Neutral Particles from Cygnus X-3 above 5×10^{17} eV

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The emission of neutral particles from Cygnus X-3 has been searched for at energies above 5×10^{17} eV, using data from the Akeno 20-km^2 air-shower array spanning the period December 1984 to July 1989. A 3.5σ dc excess is observed around the Cygnus X-3 region. This excess corresponds to a flux of $(1.8\pm0.7)\times10^{-17}$ cm^{-2}s^{-1} above 5×10^{17} eV, in agreement with the Fly's Eye data, but not the Haverah Park data. The signals do not show any 4.8-h periodicity. Their arrival times seem to be bunched in correlation with event-rate increases observed at 10^{16} eV with the Akeno 1-km^2 array.

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The detections of γ rays from Cygnus X-3 in the TeV [(3×10^{11})–10^{13} eV] and PeV (10^{14}–10^{16} eV) energy ranges have been reported by many authors.[1] Recently, at EeV (10^{18} eV) energies, an event excess from Cygnus X-3 was reported by the Fly's Eye group,[2] indicating the emission of neutral particles with a flux of $(2.0\pm0.6)\times10^{-17}$ cm^{-2}s^{-1} above 5×10^{17} eV. The Haverah Park group report that their data from 1974 to 1987 do not show any excess and they present a 95% upper limit of 4×10^{-18} cm^{-2}s^{-1} for hadronlike neutral primaries and 8×10^{-18} cm^{-2}s^{-1} for γ primaries.[3] In this paper, we report the results of a search for neutral-particle emission from Cygnus X-3 obtained with the Akeno 20- and 1-km^2 arrays, which have the advantage of measuring the electromagnetic and muon components in extensive air showers (EAS) separately, and the ability to determine the energy spectrum over a wide range.

The Akeno 20-km^2 array[4] has been in full operation since December 1984, observing showers above 10^{17} eV. It is located at a longitude of 138°30′E and a latitude of 35°30′N. There are nineteen scintillation detectors of 2.25 m^2 arranged with a ~1-km separation for measuring the electron component of the EAS. Four muon detectors (2×20 m^2, 15 m^2, and 10 m^2) are deployed within this array. In the east corner of the 20-km^2 array, there is the "1-km^2 array"[5] which has been continuously operating since 1979 for the observation of cosmic rays above 10^{16} eV. The smaller SPICA array,[6] which responds to lower-energy showers, has also been in operation since 1986; however, observations with this array will be discussed elsewhere.

The arrival directions of showers are determined by measuring the relative time difference of the incident shower particles recorded by scintillation detectors. In order to obtain a good accuracy in the arrival-time measurement of shower particles, we employ an optical-fiber-network system for the 20-km^2 array. The error in time measurement in this system is, in total, less than 30 nsec, and is negligible in determining the EAS arrival direction. However, the accuracy of arrival-direction determination depends on fluctuations in arrival time of shower particles, which is a function of the distance from the shower core.[7] The arrival direction is determined by minimizing the χ^2 values, taking account of the curvature and the thickness of the shower disk, with an accuracy of 3° for vertically incident showers of 10^{18} eV. Details of the method are described in Teshima *et al.*[8] In the case of the 1-km^2 array, the error in timing measurement depends on the length of the coaxial cable to each detector and on the shower-front structure. The overall error in arrival-direction determination is 3.5° for 10^{16}-eV vertical showers.

We have searched for neutral particles from Cygnus X-3 ($\alpha=307.7°$, $\delta=40.8°$) using data from the 10-km^2 array from December 1984 to July 1989. During the effective running time of 1.2×10^8 s (82% of real time), about 12000 showers were recorded. Of the showers that had cores inside the array, we selected 7307 showers whose zenith angles were smaller than 45°. The effective area strongly depends on the primary energy of the shower below 10^{18} eV. At 5×10^{17} eV the effective detection area is 5 km^2, which is about half of that at 10^{19} eV. Furthermore, as energy decreases, the angular resolution becomes worse. Therefore we used only the 3922 showers above 5×10^{17} eV in the present analysis.

As reported previously,[9] using the 1-km^2 array we do not observe any significant dc excess from Cygnus X-3 with any muon selection conditions at energies above 10^{16} eV. We updated the analysis to include the data obtained until July 1989 using the 1-km^2 array, and we still do not see any significant dc excess. However, in the present analysis we looked for correlations between the shower arrival times detected by the 1- and the 20-km^2 arrays. More than 400000 showers with zenith angles less than 45° were detected by the 1-km^2 array between 1984 and 1989.

