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SPORADIC AND PERIODIC 10–1000 TeV GAMMA RAYS FROM CYGNUS X-3

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ABSTRACT

During 1985 June, July, August, and October, small air showers from the direction of Cygnus X-3 were observed using the University of Utah Fly's Eye. Useful spectral information was obtained from these showers. The combined data from 1985 June, July, and August show a 3.9 σ excess at 4.8 hr phase 0.65–0.70 for showers with energies above 100 TeV. The excess flux, averaged over all phases, is $4.5 \pm 1.2 \times 10^{-13}$ cm^{-2} s^{-1}. During a short run in 1985 October, following a Cyg X-3 radio outburst, only upper limits for the fluxes were obtained.

Evidence was obtained for a sporadic outburst in 1985 June 17 UT. The outburst occurred at various phases of the 4.8 hr Cygnus X-3 period. Part of the signal above 250 TeV was near phase 0, when the companion star eclipses the neutron star in some models of Cygnus X-3. The energy flux during the outburst was about 10^{-8} ergs cm^{-2} s^{-1}, which is quite large compared with long-term periodic fluxes. Averaged over all the observing time, however, the sporadic flux is roughly comparable to the periodic flux.

Subject headings: gamma rays: general — stars: individual (Cyg X-3) — X-rays: binaries

I. INTRODUCTION

Observations of TeV (10^{12} eV) radiation from Cygnus X-3 were started by a group at the Crimean Astrophysical Observatory (Stepanian *et al.* 1977). More recently, PeV (10^{15} eV) detections of Cyg X-3 have been reported (Samorski and Stamm 1983; Lloyd-Evans *et al.* 1983*a*; Baltrusaitis *et al.* 1985*a*; Lambert *et al.* 1985; Kifune *et al.* 1986). Most of the previous observations have reported a periodic component, but not the sporadic component reported by Fomin *et al.* in 1981. The periodic effects typically have excesses in the 4.8 hr phase regions near 0.2 and 0.6. The signals are usually observed in data samples accumulated over months or years. The sporadic effects, however, were excesses which lasted several days or less and were observed at almost all phase regions (Stepanian *et al.* 1982).

During 1985 June, July, and August, observations of Cyg X-3 were done at lower energies and higher data rates than previous observations of possible γ-ray sources by the Fly's Eye. A significant amount of spectral information was also obtained. A search was carried out for sporadic and periodic emission from Cyg X-3. Data were also taken in 1985 October, following the detection of an exceedingly strong radio outburst from Cyg X-3 (Johnston 1985). A search for unusually high γ-ray flux levels following the radio outburst was carried out with these data. The results of these observations are reported below.

II. APPARATUS AND TECHNIQUES

A detailed description of the Fly's Eye apparatus has been given (Baltrusaitis *et al.* 1985*b*). Previous results from ultra–high-energy γ-ray studies by the Fly's Eye have been published (Baltrusaitis *et al.* 1985*a*, *c*; Boone *et al.* 1984). The results give evidence for emission from the Crab Pulsar vicinity, Cyg X-3, and Hercules X-1. A search for sources at all positive declinations has also been reported (Baltrusaitis *et al.* 1985*a*).

In previous work, all available mirror units were operated. The present studies were done using only a strip of mirrors which observe Cyg X-3. During 1985 June, August, and October, the number of mirrors in this strip was 9, 10, 10, and 5, respectively. The mirrors were selected to include the useful path of Cyg X-3 during the nights of each month. When Cyg X-3 was not in the field of view of a mirror, the background rate for the mirror was accumulated. Thus, the mirrors were operated in the drift-scan mode, with some mirror observing Cyg X-3 at any time during the night.

