ISSN 1063-7788, Physics of Atomic Nuclei, 2024, Vol. 87, No. 3, pp. 165–171. © Pleiades Publishing, Ltd., 2024.

ELEMENTARY PARTICLES AND FIELDS
Experiment

Search for High-Energy Gamma Quanta from the Cygnus Cocoon Source in October–November 2020

E. Okuneva(1)*, L. Sveshnikova(1), I. Astapov(2), P. Bezyazykov(3), A. Blinov(4), A. Borodin(4), E. Bonvech(1), N. Budnev(3), A. Bulan(1), P. Busygin(3), A. Vaidyanatan(5), N. Volkov(6), P. Volchugov(1), D. Voronin(7), A. Gafarov(3), E. Gres(3), O. Gres(3), T. Gres(3), O. Grishin(1), A. Garmash(5),(8), V. Grebenyuk(4), A. Grinyuk(4), A. Dyachok(3), D. Zhurov(3), A. Zagorodnikov(3), A. Ivanova(3), A. Ivanova(8),(3), M. Ilyushin(3), N. Kalmykov(1), V. Kindin(2), V. Kiryukhin(3), R. Kokoulin(2), N. Kolosov(3), K. Kompaniets(2), E. Korosteleva(1), V. Kozhin(1), E. Kravchenko(5),(8), A. Kryukov(1), L. Kuzmichev(1), A. Chiavassa(9), M. Lavrova(4), A. Lagutin(6), Y. Lemeshev(3), B. Lubsandorzhiev(7), N. Lubsandorzhiev(1), S. Malakhov(3), R. Mirgazov(3), R. Monkhoev(3), E. Osipova(1), A. Pakhorukov(3), A. Pan(4), A. Panov(1), L. Pankov(3), A. Petrukhin(2), D. Podgrudkov(1), I. Poddubny(3), E. Popova(7), E. Postnikov(1), V. Prosin(1), V. Ptuskin(10), A. Pushnin(3), A. Razumov(1), R. Raikin(6), G. Rubtsov(7), E. Ryabov(3), V. Samoliga(3), I. Satyshev(4), A. Silaev(1), A. Silaev, Jr.(1), A. Sidorenkov(7), A. Skurikhin(1), A. Sokolov(5),(8), V. Tabolenko(3), A. Tanaev(3), M. Ternovoy(3), L. Tkachev(11), N. Ushakov(7), D. Chernov(1), and I. Yashin(2)

Received November 29, 2023; revised November 29, 2023; accepted November 29, 2023

Abstract—In November 2020, the IceCube Neutrino Observatory registered a neutrino event with an energy of 150 TeV directed at the Cygnus Cocoon gamma-ray source. In the Carpet-2 experiment, as part of the Baksan Neutrino Observatory (BNO), a sharp increase in the flow of events with an energy above 300 TeV was recorded from the same direction within the angular accuracy of the events. This flux is 4 orders of magnitude higher than the expected intensity of gamma quanta of this energy region according to data in the region of less than 100 TeV. It was expected that such a powerful flare could be registered by the TAIGA-HiSCORE installation of the TAIGA astrophysical complex. We analyzed the events of the EAS recorded by the installation of TAIGA-HiSCORE for 18 h in October–November 2020 from the Cygnus Cocoon source. This article provides the upper limit of the expected excess flow.

DOI: `10.1134/S1063778824700194`

1. INTRODUCTION

Sources of PeV cosmic rays (the so called PeVatrons) can be identified by the trajectories of neutral particles (gamma quanta and neutrino) with energies above 100 TeV not disturbed by the galactic magnetic field. In 2012 the gamma telescope Fermi opened a "cocoon" in the OB2 association of the constellation of Cygnus filled by high-energy cosmic rays [1]. For the first time, the gamma radiation source in the high energy range 1–100 TeV was discovered by the HAWC mountain facility and was named the Cygnus Cocoon [2]. In the Tibet ASγ experiment, gamma radiation up to 200 TeV was recorded from the cocoon region [3], and in the LHAASO experiment [4], up

---

(1)Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia.
(2)National Research Nuclear University MEPhI, Moscow, Russia.
(3)Applied Physics Institute, Irkutsk State University, Irkutsk, Russia.
(4)Joint Institute for Nuclear Research, Dubna, Moscow oblast, Russia.
(5)Novosibirsk State University, Novosibirsk, Russia.
(6)Altai State University, Barnaul, Russia.
(7)Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia.
(8)Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia.
(9)Sezione di Torino, Instituto Nazionale di Fisica Nucleare, Turin, Italy.
(10)Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Moscow, Russia.
(11)Dubna University, Dubna, Moscow oblast, Russia.
*E-mail: `lina.okuneva.97@mail.ru`

