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Upper Limit to the Flux of Neutral Particles from Cygnus X-3 above 5×10^{17} eV

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We have analyzed data recorded by the Haverah Park extensive air-shower array above 5×10^{17} eV to search for a neutral particle signal from Cygnus X-3 as reported by the Fly's Eye group. For the period 1974 to 1987 we obtained a 95% upper limit of 4×10^{-18} particles cm^{-2}s^{-1}, in significant disagreement with the Fly's Eye signal of $(2.0\pm0.6)\times10^{-17}$ particles cm^{-2}s^{-1}. The limit assumes that the neutral particles are hadronlike. For γ-ray primaries the limit is weakened to 8×10^{-18} photons cm^{-2}s^{-1} because of the reduced sensitivity of the Haverah Park array to photon primaries.

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The Fly's Eye group[1] have reported evidence for an excess of extensive air showers from the direction of Cygnus X-3 at energies above 5×10^{17} eV. The excess was discovered in data recorded between November 1981 and May 1988. We have examined the arrival direction distribution of events of comparable energy recorded by the Haverah Park array during the period January 1974 to July 1987 (when the array ceased operation). We find no evidence for a significant signal either in the period of operation which overlaps with Fly's Eye or in the earlier period. The limit derived from our complete data set is significantly below that reported by the Fly's Eye group.

A detailed description of the use of the Haverah Park array for measurements of the energy spectrum and arrival direction distribution of cosmic rays above 10^{17} eV has been given elsewhere.[2,3] The angular resolution and energy resolution of the Fly's Eye and Haverah Park instruments are similar and the groups have reported energy spectra[4,5] which are in agreement[6] at the 10% level over the range 5×10^{17}-5×10^{18} eV relevant to the present discussion. The arrays differ in that while the acceptance of Fly's Eye[4] is about 70 km^{2}sr at 10^{18} eV, the corresponding figure for Haverah Park is only 5.5 km^{2}sr. The acceptance of both arrays is quite strongly energy dependent in this region. However, the Haverah Park array has operated at nearly 90% efficiency throughout the 13 years considered here while operation of Fly's Eye, by necessity, is restricted to moonless nights. The Fly's Eye is at a more favorable latitude (40.2°) for observing Cygnus X-3 than Haverah Park (54.0°), and at the latter site accurate reconstruction is restricted to zenith angles less than 60° because of distortions of shower symmetry caused by the geomagnetic field.[7] However, for the period 1 January 1982 to 31 July 1987 the number of events recorded at Haverah Park is similar to the number of events recorded at Fly's Eye from the region of interest (Fig. 1). The difference between the two distributions at $l>95°$ reflects the more northerly latitude of the Haverah Park array. It is clear that no signal as striking as the excess observed with Fly's Eye is present in the Haverah Park data set. The run time during this period was 1.6×10^8 s, and 9750 events above 5×10^{17} eV and with zenith angles less than 60° were registered.

Before making a more detailed comparison of the results from the two experiments the angular resolution of the Haverah Park array will be discussed. The array[2] consisted of a number of deep, large-area water-Cherenkov detectors deployed over 12 km^2. The array was triggered by signals in three of 4×34-m^2 detectors, three of which lay on the circumference of a circle of 500-m radius centered on the fourth. These detectors also provided timing signals which were used to measure the shower direction. Several studies of the random and systematic errors in shower size have been made and are

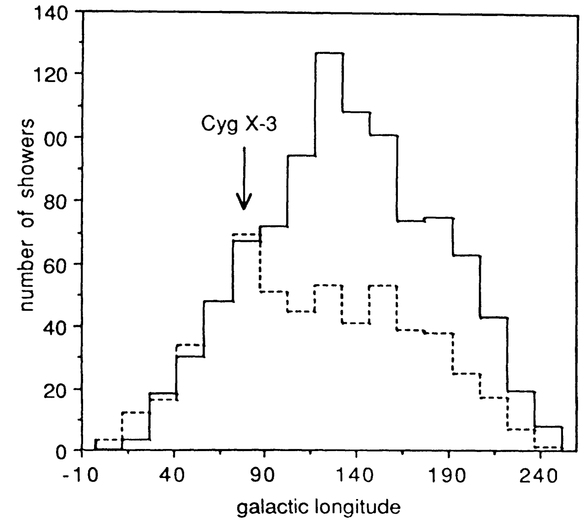

FIG. 1. The number of showers recorded at Haverah Park (solid Line) and Fly's Eye (dashed line) for a 10°-wide strip in galatic latitude, centered on $b = +1°$. The Fly's Eye data are from Fig. 1 of Ref. 1. Each bin covers 15° in galatic longitude and the bin upon which Cygnus X-3 is centered is indicated.

