CYGNUS X-3 OBSERVATION IN GAMMA-RAY ENERGY RANGE > 10^{14} eV*

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Summary. - We present experimental data on observations of Cygnus X- 3 using an air shower array. The angular resolution of the array is of the order of 1 degree and the median energy of showers is $E_0 > 10^{14}$ *eV*. During one year of observation there was no absolute excess of the number of showers from the source region and a small peak at the phase plot has only limited statistical significance. The value of UHE gamma-ray flux (if there exists any) seems to be in contradiction with values previously reported by Kiel and Haverah Park groups. We have analysed separately a sample of experimental data covering the short period in October 1985, when a radioburst from Cygnus X-3 was observed. Considerable excess of showers from the source was found in this sample: it lasted for three days with the maximal effect (40% excess) in the first one, 14th of October 1985.

1. - Introduction.

Cocconi [1] was the first who proposed to use air shower arrays for the search of discrete gamma-ray sources on the celestial sphere. The idea was to work at mountain altitude in the energy range ~ 10^{12} *eV* having angular resolution ~ 1 degree. Soon after that, however, Zatsepin and Chudakov [2] suggested to use Cherenkov detectors at sea-level for this energy range which is usually called now the region of very-high-energy (VHE) gamma-ray astronomy. A pioneering experiment was made by Chudakov with co-workers [3] and gave negative result. Nevertheless, the technique is widely used since then and some experimental groups have announced discoveries of measurable fluxes of 10^{12} *eV* gamma-rays from several sources. The bulk of these data was reported at the special workshop on VHE gamma-ray astronomy in Oootacamund, India, in 1982 [4].

The original Cocconi's idea about shower arrays was realized only in 1983 and in a different energy range.

Two papers were published nearly simultaneously, in both the famous X-ray source Cygnus X-3 had been observed and indications on positive effect were found. Morello, Navarra, and Vernetto [5] used a very simple but specially designed array with rather poor angular resolution (~ 5 degrees). They found, though with limited statistical significance, a periodic component in the air shower flux with energy 10^{13} *eV* from the source direction. Samorsky and Stamm [4] reanalysed old data of the Kiel air shower array obtained in 1976-1980 and discovered a 4.4 s. d. excess from a 3° x 4° angular domain, centred on Cyg X-3 position. The largest part of this excess, as phase analysis showed, was concentrated in a narrow phase range of 4.8 *h* period. Angular resolution of Kiel array was much better (~ 1 degree) than that of Morello et al. and the energy range was higher ($E_0 > 2 \cdot 10^{15}$ *eV*). Up to now these latter data are the most striking evidence of the existence of ultrahigh-energy (UHE) gamma-ray flux from Cyg X-3, though some details of Kiel data seem to be rather strange and unclear, namely:

1) The muon content of showers from Cyg X-3. The authors state it was very

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close to the muon content of normal cosmic ray-showers.

2) Age selection problem. Samorsky and Stamm observed the effect only for showers with s > 1.1 and there was none for showers with lower value of age parameter. But there are indications that at energies (10^{15} - 10^{16}) *eV* no essential difference between ages of gamma-ray or nucleon-initiated showers should be expected [7].

3) Enigmatic behaviour of phase peak. In [6] the authors, neglecting derivative of the period, used a constant P_0 value and obtained very sharp peak. After using in [8] more precise ephemeris of van der Klis and Bonnet-Bidaud [9] they found the phase curve to have a much more diffused peak.

The data of the Haverah Park shower array [10] partially confirmed that of Kiel as they showed a narrow peak at phase 0.2 which is just the position of the peak in the revised Kiel data [8]. But they could not observe absolute (without phase analysis) excess of showers and gave a lower value of flux. In the last paper of Haverah Park group [11], the evidence in favour of time variation of UHE gamma-ray flux from Cyg X-3 was presented. The idea of nonstability of UHE emission of Cyg X-3 was put forward also by Bhat et al. [12] in order to obtain consistency between the data of different groups (including preliminary data of present work [13].

