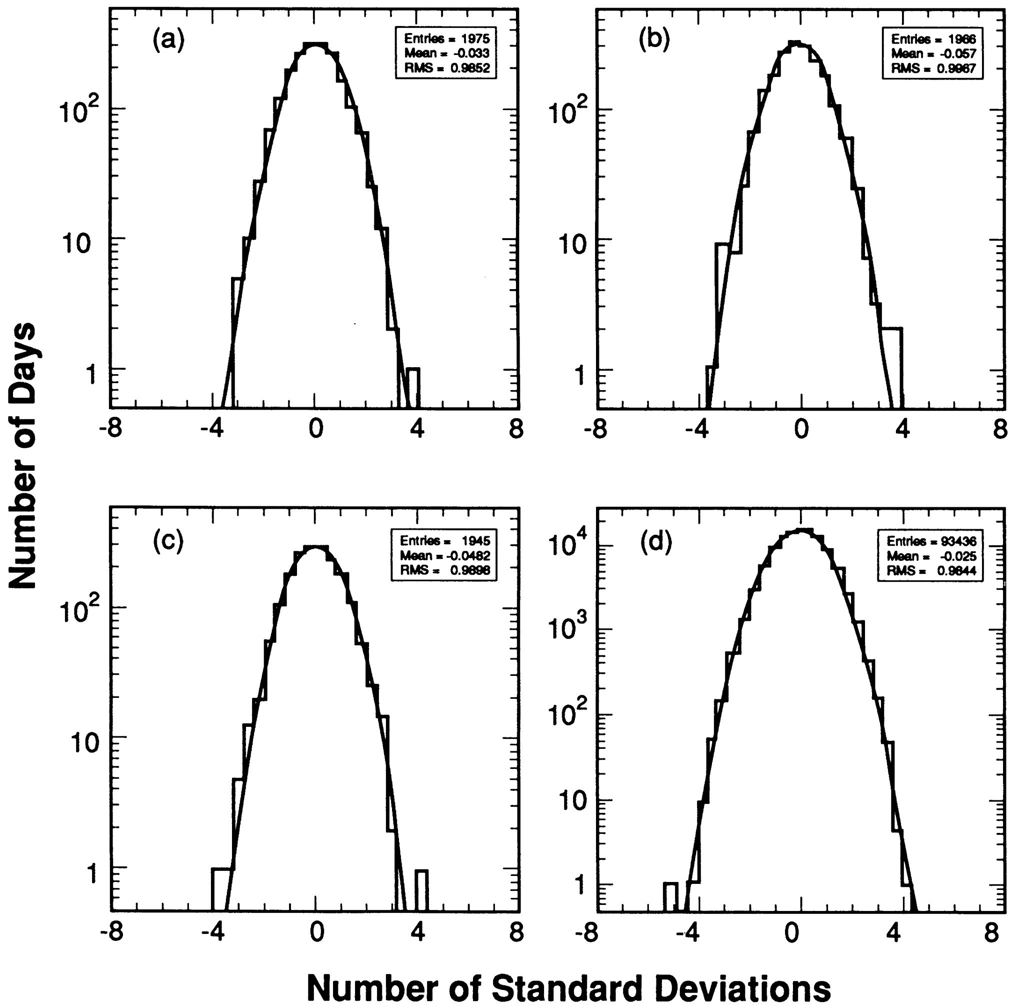

FIG. 3.—Distribution of daily excesses from (*a*) Cyg X-3, (*b*) Her X-1, (*c*) the Crab, and (*d*) the remaining 48 objects. Superposed on each of the four histograms is the best fit to a Gaussian distribution, with the parameters listed in the upper-right corner.

and 1992 April 1, respectively. Note that changing the assumed gamma-ray integral spectral index from -1.7 to -1.0 changes the upper limit for ϕ_γ by less than 10%.

6. DISCUSSION

The data set from the CYGNUS experiment, covering the period from 1986 April 4 through 1992 June 22, has been used to search for emission of UHE gamma rays from astronomical point sources. This paper describes the search for emission with a time scale of 1 day. An earlier paper (Alexandreas et al. 1991a) reported the results of a search for steady emission. These studies constitute part of a systematic search for UHE emission by the CYGNUS experiment. These null results do not preclude the possibility of episodic emission over other time scales, nor of periodic emission over any time scale. Future studies will include searches for these kinds of emission.

The null results reported here and in Alexandreas et al. (1991a) imply that there is now no strong steady UHE point source in the northern sky, nor do any of the objects on our source list strongly emit UHE gamma rays over time scales of 1 day. Our results are not necessarily in direct contradiction to previously reported detections of episodic emission because they are not simultaneous with our observations. In particular, we see no evidence for UHE emission on either the source day preceding or the source day following the reported burst of UHE gamma rays from the Crab on 1989 February 23 (Alexeenko et al. 1992), but the Crab was not overhead in Los Alamos during the time of the burst.

Active galactic nuclei have emerged as a new type of gamma-ray source (Hartman et al. 1992; Michelson et al. 1992) since this analysis was completed. A search of the CYGNUS data for evidence of UHE emission from these objects, especially Markarian 421 which was recently detected at 0.5 TeV (Weekes et al. 1992), is being pursued and will be reported elsewhere.

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REFERENCES

Alexandreas, D. E., et al. 1991a, ApJ, 383, L53
———. 1991b, Nucl. Instr. Meth. A, 311, 350
———. 1991c, Proc. 22d Internat. Cosmic Ray Conf. (Dublin), 4, 504
———. 1991d, Phys. Rev. D, 43, 1735
———. 1992, in preparation
Alexeenko, V. V., et al. 1992, J. Phys. G, 18, L83
Burnett, T. H., et al. 1990, ApJ, 349, L25
Cronin, J. W., et al. 1992, Phys. Rev. D, 45, 4385
Dingus, B. L., et al. 1988, Phys. Rev. Lett., 61, 1906
Forman, W., et al. 1978, ApJS, 38, 357
Gaisser, T. K., et al. 1989, Phys. Rev. Lett., 62, 1425
Hartman, R. C., et al. 1992, ApJ, 385, L1
Helene, O. 1983, Nucl. Instr. Meth., 212, 319
Li, T. P., & Ma, Y. Q. 1983, ApJ, 272, 317
Lloyd-Evans, J., et al. 1983, Nature, 305, 784
Michelson, P. F., et al. 1992, IAU Circ., No. 5470
Nagle, D. E., et al. 1988, Ann. Rev. Nucl. Sci., 38, 609
Protheroe, R. J. 1984, Astron. Express, 1, 33
Samorski, M., & Stamm, W. 1983, ApJ, 268, L17
Stamm, W., & Samorski, M. 1983, in Proc. 18th Internat. Cosmic Ray Conf. (Bangalore), 1, 131
Swanenburg, B. N., et al. 1981, ApJ, 243, L69
Weekes, T. J. 1992, Space Sci. Rev., 59, 315
Weekes, T. J., et al. 1992, IAU Circ., No. 5522