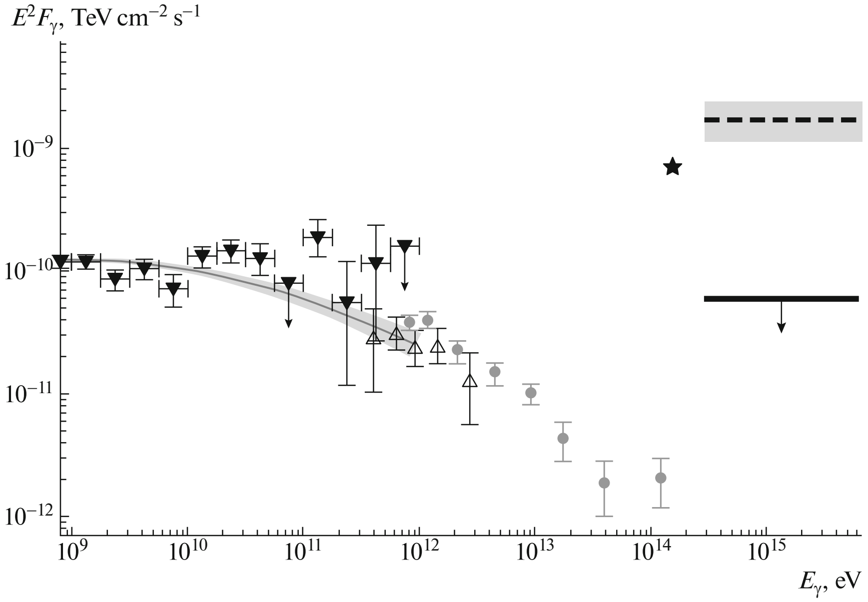

Fig. 1. Energy spectrum of gamma radiation of Cygnus Cocoon (from work [6]), measured at different installations. Gray region is the time-average flux model 4 FGL; gray triangles are the data of ARGO experiment; gray circles are the data obtained in the HAWC experiment [2]; black triangles is the flare registered by Fermi-LAT [1]; black dashed band is the γ-flare recorded in the Carpet-2 experiment [6]; black asterisk is the flux estimate from the neutrino data of IceCube [8]. Black solid line is the upper threshold of flare in October—November 2020 obtained in the current work.

to 1 PeV. Figure 1 shows the spectra obtained in the HAWC experiment, compared to spectra obtained in several other experiments. Today, the Cygnus Cocoon source is classified as PeVatron, although it is reliably unknown whether gamma quanta are produced in the source from high-energy protons or electrons [4]. The map of spatial intensity of radiation in this region obtained in the HAWC experiment [2] was presented in Fig. 2. It was shown that the sources are not point-like, but elongated.

Acceleration of cosmic rays up to energies above 1 PeV in the regions of active star formation, including Cygnus Cocoon, was discussed in the literature for a long time [5—7].

The interest to the Cygnus Cocoon source raised notedly after the registration of neutrino with an energy of 150 TeV by the Ice Cube telescope from the source region (at 0.5° from the source) on November 20, 2020 [8]. The expected flux in this case is labeled by black asterisk in Fig. 1. In the Carpet-2 experiment (Baksan Neutrino Observatory) [9], a sharp increase in the photon fluxes with energy above 300 TeV was registered from the same direction exceeding by four orders of magnitude the expected flux in this energy range (the dashed black curve in Fig. 1). The duration of the high flux of events from the region of the Cygnus Cocoon was 80 days: from October 10 to January 1.

Several hypotheses were proposed to explain the generation mechanisms of such high-energy radiation. One of the interesting hypotheses was put forward in work [10], where it was shown that, in double