At the same time keen interest in the problem has obtained new impetus following the indications of a positive effect from Cyg X-3 in high-energy muons, reported by the underground detectors NUSEX [14] and Soudan [15]. Though these muon data have produced many theoretical discussions, now they are in direct contradiction with new experimental results of Baksan [16] and Frejus [17] underground muon detectors.

We shall not go into details of the muon flux experimental situation because the problem of UHE gamma-ray flux from Cyg X-3 is also far from being resolved. To make the situation clear new projects of shower arrays purposely designed for gamma-ray astronomy are proposed and being constructed. More results should be obtained also by already existing arrays. Baksan air shower array which began to observe Cyg X-3 in July of 1984 is one of them.

2. - Apparatus and analysis.

The layout of Baksan air shower array (altitude 1700 *m* a. s. l., coordinates 43° *N*, 43° *E*) is shown in fig. 1. A central square (14 x 14) m^2 ("the Carpet") contains 400 liquid scintillators. The size of each scintillator is (0.7 x 0.7x 0.3) m^3 . Six outside detectors 1-6 have 18 scintillators of the same type each. Four of them are placed in square configuration 30 *m* from the centre of the array and two are at a distance of 40 *m*. 400 scintillators of the Carpet are divided in four groups A-D feeding a

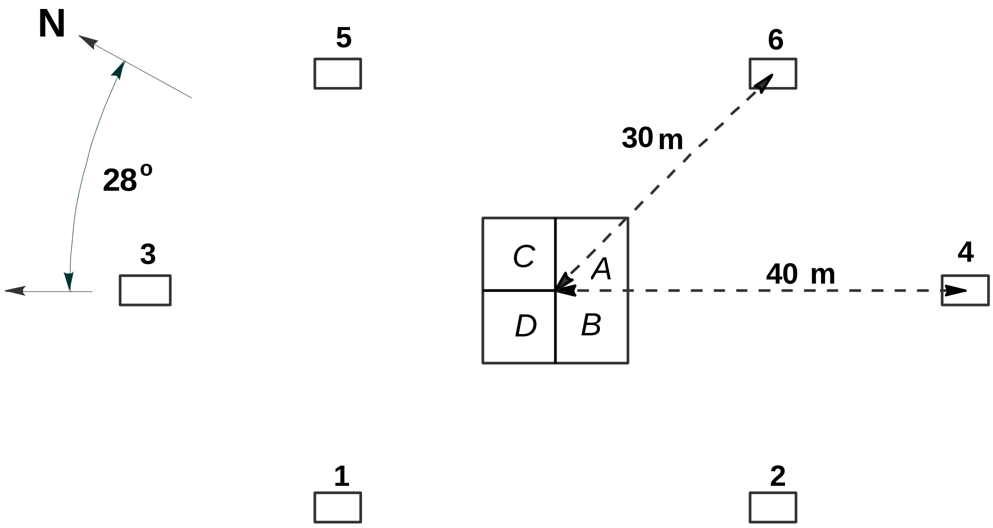

Fig. 1. - Geometry of the Baksan extensive air shower array.

fourfold coincidence circuit with output counting rate 50 per second. This signal is used as starting pulse for the measurement of delays of pulses of outside detectors. At the same time, the fivefold coincidence of this signal with the ones of detectors 1, 2, 5, 6 gives the trigger pulse for the recording system. Energy thresholds of each group of scintillators A-D correspond to 0.3 that of a penetrating particle pulse height on the area 50 m^2. The discrimination level in each channel 1-6 equals that of one penetrating particle on 9 m^2, the signals being used as stopping pulses in time measurement system measuring delays with the precision of 1 *ns*. Special electronic devices are used for the compensation of pulse height dependence of delays. The counting rate of trigger pulses is 0.9 per second. The delays and time of each event are stored in the memory of on-line minicomputer. Output of accumulated data is made once in 20 minutes.

