TAIGA — hybrid complex for multimessenger high-energy astronomy

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Hybrid complex installations TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) is designed for multi-messenger study of high energy Universe. A brief description of the TAIGA-1 pilot complex with a hybrid detector system distributed over an area of 1.1 km^2 and some of the results already obtained are presented.

Keywords: TAIGA, cosmic rays, gamma astronomy, energy spectrum.

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Introduction

Modern astrophysics is moving towards the organization of multicomponent research, enlargement and combination of facilities engaged in the registration of various components of ultra-high-energy cosmic radiation. In addition to classical optical astronomy, several channels for obtaining information about the Universe are being actively developed to study the mechanisms taking place in space accelerators inside and outside the Milky Way, and facilities are being built to record the entire spectrum of electromagnetic radiation, cosmic rays (charged particles), neutrinos, and gravitational waves. Physically, this is determined by the fact that the charged and neutral components of cosmic

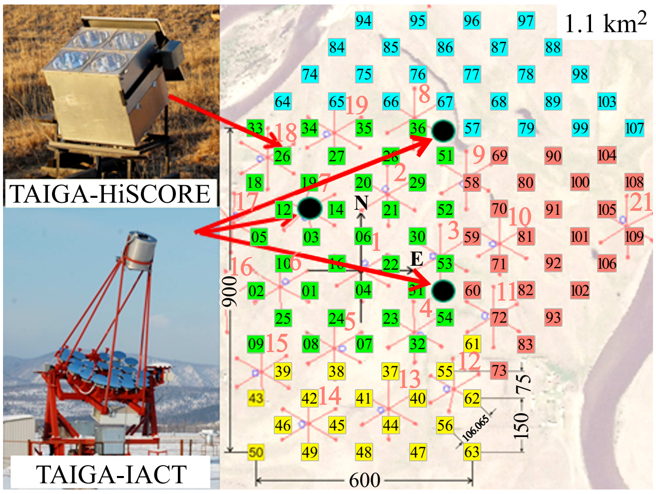

Figure 1. Relative position of the TAIGA-HiSCORE detectors (squares) and IACT telescopes of the TAIGA-IACT (circles) of the astrophysical complex TAIGA-1.

radiation from extraterrestrial sources are closely related, the joint study of nuclear fluxes, gamma quanta and high-energy neutrinos are of particular value and can provide important information for solving many fundamental problems of astrophysics and high-energy physics.

In 2022, the deployment of the first stage of the hybrid complex TAIGA-1 (Fig. 1) [1] was completed in in the Tunka Valley, 50 km from Lake Baikal. It is designed to study gamma radiation fluxes in the energy range 3–300 TeV and charged cosmic rays with energies from 100 Tev to 1000 PeV by recording extensive air showers (EAS) generated by the interaction of high-energy particles with the atmosphere. The uniqueness of the complex lies in the combined use of detectors of different types to record both Cherenkov radiation and charged particles of EAS. Imaging atmospheric Cherenkov telescopes (IACTs) of the TAIGA-IACT [2] installations, as well as wide-angle installations TAIGA-HiSCORE [3] and Tunka-133 [4] are used to record the Cherenkov radiation of EAS. Tunka-Grande and TAIGA-Muon [5] are used to record the charged component of EAS, including muons.

The high density of detectors of the TAIGA-HiSCORE array (120 optical stations in increments of 106 m on an area of 1.1 km^2) makes it possible to restore the energy of EAS with an accuracy of 10–15% and the direction of the EAS axis with the accuracy of: 0.4–0.5° for events with 4–5 triggered stations, and about 0.1° for events with more than 10 triggered stations [6,7]. The type of EAS particle (hadron/gamma) is determined by the characteristics of the Cherenkov image of the EAS in the IACTs chambers of the TAIGA-IACT facility, which are capable of detecting EAS from a distance of up to 600 m, which made it possible to place them at a sufficiently large distance from each other.

At the moment, TAIGA — the world's northernmost gamma-ray observatory. The observation program includes sources whose observation time is long enough for the northern location of the observatory: Crab Nebula, Dragonfly, Tycho Brahe supernova remnants, CTA-1, G106.3+2.7, sources in the Sygnys Coocon nebula, blazars Mk501, Mrk421, etc. The range of tasks of the complex includes:

1. Study of the energy spectrum of gamma quanta from galactic sources and search for new sources of gamma quanta with energies higher than 2 TeV.
2. Monitoring of gamma quanta flux from nearby extragalactic sources.
3. Search for gamma quanta of the TeV range from gamma-ray bursts.
4. Search for gamma quanta associated with energetic neutrinos.
5. Search for astrophysical nanosecond optical transients.
6. Investigation of the energy spectrum and mass composition of charged cosmic rays.

The main results of the study of charged cosmic rays using the TAIGA facilities are given, for example, in the papers [8,9]. Further there are some of the latest results in the field of gamma-ray astronomy.

1. Gamma Quanta Detection from Astrophysical Sources

During the two seasons 2019–2020 and 2020–2021, a gamma-ray source in the Crab Nebula was observed by the first IACT in 150 h. 618 events from gamma quanta in the energy range 5–100 TeV were singled out. The level of significance of this number of events above the background of charged cosmic rays is 12σ (Fig. 2, a). To restore the energy of gamma quanta based on the data of only one IACT telescope, an original technique based on the results of Monte Carlo calculations was used, its accuracy is about 30%. Also, 6 gamma quanta with energy above 100 TeV were found in the scope of a hybrid approach based on the data of the first IACT and the first cluster of the TAIGA-HiSCORE facility. The obtained energy spectrum coincides well with the world data in the region above 5 TeV (Fig. 2, b).

