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UPPER LIMITS FOR NORTHERN HEMISPHERE 10^{15} eV GAMMA-RAY SOURCES

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ABSTRACT

Flux limits in the range 10^{-13} to 10^{-12} cm^{-2} s^{-1} have been obtained by observing Cerenkov flashes from small air showers. Simultaneous drift scans by the 67 mirror units of the Utah Fly's Eye gave nearly full coverage of the Northern Hemisphere. During 1983, a 3.5 σ excess of showers was observed during the phase interval 0.2–0.3 of the 4.8 hr period of Cygnus X-3, but no excess was found in 1984 observations.

Subject headings: gamma rays: sources — X-rays: sources

I. INTRODUCTION

Little is known about the sources of $E \geq 10^{15}$ eV γ-rays. A variety of models has been proposed for ultra–high-energy particle acceleration and γ-ray production by Cygnus X-3 (Chanmugan and Brecher 1985; Vestrand and Eichler 1982; Stepanian 1981). The acceleration and photon production mechanisms can be studied using ultra–high-energy γ-rays. It is probable that at these energies the γ-rays are produced by energetic nuclei, not electrons (Eichler and Vestrand 1984). Thus, the 10^{15} eV (1 PeV) γ-ray sources are likely to be the first identified sources of galactic cosmic rays. Only a few PeV γ-ray sources have been observed or suggested by observations. Cygnus X-3 has been detected in the 0.03–20 PeV energy region by a number of experiments (Samorski and Stamm 1983; Lloyd-Evans *et al.* 1983; Morello, Navarra, and Vernetto 1983). It is also one of the most well established TeV γ-ray emitters (Neshpor *et al.* 1979; Danaher *et al.* 1981; Lamb *et al.* 1982). Observations of Vela X-1 (Protheroe, Clay, and Gerhardy 1984) and LMC X-4 (Protheroe and Clay 1985) have been done above 3 Pev. Somewhat contradictory observations and upper limits have been reported for 1–10 PeV γ-ray emission from the vicinity of the Crab Nebula (Dzikowski *et al.* 1983; Boone *et al.* 1984; Lambert, Lloyd-Evans, and Watson 1983).

A search for high flux PeV γ-ray sources has been performed using the University of Utah Fly's Eye cosmic-ray air shower detector (Cassiday *et al.* 1979). Using 878 photomultiplier tubes (PMTs) distributed among 67 1.6 m diameter mirrors, Cerenkov flashes were detected at night from nearly the entire sky. There were 82,898 showers with $>20{,}000$ photoelectrons in 122 hr of operation during this survey. The data were divided into an array of overlapping bins to yield upper limits for the flux of PeV γ-rays from point sources for all right ascensions and for declinations from $-10°$ to 75°. In addition, event rates from the direction of Cygnus X-3 have been studied as a function of the phase within the 4.8 hr period of that object. The observation of a signal from Hercules X-1 within this same data set is reported in another paper (Baltrusaitis *et al.* 1985).

II. APPARATUS AND TECHNIQUES

The 67 mirrors of the Fly's Eye observe mutually exclusive sky regions at fixed elevation angles and azimuthal directions. The regions have negligible overlap and cover the sky at all elevation angles above about 3°. Each mirror focuses onto 12 or 14 pairs of hexagonal-faced aluminized Winston-type light collectors and EMI 9861B PMTs. Each light collector receives light from a separate 5°6 diameter sky region.

Data taken during 1980 and 1981 were obtained with 48 mirrors. The field of view and trigger requirements for that data were described in Boone *et al.* (1984). Data from 1983 and 1984 were taken with the complete Fly's Eye (67 mirrors). For the 1983 and 1984 data, the Fly's Eye was operated at the same gain used in observing scintillation tracks of $E > 100$ PeV. In order to accept ~ 1 PeV Cerenkov flashes, a triggering condition was set up which accepted showers in which six or more PMTs in any mirror fired within 8 μs. This condition yielded a trigger rate of about 0.3 s^{-1} for the entire Fly's Eye and reduced accidental triggers to a negligible level.

