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SEARCH FOR 10^{15} eV GAMMA-RAYS FROM THE CRAB PULSAR AND SURROUNDING REGIONS

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ABSTRACT

During 1980 December and 1981 February, atmospheric Cerenkov light flashes were observed in a broad region of the sky including the Crab pulsar. The 1981 February data gave a flux upper limit of 5.3 x 10^{-13} cm^{-2} s^{-1} for 10^{15} eV γ-rays within 3°.5 of the Crab pulsar. Comparable limits were set over a declination band ä = 0°-70° and a right-ascension interval from approximately 0^h to 13^h. A weak (3.1 ó) excess from the Crab vicinity was detected on 1980 December 9. The excess may be due to a variable flux component that sometimes exceeds 2 x 10^{-12} cm^{-2} s^{-1} above 10^{15} eV.

Subject headings: gamma-rays: general - pulsars

I. INTRODUCTION

Pulsed γ-rays from the vicinity of the Crab nebula have been observed in the energy range 10^{11}-10^{13} eV by a number of experiments (Gibson et al. 1982; Gupta et al. 1978, and references therein). At higher energies, an estimate of the maximum energy of electrons, positrons, or protons produced by a pulsar is given by (Goldreich and Julian 1969)

$$E_m = 6.6 \times 10^{12}(B_{12} /T^2)\ \mathrm{eV}$$

where B1, is the surface magnetic field strength in units of 1012 gauss and T is the period in seconds. Using the parameters for the Crab pulsar NP 0532 (Taylor and Manchester 1975), results in a value of Em of 2.3 x 10^{16} eV. Measurements of the ray spectrum near this limit may help determine the mechanism by which the high-energy particles are accelerated and then interact with magnetic fields, particles, or photons, producing the γ-rays. Such studies may also elucidate the contribution of the pulsars to the primary cosmic-ray flux.

In this paper we report results of observations undertaken specifically to search for ultra-high-energy γ-rays from the vicinity of the Crab pulsar. The observations were done using the Fly's Eye cosmic-ray detector (Cassiday et al. 1979). Although the Fly's Eye was built to detect scintillation light emitted by extremely high energy (10^{17}-10^{20} eV) extensive air showers, it can also detect Cerenkov light from nearby (impact distances < 200 m) air showers of much lower energy. Because the Fly's Eye views almost the entire night sky, a search for high-energy γ-ray sources in a large angular region surrounding the Crab pulsar could also be made. During Fly's Eye operation, different mirrors of the system (see Fig. 1) simultaneously observe a selected target region in the sky as well as neighboring background regions. In effect, a number of

II. APPARATUS AND

At the time of these observations (1980 December and 1981 February), 48 out of the complete set of 67 Fly's Eye 1.6 m diameter f/1 mirrors were in operation. As shown in Figure 1, most of the sky was observed by the mirrors. At the focal plane of each mirror ate 12 or 14 hexagonal-faced aluminized Winston-type light collectors followed by an EMI 9861-B photomultiplier tube (PMT). Each of the light collectors receives light from a different 2º.8 half-angle hexagonal region in the sky.

Event data were stored for shower signals that passed certain triggering requirements, which were slightly different in the December and February runs. In the December run, a trigger was obtained when three PMTS in a mirror received a signal corresponding to a light density of about 1500 photons m -z within a 2 Its interval. A rate of triggers of about 0.4 s^{-1} was obtained from the entire system. In the February run, the trigger requirement was two PMTS detecting light within 2 ìs. The PMT high voltages and signal thresholds were adjusted in February to give event rates similar to those obtained in December. These PMT thresholds were high enough so that true accidental coincidences of two or three PMTS in a mirror unit were insignificant.

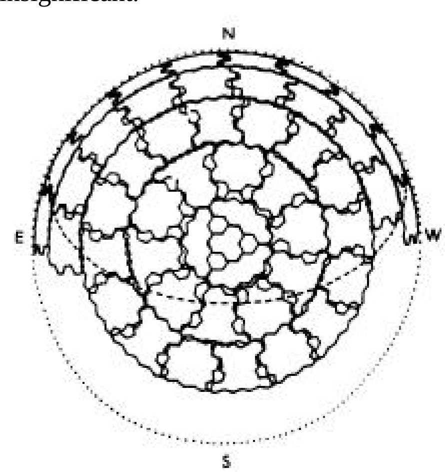

FIG. 1.-Projected field of view of the 48 Fly's Eye mirror units operation during the data runs. The zenith is at the center, and the horizon is along the dotted lines. Units in the three near vertical rings contain 12 hexagonal light collectors, and the others contain 14. The Crab trajectory follows the dashed line.

