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To cite this article: E B Postnikov *et al* 2020 *J. Phys.: Conf. Ser.* **1690** 012023

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First detection of gamma-ray sources at TeV energies with the first imaging air Cherenkov telescope of the TAIGA installation

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Abstract. TAIGA array addresses gamma-ray astronomy at energies from a few TeV to several PeV as well as cosmic ray physics from 100 TeV to several EeV. A 1 km² TAIGA setup will consist of 120 wide-angle detectors of the Cherenkov timing array TAIGA-HiSCORE and three imaging air Cherenkov telescopes with the field of view diameter of 9.6°. In this paper, first experimental results of the first operation stage are presented: signal detection from two gamma-ray sources, the Crab Nebula and Markarian 421, by the first IACT in stand-alone mode. The detected signal is shown to be in agreement with the Monte Carlo expectation. In future, gamma-ray signal will be detected by a larger number of TAIGA telescopes as well as the TAIGA-HiSCORE array, that is, in combined operation mode.

1. Introduction

TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma-ray Astronomy) is located near Lake Baikal in the Tunka Valley (Republic of Buryatia, Russia). It comprises several facilities measuring the parameters of extensive air showers (EASes) generated by the interaction of cosmic rays or high-energy gamma rays with the atmosphere. In this way, measurement accuracy is enhanced by a combination of different detection systems.

The main idea of TAIGA is a cost effective approach for building a large area installation with a joint operation of two different types of gamma-ray detectors: timing non-imaging stations and Imaging Air Cherenkov Telescopes (IACTs). Non-imaging technique detectors have such advantages as a relatively cheap price and a wide field of view. They cannot distinguish between gamma rays and cosmic ray background, but for this purpose small-size IACTs, also of a relatively low cost, are placed between timing stations at distances exceeding those for conventional arrays of IACTs.

Being the northernmost IACT, TAIGA provides some advantages for observing the sources with large declinations. For example, the gamma-ray source in Tycho's supernova remnant will remain within the field of view of the installation for 500 hours per year [1].

First gamma-ray sources are detected by TAIGA using conventional operation of an IACT in stand-alone mode, to test the facility and prepare its full mode operation for the near future.

2. TAIGA installation

A distinctive feature of TAIGA is that it is a hybrid instrument aimed at detection of gamma radiation. Its basic gamma-ray facility is a network of IACTs [2]. At present, IACTs are the main instruments for the ground-based very-high-energy gamma-ray astronomy in the world [3]. Their sensitivity can yet be improved through stereoscopic imaging with arrays of multiple telescopes [3]. In TAIGA, stereoscopic imaging will be available for gamma-ray EASes with energy greater than ~10 TeV due to relatively large distance between the telescopes: the first three TAIGA telescopes are located at distances of ~320 m, ~400 m, and ~500 m from each other respectively.

Gamma-rays with energy above ~30 TeV will be detected with hybrid imaging, a hybrid technique that makes use not only of data from the IACT, but also from another important TAIGA facility, an imaging array TAIGA-HiSCORE [4]. In that case, the EAS parameters such as the core location, energy, and arrival direction are obtained with high precision by the timing

technique of TAIGA-HiSCORE [5], whereas gamma-ray/cosmic ray identification problem is solved by analysing IACT images.

In addition to the foregoing, gamma rays with energy below $\sim 10\text{--}15$ TeV can be detected with a stand-alone TAIGA-IACT, which is a subject of this paper.

3. Current status

The first stage of TAIGA is a 1 km^2 area installation with 120 wide-angle timing stations and 3 IACTs. Commissioning of this phase will be complete in 2021 (first two IACTs have already been installed and commissioned, first one in 2016, and second one in January 2020; the third telescope was sent to Siberia in April 2020 and has already been installed but with neither mirrors nor camera due to COVID-19 work restrictions).