summarized elsewhere.[8] These suggest that the angular accuracy is well described by Gaussian distributions with deviations,

$$\begin{aligned} \sigma_\theta &= 2.5° \sec\theta, \quad \text{for } 0° < \theta \le 60°\,, \\ \sigma_\theta &= 2.5° \operatorname{cosec}\theta, \quad \text{for } 15° < \theta \le 60°\,. \end{aligned} \tag{1}$$

In addition to these studies, we have made two independent checks on the pointing accuracy of the array.

(i) A group from Durham University[9] operated on array of air-Cherenkov light receivers adjacent to several of the central water-Cherenkov detectors. Work reported by Craig, McComb, and Turver[9] confirmed the pointing accuracy and the error estimates given above.

(ii) Since March 1986 the Leeds group have operated an array of $32 \times 0.8\text{-m}^2$ scintillation detectors[10] designed for optimum angular resolution for ultrahigh energy γ-ray astronomy. This array is located about the center of the 12-km^2 array and during the period March 1986-July 1987, 196 events above 10^{17} eV were recorded by both instruments. The rms space-angle difference between the arrival directions determined from the two arrays is $2.4 \pm 0.1°$; separate studies[11] suggest that the scintillator array has an angular point spread function width of less than 1° for the largest events.

These comparisons provide clear evidence that the absolute pointing of the array is not in error, in addition to confirming the angular resolution estimates.

In reconstructing the arrival directions an average radius of curvature R of the shower front was used which is described by[12]

$$R = \{1.9 + 3\log_{10}[10\rho(600)]\}(\sec\theta)^{1.5}\ \text{km}\,,$$

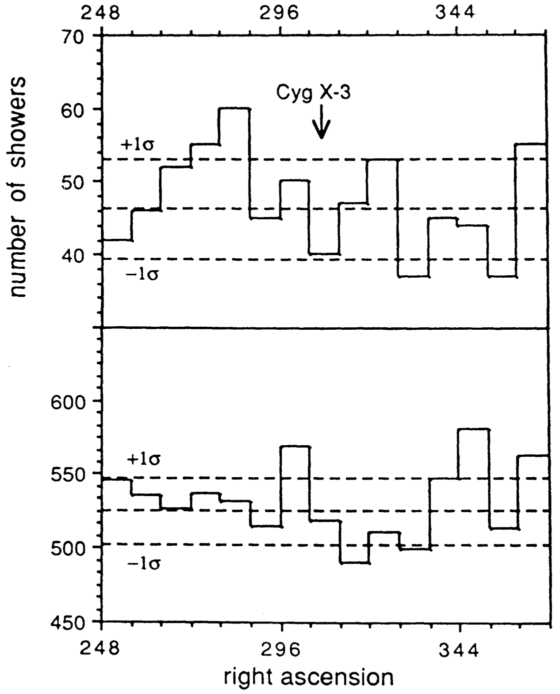

FIG. 2. The number of showers recorded as a function of right ascension for 15 bins, 8° wide, centered on Cygnus X-3. The upper histogram is for bins which are 6° wide in declination while the lower histogram shows the number of events for declinations above −6°.

where $\rho(600)$ is the water-Cherenkov density at 600 m from the shower core. The relationship between $\rho(600)$ and energy is

$$E = 7.04 \times 10^{17} \rho(600)^{1.018}\ \text{eV}$$

for vertical showers.[2] Uncertainties in R (which are expected from fluctuations in shower development) of approximately ±20% lead to additional uncertainties in the direction of 0.7°. Thus the solid angle uncertainty of 5.5×10^{-3} sr is comparable to the $2° \times 9°$ uncertainty typical of Fly's Eye events.[1]

The long and nearly continuous operation of the Haverah Park array makes it convenient to discuss arrival direction distributions in right ascension (RA) and declination (δ). The prior expectation is that the events will be uniformly distributed in the former coordinate if the arrival direction distribution is isotropic. While broad anisotropies described by first harmonic amplitudes of a few percent possibly exist[13] no point source had been claimed at such high energies before the report of Cassiday *et al.*[1] In Fig. 2 we show the distribution in events for 120° of RA centered on Cygnus X-3. Bins in RA are 8° wide: In the upper part of the plot the declination strip is 6° wide, while in the lower section events summed over $-6° < \delta \le 90°$ are presented. We find no excess in the bin centered on Cygnus X-3. The exposure of the array in right ascension, as judged by the number of events recorded, is uniform over the range of interest, at at level consistent with that expected from previous work.[13]