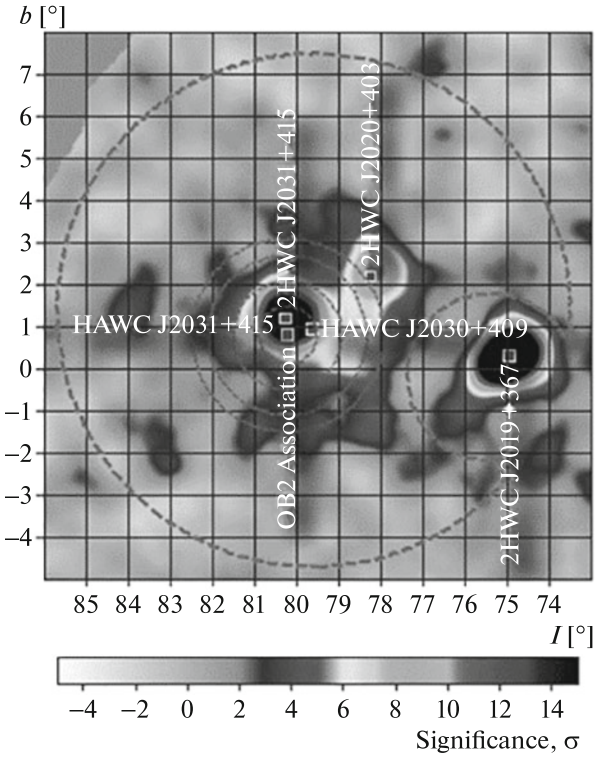

Fig. 2. Intensity map of gamma radiation from Cygnus Cocoon region obtained in HAWC experiment [2].

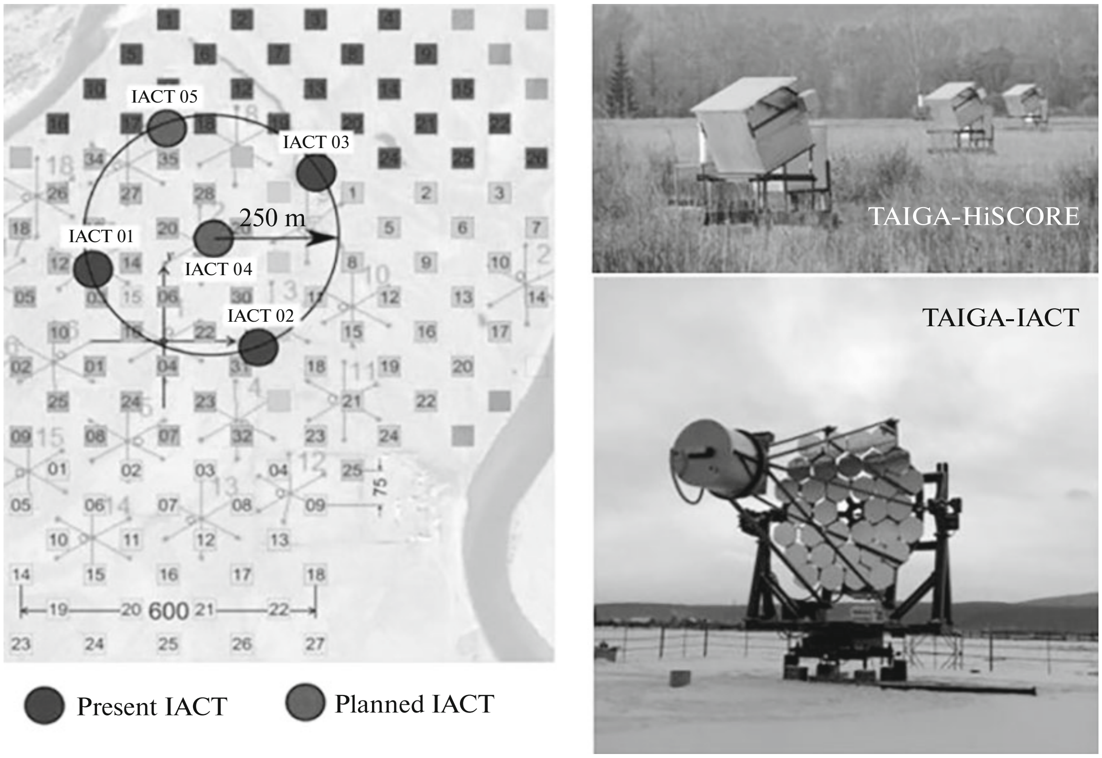

Fig. 3. Astrophysical complex TAIGA: main detectors are (*c*) imaging atmospheric Cherenkov telescopes (bottom right panel) and (*b*) wide-angle HiSCORE stations (top right panel). (*a*) Plan of detector placement (left panel).

systems, protons can efficiently accelerate to PeV energies in the regions of collision between the relativistic wind from a pulsar and the star wind from a massive star. Gamma quanta and neutrinos of high energies may produce both at collision of an accelerated proton and a proton of star wind (the pp reaction) and at interaction between protons and ultraviolet photons (the $p\gamma$ reaction). To produce pions in the $p\gamma$ reaction the proton energy must be above 10 PeV, which results in the production of gamma quanta with an energy above 100 TeV. It was shown in paper [10] that a situation is possible when a flux of gamma quanta from the $p\gamma$ reaction in the range of several hundred teraelectronvolts is substantially larger than the flux of gamma quanta from the pp reaction in this energy range, and in this case the flux of gamma quanta with an energy of 10 PeV is compared to the flux of gamma quanta with an energy of 100 TeV.