The observed Cerenkov flashes nearly always have a very large signal (equivalent to $\sim 10{,}000$ photoelectrons) in a single PMT, and much lower signals in neighboring PMTs. Simulations show that the signals in the lower amplitude PMTs (at angles of $\geq 5°$ from the direction of the highest intensity Cerenkov light) are primarily produced by Cerenkov light emitted by shower particles which are relatively near the detector. The PMT which receives a very large amplitude signal receives light which comes primarily from the region in which the shower size is near maximum.

Calculated angular distributions of electrons in air showers (Hillas 1982) and shower size versus depth curves (Gaisser and Hillas 1977) were used to calculate light production by proton-initiated showers. These results, together with a model of the atmospheric transmission properties (Elterman 1965), were then used to calculate the detector response to the primary cosmic-ray spectrum (Linsley 1983) and to a less steep γ-ray spectrum. The estimated median energy of the accepted primary cosmic ray showers is approximately 1 PeV as shown in Figure 1. The triggering efficiency for γ-rays is expected to be very nearly the same as for protons. We estimate a factor of 2 uncertainty in the median energy of the accepted data. The air shower direction is taken as the center of the largest amplitude PMT in each shower. As in Boone *et al.* (1984), we estimate a directional uncertainty of about 3°5.

Since each light detector unit is fixed in direction in terrestrial coordinates, the actual event rate produced by an isotropic cosmic-ray distribution will be nearly constant at a fixed declination and hour angle. For each declination band, the event rate was measured as a function of hour angle for each night's data. An expected number of showers in a specified

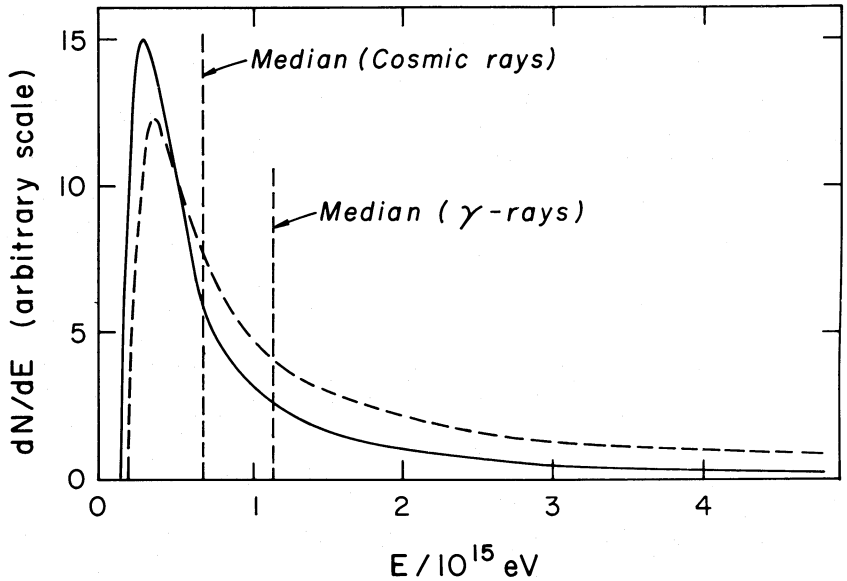

FIG. 1.—The distribution of primary energies contributing to the rate of Cerenkov flashes yielding signals of ≥20,000 photoelectrons in the Fly's Eye light detectors. The solid line assumes a primary cosmic-ray differential spectral index, $\gamma = 2.5$. The dashed line assumes a spectral index for primary γ-rays of 2.0.

target direction was calculated by summing the products of (*a*) the event rate at each hour angle by (*b*) the time interval during which the target region was observed at the particular hour angle. A small adjustment was made to take into account the variation of detector rate at different time intervals during the night. This adjustment was small, however, since the detector rate varies by $<2\%\ \mathrm{hr}^{-1}$ during each night. These expected numbers of showers were compared with the observed numbers in order to obtain the γ-ray intensity upper limits described in the next section.