4. TAIGA-IACT

The first IACT of the installation is of Davies-Cotton type [6]. The telescope has an area of 8.2 m^2 as a total of 29 spherical mirror tiles with a 60-cm diameter each; its focal length is 4.75 m. Additional 5 mirrors are yet to be added to the first TAIGA-IACT to increase its area to 9.6 m^2 .

The camera of the telescope includes 560 photomultipliers (PMTs) as pixels: each of them is of XP1911 type with a 19-mm diameter. The field of view of the camera has a diameter of 9.6° (0.36° per pixel). It has modular structure with 28 PMTs per one cluster. Integration time of the data acquisition system is $\approx 35\text{ ns}$ [7].

Cherenkov radiation from an EAS falls on the telescope mirror tiles, reflects from them, and illuminates some of the camera PMTs. The image of the Cherenkov light from a shower generally forms an elliptical light spot with a central peak, and its shape and orientation contains information to identify the primary particle type: gamma ray or a charged cosmic ray.

5. Data

For the Crab Nebula detection, approximately 44 hours of data collected from October 2019 to December 2019 were used. The Crab Nebula observations were made in the so-called "wobble mode", or "The False Source method" [8]. In this observation mode, the IACT pointing has an offset of 1.2° in right ascension with respect to the position of the Crab Nebula itself.

This observation technique makes it possible to estimate the cosmic-ray background (during the so-called "off-source observations") under the same conditions and at the same time as during the "on-source" ones, which means minimizing possible systematic differences in the acceptance for on-source and off-source regions on the camera. Such differences could be caused, for example, by a change in the weather during the observation. The wobble mode of observation also provides an efficient use of the limited duty cycles of the telescope.

For detection of Markarian 421 (Mrk 421), observation data were collected from November 2019 to February 2020 for approximately 62 hours total. The same wobble mode with the same wobble distance of 1.2° was also applied during observations.

In TAIGA location, observation conditions for this source are better than for the Crab Nebula (minimal zenith angle is $\sim 15^\circ$ as compared with $\sim 30^\circ$ for the Crab Nebula). Better zenith angle makes both cosmic-ray background and the gamma-ray energy threshold lower. However, Mrk 421 has a strong variability of the flux, and the low flux state is on average approximately a factor of 0.3 of the Crab Nebula flux [9].

For the results presented in this paper, zenith angle cut of 42° was applied for the Crab Nebula observations, and 25° for the observations of Mrk 421. Therefore, the total zenith angle interval of $\approx 29^\circ\text{--}42^\circ$ was analysed for the Crab Nebula, and the interval of $\approx 14^\circ\text{--}25^\circ$ for Mrk 421.

6. Data analysis

Data analysis stages included, first, pedestal removal from the raw data obtained in codes of analog-to-digital converter (ADC) and conversion of these data from ADC codes to photoelectrons (p.e.). Next, the PMTs nearest to the bright star position on camera were excluded from subsequent analysis. For this paper, only ζ Tauri with the B magnitude 2.8 was excluded from the Crab Nebula analysis [10], and no star was excluded from the analysis of Mrk 421.

The image cleaning procedure [11] to reconstruct the shower image above night sky background (NSB) was performed on the next stage using the standard way: all the image pixels were excluded from subsequent analysis except the "core pixels", i.e. those with the amplitude above a "core threshold" and at least one neighbour pixel above a "neighbour threshold", and the neighbour pixels themselves. Core threshold value of 6σ of NSB and neighbour threshold value of 3σ of NSB were used.

Next, the image analysis was performed using conventional technique, the so-called dynamical cuts [12], which means energy-dependent cuts on the image parameters introduced by M. Hillas [13]. To be more precise, the cuts depend on the "image size" parameter proportional to the energy of primary particle: the image size is a sum of amplitudes of all the PMTs after the bright star removal and NSB removal during image cleaning.

Set of cuts on Hillas parameters used for the Crab Nebula detection is given below. Their values were determined in Monte Carlo simulation of the TAIGA-IACT [14] as ones to sufficiently suppress cosmic-ray background.