Angular resolution of array for the trigger described above was estimated experimentally using the distribution of differences of delays. For any azimuthal direction of a shower, two parallel pairs of outside detectors are in equal conditions. So the difference between pairs

$$\Delta t = (t_1 - t_2) - (t_3 - t_4)$$

characterizes the uncertainty in direction reconstruction. The nonstability of start signal which is big due to large linear dimensions of the Carpet is excluded from this value. The root mean square of Δt determined in a large sample of data is equal to 5.2 *ns* and corresponds to the angular resolution for vertical showers $\sigma_\theta \sim 1.1$ degrees.

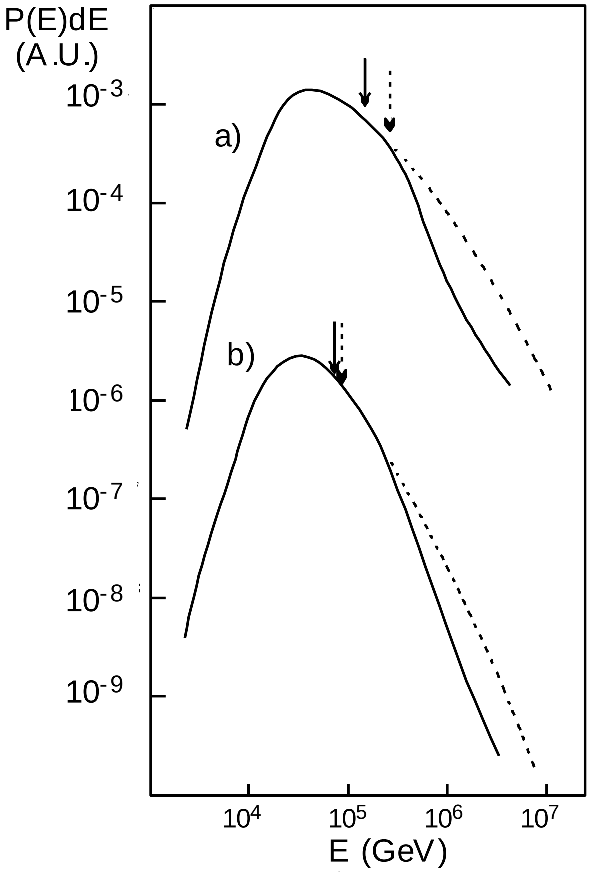

Fig. 2. Differential spectra ot showers, registered by the array, for different power spectra: a) of gamma-rays near the source (γ = 2.1, interstellar absorption has to be taken into account); b) of cosmic rays near the Earth (γ = 2.7). Full lines show the results of calculations including interstellar absorption. The median energies are shown for the different cases.

The energy of individual showers was not measured and the calculated spectrum of registered showers essentially depends on the assumed spectrum of gamma-rays from the source. Figure 2 presents differential distributions of shower energies for given trigger and two values of power law exponent of gamma-ray spectra: γ = 2.7 corresponding to the spectrum of primary cosmic rays, and γ = 2.1 which can be considered as "reference spectrum" for the experimental data on Cyg X-3 gamma-ray emission in a wide energy range. The effect of taking into account interstellar absorption of gamma-rays by microwave background radiation due to $\gamma\gamma \rightarrow e^+e^-$ process is also shown in fig. 2. For γ = 2.7 spectrum the absorption slightly changes the median energy of distribution (it equals to $7 \cdot 10^{13}$ *eV* instead of $8 \cdot 10^{13}$ *eV*) . For the flat γ = 2.1 spectrum the effect is considerable; median energy changes from $3.3 \cdot 10^{14}$ *eV* to $1.6 \cdot 10^{14}$ *eV* .

