Technical Physics, 2023, Vol. 68, No. 12

Observation of astrophysical objects with the TAIGA−HiSCORE installation

© V.S. Samoliga

Institute of Applied Physics, Irkutsk State University,
664003 Irkutsk, Russia
e-mail: vladimir.samoliga@yandex.ru

Received May 12, 2023
Revised July 21, 2023
Accepted October, 30, 2023

This paper presents the results of the sky survey with the TAIGA-HiSCORE installation, an array of 120 wide-angle Cherenkov light detectors spread over an area of 1 km^2. Data analysis is made for 2 winter seasons (2019−2021) at cosmic ray energies above 200−500 TeV. A modified method of background estimation is tested. Signal significance is estimated using classical Li-Ma method.

Keywords: Gamma-ray astronomy, Crab nebula, background estimation, signal significance.

DOI: 10.61011/TP.2023.12.57736.f215-23

The TAIGA-HiSCORE is an array of wide-field detectors of atmospheric Cherenkov radiation occurring in extensive air showers (EAS). It is part of the hybrid gamma-ray observatory TAIGA [1]. The purpose of ground-based gamma-ray astronomy facilities is to distinguish the signal from gamma-ray sources against the background of the cosmic ray flux. An important task for estimation the significance of a signal is to estimate the background.

This paper is devoted to the development of a method for estimating the background and the significance of the signal in the vicinity of astrophysical objects. There are several methods for estimating the background and their modifications used in a number of gamma-ray astronomy experiments. In the paper [2] 4 basic methods are described: equal zenith angles, surrounding windows, direct integration, and time replacement. The choice of the method in this work is determined by the peculiarities of the TAIGA-HiSCORE installation. Its optical detectors have a constant inclination 25° to the south to maximize the observation time of the Crab Nebula. The angular sensitivity of the detectors has a complex shape and asymmetry associated with the orientation of the photomultipliers [3]. In such conditions, the method of equal zenith angles is not applicable.

In this paper, a modified method based on the methods of direct integration and time substitution is used. The sky in coordinates (RA, Dec) is divided into cells with a width of 5° RA with fixed declination boundaries $\mathrm{Dec}_0 \pm 2.5°$, where Dec_0 — declination of the observed object. The cell that contains the observed object in its center is called the signal cell, the rest of the cells are background. Events from the signal and background cells are recorded in the corresponding datasets. The background is recorded only from background cells that follow the same path as the signal cell in the field of view of the installation. In this way, the same distribution of events in the cells is ensured, due to the zenith angle of observation and the angular sensitivity of the installation. Depending on the duration of the session, the total observation time of the background T_{off} is 5−25 times the observation time T_{on} of the signal cell.

The heterogeneity of the distribution in the cells can be due to the dependence of the flow of events on time. This is mainly due to weather conditions, such as the onset of clouds. To consider this factor, there are 2 options for selecting sessions: a strict and non-strict. Strict selection analyzes only sessions with a number of events in the signal cell $\tilde{N}_{on}$ that deviates from the average background number by no greater than 5%:

$$\frac{|\tilde{N}_{on} - k \cdot \tilde{N}_{off}|}{k \cdot \tilde{N}_{off}} < 5\%, \tag{1}$$

where $\tilde{N}_{off}$ — is the total number of background events per session, $k = T_{on}/T_{off}$. At non-strict selection, sessions with a large deviation are allowed, but they contain only those background cells that were in the field of view of the installation at the same time as the signal cell. The condition (1) also applies to this data. Further, the signal cells of the sessions are summed up to form signal and background data sets. The display of these sets on the reference grid (RA, Dec) form a signal and background map.

Based on these maps, a signal significance map is built. In the paper [4] a review and analysis of methods for estimation the significance of a signal is carried out. Based on the conditions of applicability, the classical Li-Ma formula [5] is used in this paper:

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

where $k = T_{on}/T_{off}$, and N_{on} and N_{off} — are the number of events that fall into some observation window on the