In order to search for point sources, we employed a similar method to that developed by the Fly's Eye group.[2] The error function with σ is applied to the direction of each shower, and the event fraction is calculated in each cell ($1° \times 1°$) of the celestial sphere around the shower direction. Then, the fractions are summed for each cell in equatorial coordinates. The error in the determination of the arrival direction was taken to be $3° \times \sec\theta$ for each shower, where θ is the zenith angle. The expected event densities, after taking into account the irregularity of the observations in sidereal time, are derived from the distribution of observed showers as follows: First, we derived the directional response function of the array $f(\phi,\delta)$, by summing the event density in each hour angle (ϕ) and declination (δ) bin, and then dividing by the total number of showers. Second, this response function was transformed into equatorial coordinates using the observation efficiency in sidereal time. In each declination band, the standard deviation of event density was derived from the rms deviation from expected density.

In Fig. 1, the significance of the density excess around Cygnus X-3 is shown together with the arrival direction of each event. It appears that a 3.5σ dc excess exists near the direction of Cygnus X-3. The distribution of σ in the whole celestial sphere (about 1000 independent areas) observed by the Akeno array follows the error function, and the above excess is the largest. Therefore the chance probability is conservatively estimated to be less than $\sim 10^{-3}$. However, the peak position deviates from the direction of Cygnus X-3 by 2°–3°, and the statistical significance at the position of Cygnus X-3 is 2.7σ. Systematic effects in the experiment have been carefully reduced, but still, we cannot exclude the possibility of the amount of deviation. The possibility that the positional deviation is due to the scarcity of the signals is evaluated by a Monte Carlo simulation. With the present number of events the probability that the peak shifts away from the point source by more than 2° is about 10%. Additional signals from other nearby sources may be another possibility.

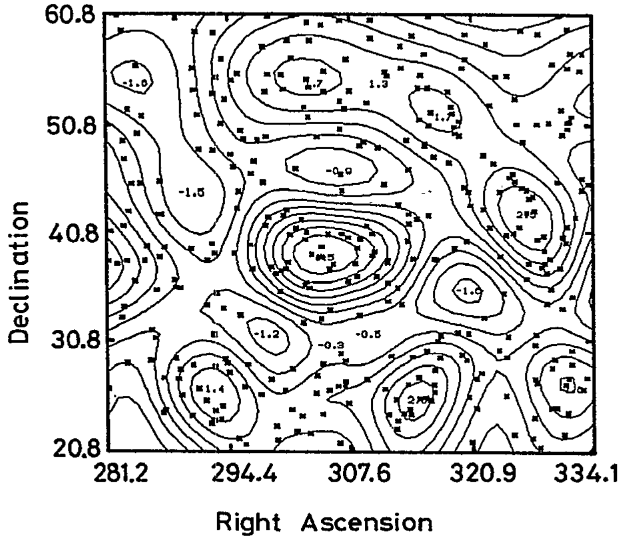

FIG. 1. The significance of the density excess at energies above 5×10^{17} centered on Cygnus X-3 (Akeno 20-km^2 array data) shown by contour lines of 0.5 steps with the arrival direction of each event.

The radial distribution of events around the peak, $R(r) = N_{\rm obs}(<r)/N_{\rm exp}(<r)$, is shown in Fig. 2, where r is the opening angle from the center of the peak ($\alpha = 305.5°$, $\delta = 39.0°$). $N_{\rm exp}$ is derived from the off-source event number in the same declination band (the total number of off-source events is about 40 times greater than on-source events). In this figure, the statistical significance of the excess becomes largest, 3.7σ using the Li and Ma method,[10] when $r = 4°$: $N_{\rm obs} = 27$ events and $N_{\rm exp} = 11.6 \pm 0.6$ events. The number of excess events is 15.4 ± 4.8. In order to estimate the true number of signal events, we carried out a Monte Carlo simulation to generate peaks of the same significance, by assuming signals from Cygnus X-3 above the uniform cosmic-ray background. The simulation revealed that it requires 20 ± 7 signals, implying that 20%–30% of the signals deviate outside the 4° circle.

We calculated the total exposure of 1.1×10^{18} cm^{2}s for Cygnus X-3 by comparing the number of background events (11.6 ± 0.6) with the integral cosmic-ray energy spectrum, $F(\geq E) = 1.6\times10^{-16}\ [E/(10^{18}\ {\rm eV})]^{-2.08}$ cm^{-2}s^{-2}sr^{-1}, obtained by the present experiment. Using this exposure and the excess counts, 20 ± 7, the associated flux from the direction of Cygnus X-3 is

$$(1.8 \pm 0.7)\times10^{-17}\,{\rm cm}^{-2}{\rm s}^{-1}\ \ (E \geq 5\times10^{17}\,{\rm eV}).$$

We carried out an analysis of the 4.8-h periodicity of Cygnus X-3 using the van der Klis–Bonnet-Bidaud ephemeris (cubic equation)[11] after a barycentric correction. We do not see any significant modulation (the ob-