III. OBSERVATIONS AND RESULTS

The observations during 1980 were made during 7.9 hr on December 9. Other observation periods were 1981 February 1–7 (26.8 hr), 1983 July 9–13 (25.1 hr), 1984 August 26–29 (20.1 hr), and 1984 September 25–29 (42.4 hr). The 1980 and 1981 observations covered the R.A. intervals from about 1^{h}–17^{h} and the 1983 and 1984 observations covered the R.A. intervals 16^{h}–24^{h} and 0^{h}–7^{h}.

The sky survey for γ-ray sources was done in angular bins of declination interval 7°.2 and in right ascension intervals of 0.48 sec δ^{h}, where δ is the declination. A grid of overlapping bins with centers separated by 3°.6 in declination and $0^{\mathrm{h}}.24$ in right ascension was searched for excesses of observed counts above the background expectations. Because the background intervals were too small compared with the target regions at very high declinations, the search was done only for regions with the declination, δ, less than 75°.6, with the largest declination of the bin centers at 72°. At large negative declinations the data rate is too low to allow significant upper limits to be set.

The data were used both to search for point sources and to derive upper limits for the flux from any point sources in each region. The search for point sources was carried out separately for each month's data and for the combined data. The distributions of the numbers of directional bins as a function of the probability of observing as many as or more counts than the number actually observed are shown in Figure 2. Bins with events in excess of expected values should show up as a bump above the straight line representing the distribution based on statistical fluctuations alone. Figure 2*a* shows the distribution of bins from all the monthly data sets. Except for a few excess bins near 10^{-4}, the distribution is consistent with that based on random deviations. In Figure 2*b* the observations from all monthly runs are combined in each directional bin. Again, a few extra bins may be present in the low probability region.

Since each monthly plot contained data in ~ 1600 bins and the combined plot had results in over 2000 bins, only bins with probabilities less than 10^{-4} will be discussed here. Two such bins occurred in the monthly data sets. One was in 1980 December and the other was in 1983 July. The right ascensions of the bin centers were $7^{\mathrm{h}}26^{\mathrm{m}}$ and $22^{\mathrm{h}}5^{\mathrm{m}}$, and the declinations were 18°.0 and −25°.2, respectively. The probabilities of the excesses occurring at random are 6×10^{-5} and 8×10^{-5}. The Galactic latitudes are 16°.2 and −53°.3. Thus they are not near the Galactic plane. They do not correspond to directions of the γ-ray sources in the 2CG catalog or with the possible PeV sources listed in Stamm and Samorski (1984). It is notable that the only source candidate in the combined data was present in a monthly data set. The improved statistics available in the combined data did not result in the appearance of additional sources. The candidate source in the combined data is essentially identical with the 1983 July source, since it occurred in a region in which other months did not contribute a significant amount of data. It seems likely that these possible sources are statistical fluctuations, perhaps affected by small undiscovered systematic effects.

Figure 3 displays the upper limits for steady fluxes of PeV γ-rays produced from point sources. The maximum signal to background ratio, S/B, was used to calculate the γ-ray flux limit, F, using the relation

$$F = \frac{S}{B} I\Omega , \quad (1)$$

where I is the primary cosmic-ray intensity (Linsley 1983), and Ω is the solid angle of the bins. Both F and I are determined for shower energies of $E > 1$ PeV. The relation assumes that the collection area for observing showers produced by cosmic rays