During the June, July, and August runs, data were recorded for Cerenkov flashes yielding more than 800 photoelectrons in any photomultiplier tube in any mirror. The pulse-amplitude threshold was set to give rates of accepted flashes of about 0.4 Cerenkov flashes per second in each mirror. The trigger rate for the entire detector was about 3.7 Hz, yielding 1.27 million events in a total of 94.6 hr of useful operating time. The data were taken during 44.3 hr on June 9, 11–19, and 22 (UT). 6.3 hr during July 25 and 26, and 44.0 hours from August 12–15 and 19–22.

The single tube triggering requirement allowed showers of energies above about 10 TeV to be accepted. This is lower than the threshold that was used previously ($\sim$500 TeV). The dynamic range was about 2 orders of magnitude. This allowed a significant amount of spectral information to be obtained from the observed flashes.

A 7° × 7° square region centered on Cyg X-3 is defined as the target region. The size of the target region is consistent with the estimated angular resolution and is the same as was used in previous studies. During each night, the triggering rate of each photomultiplier tube was determined for the total time during which the tube was not viewing the target region. The expected number of events from a tube when it views the target region is given by the product of this triggering rate and the time interval in which the tube viewed the target region. The total number of expected events was obtained by adding the expected numbers from the different tubes which passed through the target region.

Only data taken during times when all the mirrors had stable event rates were accepted. The stability requirement

involved dividing a night into $\frac{1}{8}$ hr intervals and observing the deviation in each mirror from the average rate in the mirror during that night. If two or more mirrors deviated by more than 3.5 σ or if one mirror deviated by more than 5 σ the interval was not used in the analysis.

The Cyg X-3 γ-ray spectrum has been reported to be quite flat (integral spectral index ≈ 1) by Samorski and Stamm (1983) and Lloyd-Evans *et al.* (1983*b*). In addition, the detector triggering efficiency for 10 TeV was a relatively low fraction ($\sim 10\%$) of that at 100 TeV. Because of these circumstances, it seemed plausible that improved sensitivity could be obtained for a γ-ray signal in the presence of a steeper cosmic-ray background spectrum by examining the pulse spectrum in the data. Because the shower's energy can be accurately determined only by knowing the impact parameter (the distance to the nearest point on the shower axis) relative to the Fly's Eye as well as the detected pulse height, only broad intervals of energy were used in the analysis. The approximate energy was evaluated for each shower by assuming that the impact parameter was 50 m.

The choice of 50 m is arbitrary, but some justification of this value can be made. If the impact parameter were accurately known, a Cerenkov flash of a certain number of photoelectrons would come from showers within a narrow energy range. But the impact parameter is not measured. By using a calculated Cerenkov light lateral distribution based on results of Hillas (1982) and assuming a power-law γ-ray spectrum, we calculated the distribution of shower energies producing detected flashes of a fixed number of photoelectrons. This resolution function was calculated separately for a differential spectral index of 2.0 and 2.75. For both cases the resolution function was peaked within 10% of the energy value obtained by assuming that the impact parameter was 50 m. The distribution fell to half its peak value at energies within a factor of 2 of the energy at the maximum of the distribution. Almost no contribution came from showers at less than 50% of the peak energy, but the distribution has a long, low-amplitude tail on the high-energy side.

III. EXCESS EMISSION FROM THE CYGNUS X-3 DIRECTION

The total number of observed events was compared with the expected number to see whether a signal is indicated by the data. For showers with E in the range 10–100 TeV, there were 27,522 observed and 27,605 expected showers in the target region centered on Cyg X-3. The "excess" is -83 ± 166 events.

For the remaining decade with significant numbers of events (100–1000 TeV), the observed and expected numbers are 4651 and 4443, respectively. A 4.7% excess, amounting to 208 ± 67 events, is present. This 3.1 σ excess suggests that a signal may be present in the higher energy part of the data.

The 4.7% excess in the upper E interval is apparently not due to systematic effects of the overall normalization type, since the expected and observed numbers of showers agree to within 0.3% in the lower energy interval. More specific results concerning sporadic and periodic emission are discussed in the following two sections.