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The triggering requirements are unusual in that they require light to be detected in a larger angular range than the rms angular spread of the Cerenkov light received at a mirror from small air shower (Browning and Turver 1977). The most tense light comes from a direction close to that of the maximum size of the shower. However, light of lower intensity produced by electrons that penetrate nearly to ground level is present at angles of ~5° from the region of maximum light intensity. The triggering requirement raises the threshold of detected showers to about 3 x 10^{14} eV.

PMT count rates are affected in a well-known way by the variations of background starlight in different parts of the sky (Chudakov et al. 1964). Background light causes statistical fluctuations in the number of PMT photoelectrons, which are more frequent when the background light intensity is greater. These statistical fluctuations can drive a marginal signal pulse above threshold. On the basis of measurements of thresholds required to maintain constant count rates in the normal operation of the Fly's Eye, this effect gives only a 2% enhancement of the triggering rate at R.A. ~ 6^h. Such an effect is negligible compared with the effect of statistical fluctuations in the data discussed here.

Recorded data for an accepted event include (1) the identities of all PMTS that triggered; (2) the times at which each PMT triggered (50 ns resolution); and (3) integrals of the signal pulse from triggering PMTS. The 50 ns triggering time resolution is relative to other PMT triggering times in a shower. The absolute time accuracy was about 1 s during these observations, so that analysis of the data within the 33 ms Crab period was not possible.

The minimum energy of detected showers was estimated by using calculated photon densities (Smith and Turver 1973) for showers observed near the core. Photon densities were obtained by adding the signals of the PMTS that were above threshold and converting them to light yields using Fly's Eye sensitivities determined previously for the high-energy air shower work.

We can verify that the rate of detected cosmic-ray showers above a given threshold energy is what is expected. For showers with large enough signals that the triggering conditions are always satisfied, measured photon densities imply a threshold of 3 x 10^{15} eV. This energy value can be checked against another estimate based on measured triggering rates, the known spectral flux of primary cosmic rays (Hillas 1981) and the estimated effective area of the array (40,000 m^2 Such an estimate implies an energy threshold of 1.8 x 10^{15} eV. These estimates are in reasonable agreement with each other. We estimate a factor of 2 uncertainty in the shower energy thresholds.

Electromagnetic showers that have typical zenith angles of 30^o reach maximum size at 4-5 km above the Fly's Eye. These are detected at distances of 150 m from the shower core. This produces an inherent uncertainty of about 2 in our direction measurements. The shower image almost always has a well-defined maximum intensity in a single PMT. This results in an uncertainty equal to the PMT half-angle of 2:8. The angular resolution was estimated by combining these uncertainties, giving a directional uncertainty of 3.4. Data were binned in angular regions with a declination range of 7º and a right ascension range of $0.^h5$.

Each mirror unit of the Fly's Eye points in a fixed direction In the local coordinate system. In celestial coordinates, the mirror unit is fixed in declination, ä. and its right ascension, ó,

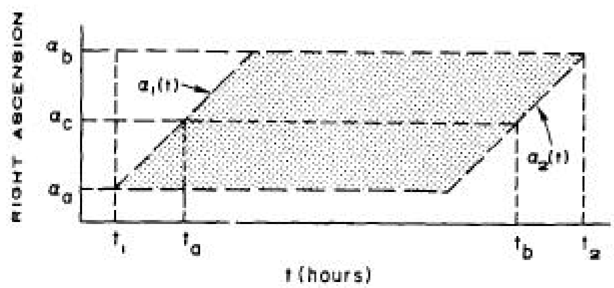


FIG. 2.-Boundaries of the drift scans. Events were accepted for which the right ascension fell within the shaded area. The time and right-ascension parameters are defined in the text.

increases linearly with time, parallel to the lines á$_1$(t) and á$_2$(t) in Figure 2. The starting and finishing times of a data run are designated by t_1 and t_2. For examination of the Crab pulsar, the range of x of interest consists of five half-hour bins with ac, the right ascension of the Crab pulsar, in the middle of the third bin. For this analysis, only those light detectors were included that pass through the entire right-ascension interval from á$_a$ to á$_b$ within the time interval from t_1 to t_2. Events that satisfy this right-ascension cut are in the shaded region of Figure 2. The declination cut is 18°.48 < ä < 25°.48. Between times t_a to t_b, some PMT is always pointed in the direction of the Crab pulsar.