For events recorded by two or more IACTs, new methods were used to isolate events from gamma quanta and new approaches to reconstructing the direction of arrival and energy of the event, which improve gamma-hadron separation compared to detection by a single telescope. The approaches developed on the basis of Monte Carlo calculations were applied to the events recorded by the two telescopes during the 2020–2021 season. For 36 h observations, a signal with a significance of 5σ was obtained and the energy spectrum was restored, which is in good agreement with the results of the HAWC and LHAASO high-altitude installations.

2. Observation of Gamma-ray Bursts

One of the important tasks for the TAIGA-1 complex is the search for the high-energy part of gamma-ray burst

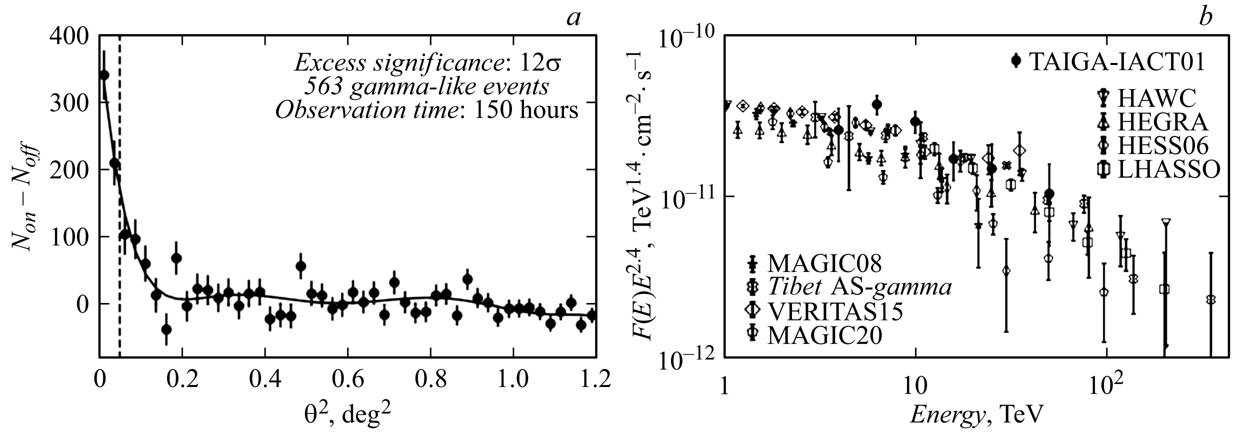

Figure 2. *a* — distribution by parameter Θ^2 (Θ — angle between the direction of the source and the direction of arrival of this event; *b* — gamma-ray spectrum from the Crab Nebula from one IACT data per 150 h observations.

radiation. The software for controlling the telescopes of the TAIGA-IACT [10] is implemented using the EPICS (Experimental Physics and Industrial Control System) package. Sources are observed in the wobble [11] mode, which makes it possible to estimate the flux of gamma quanta from the source and the background of cosmic rays using the same data set. In December 2022, a scheduler function was added to the telescope control software, which allows you to automatically perform the tasks of scheduled observation of sources and observations by alerts from NASA's General Coordinates Network (GCN) [12]. At this stage, the program automatically receives, analyzes and adds to the database information on gamma-ray bursts registered by the SWIFT and FERMI spacecraft. In future, it is planned to include messages from neutrino detectors IceCube, Baikal-GVD, ground-based gamma-ray observatories, etc. When an alert is received, the corresponding telescope pointing task is automatically added to the scheduler with an increased priority and automatically started to execute with a stop for scheduled observations. Based on the test results, the maximum time to re-aim to a gamma-ray burst (if the telescope needs to perform a full rotation in azimuth) from the time of receiving an alert from the GCN to the start of the data set is 160 s. Currently work is underway to improve this rate and create programs to handle alerts from other experiments.

After December 21, 2022, 5 pointings to real gamma-ray burst sources were performed using the IACTs of the TAIGA-IACT facility, including: the radio galaxy NGC 1275, long gamma-ray bursts GRB 221226A, GRB 230321B and GRB230116575, the binary pulsar Be/X-ray LS V +44 17. The obtained experimental data are being processed.

Conclusion

The first results obtained with the help of the TAIGA-1 complex confirm the effectiveness of the hybrid approach for studying the flux of ultra-high-energy gamma quanta and solving problems of multi-messenger astronomy astronomy. The possibility of extracting gamma quanta with an energy above 100 TeV using an IACT and a wide-angle TAIGA-HiSCORE facility has been experimentally proved. The effective area of the complex TAIGA-1 in the scope of the hybrid approach is a value of the order of 1 km^2, which is at least an order of magnitude larger than that of other Cherenkov gamma-ray telescopes (H.E.S.S, VERITAS, MAGIC) and is 1.5 times larger than effecive area of the LHAASO facility. Sensitivity of the complex TAIGA-1 for the detection of gamma quanta with the energy of 30–300 TeV from local sources — $2.5 \cdot 10^{-13}$ TeV/cm^2 s for 300 h observations. This result is important, among other things, for the preparation of the design of the future TAIGA-10 facility with a hybrid detector system on an area of 10 km^2, which will make it possible to study gamma quanta fluxes from local sources to PeV-energies. In the coming years, the TAIGA-1 complex will be supplemented by two more IACT.

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Conflict of interest

The authors declare that they have no conflict of interest.

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