IV. EVIDENCE OF SPORADIC EMISSION

Searches were made for sporadic and periodic emission. The sporadic emission search was done for each night's data in 4 half-decade intervals covering the energy range of the data, from 10 TeV to 1000 TeV. For each E bin the expected number of showers was obtained using the method described in the previous section. The χ^2 test was applied to each night's data. The statistical uncertainty in the expected numbers was included in the estimated errors used in calculating χ^2. The probability of the χ^2 value was evaluated for 4 degrees of freedom.

For the 21 nights, 16 probabilities were in the range 0.1–1, three were in 0.01–0.1, one was in 0.001–0.01, none were in 0.0001–0.001, and one was in 0.00001–0.0001. Any night with a probability less than 0.001 is unlikely to have occurred by chance, since a random sample of 21 probabilities would have only about a 5% chance of including such a small value.

The most remarkable night was 1985 June 17 UT. The chance probability of the χ^2 value was 8.5×10^{-5}, equivalent to a 3.9 σ effect on that night. The probability of a result this significant occurring once in 21 nights is 0.0018. In the 4 half-decade intervals in the range 10–1000 TeV, the observed (expected) numbers of showers were 540 (479. 4), 393 (359.0), 97 (84.1), and 29 (14.3). The significances of these exesses are equivalent to 2.6, 1.7, 1.3, and 3.6 σ, respectively. Although a large χ^2 can also result from deficits in some energy bins, all of the bins in this case show an excess, with the most significant effect in the highest bin. The total number of events during this night was 1059, with 936.8 ± 12.3 expected, corresponding to a 3.7 σ excess.

The shape of the pulse-height spectrum (E distribution) was also remarkable during this night. Figure 1 shows the spectrum for June 17 as well as for the preceding and following nights. The shapes of the distributions agree quite well with the expected shapes, except on June 17, when an excess is evident above about 250 TeV. (The detailed shape varies from night to night because of differing exposure times of the photomultiplier tubes at various zenith angles.)

The effect described here is evidence for an outburst of ultra–high-energy γ-rays from Cyg X-3 on 1985 June 17. The observation was made from 6:21 A.M. until 10:11 A.M. UT. The flux during this time can be estimated by

$$F = (S/B) f I \Omega ,$$

where S is the number of events making up the apparent signal, B is the expected number of showers from cosmic rays, I is the integral cosmic-ray intensity, and Ω is the solid angle subtended by the angular bin in which data were accepted. The quantity f is an adjustment of the flux which must be made because a γ-ray shower produces about 60% more Cerenkov light than a hadronic shower of the same energy. As a result, the apparent amplitude of a γ-ray spectrum is enhanced by a factor of 2.2 and $f = 0.45$. For showers above $E = 10$ TeV, the sporadic flux during the 3.8 hr observation period was $2.8 \pm 0.8 \times 10^{-10}$ cm^{-2} s^{-1}. Above 100 TeV, the flux was $6.1 \pm 2.4 \times 10^{-12}$ cm^{-2} s^{-1}. If we average these sporadic fluxes over 21 nights of observations, the average fluxes are $1.1 \pm 0.3 \times 10^{-11}$ cm^{-2} s^{-1} and $2.5 \pm 1.0 \times 10^{-13}$ cm^{-2} s^{-1} above 10 TeV and 100 TeV, respectively.

The 4.8 hr phase dependence of the data from 1985 June 17 was examined. The ephermeris (van der Klis and Bonnet-Bidaud 1981) gave 0.86 as the phase at the start of the night's data and 0.66 as the end. The data are compared with the expected results for each phase in Figure 2*a*. The excess occurs in more than one phase interval and is most prominent in phase regions outside those in which periodic effects are usually detected for Cyg X-3.