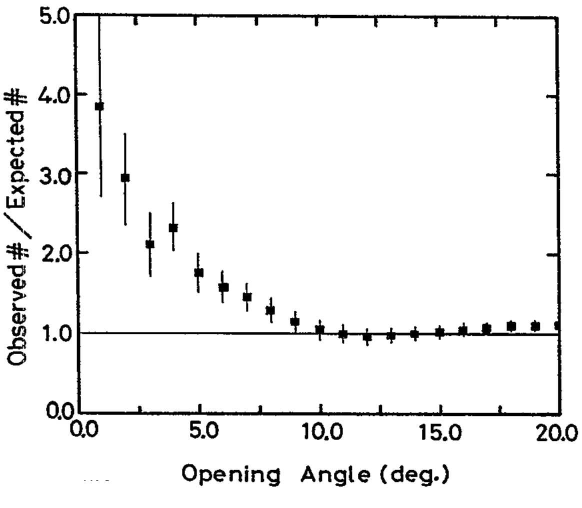

FIG. 2. The radial distribution of events around the peak ($\alpha = 305.5°$, $\delta = 39.0°$).

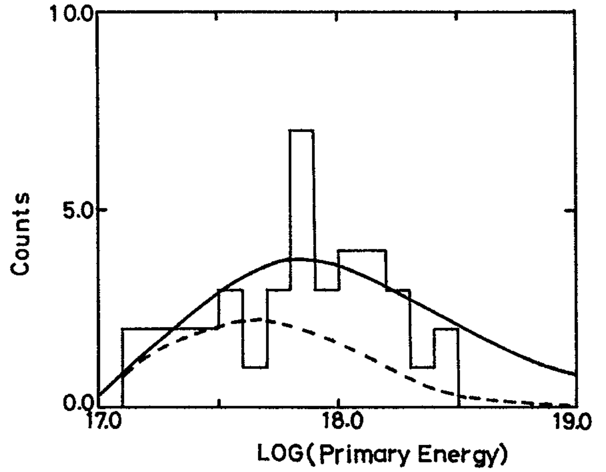

FIG. 3. The energy distribution of observed events from the direction of Cygnus X-3. The dashed line shows the expected background cosmic rays with the present energy-dependent effective area. The solid line shows the combined spectrum obtained by adding a spectrum with an exponent of −1.1, normalized to the observed excess events between 10^{17} and 3×10^{18} eV, to the expected background.

tained Rayleigh power is 0.4).

In Fig. 3, the energy distribution of observed events within a 4° circle centered on the peak is shown. The dashed line shows the expected background cosmic rays obtained from the event distribution of the same declination band of Cygnus X-3. The solid line shows the combined spectrum obtained by adding a spectrum with an exponent of −1.1, normalized to the observed excess events between 10^{17} and 3×10^{18} eV, to the expected background. If the energy spectrum extends further with the present exponent, we expect five events above 3×10^{18} eV, but we observed no event above this energy.

The time distribution of events from the direction of the Cygnus X-3 observed by the 20-km^2 array seems to be inconsistent with a random sampling from a uniform distribution. We examined the correlation between the event rate obtained from the 20-km^2 array and that from the 1-km^2 array. Two correlated increases of event rate between these two independent experiments are found; one is around JD (Julian day) 2446550 (April–May 1986) and the other is JD 2447620 (March–April 1989). In Figs. 4(a) and 4(b), the time distributions of events around Cygnus X-3 (within a circle of 8° radius centered on the direction of Cygnus X-3 for both experiments) are shown for these durations as a function of Julian day. The details of the event-rate increase are listed in Table I. The former increase of event rate coincides with the duration of the γ-ray burst reported by Dingus *et al.*[12] above 50 TeV and by Alexeenko *et al.*[13] above