III. OBSERVATIONS

The mode of operation used in this search was incompatible with the normal operation of the Fly's Eye. In order to minimize the interference with the normal Fly's Eye operation, Cerenkov flash observations were limited to 1980 December 9 and five nights in 1981 February. Data were taken on cloud free moonless nights. Data taken on the nights of 1981 February 3 and 4 were rejected because frost was detected on the mirrors and light collectors in the late parts of those nights, along with decreases of the data rate. The dates of the accepted runs were 1980 December 9 and 1981 February 1, 6, and 7. The lengths of the four runs (t_2 - t_1) were 6.2, 4.7, 5.8, and 5.2 hours, respectively.

The data from 1980 December 9 gave results different from those from 1981 February. Table I shows the December data in five right-ascension bins, with the third bin centered on the Crab pulsar. Data are binned for three different threshold energies. The numbers of showers above each threshold energy are given, where the threshold energy, E_t, was estimated from assessed photon densities. The 10^{15} eV data are plotted in Figure 3.

The statistical significance of the peak near the Crab pulsar can be determined by testing the hypothesis that the count rate

TABLE I

DATA FROM 1980 DECEMBER 9

E_t (eV)	$\alpha_C - 1^h$	$\alpha_C - 0^h5$	α_C	$\alpha_C + 0^h5$	$\alpha_C + 1^h$
3×10^{14}	39	41	58	38	39
1×10^{15}	26	23	40	22	22
3×10^{15}	9	9	17	4	13

NOTE.—Numbers of events above threshold energies, E_t, are given for right-ascension bins in the vicinity of the Crab pulsar. The right ascension of the Crab pulsar is indicated by α_C.

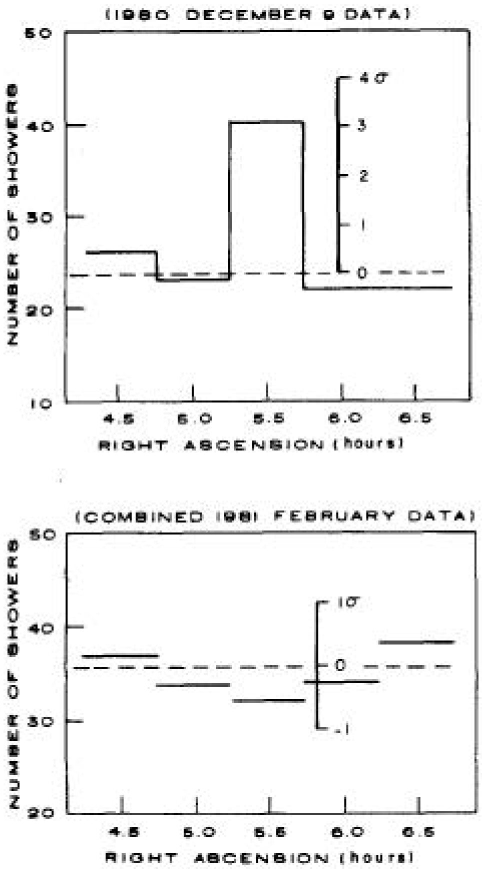


Fig. 3.-Drift-scan results with a 10^{15} eV threshold for a 7º declination band centered on the Crab Nebula: (top) 1980 December data show a 3.1 á peak near the Crab Nebula; (bottom) 1981 February data show no peak.

near the Crab pulsar's right ascension is consistent with the count rate obtained in the other four bins. In Table 2 the average background count, B, is given in the second column. The signal, S, is the number of counts above the background for the Crab pulsar data and is compared to ó to obtain the significance of the peak. The uncertainty in the average background from the four bins is $(4B)^{1/2}/4 = (B/4)^{1/2}$. Assuming that this background is also present in the Crab pulsar bin, its uncertainty is $B^{1/2}$, so that the combined uncertainty for the two independent sources of error is $ó = (1.25B)^{1/2}$. The ratio S/ó is given in Table 2. The statistical significance of the peak is maximum near 10^{15} eV. The flux of γ-rays is given by

$$F = IUS/B , \qquad (2)$$

where I is the background cosmic-ray flux from Hillas (1981) and 0 is the solid angle of the 7° x 7°5 bin in which S was measured. It is implicitly assumed that the entire γ-ray flux from the Crab pulsar is contained within the angular bin. The