In Table I we show the number of events, N, observed in the $8° \times 6°$ source bin and the mean background B (estimated from 44 identical off-source bins in the same declination strip) as a function of epoch and energy. The fraction of point-source events which fall in the source bin is approximately 0.7, the bin having been selected as a compromise between what would be appropriate for the best and worst accuracies of Eq. (1). The effective acceptance for the whole observation period above 5×10^{17} eV is 3.7×10^{18} cm^{2}s. Hence for the flux [$(2.0\pm0.6)\times10^{-17}$ cm^{-2}s^{-1}] reported by the Fly's Eye group above the same energy, a signal of 52 ± 15 would have been expected above a background of 46.1; for the overlap period the corresponding expectation is 23 ± 7 above $B=20.0$.

An upper limit to the flux from our result can be derived using conventional methods.[14] The 95% upper limit of the signal, for the whole observing period above 5×10^{17} eV, is 10.9 events. Assuming that the energy spectrum of the hypothetical neutral primaries is the same as that of cosmic rays and adopting an integral intensity[8] of 8.2×10^{-16} cm^{-2}s^{-1}sr^{-1}, we derive an upper limit to the flux of 4×10^{-18} particles cm^{-2}s^{-1}. For the period 1 January 1982 to 31 July 1987 which overlaps most of the Fly's Eye observation period the 95% estimate of the flux is 5×10^{-18} particles cm^{-2}s^{-1}.

The fluxes and expected numbers have been calculated on the assumption that the sensitive area of the Haverah Park array is that appropriate to hadronic primaries. In particular, the collecting area for neutron primaries will be identical to that for protons. The Haverah Park array is, however, somewhat less sensitive to γ rays than to hadronic primaries at these energies (assuming that the μ component is suppressed in γ-ray showers as expected). The appropriate collecting area has been evaluated using a lateral distribution which was computed for γ-ray primaries during an early search[15] for a diffuse γ-ray background above 5×10^{17} eV. For this calculation a one-dimensional treatment was adopted down to electron and photon energies of 1000 GeV, below which a three-dimensional treatment, down to 4 MeV, was used. The characteristics of the water-Cherenkov detectors were included in the evaluation of $\rho(600)$, the Cherenkov density. From this calculation we derive the appropriate acceptance, for the whole observation period, above 5×10^{17} eV to be 1.7×10^{18} cm^{2}s so that the upper limit to the flux of γ-ray primaries is 8×10^{-18} cm^{-2}s^{-1}. The conflict between the two experimental measurements is thus less sharp.

TABLE I. The number of events, N, observed in the $8°\times6°$ bin centered on Cygnus X-3 are listed with the mean background, B, calculated from 44 identical off-source bins in the same declination strip. Data are shown as a function of energy both for the period of overlap with Fly's Eye and for the whole observing period.

	1982–1987		1974–1987	
Energy (eV)	N	B	N	B
$>5\times10^{17}$	11	20.0	40	46.1
$>1\times10^{18}$	8	7.6	18	17.3
$>2\times10^{18}$	3	2.6	9	5.8
$>4\times10^{18}$	2	0.8	6	1.9

The Fly's Eye group[1] adopted an ingenious method to obtain contour plots of the intensity in the sky region near Cygnus X-3. We have developed a similar technique but find no peaks in the contour distributions greater than expected by chance. We have also period analyzed our data using the Molnar ephemeris adopted by the Fly's Eye group. Data were binned in phase intervals of 0.1 and 0.05 but no significant peaks were observed: In particular, we find no evidence for emission near phase zero as observed by the Fly's Eye group above 5×10^{17} eV[1] and at 10^{15} eV.[16]

Above 4×10^{18} eV (Table I) there is an excess of 4.1 events above an expectation of 1.9. The Poissonian probability of observing 6 or more when 1.9 are expected is 0.013. Exposure of much larger areas than presently available is clearly needed.

In conclusion, we have no evidence to support the contention that there is a beam of neutral particles from Cygnus X-3 at a flux as high as that claimed by the Fly's Eye group.

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