In paper [11] of the LHASSO collaboration, the researchers received a flux of gamma quanta from the same direction of the region of active star formation Cygnus X until several petaelectronvolts, with a spatial distribution $\sim 1/r$ up to 50 pc, which implies the presence in the OB2 association of superpevatrons accelerating to at least 10 PeV [11]. These results confirm the possibility of existence of 10-PeV protons in the OB2 association incorporated in the model of paper [10].

At the astrophysical complex TAIGA [12–14], a wide-angle Cherenkov facility TAIGA-HiSCORE (today having an area of approximately 1 km^2) is intended to register gamma quanta with an energy above 50 TeV. The facility registers extensive atmospheric showers (EASs) at night in moonless periods. We can anticipate that such powerful outburst must be registered in this experiment. In the current work we analyze the EAS events recorded by the TAIGA-HiSCORE facility during October and November observation sessions in 2020 from the direction towards the Cygnus Cocoon source. By the data obtained by the TAIGA-HiSCORE facility we calculate the upper limit of the expected excess flux in the direction towards Cygnus Cocoon with an energy above 200 TeV.

2. TAIGA-HISCORE INSTALLATION

The TAIGA-HiSCORE facility (Fig. 3) [12–14] is a network of 120 wide-angle Cherenkov stations placed at a distance of 106 m from each other in an area of 1.1 km^2 grouped into four clusters and intended to register Cherenkov radiation from EAS. We understand the cluster as a part of the facility with a separate data acquisition center. All four clusters are synchronized.

The optical station includes four photomultipliers 20 cm in diameter (ET 9352 or Hamamatsu R5912),

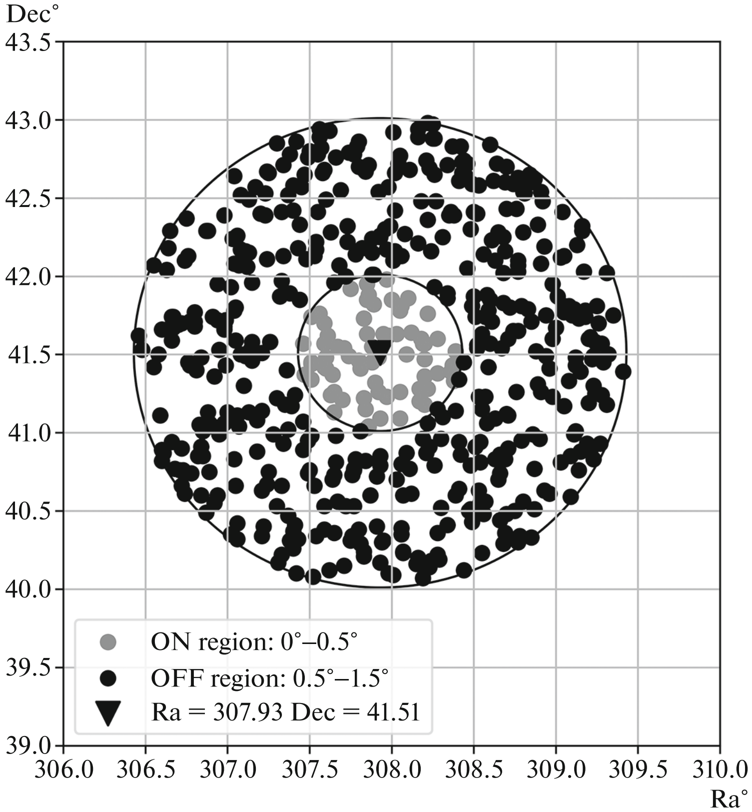

Fig. 4. Region of "ON" source (gray dots) and background region "OFF" (black dots) relatively to source coordinates Ra = 307.93 and Dec = 41.51.

equipped by the Winston cone 0.4 m in diameter with a survey angle of ±30° increasing the photomultiplier area by 4 times. Each station is connected to a data acquisition center by the optic-fiber cable for data transfer and synchronization. The accuracy of reconstructing the direction of EAS arrival depends on the number of triggered stations. The angular resolution is 0.4°–0.5° for events with 4–5 triggered stations and approximately 0.15° for events with more than 10 triggered stations [13].