The excess flux was especially obvious above $E = 250$ TeV in Figure 1. The phase distribution of these data is shown in

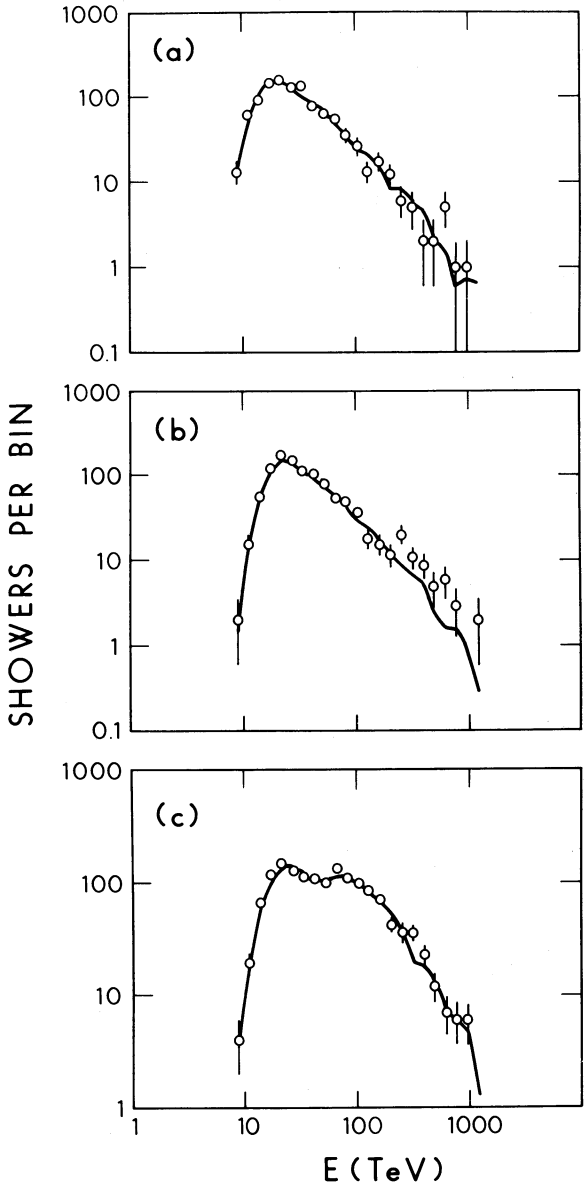

FIG. 1.—Spectrum of pulse heights (converted to estimated energies, E) for (*a*) June 16, (*b*) June 17, and (*c*) June 18, UT. Observed numbers of showers (*open circles*) are compared with the expected numbers (*curves*). A sporadic excess is visible at high E in (*b*).

Figure 2*b*. Emission appears to be present near phase 0.0 in the 4.8 hr period. The possible significance of this will be discussed in § VII.

V. EVIDENCE OF PERIODIC EMISSION

The large data sample of the 21 nights taken together allowed a sensitive test for the presence of a signal with the 4.8 hr period of Cyg X-3. Separate χ^2 tests were done with 20 phase bins for data in the intervals $E = 10$–100 TeV and $E = 100$–1000 TeV. For the lower energy data, the χ^2 value was 24.1 for 20 degrees of freedom. The corresponding probability was 0.24. The numbers of excess counts in each phase bin are plotted in Figure 3*a*, and no remarkable excesses are present.

For the higher energy data, χ^2 was 46.5, and the corresponding probability was 7.0×10^{-4}. The high χ^2 is mostly produced by a 3.9 σ excess in the phase bin 0.65–0.7. (See Fig. 3*b*). There were 534 showers observed, with 448.7 $\pm$ 4.4 expected in this bin. During June, July, and August there were 458, 8, and 68 observed events and 395.0 6.2, and 47.4 expected events, respectively, in this bin. The excesses in June and August are each significant at about the 3 σ level.

The excess flux (averaged over all phases) in the phase bin 0.65–0.7 is $4.5 \pm 1.2 \times 10^{-13}$ cm^{-2} s^{-1}. This is the integral flux for showers above 100 TeV. For the equivalent flux above 10 TeV, only an upper limit was obtained. The upper limit is 1.4×10^{-11} cm^{-2} s^{-1} at the 95% confidence level.

