Search for cosmic gamma rays of ultra-high energies with the Baksan air shower array

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Abstract. Recently two collaborations (Tibet ASγ and HAWC) almost simultaneously reported about their measurements of ultra-high-energy (> 100 TeV) gamma rays from the Crab Nebula. The Baksan air shower array (BASA) recorded a burst from this very source as long ago as more than 20 years. At the moment the new experiment on gamma ray astronomy (Carpet-3 project) started at Baksan, and it is appropriate to recall old results of BASA to be compared with the new results, already published and expected.

1. Introduction

In [1] the Tibet ASγ Collaboration announced about detection of 100 TeV photons from the Crab Nebula. However, their statement “This is the first detection of photons with \( E > 100 \text{ TeV} \) from an astrophysical source” (see abstract in [1]) is not true. Not only because of the fact that the HAWC Collaboration almost simultaneously published [2] a very similar detection of the same source. Some people pretended to detect positive signals from different sources in this or even higher energy range rather long ago, during the Cygnus X-3 campaign in early 1980s. At that time the gamma ray astronomy of ultra-high energies (\( E_{\gamma} > 10^{14} \text{ eV} \)) was at a peak of activity in connection with sensational data of the Kiel University group that reported about a signal detected from the X-ray source Cygnus X-3 in this energy range. Later it became clear that this result was obviously wrong, but it stimulated many experimental and theoretical works on the problem. A lot of experimental efforts (for example, special EAS array called Cygnus was urgently constructed) were made and witty hypotheses put forward (a hypothetical new elementary particle cygnet was suggested, as well as quark confinement violation etc.).

The BASA took part in this activity, and some results of its observations lasting several years are worthy of noting.

2. The BASA old results on astrophysical sources

Figures 1 and 2 taken from [3] present the results of Cygnus X-3 observations in DC mode for several years. Since no energy reconstruction was made for individual events, calculated energy distributions were used for flux estimations. Power-law distribution was postulated for gamma rays with two spectral indices: either 2.1 as presumed for the spectrum in the source or 2.7 coinciding with background cosmic ray spectrum. In both cases cosmic MWB absorption was taken into account, and
one can see its effect in Fig. 1 (distributions without absorption are shown by dashed lines): two arrows demonstrate the median energy in each spectrum. The upper limits a) and b) derived from BASA data in Fig. 2 correspond to spectra a) and b) of Fig. 1. One can see in Fig. 2 that the Kiel group was not alone in recording positive signal from Cyg X-3. In addition to the Kiel data mentioned above

Fig. 1. Calculated energy distributions of gamma ray EAS for two primary spectra with exponents equal to 2.1 and 2.7 with and without (dashed line) MWB absorption taken into account. Arrows show median values. The plot is taken from [3].

Fig. 2. The upper limits of BASA on the gamma ray flux and some definite fluxes presumably measured by several groups (squares for Plateau Rosa, diamonds for Kiel and black circles for Haverah Park). The plot is taken from [3].

Fig. 2 shows definite fluxes measured by Plateau Rosa and Haverah Park experiments. However, the BASA results are in obvious contradiction with their measurements; only upper limits were obtained by us for steady flux from the source. But in addition to this result, BASA detected during that campaign a couple of burst-like events: one from the Cyg X-3 and another from the Crab Nebula.

3. Burst in the Cygnus X-3 on October 14-16, 1985
For three days in October 1985 the signal from the Cyg X-3 angular cell exceeded the background value significantly. This event was interpreted as a burst of high-energy gamma ray emission [4], especially when it was found that a powerful outburst of radio emission had been detected from Cyg X-3 several days before. It is worthwhile to note that this radio burst was the strongest over the entire history of observations. Also, soon after it the Gulmarg gamma ray telescope in India detected significant signals from Cyg X-3 on October 10 and 12 [5].

In [6] V.S. Berezinsky made an attempt to construct a model explaining considerable delays between the radio signal and VHE and UHE gamma signals in this event. The Berezinsky’s model was based on information about the source available at that time. To check it in the light of present-day knowledge would be of great interest, but this is out of the scope of this paper. Nevertheless, it is
worthwhile to note that in recent times coordinated observations of ground-based radio telescopes and satellite gamma ray telescopes [7] proved that “the γ-ray activity is related to the level of radio flux”.

4. Burst in the Crab Nebula on February 23, 1989
First announcement about this burst was made during the International Workshop on Gamma-Ray Astronomy in Crimea in 1989 [8]. An increase of intensity of EAS was detected by the Carpet air shower array of the Baksan Neutrino Observatory on February 23, 1989. After this communication the group at Kolar Gold Fields in India confirmed this result of Baksan and published a paper [9] on simultaneous detection of a gamma-ray burst in the Crab Nebula at ultra high-energies independently by two EAS arrays. Final publication [10] by the Baksan and Durham University teams summarized the data of all arrays that could observe the source on this day. It was demonstrated that with different significance the burst had been detected by all air shower arrays located in the longitude range from India to Italy (KGF, Tien Shan, Baksan and EAS-TOP). Thus, the total duration of the observed effect was no longer than about 7 hours. One can speak also about a possible decay of intensity whose maximum probably fell on observations with the KGF array. Also, phase irregularity of the signal associated with the Crab pulsar PSR B0531+21 was found both in Baksan and KGF data. Especially clearly this effect is seen in the Baksan data: almost total excess of events is concentrated in a single phase bin (one tenth of the pulsar period). At the same time these excess events demonstrate a sort of a periodic structure being distributed in three bunches with duration from 40 min to one hour.