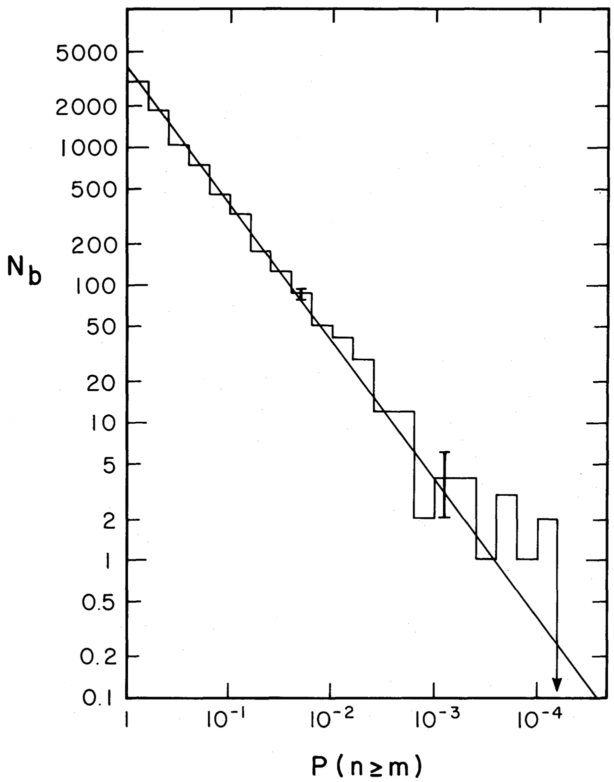

FIG. 2*a*

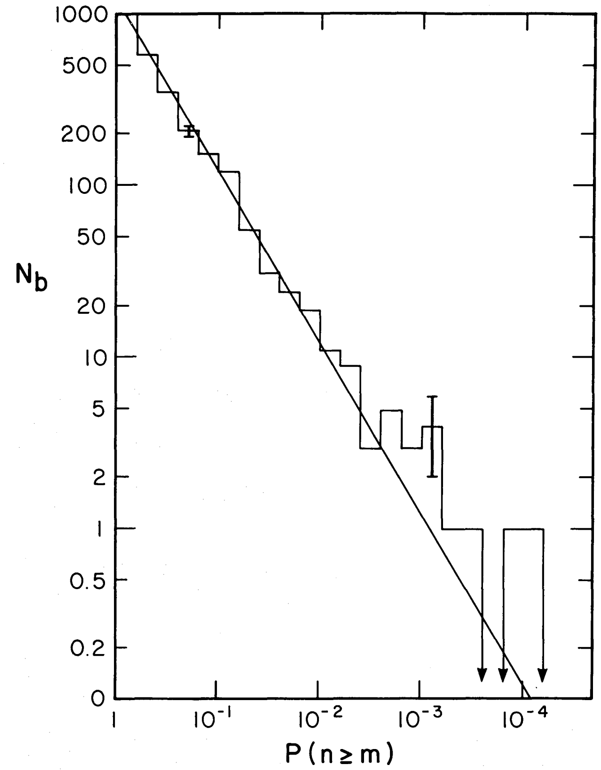

FIG. 2*b*

FIG. 2.—Distributions of numbers of directional bins in the Northern Hemisphere survey as a function of the probability of observing a number, *n*, of showers greater than or equal to the observed number, *m*. The straight lines give the distribution expected from statistical fluctuations. In the first plot, bins from separate monthly runs are counted separately, in the second part they are combined.