At the beginning of § III it was noted that the E interval 10–100 TeV showed no excesses of events in the 1985 summer runs. No periodic excess was found in the lower E interval, but some sporadic signal is present in this interval in data from June 17. If we exclude June 17 data, the excess in the 10–100 TeV energy interval is -178 ± 164. This number is consistent with a -1 σ fluctuation of the cosmic-ray background.

The observed total number of events in the 1985 summer data in the 100–1000 TeV interval exceeded the expected number by 208 $\pm$ 67. Since almost none of the excess from the sporadic effect occurred in the 0.65–0.7 phase interval of the periodic effect, the sum of the periodic excess (85.4 $\pm$ 23.1) and the sporadic excess (61.6 $\pm$ 23.2) can be used to estimate the excess from the two types of signal. This sum is 147 $\pm$ 33 events and is consistent with the total excess in the 100–1000 TeV data.

VI. THE 1985 OCTOBER RESULTS

Following the report of an unusually large radio outburst from Cyg X-3 in 1985 October a special run was done to search

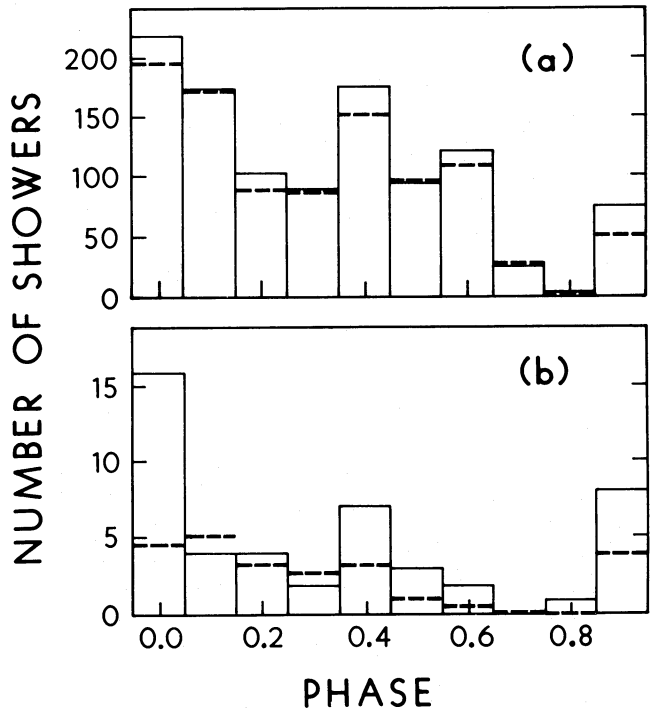

FIG. 2.—Dependence of the observed (*solid lines*) numbers of showers on the 4.8 hr phase of Cyg X-3. These results are for 1985 June 17, the night of the apparent sporadic effect. (*a*) All E; (*b*) $E > 250$ TeV only. Bin boundaries are shifted to emphasize emission near phase 0 in (*b*).