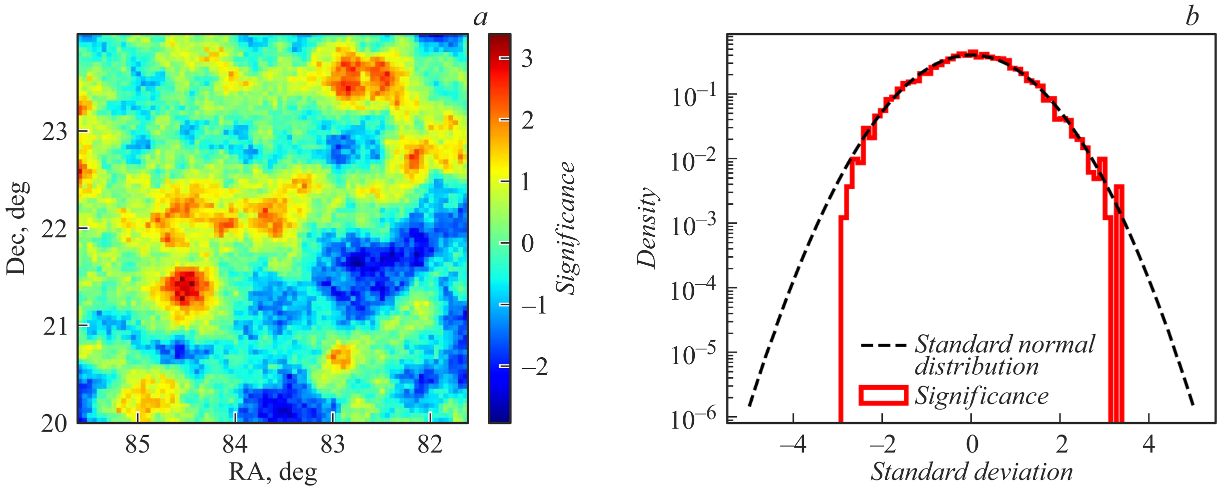

Figure 1. Crab Nebula Significance Map $4^\circ \times 4^\circ$ (a) and univariate significance distribution (b) at non-strict session selection.

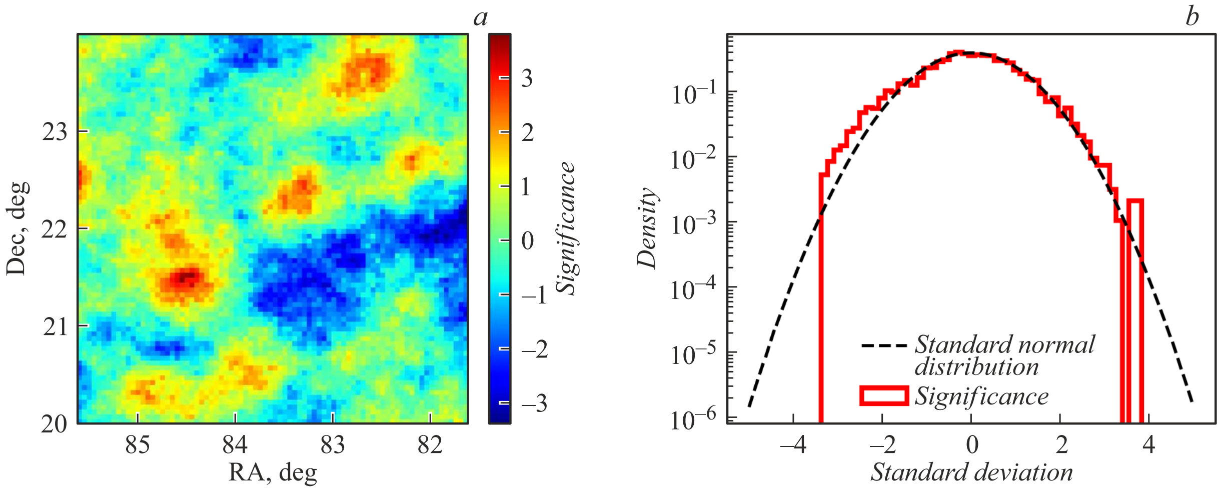

Figure 2. Crab Nebula Significance Map $4^\circ \times 4^\circ$ (a) and univariate significance distribution (b) in strict session selection.

signal and background maps, respectively. In this work, the observation window is set to 3σ-neighborhood of the observation direction (RA_j, Dec_j). The observation window is defined by the angular resolution $\sigma = 1.516\,\sigma$ and contains 98.89% of events from the point source. The window moves across the signal and background maps on the same grids with step of 0.05°, and at the corresponding points on the significance map, the value S is marked. To avoid distortion of the S value at the edges of the significance map, it is plotted with the size $4^\circ \times 4^\circ$.