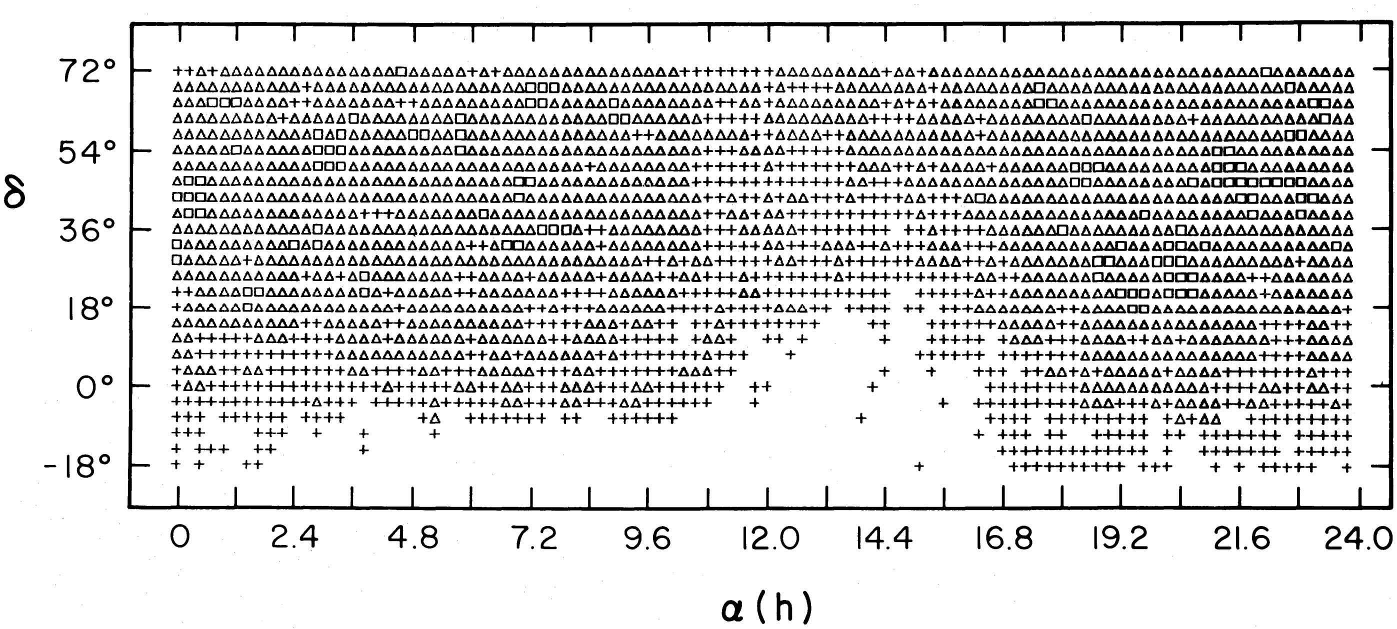

FIG. 3.—Flux upper limits at the 95% confidence level are represented by the following symbols: squares ($F < 3 \times 10^{-13}$ cm^{-2} s^{-1}), triangles ($3 \times 10^{-13} < F < 10^{-12}$ cm^{-2} s^{-1}), and plus signs ($10^{-12} < F < 3 \times 10^{-12}$ cm^{-2} s^{-1}).

is equal to that of γ-rays. This assumption is expected to be approximately true in our data.

The expected and observed numbers of events in each bin were used together with a maximum likelihood method (Hearn 1969) to obtain the maximum value of the signal-to-background ratio at the 95% confidence level. For bins in which the ratio of the target exposure to the background exposure was greater than 0.1, a procedure described by Protheroe (1984) was used. This method properly accounted for statistical fluctuations in the background which became important when the background exposure was not much larger than the target exposure. It can be seen from Figure 3 that for most of the bins with declinations between 0° and 72°, the upper limits are less than 10^{-12} cm^{-2} s^{-1} and some are less than 3×10^{-13}cm^{-2} s^{-1}.

The data in the vicinity of the Crab Nebula, taken in 1980 and 1981, were discussed previously (Boone *et al.* 1984), as were 1983 data from Hercules X-1 (Baltrusaitis *et al.* 1985). The 1983 and 1984 data include the Cygnus X-3 vicinity. An angular bin of the same size as those used in the survey described above, but centered on the Cygnus X-3 direction, contained 419 showers while 391.8 were expected. The 95% confidence level upper limit for the signal-to-background ratio is 0.20 and equation (1) gives $F < 7.3 \times 10^{-13}$ cm^{-2} s^{-1}.

The ephemeris (Van der Klis and Bonnet-Bidaud 1981) of Cygnus X-3 allows the data within a region centered on Cygnus X-3 to be plotted as a function of the phase within the 4.8 hr period. This ephemeris was used by Lloyd-Evans *et al.* (1983) but not by Samorski and Stamm (1983). The results for the combined 1983–1984 data are shown in Figure 4*a*, using 10 bins as was done by Samorski and Stamm. A 2.2 σ excess is observed in the third bin. In our combined data, the 95% confidence level upper limit on the signal-to-background ratio in the third bin is 0.86. The time-averaged signal-to-background ratio has an upper limit of 0.086. The upper limit for the γ-ray flux within the phase interval 0.2–0.3 is 3.1×10^{-13} cm^{-2} s^{-1}.