The following method of data analysis was used. We compare the counting rate of showers in a circular on-source angular cell of 2.5° radius with the background counting rates in four off-source cells of the same form and size. The centres of one pair of off-source cells are shifted from the source position by $\pm$ 5° in declination, those of the other pair are shifted by 6.6° = (5°/Cosδ) in right ascension. With this choice all off-source cells are in contact with and have the same solid angle as the Cygnus cell. The data were corrected for total counting rate from all directions (to exclude the effect of atmospheric pressure) and angular distribution of showers. After heliocentric correction of time the events from Cygnus cell and mean background (a quarter of total counting rate in four off-source cells) were phase-analysed using ephemeris from [9].

3. - Results.

Cygnus X-3 was observed during one year, from July 1, 1984 to June 30, 1985, five hours per day (2.5 h from culmination). More than $4 \cdot 10^6$ atmospheric showers were recorded. Between them 22496 showers are from the Cygnus cell and 90530 from

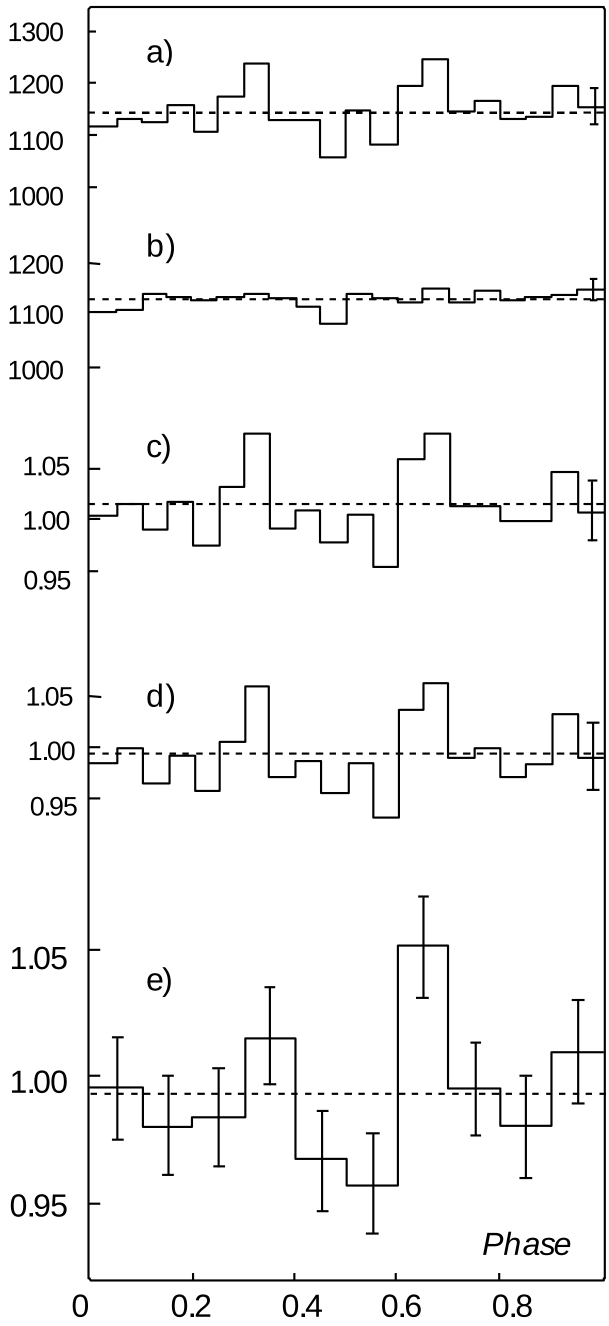

Fig. 3. - Phaseograms obtained by folding the data with the Cygnus X-3 ephemeris: a) of the real number of events from the Cygnus cell (ON); b) of the mean value of the four off-source cells (OFF); c) of the ON/OFF ratio uncorrected; d) of the previous ratio after corrections for the atmosplleric absorption and variations of the atmospheric pressure; e) the same as the previous one binned into 10 steps.

the four off-source cells. The ratio of phase curves of on-source cell and average off-source cell is given in fig. 3. There is no absolute excess of showers from Cygnus cell, the average value of ratio in fig. 3 being equal to 0.993 $\pm$ 0.008. The peak at phase 0.6 has rather low statistical significance (2.8 s. d.).