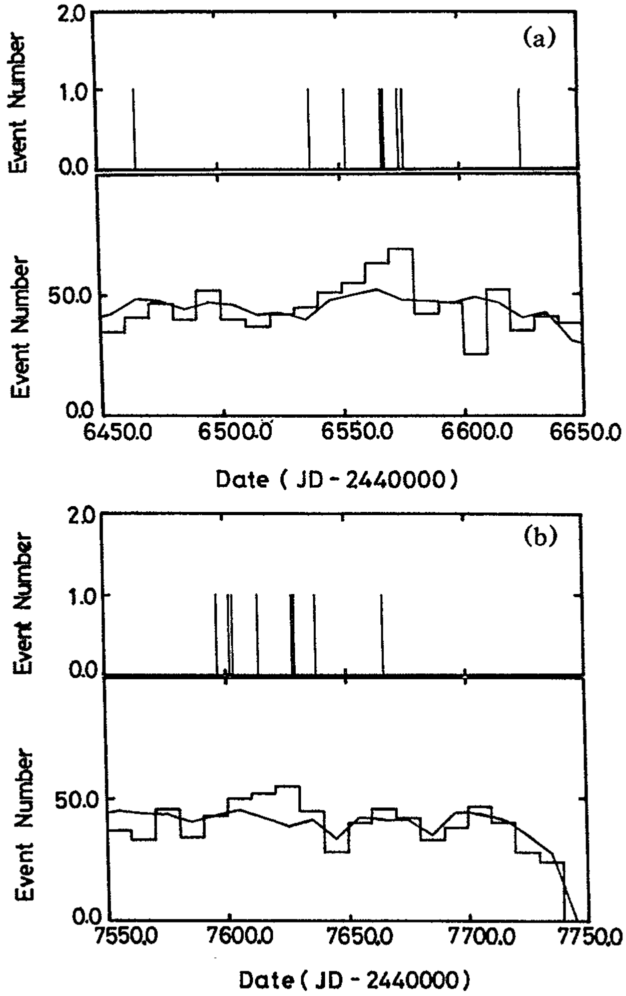

FIG. 4. The time distributions of events inside an 8° circle centered on Cygnus X-3, for durations (a) around JD 2446550 (April–May 1986) and (b) around JD 2447620 (March–April 1989). The upper panels are from the 20-km^2 array ($E \geq 5\times10^{17}$ eV), the lower ones from the 1-km^2 array ($E \geq 10^{16}$ eV). The connected lines in the lower panels show the expected value.

TABLE I. The correlated event-rate increases observed by the Akeno 20- and 1-km^2 arrays. The former increase coincides with the duration of the γ-ray burst reported by Dingus *et al.* (Ref. 12) above 50 TeV and by Alexeenko *et al.* (Ref. 13) above 200 TeV.

		20 km^2			1 km^2	
Duration (JD−2440000)	$N_{\rm obs}$	$N_{\rm exp}$	$P_{\rm ch}$	$N_{\rm obs}$	$N_{\rm exp}$	$P_{\rm ch}$
6538–6577	6	1.7	0.0080	283	237.9	0.0026
7597–7637	7	1.7	0.0019	245	210.8	0.012

200 TeV.

In the 20-km^2 array, muon contents above a threshold energy of 0.5 GeV are measured for a limited number of showers. So far, the muon data are not enough to derive results on the muon content of the excess showers. The showers ($\geq 10^{16}$ eV) from the direction of Cygnus X-3 including excess ones observed by the 1-km^2 array during April and May 1986, and during March and April 1989, do not show any significant muon-poor feature.

We have possibly detected 20 ± 7 particles with energies (5×10^{17})–(3×10^{18}) eV from Cygnus X-3. The time-average flux is consistent with the result obtained by the Fly's Eye group.[2] These fluxes are in good agreement with an extrapolation of reported TeV γ-ray fluxes with an integral exponent of -1.1. However, our data show that the flux is not constant in time. If we assume the event-rate increases are limited to the periods JD 2446538–2446577 and JD 2447597–2447637, the fluxes during these ~40-day periods are a factor of 10 larger than the above average flux.

Since the present events are concentrated within ~4° of Cygnus X-3, and the arrival times are possibly bunched into ~40-day periods, protons cannot be candidates, given the galactic magnetic field of 3 μG. The energy spectrum of signals below 10^{18} eV may play an important role in distinguishing whether the primary particles are γ rays or neutrons. Though the present 20-km^2 data are not enough to distinguish between these two particles, the 10^{16}-eV events cannot be neutrons. The assumption of a primary γ-ray spectrum with power index of -1.1 can well explain the energy distribution of the present results. Gamma rays above 10^{16} eV are not attenuated by interactions with the 2.7-K background radiation, and fluxes during April and May in 1986 at 50 TeV,[12] 200 TeV,[13] 10^{16} eV, and 10^{18} eV are smoothly connected with an exponent of ~ -1.0.

The Haverah Park results do not show any excess showers and their flux upper limit is 20% of the time-averaged flux reported here if the primaries are neutrons, and 40% if they are γ rays, in contradiction with the Fly's Eye and the present results. This discrepancy is serious even in the case of γ rays, since there is no significant muon-poor feature for the burst events (reported here) at 10^{16} eV. Further data on the muon content at 10^{19} eV is highly desirable. Though the fluxes of the Fly's Eye data and ours coincide with each other, there are discrepancies in the 4.8-h phase distributions, energy spectra, and the peak positions in celestial coordinates. We are expecting to resolve these discrepancies with a new 100-km^2 array, AGASA (Akeno Giant Air Shower Array), which is currently being constructed at Akeno by the AGASA Collaboration.

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