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Observations of the Boomerang Nebula with the TAIGA-HiSCORE facility

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An analysis of the TAIGA-HiSCORE data was conducted to evaluate the signal from the Boomerang Nebula region.. A comparison of the results obtained without and with gamma-hadron separation has been performed. The significance distribution follows a normal law, indicating the predominance of background events. The obtained results confirm the necessity of improving gamma-hadron separation methods, in particular, through the commissioning of new components of the TAIGA complex (scintillation and water Cherenkov detectors). This will enhance the sensitivity to gamma-ray sources with energies above 100 TeV.

Keywords: cosmic rays, extensive air showers, gamma-ray astronomy, background estimation, signal significance.

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One of the important fields of astrophysics is to search for cosmic ray accelerators, the so-called PeVatrons, by recording their gamma radiation with the energy of more than 100 TeV. These sources are searched for and studied, in particular, by means of the TAIGA-HiSCORE Cherenkov facility [1] of the TAIGA astrophysical complex (Tunka Advanced Instrument for cosmic rays and Gamma Astronomy) [2]. It is an array of 120 detectors that are distributed over the area of 1.1 km^2 and designed to record Cherenkov radiation of extensive air showers (EAS). The detectors are wide-angle optical stations with four photomultiplier tubes equipped with light concentrators, which are Winston cones with an half-acceptance angle of 30°.

The TAIGA complex is located at the latitude of 51.8° N. The optical stations of the TAIGA-HiSCORE facility can have two operating positions: they are directed towards the zenith or inclined by a zenith angle of 25° towards the south. The inclination towards the south is required for observing the Crab Nebula that has declination of $+22^\circ\,00'\,52.1''$ and other sources with declinations $+2^\circ - +52^\circ$. The vertical position makes it possible to observe the sky within the declination range $+27^\circ - +77^\circ$. According to data of the LHAASO experiment [3], this range includes several gamma-radiation sources with the energies of more than 100 TeV. Of special interest is a supernova remnant SNR G106.3+02.7 in the region of the Boomerang Nebula that has declination of $+61^\circ\,10'\,00''$. This source belongs to a class of extended ones and has a comet-like form that can be divided into a head and a tail region. For this reason, gamma radiation from this source was recorded in a number of experiments within the coordinate ranges $RA = 336.3^\circ{-}337.6^\circ$, $Dec = 60.6^\circ{-}61.3^\circ$ [4–8]. The SNR G106.3+02.7 is available for observations with the TAIGA-HiSCORE facility mainly from September to December. Taking into account the area of the TAIGA-HiSCORE facility, which is $\sim 1\,\mathrm{km}^2$, and operation in moonless nights, the SNR G106.3+02.7 source can be observed for up to 250 h for the season and one can record up to 30 gamma quanta with $E > 100$ TeV and up to 110 gamma quanta with $E > 50$ TeV.

The gamma-quantum flux is extremely low as compared to background hadron space radiation. Therefore, it is important to correctly estimate the background in order to separate a signal. The study [9] describes four methods of background estimation when handling data of ground-based gamma-astronomy facilities. Sensitivity of the facilities can have a space and a time dependence. This limits the use of methods that rely on a large sky area or long observation time for background estimation. Thus, the study [10] has demonstrated the influence of weather conditions during measurements on signal significance estimation. Moreover, a method of equal zenith angles has a limitation for operating zenith angles $\geq 11.6^\circ$, while the SNR G106.3+02.7 source is elevated to the zenith angle of 9.2°.

The present study analyzes experimental data that were obtained during the periods from October to December, 2022 and from September to October, 2023, when the TAIGA-HiSCORE optical stations were directed to the zenith. Altogether, the SNR G106.3+02.7 source was observed for 143 h for these two seasons. According to our calculations using the source spectrum from the study [3], up to 62 gamma quanta with $E > 50$ TeV could have been recorded for this time. An event sample is limited by the sky area within the limits $RA = RA_0{-}5^\circ{-}RA_0{+}5^\circ$, $Dec = Dec_0{-}5^\circ{-}Dec_0{+}5^\circ$, where $RA_0 = 337^\circ$, $Dec_0 = 61.17^\circ$ are coordinates of the gamma-radiation source with $E > 100$ TeV according to the data of the LHAASO experiment. We have also applied the criteria of the ≥ 6 activated stations during EAS recording and a position of the EAS axis inside a facility