In [11] it was noticed that this triple structure is very similar to that of the Crab flare in September 2007 in which the AGILE team found three short flares (F1, F2, and F3), the only difference being a scale factor of order of 20: days at 100 MeV and hours at 100 TeV.

5. Significance of old UHE gamma-ray bursts and of present-day results
For the first of above discussed events (Cyg X-3 burst on 14-16 October 1985) the probability of random occurrence was estimated as $10^{-5}$ (see [4]), and its significance is additionally supported by preceding radio flare, VHE signal, and a reasonable model that reproduced the observed delays.

As for the February 23, 1989 Crab burst, the combined probability of random coincidences was calculated in [8] to be even less, as low as $1.25 \times 10^{-7}$. Strange to say, but these figures suggest better significance than those of the newest results on the Crab Nebula flux published by the Tibet AS + MD and HAWC collaborations.

6. The Carpet-3 project and its status
The results discussed above were obtained with the Carpet air shower array many years ago. This old array was modernized more than once. One can see the original configuration of this facility in Fig. 4, where the next modification, Carpet-2 is shown. Its main part, a carpet of 400 detectors with liquid

Fig. 3. The Cyg X-3 event in October 1985 as seen in UHE gamma rays by BASA (upper panel) and in the radio waveband (lower panel). The arrows in the figure taken from [6] show the maximum of radio flare and the time of detection of a signal by the Gulmarg gamma-ray telescope in India (energy threshold is 6 TeV). The model of paper [6] explains different delays of gamma rays in different energy ranges.
scintillators (total area is 200 m²) was constructed as a model of one plane of the future Baksan Underground Scintillation Telescope (BUST) that was under construction at that time. In spite of applied purpose of its creation, the Carpet array appeared to be extremely convenient for cosmic ray studies. The most important results obtained with the Carpet during its long history are listed in paper [12] (the gamma ray astronomy results presented above are among them). The plan to supply the Carpet array with a large-area muon detector resulted in construction of three underground tunnels for installing there plastic scintillators. Due to lack of funding only one of these tunnels was equipped with 1 m² plastic scintillation detectors (total area is 175 m²), and thus the Carpet-2 configuration came into being (see Fig. 4). Recently the Carpet-3 project [13, 14] was put forward, which is under realization at the moment (see Fig. 5). The motivation for this new experiment, as before, was to supply the EAS array with a large-area muon detector in order to use the method of selection of muon-poor showers for measurement of UHE diffuse gamma rays of cosmic origin.

Fig. 4. The Carpet-2 array: Carpet of 400 m² of liquid scintillators in the center with six remote detectors of area of 9 m² of scintillators in each, and a first version of the Muon Detector (175 m² of plastic scintillators under overburden of 2 m of rock).

Fig. 5. The first version of the Carpet-3 project. The figure is rotated clockwise by 90°. Blue rectangles represent old scintillation detectors and red squares are for new ground-surface scintillation detectors. Cyan color shows present area of the MD (410 m²). There is still a possibility to increase this area in future up to more than 600 m².

This method is a popular trend nowadays, and Tibet AS + MD result [1] is an example of its successful application to point-like sources. The main aim of the Carpet-3 project is to search for diffuse cosmic gamma rays. The interest towards this problem has increased due to the results of the IceCube experiment in which high-energy neutrinos of astrophysical origin were detected. If such neutrinos are a result of decays of charged pions in the Galaxy, neutral pions of the same energies should exist, contributing to the flux of gamma rays with energies above 100 TeV. In the Carpet-2 experiment the energy threshold is higher than that planned for Carpet-3, and [15] presents the upper limit on the flux of gamma rays > 700 TeV obtained for 9.2 years of net exposure time. The point-like sources were also searched for during the Carpet-2 experiment, and the upper limits for several predefined sources (the Crab Nebula, Cygnus X-3, Mrk 421 and Mrk 501) are published in [16]...
together with 95% CL upper limits on PeV photon fluxes from stacked directions of high-energy IceCube neutrino events.

In Fig. 6 the expected sensitivity of Carpet-3 is presented and compared with earlier experiments. It is seen that rather low energies, where efficiency of giant air shower arrays drops down, are a promising domain for Carpet-3. Unfortunately, because of serious damage to the array due to a natural hazard (flood of nearby mountain river) a certain delay in realization of the project occurred. At the moment all repair works are accomplished, and the muon detector with an area of 400 m$^2$ is finished and ready to start data taking.

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