Upper limits of UHE gamma-ray flux near Cygnus X-3 source obtained in the present work are shown in fig. 4 together with the fluxes of Kiel [6] and Haverah Park [10] groups corrected for interstellar absorption. One upper limit was obtained at 95% confidence level from the absence of excess without phase analysis, the other one was deduced from the absence of excess at phase 0.2 where a signal was observed in these two experiments. If one assumes constant luminosity of the source there is an obvious contradiction of the fluxes measured in Kiel and Haverah Park experiments and our upper limit. However, all data can be consistent in the case of a constantly decreasing luminosity, as suggested in paper [12], because Kiel data were accumulated in 1976 - 1980, results from paper [10] were obtained in Haverah Park in 1979 - 1982 and present work gives the flux of 1984-1985. More recent data of Haverah Park [11] show the disappearance of the 0.2 phase peak and the presence of a new one at phase 0.6. This was obtained approximately at the same time as our present data and is more or less in accordance with the phase curve of fig. 3. Thus we deduce the possible flux corresponding to not very significant phase 0.6 peak at fig. 3. Without absorption, the value of integral flux is equal to

$$I_\gamma (E_\gamma > 3.3 \cdot 10^{14} eV) = (4.4 \pm 2.0) \cdot 10^{-14} \ cm^{-2} s^{-1},$$

with the absorption taken into account we have

$$I_\gamma(E_\gamma > 1.6 \cdot 10^{14} eV) = (1.5 \pm 0.7) \cdot 10^{-13}\ cm^{-2}s^{-1}.$$

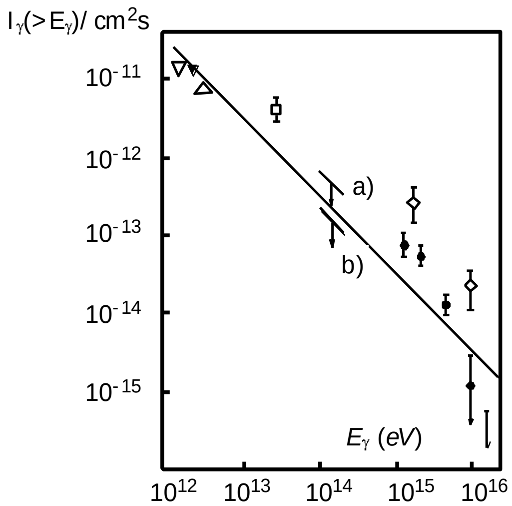

Fig. 4. - Comparison of the upper limit obtained in this experiment (a) from the absence of an absolute excess; b) from the absence of an excess at phase 0.2) with other experiments:
(▽△ Cherenkov light data (4);
□ Plateau Rosa (5);
◇ Kiel (6);
● Haverah Park (10)).