TABLE 3

Data from 1981 February 1, 6, and 7

E, (eV)	$\alpha_C - 1^h$	$\alpha_C - 0^h5$	α_C	$\alpha_C + 0^h5$	$\alpha_C + 1^h$
3×10^{14}..........	62	53	48	55	60
1×10^{15}..........	37	34	32	34	38
3×10^{15}..........	18	9	12	15	19
1×10^{16}..........	2	1	3	2	7

uncertainty in the flux Is not the same as the Q used above for testing the null hypothesis, but is given by

$$ó_F = [(B + S) + B/4]^{1/2} = (1.25B + S)^{1/2} , \qquad (3)$$

since B + S is the square of the signal-region uncertainty and B/4 is the square of the background uncertainty. The uncertainty d arises from statistical fluctuations only and does not include systematic effects such as the effect of the threshold energy uncertainty on 1 in equation (2) and the experimental uncertainty in 1 itself.

A count-rate peak was not observed near the Crab pulsar in the February run. The peak observed in the December run reached a significance of 3.1 Q in one of three energy ranges. Although the three ranges are not entirely independent, we will be conservative and treat them as independent data sets. In the February run, four energy ranges were used because the chosen running conditions gave a wider dynamic range. There were three acceptable runs in February, yielding a total of 12 semi-independent sets of data in February and three in December. The probability of having an effect 3.1 ó is 1.9 x 10^{-3}. Therefore, the probability of seeing a 3.1 ó peak in the 15 trials can be conservatively estimated to be 15P (3.1 ó). The estimated confidence level for a detection of a narrow anisotropy near the Crab pulsar is 1 - [15(1.9 x 10^{-3})], or 97%. This result implies that the Crab is quite likely a sporadic high-energy γ-ray source. However, its statistical significance is not high enough to allow us to make such a claim with much confidence.

The counts, N, from the February runs are shown in Table 3, and the 10^{15} eV data are shown in Figure 3. The combined data as well as the data from each night do not show any evidence of an excess in the direction of the Crab pulsar. Using a maximum-likelihood method (Hearn 1969), upper limits were obtained at the 68% confidence level (corresponding to 1 ó) for an excess flux in the vicinity of the Crab pulsar. These limits are given in Table 4 and are plotted in Figure 6.

Although the present study was motivated by the results of a previous observation of the immediate vicinity of the Crab nebula (Dzikowski et al. 1981), Cerenkov flashes from a very broad angular region of the sky were accepted in our search. The combined December and February data can be used to check that the numbers of events seen in the numerous

TABLE 2

Analysis of the December Data

E, (eV)	B	S	S/σ	Flux (cm^{-2} s^{-1})
3×10^{14}..........	39.25	18.75	2.7	$8.2 \pm 3.1 \times 10^{-12}$
1×10^{15}..........	23.25	16.75	3.1	$2.1 \pm 0.7 \times 10^{-12}$
3×10^{15}..........	8.75	8.25	2.5	$3.3 \pm 1.3 \times 10^{-13}$

TABLE 4

Analysis of the February Data

E, (eV)	B	N	Flux Upper Limit (cm^{-2} s^{-1})
3×10^{14}..........	57.50	48	1.7×10^{-12}
1×10^{15}..........	35.75	32	5.3×10^{-13}
3×10^{15}..........	15.25	12	8.8×10^{-14}
1×10^{16}..........	3.00	3	4.5×10^{-14}

