Detection of extremely high-energy cosmic rays from the Cygnus X-1 and Cygnus X-3 binary systems

G. V. Kulikov, V. G. Pogorelyĭ, A. A. Silaev, V. I. Solov'eva, V. P. Sulakov, A. V. Trubitsyn, and G. B. Khristiansen
Scientific-Research Institute of Nuclear Physics, M. V. Lomonosov Moscow State University

(Submitted 30 July 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 6, 249–251 (25 September 1987)

Data obtained at Moscow State University's extensive-air-shower installation on the detection of cosmic rays with an energy $\sim 10^{15}$ eV from point sources by the extensive-air-shower method are reported. An excess of "old" showers was observed from Cygnus X-1 in 1985 and 1986. This excess amounts to 3.8 standard deviations.

The installation for detecting extensive air showers[1] is at lattitude 55.75° N, longitude 37.5° E, and is 192 m above sea level. The central part of the installation, 200 m in radius, is used for research. The position of the shower axis, the parameters s (which characterizes the spatial distribution of charged particles in the shower), and the total number of articles at the observation level, N_e, are determined with a large number of detectors consisting of Geiger counters.

The direction of the shower axis is found with the help of a system of seven scintillation counters which detect the arrival times of the shower particles. Six of the detectors, each having an area of 0.5 m^2, are arranged at the vertices of a hexagon with a side of 60 m; the seventh, with an area of 1m^2, is at the center of this hexagon. The error in the determination of the direction of the shower axis in space is 3°.

For the analysis we selected events with zenith angles $\theta \leqslant 40°$, with axes lying no further than 30 m from the center of the installation, and with $N_e \geqslant 10^5$ particles.

The observation periods and the statistics of events are listed in Table I.

To identify a source having the equatorial coordinates δ_0 (declination) and α_0 (right ascension), we selected from the total number of showers those showers whose declinations fell in the band $\delta_0 \pm 3°$. This band was partitioned into identical cells each 8° in size, along the right-ascension scale in such a way that the source was at the

TABLE I.

Observation period	Working time of apparatus, h	Number of showers detected	Number of showers selected
1/11/84–23/6/85	4260	8.5×10^4	3.0×10^4
16/10/85–09/9/86	6400	1.3×10^5	4.9×10^4

center of one of the cells. For each cell we determined the number of showers arriving from it, n_j, and the time at which the cell is observed by the installation, t_j.

We examined the declination band from the Cygnus X-1 source, with the coordinates $\alpha_0 = 19^h 56^m$ and $\delta_0 = 35°$. Analysis of the dependence of the flux of all selected extensive air showers on the right ascension showed that there is no statistically significant excess flux over the background in the cell from Cygnus X-1.

However, if we introduce an additional selection of showers on the basis of the age parameter s—specifically, if we select only the "old" showers with $s \geqslant 1.3$ (according to the electromagnetic cascade theory, we would have $s \sim 1.3$ at sea level for showers which are produced by γ rays and which have $N_e \sim 10^5$—we find that the picture changes substantially for Cygnus X-1. Over the period from 16 October 1985 to 9 September 1986, the right-ascension distribution of the flux (Fig. 1) reveals an excess of "old" showers from the cell with Cygnus X-1 (21 showers at a background level of 29). This excess amounted to 3.8 standard deviations.

The flux F corresponding to the observed excess of showers is found from the formula[2] $F = I\Omega(S/B)$, where I is the intensity of extensive air showers, Ω is the cell size, expressed in steradians, S is the signal, and B is the background (this formula holds under the assumption that the structure and angular distribution are approximately the same for photon showers and nuclear showers). Under the assumption that

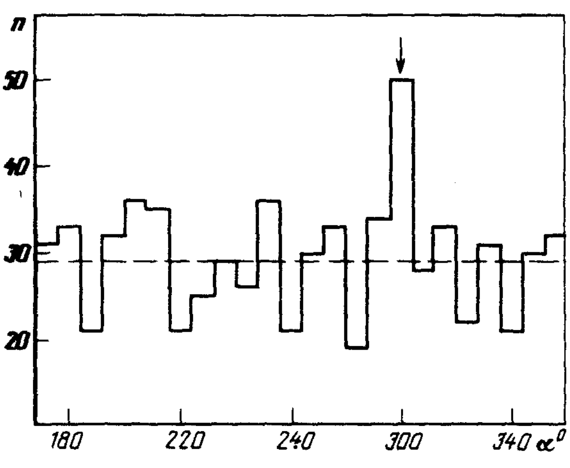

FIG. 1. Right-ascension distribution of events for the declination band of Cygnus X-1. Here n is the number of events referred to the observation time of Cygnus X-1.