A more severe upper limit can be obtained using the data from 1984, only. The phase distribution for this data is shown in Figure 4*b*. In the third bin (the special significance of which

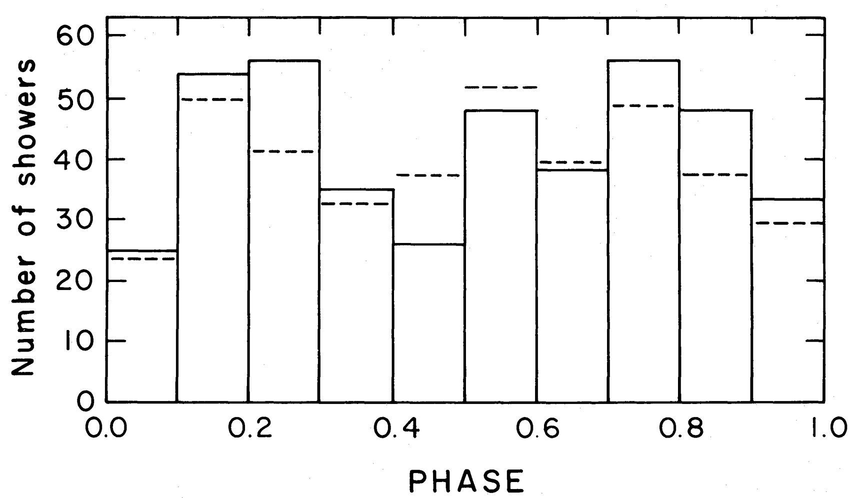

FIG. 4*a*

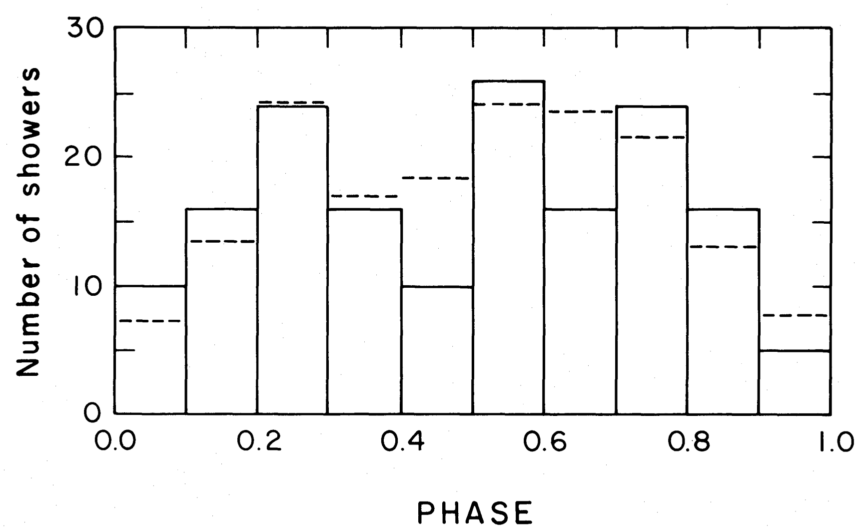

FIG. 4*b*

FIG. 4.—(*a*)–(*c*) Light curves within the 4.8 hr Cygnus X-3 period for the (*a*) combined 1983 and 1984 data, (*b*) the 1984 data, and (*c*) the 1983 data. Expected background levels are shown by the dashed lines. (*d*) Statistical significances of excesses are plotted for the 1983 data.