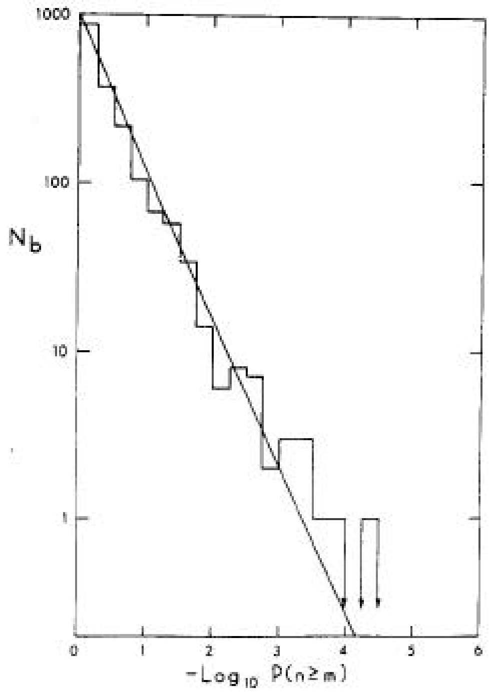
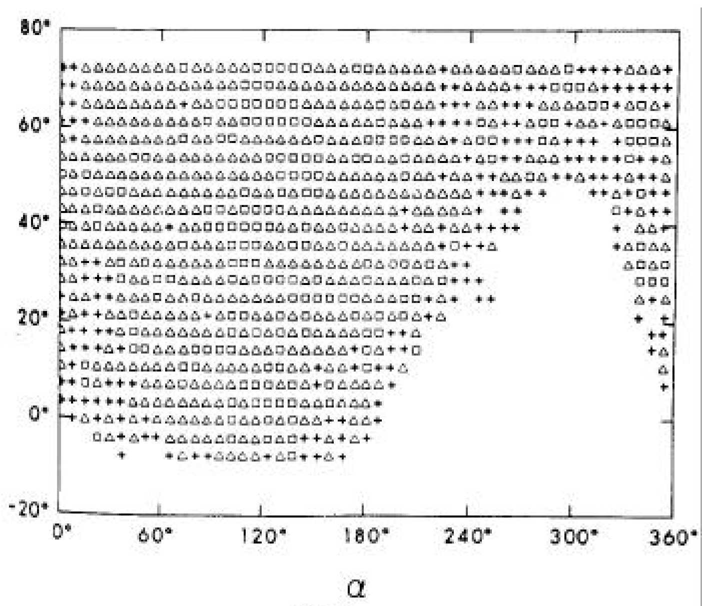


FIG. 4.-Distribution of numbers of angular bins vs. Poisson probability of having m or more counts in a bin, where m is the observed number of counts. The smooth, nearly straight curve is the expected distribution assuming that a systematic 3 uncertainty in the count rate exists in addition to the Poisson fluctuations.

angular regions covering the entire Fly's Eye field of view are consistent with statistical fluctuations. For this analysis, bins of 7°.2 in declination, ä, and 7°.2/cos ä in right ascension were used. Overlapping bins centered on a 3.°6 x 3.°6 grid were used in order to avoid missing sources because of arbitrary bin centering. The expected number of counts in a specific celestial region was calculated by obtaining the rates in bins in Earth fixed coordinates when the designated celestial region was not in view. These rates were used to calculate the expected number of counts for the time intervals when the region of interest was in view. Expected numbers of counts were obtained for over 1800 celestial regions ranging over declinations 0°-70° and right ascensions 0"-13", a very broad region of the sky. The Poisson probability for receiving a number of counts equal to or exceeding the observed number was calculated for each celestial bin. The numbers of bins are shown as a function of the calculated probability in Figure 4. The nearly straight line shows the background distribution due to Poisson statistical fluctuations combined with a Gaussian systematic error distribution with ó equal to 3% of the predicted values. This broadening of the Poisson distribution is required by the data and is probably due to the small triggering enhancements expected from background light intensity variations described in § II None of the bins show an excess that is extremely improbable. The likelihood of obtaining a bin as improbable as the lowest-probability bin in a sample of this size is about 30%, according to the background distribution. We conclude that large systematic errors are not present and that we have not detected any γ-ray sources in this survey (with the possible exception of the Crab, discussed earlier.)