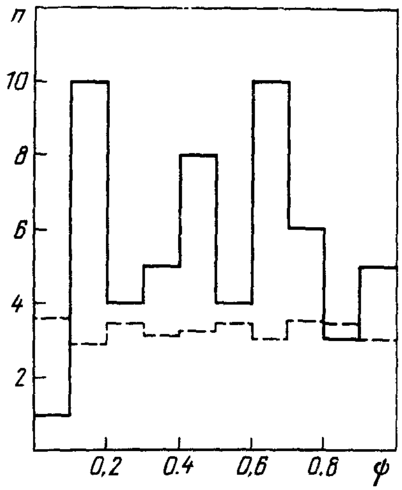

FIG. 2. Phase curve for Cygnus X-1.

the excess showers are showers from γ rays, we estimated their energy from electromagnetic cascade theory. The excess flux turned out to be $F = (5.4 \pm 1.8) \times 10^{-13}$ $cm^{-2} \cdot s^{-1}$ for $E_0 = 7 \times 10^{14}$ eV. In calculating the flux we assumed $\Omega = 1.1 \times 10^{-2}$ and $I = 1.7 \times 10^{-10}$ $cm^{-2}\, s^{-1} \cdot sr^{-1}$. We also took the fraction of "old" showers to be 0.371, in accordance with the experimental data.

Since the Cygnus X-1 system is a binary star with a revolution period of 5.6 days (known from optical observations), we carried out a phase analysis using the ephemeris of Ref. 3: a zero phase $t_0 = 2441163.45$ JD and a period $p = 5.0004$ days. Figure 2 shows the results of this phase analysis for the old showers over the observation period from 16 October 1985 to 9 September 1986. The dashed line is the phase curve calculated under the assumption that Cygnus X-1 radiates uniformly with an intensity equal to the mean value for the declination band under consideration. In these calculations we allowed for the different observation time of each phase and the angular distribution of the extensive air showers. It can be seen from Fig. 2 that there is a concentration of the radiation at certain phases: an excess of 7.1 showers at phases of 0.1–0.2 and also at 0.6–0.7, at a background level of 2.9. The flux corresponding to the excess at each of these phases is $F = (3.6 \pm 1.1) \times 10^{-13}$ $cm^{-2} \cdot s^{-1}$. The existence of these two phases correlates with measurements in the optical range.[3]

A corresponding analysis of showers from Cygnus X-1 between 1 November 1984 and 23 June 1985 showed that there is no excess flux of old showers from the cell holding this source. The phase analysis leads to the same conclusion.

With regard to the source Cygnus X-3 ($\alpha_0 = 20^h 30^m, \delta_0 = 40°,9$), we note that in none of the periods considered was there an excess flux (without a phase analysis), either for all showers or for old showers. A phase analysis of the showers from Cygnus X-3 was carried out with the help of the ephemeris of Ref. 4 for the epoch closest to our measurements: $t_0 = 2444377.4407$ JD, $p = 0.199679$ days. A correction was made for the orbital motion of the earth.

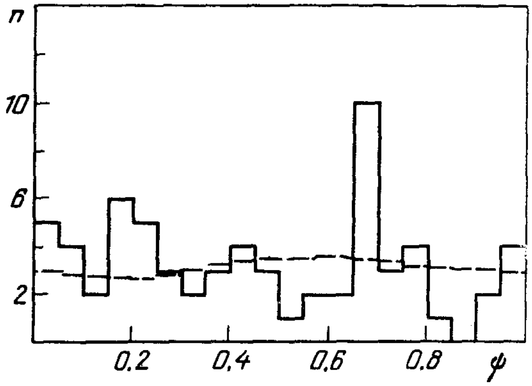

FIG. 3. Phase curve for Cygnus X-3.

Over the period from 1 November 1984 to 23 June 1985, the sharpest peak for all showers on the phase curve (Fig. 3) appeared in the phase interval 0.65–0.70: an excess of 6.5 showers at a background level of 3.5. No statistically prominent phase was observed during the second period. The flux from Cygnus X-3 corresponding to the excess of showers at the phase of 0.65–0.70 is $F(\geqslant 7\times 10^{14}\ \text{eV}) = (1.7\pm 0.8)\times 10^{-13}\ \text{cm}^{-2}\cdot\text{s}^{-1}$ and is consistent with the data available, in view of the large scatter in those data.[5] The phase corresponding to the maximum of the emission of Cygnus X-3 evolves from 0.2–0.3 in 1976–1980 (the Kiel group) to 0.6–0.7 in 1984–1986 (data from the present study and from the Kover apparatus at Baksan).

Analysis of the data on muons with energies above 10 GeV in the selected extensive air showers shows that, on the average, the fraction of muons in the showers from Cygnus X-1, and Cygnus X-3 is 0.8 ± 0.1 of the figure for normal extensive air showers.

[1]S. N. Vernov *et al.*, in Proceedings of the Sixteenth International Cosmic Ray Conference, Kyoto, 1979, Vol. 8, p. 129.
[2]R. M. Baltrusaitis *et al.*, in Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, 1985, Vol. 1, p. 234.
[3]V. M. Lyutyĭ, Astron. Zh. **62**, 731 (1985) [Sov. Astron. **29**, 429 (1985)].
[4]M. Van der Klis and J. M. Bonnet-Bidaud, Astron. Astroph. **95**, L5 (1981).
[5]A. A. Watson, in: Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, 1985, Vol. 9, p . 111.

Translated by Dave Parsons