Fig. 1 shows the results of observations of the vicinity of the Crab Nebula for 2 winter seasons from 2019 to 2021 a strict selection of sessions. Angular resolution $\delta = 0.2^\circ$ is applied, which gives a viewing window radius of about 0.4°. In the 3σ-neighborhood of the source, 722 events were collected for 85.5 h observations. The expected number of gamma-ray events during this period is between 7 and 12 according to the gamma-ray spectrum of the Crab Nebula in the range 100–250 TeV [6]. At non-strict selection of sessions, 1531 events were collected in the 3σ-neighborhood of the source for 204 h observations (Fig. 2). During this time, 17–30 gamma-ray events are expected.

Based on the number of background and signal events in the observation window, one can estimate the amount of background suppression required to achieve the significance of the $S \geq 5$ signal from the Crab Nebula. First of all, improving the angular resolution from 0.2 to 0.1° can reduce the background by a factor of 4. When this condition is met, the required background suppression by gamma-hadron separation methods is 70–75 times for strict sessions and 16–20 times for non-strict session selections. This background suppression is planned to be achieved and tested on the existing TAIGA-1 complex with the help of inexpensive so-called small Cherenkov telescopes, and to be fully used in the future TAIGA-10 facility with a hybrid detector system on an area of 10 km^2.

In this paper, gamma-hadron separation was not used, so the particle flow can be considered uniform. In this case, the significance of the signal must have a standard normal distribution with variance $D_0 = 1$, which needs to be verified. For this purpose, the tests of Kolmogorov–Smirnov and D'Agostino–Pearson, suitable for a large sample [7], were used: in this paper, $n = 6400$ — the number of pixels on the map. The test results show that the distribution of significance is different from normal for strict and non-strict selection. At the same time, the variance under strict selection is $D_1 = 0.94$ (Fig. 1), and with non-strict selection — $D_2 = 1.16$ (Fig. 2).

Thus, the applied method of background estimation has limitations related to weather conditions during observations. Exclusion of sessions with temporal heterogeneities from the analysis (strict selection) reduces the total observation time by more than 2 times and leads to an underestimation of signal significance by 2.7% (at $S = 3$). The use of sessions with heterogeneities (non-strict selection) leads to an overestimation of signal significance by 6.7%. It is possible to use the obtained values as corrections when evaluating the significance of the signal. Further, it is planned to compare the described method with the surrounding window method. It is considered to be the most resistant to spatial and temporal heterogeneities in observations.

Funding

The work was carried out at the USU „Astrophysical Complex MSU-ISU" (agreement EB-075-15-2021-675). Supported by the Ministry of Science and Higher Education (projects FZZE-2020-0024, FZZE-2023-0004).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] N. Budnev et al, in *16th Vienna Conference on Instrumentation (VCI2022)*, ed. by D. Bortoletto, R. Klanner, P. Krizan, F. Parmigiani, N. Toge, D. Wehe (Nucl. Instrum. Meth. A, 2022), v. 1039, p. 167047. DOI: 10.1016/j.nima.2022.167047

[2] Y. Wang, M. Zha, S. Hu, C. Gao, J. Zhang, X. Zhang, JINST, **17**, 12003 (2022). DOI: 10.1088/1748-0221/17/12/P12003

[3] V. Samoliga, A. Pakhorukov, in *International Conference on Instrumentation for Colliding Beam Physics*, ed. by M.N. Achasov (J. Instrumentation, 2020), v. 15 (07), p. 07010. DOI: 10.1088/1748-0221/15/07/c07010

[4] Y. Nan, S. Chen, in *35th International Cosmic Ray Conference*, ed. by Y. Kwak, H.S. Lee, S. Oh, I.H. Park (Proceedings Sciense, 2018), v. 301, p. 879. DOI: https://doi.org/10.22323/1.301.0879

[5] T.P. Li, Y.Q. Ma. Astrophys. J., **272**, 317 (1983). DOI: 10.1086/161295

[6] F. Aharonian et al. Chinese Physics C, **45** (2), 025002 (2020). DOI: 10.1088/1674-1137/abd01b

[7] B.Y. Lemeshko, S.B. Lemeshko. Metrologiya, **2**, 3 (2005).

Translated by 123