The survey described above allows upper limits to be assigned to the γ-ray flux from nonvariable point sources. Results are shown in Figure 5. For this figure, neighboring right ascension bins are combined, giving 3°.6 x 7.°2 bins. Over a



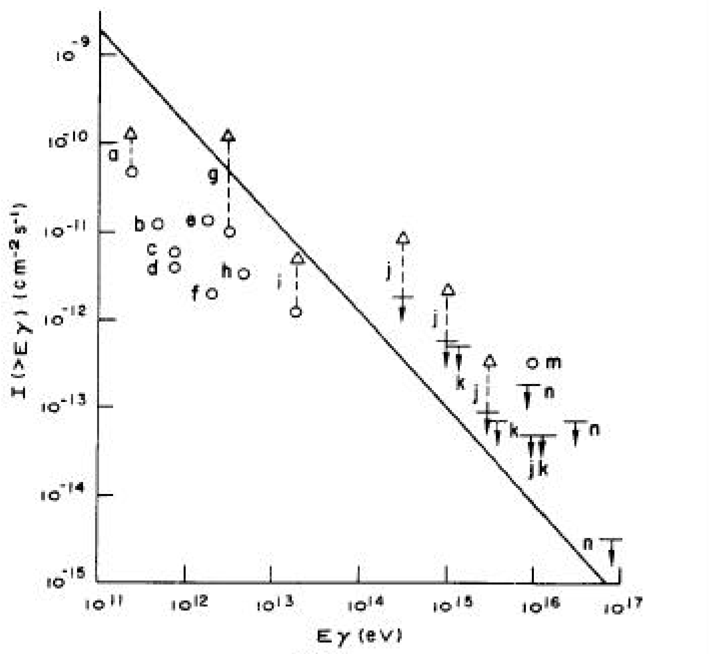


FIG. 5.-Summary of γ-ray flux upper limits. Symbols used for limits (in $cm^{-2}\ s^{-1}$); squares, less than 3 x 10^{-13}; triangles, 3 x 10^{-13} 10^{-12}; crosses 10^{-12} -3 x 10^{-12}. Limits are at the 90%, confidence level. Angular regions are centered at á = 1.°8 + 7.°2 x j, ä = 3.°6 x k, where j and k are integers.

FIG. 6-Spectrum of ultra-high-energy γ-rays from the Crab pulsar region. Triangles are "high flux" observations made during single nights; circles show measurements averaged over longer times. Above 10^{14} eV upper limits are also shown. Where experiments obtained both "high flux" and longer-term averages or upper limits, dashed lines connect the pairs of results. The solid line is the extrapolation of the spectrum of McBreen et al. (1973) which applies to average fluxes of from 1.5 key to 2 GeV ,γ-rays. Letters represent the following observations: a, Fazio et al. 1972; h, Gupta et al. 1978; c-e, Grindlay, Helmken, and Weekes 1976; j; Jennings et al. 1974; g, Gibson et al. 1982; h, Porter et al. 1976; i, Erickson, Fickle, and Lamb 1976; j, present authors, 1980 December data (triangles) and 1981

wide angular region, upper limits of 3-10 x 10^{-13} cm^{-2} s^{-1} are obtained.

IV

Dramatic evidence for the variability of the Crab pulsar was obtained by the Durham group (Gibson *et al.* 1982). Using four Cerenkov telescopes, a pulsed signal was obtained with a high confidence level (chance probability < 10^{-6}) in a 15 min period on 1981 October 23. The threshold was 3 x 10^{12} eV, and the flux during the most significant 15 min period was 2.0 ± 0.3 x 10^{-10} cm^{-2} s^{-1}. However, the average flux for the entire 34 hours of observations is of the order of 10^{-11} cm^{-2} s^{-1}. That experiment demonstrates that the variability of the Crab pulsar flux of ultra-high-energy γ-rays is both extreme and rapid.

Evidence for E 10 ^{16} eV γ-rays from an extensive air shower array and muon detectors has been reported by the Lodz group (Dzikowski *et al.* 1981) from data taken in 19681971 and in 1975-1979. A flux level of 3 ±2 x 10^{-13} cm^{-2} s^{-1} and a statistical significance of 3.6 ó was reported. During 1978 and 1981, an extensive air-shower array and muon array (Hayashida *et al.* 1981) obtained an upper limit of showers from the direction of the Crab pulsar (angular resolution
2:5), roughly an order of magnitude lower than the Lodz results. Because of the possible variability of the γ-ray flux, the experiments are not necessarily contradictory.