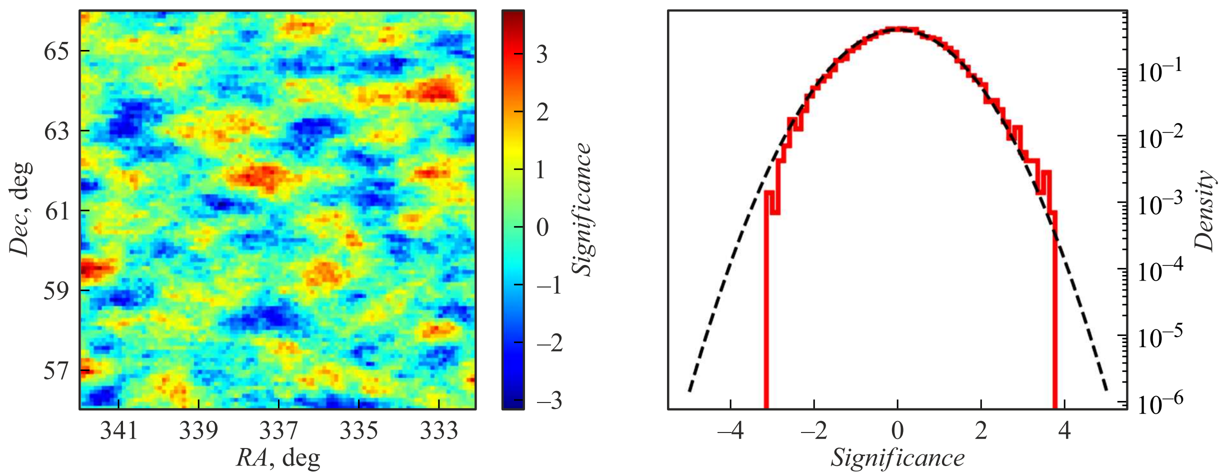

Figure 1. On the left — a signal significance map in the region of the Boomerang Nebula for unclassified events. On the right — significance distribution (the red line) and standard normal distribution (the dashed black line).

perimeter, thereby providing detector's angular resolution of about $0.16°$.

The background is estimated using the so-called frame method. This method is resistant to variation of angular sensitivity of the facility and does not depend on the zenith angle of observations. The essence of the methods is as follows.

First of all, a studied area of the sky is divided into cells $0.1° \times 0.1°$ in the second equatorial system of coordinates. The each cell is assigned with a sum of recorded events from a neighborhood caused by angular resolution of the facility. Thus, angular resolution $R_{68} = 0.16°$ is assumed in the present study, thereby meaning that 68 % of the events that come out from a point source are restored with an angular error of at most $0.16°$. By assuming a model of two-dimensional normal distribution for the angular error, we find that the $2 \cdot R_{68}$-neighborhood of the source includes 98.96 % of the events, which can be considered to be a full source signal.

Then a background level in each studied cell of the sky is determined as an average value of background on a sky area as a rectangular frame around the studied cell. The frame has a thickness of $0.1°$ RA for vertical sides and $0.1°$ Dec for horizontal sides. A frame size is pre-defined based on angular resolution of the facility. In order to prevent events from the studied cell's neighborhood going into the frame during background estimation in it, the distance between the cell and the frame shall be at least $4 \cdot R_{68} = 0.64°$. The frame width in the coordinates RA is proportional to $1/\cos(Dec)$. Thus, with declination $Dec = 61.17°$ the neighborhood of the point RA_i with the radius of $0.64°$ includes the values $RA = RA_i - 1.33 - RA_i + 1.33$. For operation at the abovesaid sky area, we took maximum frame sizes corresponding to declination at an upper edge of the area $Dec = 66.17°$ with coverage $RA_i - 1.58 - RA_i + 1.58$. Rounding to tenths of a grade and stepping back from the studied cell by $1.5°$ and $0.6°$ in RA and Dec, respectively, we obtain that the 92-cell frame is formed around the studied cell.

Signal significance in the studied cell is estimated using the classical Li–Ma formula [6]:

$$S = \sqrt{2} \cdot \left\{ N_{on} \cdot \ln\left(\frac{(1+k) \cdot N_{on}}{k \cdot (N_{on} + N_{off})} \right) + N_{off} \cdot \ln\left(\frac{(1+k) \cdot N_{off}}{N_{on} + N_{off}} \right) \right\}^{1/2}, \quad (1)$$

where N_{on} is a number of events in a certain observation window, in which the source is assumed to be; N_{off} is a number of events in the same window without the source, i.e. background events; $k = T_{on}/T_{off}$ and T_{on} and T_{off} is a time of observation of the source and the background, respectively. In case of the frame method, N_{on} is a number of events in the studied cell, N_{off} is a number of events in the frame. The cell and the frame are simultaneously observed, but since the frame consists of 92 cells, then $k = 1/92$.