Image size $S \geq 125$ p.e.,

the distance between the source position and the image center of gravity $0.36^\circ \leq dist \leq 1.44^\circ$,

image width $0.024^\circ \leq w \leq 0.068^\circ \times \lg(S/1p.e.) - 0.047$,

image length $l \leq 0.31^\circ$,

image concentration $Conc_2 \geq 0.54$ (the ratio of the total of two largest amplitudes in the image to the whole image size), angle $\alpha \leq 10^\circ$ (the angle between the image axis and the direction to gamma-ray source, which should be close to zero for gamma rays because their images are oriented towards the source position on camera).

According to Monte Carlo [14], such cuts suppress cosmic-ray (proton and helium) background by a factor of ~ 2700 though losing 77% of gamma rays (these values are obtained after cutting the image size, that is only for gamma rays above the energy threshold of 3–4 TeV).

Corresponding cuts for Mrk 421 detection were:

$S \geq 172$ p.e.,

$0.5^\circ \leq dist \leq 1.25^\circ$,

$w \leq 0.068^\circ \times \lg(S/1p.e.) - 0.045$,

$l \leq 0.31^\circ$,

$Conc_2 \geq 0.44$,

$\alpha \leq 8^\circ$.

Monte Carlo showed that such cuts suppress cosmic-ray background by a factor of ~ 1800 losing 85% of gamma rays (after cut on the image size $S \geq 172$ p.e., p.e. corresponding to the gamma-ray energy threshold of 2–3 TeV).

Different sets of cuts were also optimized for losing not more than 50% of gamma rays; corresponding results are to be reported in the near future.

7. Results

After comparison between on-source and off-source measurements, gamma-ray candidate excess with the statistical significance of 5.77σ [15] is observed (568 on-source events versus 390 off-source ones) for the Crab Nebula. For Markarian 421, 48 on-source events were found versus 11 off-source events (5.0σ statistical significance).

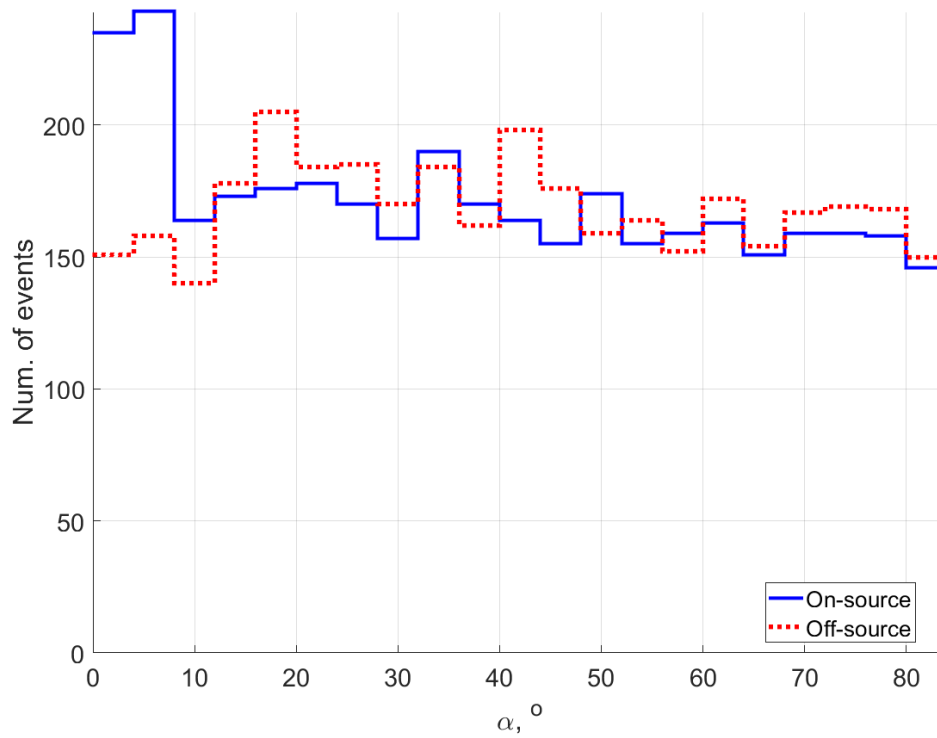


Figure 1. Gamma-ray excess for the Crab Nebula observations.