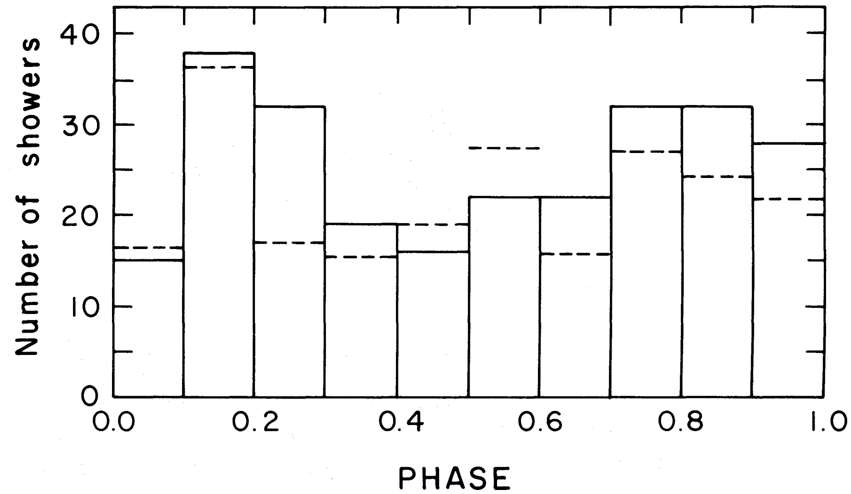

FIG. 4*c*

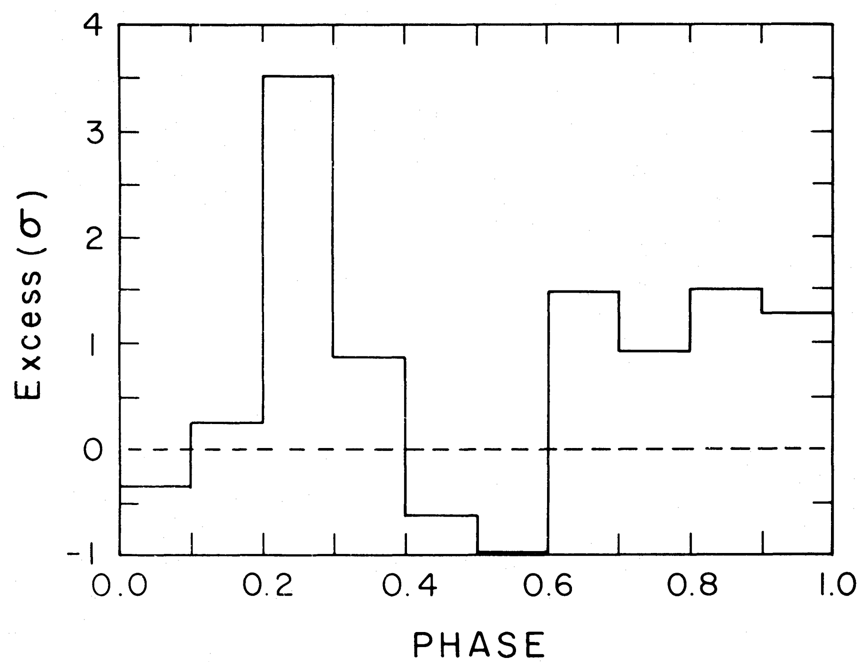

FIG. 4*d*

is discussed below) there were 24 observed events, with 24.3 expected. The flux upper limit for phase 0.2–0.3 is 2.0×10^{-13} cm^{-2} s^{-1}.

The 1983 data gave 256 events in the Cygnus X-3 direction, with 220.5 ± 15.8 expected. Allowing for the statistical fluctuation in the sample used to obtain the prediction as well as the statistical fluctuation expected in the observed data gives 15.8 for the combined statistical uncertainty. There is, therefore, a 2.2 σ excess in the Cygnus X-3 direction which is not significant in itself. However, in bin 3 of Figure 4*c*, 32 events were observed, with 16.9 expected. By the method used above, this is a 3.5 σ excess. See Figure 4*d*. A Monte Carlo calculation, allowing the numbers in the background and target regions to fluctuate, gave 1.4×10^{-3} as the probability that this peak occurred by chance. Since distributions were considered separately for each year's data and the combined data, the probability is estimated to be 3 times larger or 4×10^{-3}. This gives a 99.6% confidence level that Cygnus X-3 was observed in the 1983 data.

Lloyd-Evans *et al.* (1983) found a peak in the phase interval 0.225–0.25. Samorski and Stamm saw an excess in the bin 0.3–0.4. An adjustment of -0.11 in phase is needed to adjust the Samorski and Stamm (1983) results to the ephermeris used here and by Lloyd-Evans *et al.* (1983). Consequently, the two data sets predict that a signal should be found in the phase bin 0.2–0.3 in the same bin in which our signal appears.