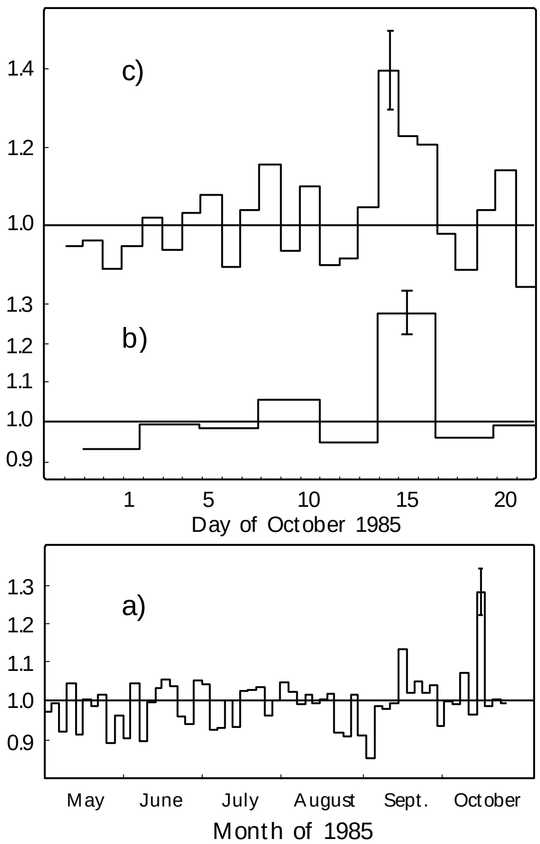

Fig. 5. - ON/OFF ratio for the epoch May-October 1985 (a)), and expanded for the duration of the October burst (b) 3-day step, c) 1-day step).

In October of 1985 a powerful radioburst of Cygnus X-3 was observed. According to an informative letter of the Naval Research Laboratory, Washington, the flux of radioemission was 1 Jy on October 1, reached 30 Jy on October 9 and then fell down to 2 Jy on October 13. We have checked our data around these dates and have found a considerable increase of counting rate from the Cygnus cell during a three-day period, October 14-16 (see fig. 6). Tile maximal excess reaches 40% in the first day, 14th of October. It is interesting to note that the increase is observed not at the maximum of radioburst, but after the end of it. Instrumental origin of observed excess is easily excluded, as it is seen only in a narrow-angle cone, while the total counting rate did not increase during all the period shown in fig. 5 and earlier. As a statistical fluctuation, the effect has very low probability, according to our estimate less than 10^{-5}. Nevertheless we cannot consider the data of fig. 6 as decisive proof of burst activity of the source. Final evidence could be obtained by several shower arrays simultaneously. Thus it is highly desirable that all existing experimental data of the period in question be collected together and carefully compared. At the same time it is interesting to recall that earlier there were indications in the lower-energy range of 10^{12} eV (e. g. [18]) on increasing gamma-ray flux from Cygnus X-3 just after radiobursts.

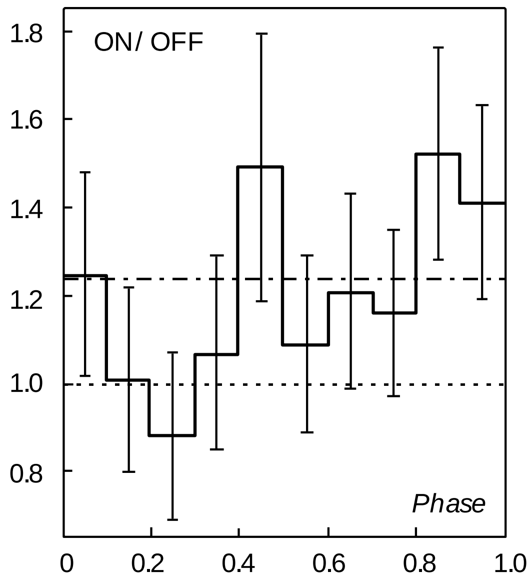

Fig. 6. - Phaseogram of the ON/OFF ratio for the epoch October 14-16, 1985; the dash-dotted line shows its mean value, while the dashed line shows the mean value of the average off-source cell.

Phase analysis of the 14-16 October data sample shows the absence of narrow peaks in phase curve (fig. 6). The statistics of the curve is obviously not enough to distinguish between uniform and quasi-sinusoidal phase distributions.

As a result of our analysis, we can conclude that there might be two forms of Cygnus X-3 activity at 10^{14} eV: burstlike with the flat 4.8 h period phase curve and sharp-phase-peak emission, variable on the time scale of years. Both are not established with undoubtful certainty but, if real, they should probably represent phenomena of quite different nature.

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