A suitable description of the time-averaged spectrum of the Crab pulsar obtained over the range of photon energies 1.5 keV-2 GeV is

$$I(>E) = 0.95E^{-1.08} \tag{4}$$

(McBreen *et al.* 1973), where E is in keV and I is in cm^{-2} s^{-1} In Figure 6 this expression is shown extrapolated to higher energies. Between 10^{11} and 10^{14} eV, the time-averaged flux measurements fall approximately an order of magnitude below the extrapolated spectrum, although the peak flux measurements approach or exceed the extrapolated value. Above 10^{14} eV, even the upper limits of the average fluxes are above the extrapolation, because of the limitations of the experimental sensitivities. The 1980 December observations reported here together with the lower-energy observations are consistent with the presence of a sporadic component with a relatively flat spectrum between 10^{11} and 10^{15} eV.

In this experiment and that of Dzikowski *et al.* (1981) absolute millisecond-accuracy timing was not available and the angular resolution was not precise. Consequently, the association of the effects with the Crab pulsar is not certain. The direction of the excess flux observed in this experiment is about 6° from the galactic plane. Within 5° on either side of the galactic plane and at the galactic longitude of this experiment's excess flux, another experiment observed an excess of 10^{11}-10^{12} eV γ-rays from an extended region (Weekes, Helmken, and Grindlay 1979). In the present experiment, however, the time scale of the variability of the possible source is not consistent with an extended source of angular width more than a few degrees at distances of more than a few parsecs.

REFERENCES

Browning, R., and Turver, K. E. 1977, *Nuoro Cimento, 38,* 223.

Cassiday, G. L.. Bergeson, H. E., Loh. E. C.. Elbert, J. W., and Steck, D. 1979, in *Cosmic Rats and Particle Phi-sics-1978* (New York: American Institute of Physics), p. 417.

Chudakov, A. E.. Dadykin, V. L. Zatsepin, V. I., and Nesterova, N. M. 1964, *Proc. Leheder Phys. Inst., 26. 100.*

Craig, M. A. B.. Orford, K. J., Turver, K. E., and Weekes, T. C. 1981, *Proc. 17th Internat. Cosmic Ray, Conf., 1,* 3.

Dzikowski, T., Gawin, J., Grochalska, B., Wasilewski. A., and Wdowczyk, J. 1981, *Proc. /7th Internat. Cosmic Ray Con(., 1,* 8.

Erickson, R. A., Fickle, R. K., and Lamb, R. C. 1976, Ap. *J., 210,* 359.

Fazio, G. G., Helmken, H. F., O'Mongain, E., and Weekes, T. C. 1972, Ap. *J. (Letters), 175.* L117.

Gibson. A. 1.. Harrison, A. B., Kirkman, I. W., Lotts, A. P., Macrae, J. H., Orford, K. J., Turver, K. E., and Walmsley, M. 1982, *Nature, 296,* 833.

Goldreich, P., and Julian, W. H. 1969, Ap. *J.,157,* 869.

Grindlay, J. E.. Helmken, H. F., and Weekes, T. C. 1976, Ap. *J., 209,* 292.

Gupta, S. K., Ramana Murthy. P. V.. Sreekantan. B. V., and Tonwar, S. C. 1978, Ap. *J., 221,* 268.

Hayashida, N., Ishikawa, F., Kamata, K., Kifune, T., Nagano, M., and Tan, Y. H. 1981, *Proc. 17th Internat. Cosmic Ray Conf., 9,* 9.

Hearn, D. 1969, *Nucl.* Instr. *Methods, 70,* 200.

Hillas, A. M. 1981, Proc. 17th Internat. Cosmic Ray Conf., 13, 69.

Jennings, D. M., White, G., Porter, N. A., Mongain, E., Fegan, D. J., and White, J. 1974, *Nuovo* Cimento. 20, 71.

McBreen, B., Ball, Jr. S. E., Campbell, M., Greisen, K., and Koch, D. 1973, Ap. J., 184, 571.

Porter, N. A., Delaney, T., Helmken, H. F., and Weekes, T. C. 1976, Nuovo Cimento, 32B. 514.

Smith, G. J., and Turver, K. E. 1973. Proc. 13th Internat. Cosmic Ray Conf., 4, 2369.

Taylor, J. H., and Manchester. R. N. 1975, A.J., 80, 794.

Weekes, T. C., Helmken, H. F.. and Grindlay, J. E. 1979, Proc. 16th Internat. Cosmic Ray Conf. 1, 132.

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