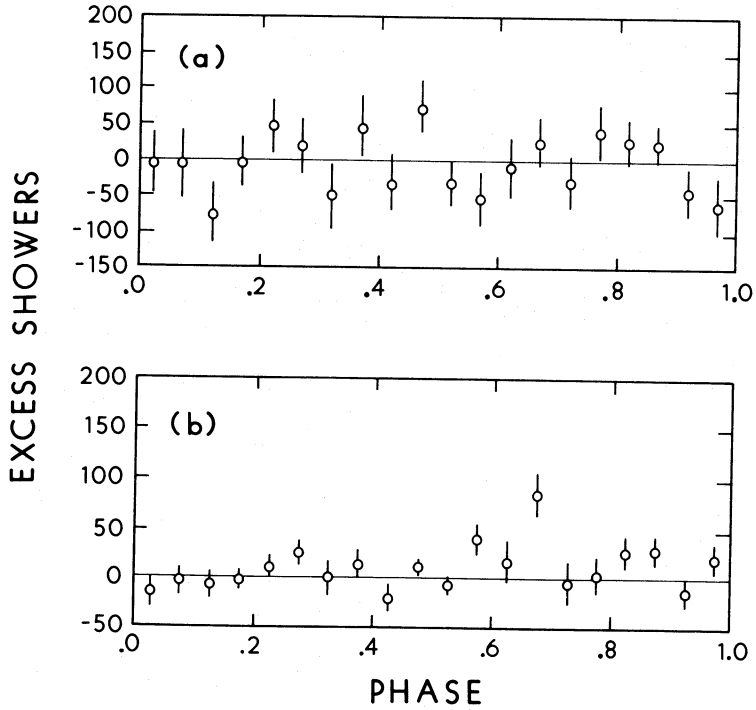

FIG. 3.—Combined data from 1985 June, July, and August. Observed minus expected numbers are given as a function of the 4.8 hr phase. (*a*) E = 10–100 TeV; (*b*) E = 100–1000 TeV. The upper E interval shows an excess in phase 0.65–0.70.

for a large outburst of PeV γ-rays. Data were obtained on the nights of 1985 October 17, 18, and 19 UT. A total of 14.3 hr of observations and 91,000 events were obtained. Unlike the summer runs, the event trigger consisted of a fast coincidence between two photomultiplier tubes in any mirror. As in the summer runs, the tube thresholds were kept fixed throughout the night.

Figure 4*a* shows the observed and expected numbers of events in 10 phase intervals of the 4.8 hr period of Cyg X-3. This is for data from all three nights and includes the entire E interval. No excess is apparent, and the χ^2 value is 0.76 per degree of freedom. There was near agreement between the total expected number of events (2883) and the observed number (2871). The expected numbers of events on the three nights were, in order, 737, 1085, and 1060. The corresponding observed numbers were 732, 1067, and 1072, in good agreement with the expected numbers.

The distribution of phases of showers with $E > 100$ TeV is shown in Figure 4*b*. No significant enhancements are present. The observed and expected total numbers of events are 451 and 454.

No sporadic or periodic effects were detected in this short data run. For E above 10 TeV, the upper limits for fluxes in the phase intervals 0.2–0.3 and 0.6–0.7 were 4.3×10^{-11} cm^{-2} s^{-2} and 8.8×10^{-11} cm^{-2} s^{-1}, respectively. For E above 100 TeV, these upper limits are 2.2×10^{-12} cm^{-2} s^{-1} and 1.3×10^{-12} cm^{-2} s^{-1}. These flux limits, although obtained for specific phase intervals, are averaged over all phases.

VII. DISCUSSION OF THE RESULTS

The observed fluxes and upper limits are shown in Figure 5. The sporadic flux was very high during the 3.8 hr interval when it was observed. But averaged over the entire summer's operating time it is comparable to the periodic signal. The periodic flux is present at a level not far from the Lloyd-Evans *et al.* (1983*b*) parameterization at 100 TeV. The periodic flux could be present at a similar fraction of the Lloyd-Evans *et al.* flux at