The phase bin widths were chosen to be 0.1, following Samorski and Stamm (1983). However, a bin centered on 0.27 but 0.04 wide gave 16 observed, 4.2 expected. It appears that most of the possible signal is concentrated within a more narrow phase interval than 0.1, in agreement with Samorski and Stamm (1983) and Lloyd-Evans *et al.* (1983).

The phases of the present observations in the $34^{d}.1$ period of Cygnus X-3 are of interest. Using the epoch 2,443,820.5 JD and the period 34^{d}.1 (Molteni *et al.* 1980), the phase interval of data in 1983 August is 0.01–0.13. Combining effects of uncertainties in the epoch and period, there is a systematic uncertainty of 0.14 in these phases and an uncertainty of 0.19 in the 1984 phases. As described above, the signal was detected in the 1983 data, but not in the 1984 August data (phase interval 0.15–0.24) and the 1984 September data (phase interval 0.02–0.15).

IV. DISCUSSION AND CONCLUSIONS

At flux levels near those at which Cygnus X-3 is detectable, no previously unknown sources were found in this survey. The periodic nature of Cygnus X-3 was of great assistance in its detection, however, and it would have been missed in the survey if its detailed properties were not known. Precise orbital and pulsar period data from Hercules X-1 was also necessary in order to detect its signal in this data set (Baltrusaitis *et al.* 1985). The 1983 data on Cygnus X-3 showed a flux of $(3.2 \pm 1.2) \times 10^{-13}$ cm^{-2} s^{-1} and the 1984 data gave an upper limit of 2.0×10^{-13} cm^{-2} s^{-1}. There is not significant disagreement between these results, although they suggest that further observations should be carried out to study possible variability of the PeV γ-ray fluxes from Cygnus X-3. For studies of short-term variability, detectors with high data rates, such as the Fly's Eye, are particularly useful.

For purposes of comparing with other experiments, it should be noted that the flux error given above is from statistics, only. Other sources of error, such as triggering biases of γ-rays relative to cosmic-ray nuclei, and the uncertainty in the primary cosmic-ray spectrum, are not included. The fluxes and flux limit values may be high because heavy nuclei trigger less efficiently than protons or γ-rays, but no such factor was included in equation (1). On the other hand, the flux limit values may be slightly low because fluxes from possible sources in certain sky locations may not be entirely enclosed within any one of the overlapping bins. These effects could give rise to a factor of 2 error in the stated fluxes or flux limits.

The 1983 flux is 4.3 times the flux observed at Kiel by Samorski and Stamm (1983). However, their energy threshold was 2 times higher, and it is not difficult to reconcile these observations. The combined 1983 and 1984 Fly's Eye data give a (not statistically significant) flux of $(9.5 \pm 7.0) \times 10^{-14}$ cm^{-2} s^{-1} in the third phase bin, and there is no discrepancy between this result and the Kiel results. The phase at which PeV γ-ray emission occurs within the 4.8 hr period agrees very well between the two experiments when the same ephemeris is used.

Our 1983 results and the Kiel results imply higher fluxes than those obtained by the Haverah Park experiment of Lloyd-Evans *et al.* (1983). Because of the possible variability of the PeV γ-ray output of Cygnus X-3, the discrepancy between our flux and that from Haverah Park may not be a serious problem. The 34^{d}.1 period of Cygnus X-3, observed in the X-ray data (Molteni *et al.* 1980), may be relevant. The Haverah Park observations were made during a large number of complete 34^{d}.1 cycles. The intervals of the monthly Fly's Eye runs were shorter than 0.15 periods, and all the data from Cygnus X-3 happened to be taken within an interval of about 0.25 periods. Lower energy data from Morello *et al.* (1983) and Dowthwaite *et al.* (1983) suggest that the Cygnus X-3 γ-ray flux may depend on the phase of the 34^{d}.1 period. We do have close agreement with the Haverah Park results on the phase within the 4.8 hr period of the multi–PeV γ-ray emission from Cygnus X-3.

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