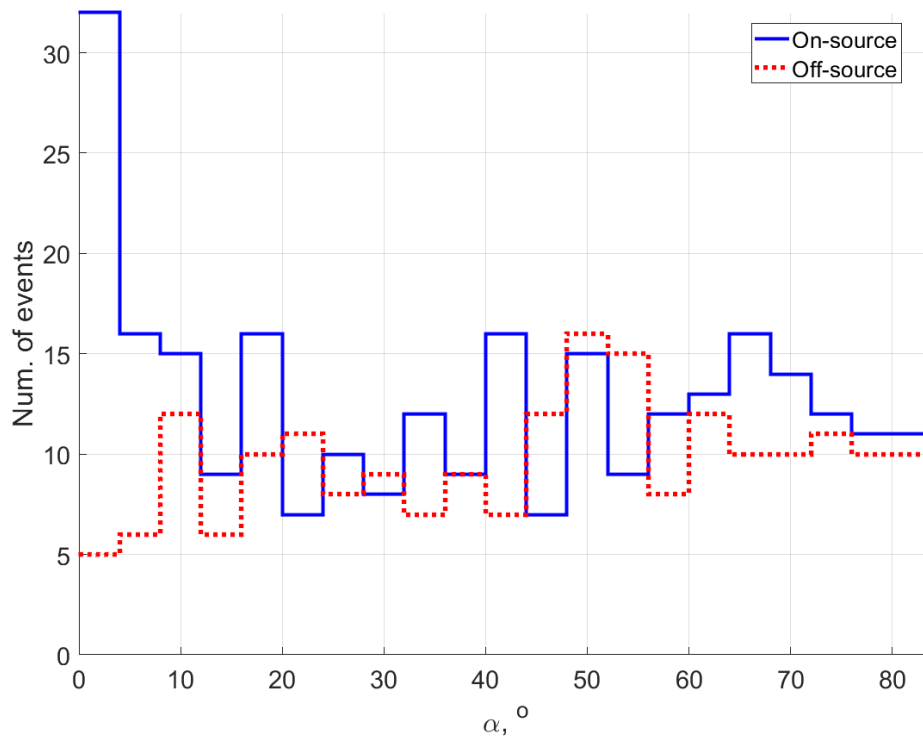


Figure 2. Gamma-ray excess for the observations of Markarian 421.

The gamma-ray excess histograms are plotted in figure 1 (the Crab Nebula) and figure 2 (Mrk 421). On these histograms, the angle between the image axis and the direction to the source is binned with the 4° step. The interval of 0° – 10° contains the excess of 178 events for the Crab Nebula; the interval of 0° – 8° with 37 events above the background was chosen for Markarian 421.

Monte Carlo simulations revealed good agreement with the results obtained: for the Crab Nebula, the estimated number of gamma rays after cuts is ~ 150 – 200 depending on the fit of the Crab Nebula spectrum. These estimates correspond well with the value of 178 gamma rays (Non–Noff) in experiment. For Mrk 421, the number of gamma rays was calculated to be 34.9 for the fit of the Mrk 421 low flux state [16] versus 37 gamma rays in experiment.

8. Conclusions

The Crab Nebula gamma-ray excess in the energy interval ~ 4 – 30 TeV resulted in a value of 178 events per 44 hours of observation (5.8σ statistical significance). Corresponding excess for Markarian 421 was determined in the interval ~ 3 – 10 TeV; its value is 37 events per 62 hours of observation (5.0σ). Monte Carlo simulations are in good agreement with these results. In future, more refined analyses will be performed using different sets of cuts and different techniques for gamma-ray selection. Joint analysis of data from a few telescopes and the TAIGA-HiSCORE timing array will also be conducted.

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