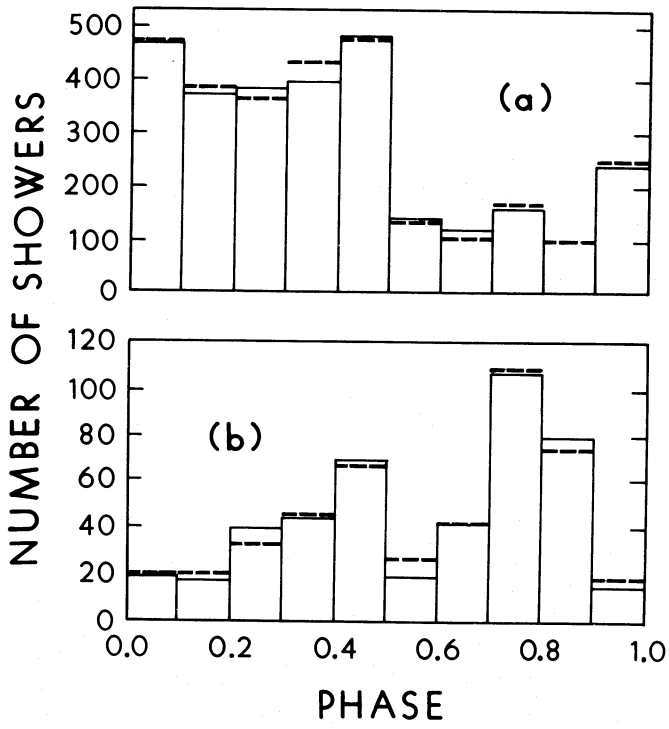

FIG. 4.—Data from 1985 October 17, 18, and 19, following the Cyg X-3 radio outburst. Observed (*solid lines*) and expected (*dashed lines*) numbers are in good agreement for (*a*) all E and (*b*) $E > 100$ TeV. Flux limits are given in the text.

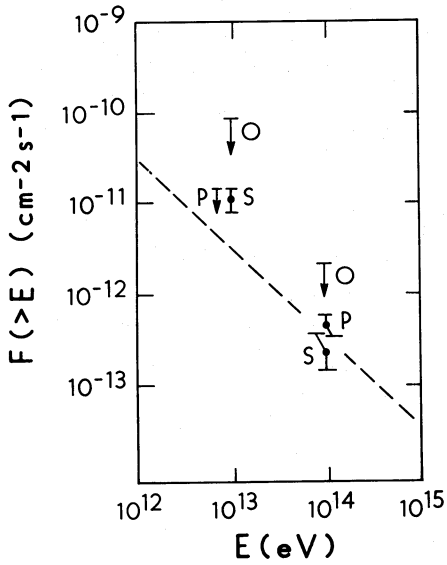

FIG. 5.—Observed flux values and flux upper limits are given for the 1985 October run (*O*), periodic signals in 1985 summer (*P*), and the 1985 June 17 sporadic effect, averaged over the total summer observing time (*S*). The dashed line is a comparison spectrum from Lloyd-Evans *et al.* (1983*b*).

10 TeV and still be consistent with the upper limits. Because of the smaller amount of data taken in 1985 October, it is not possible to rule out a periodic flux at the level observed in the summer data.

A comparison of the sporadic flux above 10 TeV with that above 100 TeV shows a decrease with increasing energy comparable to that of the the primary cosmic-ray spectrum. If we assume that the differential flux has about the same spectral shape between 10 TeV and 1000 TeV as the primary cosmic-ray spectrum, the energy flux during the sporadic emission on 1985 June 17 was about 10^{-8} ergs cm^{-2} s^{-1}. Using 12 kpc (Dickey 1983) as the distance to Cyg X-3 and assuming isotropic emission, and luminosity during this 3.8 hr episode was about 10^{38} ergs s^{-1}. This is comparable to estimates of the Eddington luminosity for Cyg X-3 (Gaisser *et al.* 1986). The outburst was shorter than about 48 hr because it was not observed during the preceding or following nights.

From the dependence of the sporadic signal on the zenith angle Stepanian *et al.* (1977) concluded that the spectral slope is steeper than the primary cosmic-ray spectrum. Comparison of our sporadic fluxes above 10 and 100 TeV gives an integral spectral slope of 1.7 ± 0.3. This is near the value for the primary cosmic-ray spectrum. It should also be noted that the 100 TeV flux is strongly affected by the enhancement above 250 TeV that is apparent in Figure 1*b*. This enhancement tends to decrease the spectral slope. The Crimean data were for a threshold of 2 TeV, and the results would not have been influenced much by an enhancement above 250 TeV. Consequently, there is no significant discrepancy between the spectral slope conclusions of the Fly's Eye and those of the Crimean experiment.