Fig. 1 shows results of data analysis without applying gamma-hadron separation. Distribution of signal significance corresponds to the normal law ($\mu = 0.06$, $\sigma = 0.98$), which is expected with a weak signal from the source and without background suppression. Thus, in the point $RA_0 = 337°$, $Dec_0 = 61.17°$ 1941 events are recorded at the average background of 1938.7 and the excess of the full signal level above the average background level is 2.3 events, which corresponds to 0.05σ. At the same time, the 1941 events include the expected 62 gamma quanta.

A method of reduction of the hadron background is proposed to be a parameter dH, which is a difference between the EAS maximum and the observation level, which is expresses in g/cm^2, i.e. $dH = (X_{\max} - X_{obs})/\cos(Ze)$. Using the experimental data of dH, one can express the parameter $P_{80/200}$ described in the study [12], which is equal to a ratio of a density of recorded Cherenkov photons

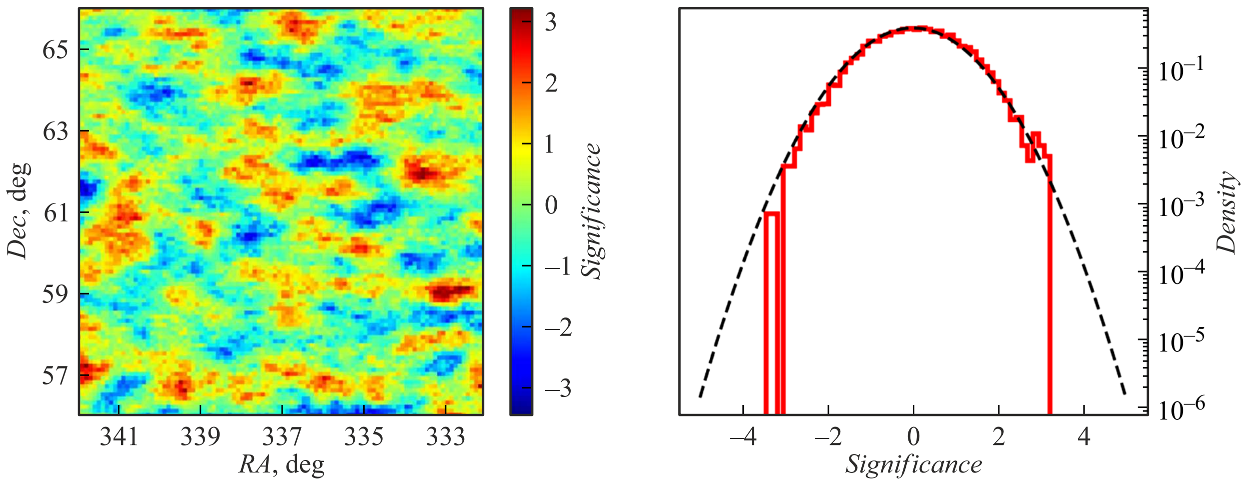

Figure 2. On the left — a signal significance map in the region of the Boomerang Nebula for events classified by the parameter dH. On the right — significance distribution (the red line) and standard normal distribution (the dashed black line).

at the distance of 80 and 200 m from the EAS axis: $dH = 30 + (9.8 - P_{80/200})/0.013$. Based on simulation results, it is obtained that the EASes from heavy nuclei (oxygen, iron) have the value $dH > 450\,\text{g/cm}^2$. Below this threshold is $\sim 30\,\%$ of the proton EASes and $\sim 60\,\%$ of the gamma-induced EASes. Fig. 2 shows the results with applying this criterion to a data set. The point $RA_0 = 337°$, $Dec_0 = 61.17°$ includes 615 events at the average background of 607, which is 0.32σ. The background level after applying the criterion $dH < 450\,\text{g/cm}^2$ is 31.2 % of the initial level, thereby agreeing with the simulation results. Then, it is expected that the source signal is decreased to ~ 37 gamma quanta. Thus, the proposed method is not a quite strong method of gamma-hadron separation, which provides normal distribution of signal significant as in the case without it.

The performed analysis has not revealed a statistically significant signal from the SNR G106.3+02.7 in the TAIGA-HiSCORE data, thereby agreeing with expectations for the weak sources under conditions of the high hadron background. The obtained results demonstrate that it is necessary to further improve the methods of gamma-hadron separation and data accumulation. Thus, in 2019 deployment of the TAIGA-Muon scintillation facility [13] (a network of detectors of electron-photon and muon components of EASes) was launched to include it in the TAIGA complex. It is also planned to supplement the complex with a network of the water Cherenkov detectors of the volume of $50\,\text{m}^3$ at the depth of 2.5 m. In the future, with an increase of statistics and application of more rigid criteria of selection, joint operation of the said facilities can contribute to investigation of the PeVatrons, especially, the sources with declination $+27° - +77°$.

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Conflict of interest

The author declares that he has no conflict of interest.

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