In an appealing model of ultra–high-energy γ-ray production in Cyg X-3, particles accelerated by a neutron star generate γ-ray fluxes by collisions with the limb of the companion star (Vestrand and Eichler 1982). Periodic fluxes would be expected at two phase intervals of the 4.8 hr orbital period. A sporadic component which occurs at many different phases is not simply explained by this picture. In addition, Figure 2*b* gives support for emission near phase 0, when the X-ray emission is near minimum. This observation appears to favor models in which there is not a true eclipse of the neutron star at phase 0. An alternative explanation is the beam magnetic steering mechanism proposed to explain Hercules X-1 TeV γ-ray fluxes observed during the eclipse of the X-ray source by the companion star (Gorham and Learned 1986). With stronger magnetic fields, the mechanism might allow particles produced near the neutron star at phase 0 to generate γ-rays on the limb of the companion star. But the simplest form of this model would not produce sporadic effects at every phase of the 4.8 hr period.

The apparent implications of the sporadic flux component suggest that further studies should be made of this effect, especially with higher statistics. Because the effects are short-lived, systems with low energy thresholds and large collection areas are required to obtain the necessary large count rates.

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REFERENCES

Baltrusaitis, R. M., *et al.* 1985*a*, *Ap. J.*, **297**, 145.
Baltrusaitis, R. M., *et al.* 1985*b*, *Nucl. Instr. Meth.*, **A240**, 410.
Baltrusaitis, R. M., *et al.* 1985*c*, *Ap. J.* (*Letters*), **293**, L69.
Boone, J., Cady, R., Cassiday, G. L., Elbert, J. W., Loh, E. C., Sokolsky, P., Steck, D., and Wasserbaech, S. 1984, *Ap. J.*, **285**, 264.
Dickey, J. M. 1983, *Ap. J.* (*Letters*), **273**, L71
Fomin, V. P., Neshpor, Yu. I., Stepanian, A. A., Zyskin, Yu. L., and Vladimirsky, B. M. 1981, *Proc. 17th International Cosmic Ray Conf.* (Paris), **1**, 28.
Gaisser, T. K., Stecker, F. W., Harding, A. K., and Barnard, J. J. 1986, *Ap. J.*, **309**, 674.
Gorham, P. W., and Learned, J. G. 1986, *Nature*, **323**, 422.
Hillas, A. M. 1982, *J. Phys. G: Nucl. Phys.*, **8**, 1461.
Johnston, K. 1985, private communication.
Kifune, T., *et al.* 1986, *Ap. J.*, **301**, 230.
Lambert, A., Lloyd-Evans, J., Perrett, J. C., Reid, R. J. O., Watson, A. A., and West, A. A. 1985, *Proc. 19th Internat. Cosmic Ray Conf.* (La Jolla), **1**, 71.
Lloyd-Evans, J., Coy, R. N., Lambert, J., Lapikens, J., Patel, M., Reid, R. J. O., and Watson, A. A. 1983*a*, *Nature*, **305**, 784.
———. 1983*b*, *Proc. 18th Internat. Cosmic Ray Conf.* (Bangalore), **9**, 65.
Samorski, M., and Stamm, W. 1983, *Ap. J.* (*Letters*), **268**, L17.
Stepanian, A. A., Fomin, V. P., Neshpor, Yu. I., Vladimirsky, B. M., and Zyskin, Yu. L. 1982, *Proc. Ooty Workshop on Very High Energy Gamma Ray Astronomy* (Bombay: Tata Institute), p. 43.
Stepanian, A. A., Vladimirsky, B. M., Neshpor, Yu. I., and Fomin, V. P. 1977, *Proc. 15th Internat. Cosmic Ray Conf.* (Plovdiv), **1**, 135.
van der Klis, M., and Bonnet-Bidaud, J. M. 1981, *Astr. Ap.*, **95**, L5.
Vestrand, W. T., and Eichler, D. 1982, *Ap. J.*, **261**, 251.

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