3. OBSERVATION OF THE CYGNUS COCOON SOURCE BY TAIGA-HISCORE INSTALLATION

To register gamma quanta, the hadron flux in the TAIGA experiment is suppressed by the shape of image [15–17], registered by the IACTs (Imaging Atmospheric Cherenkov Telescopes), and angle between the measured EAS direction and direction to the source. The total suppression coefficient of background from charged cosmic rays is approximately 10^4. For higher-energy events above 100 TeV, it is more efficient to use a hybrid method: the HiSCORE stations and the IACTs [17]. By the data of the stations of the TAIGA-HiSCORE facility, the shower parameters are determined, including the angle of shower arrival, and the data about the image shape in the IACTs are used to separate gamma-like events. However, during the studied outburst, in October–November 2020, the region of the Cygnus Cocoon source was not observed by the IACTs; therefore, to measure the flux from this source, we used only the data about the direction of EAS arrival.

We analyzed the data of the TAIGA-HiSCORE facility (13 days of observation, 18 h), close in time to the maximum of the gamma outburst detected in the Carpet-2 experiment and to the time of neutrino detection in the IceCube experiment. To reveal the excess of events from the Cocoon, two regions were selected (Fig. 4): ON—the region in the direction towards the source in the range 0°–0.5° and OFF—the region of background measurements in the ring 0.5°–1.5° around the direction towards the source. The boundary 0.5° corresponds to conclusions of papers [1, 2] about the angular dimensions of the source. We considered only those time periods when the source and the background region surrounding the source are completely in the field of view of the optical stations of the TAIGA-HiSCORE facility. Within the field of view (±25°) the spread of the angular sensitivity by the optical stations is sev-

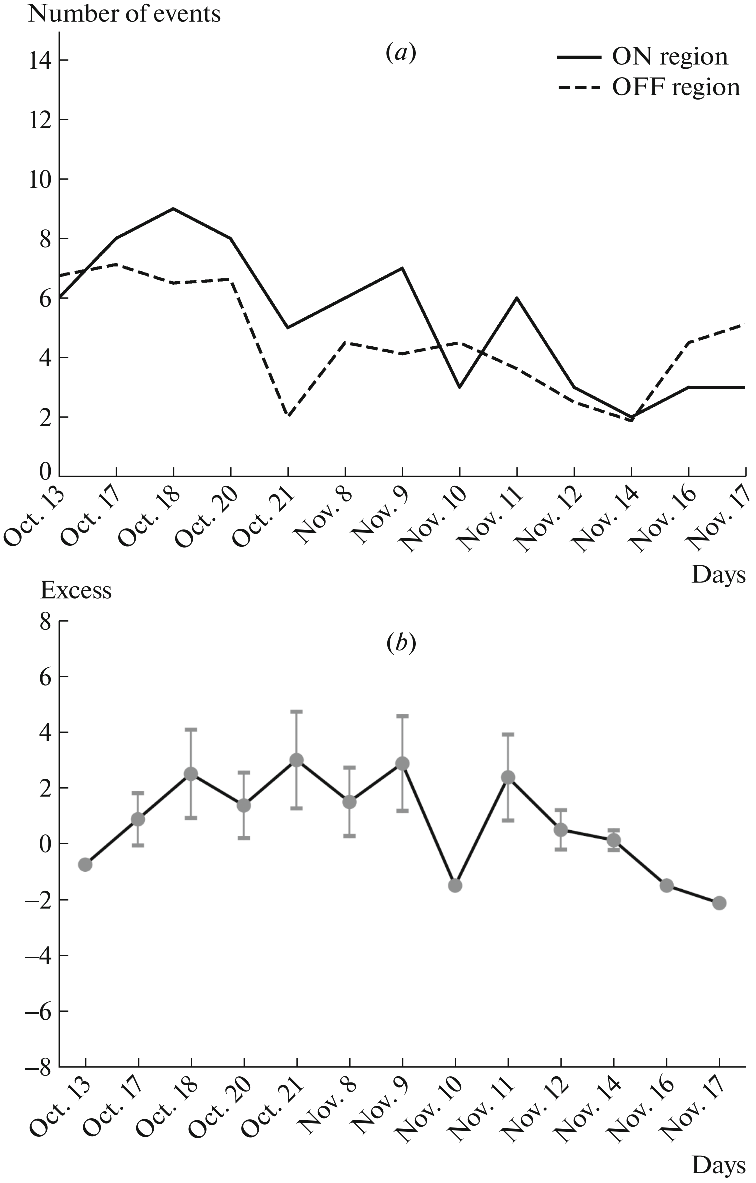

Fig. 5. (*a*) Number of events from source N_{ON} and background N_{OFF} and (*b*) excess of events for all days of Cygnus Cocoon observations.

eral percent, which does not affect the registration of the facility as a whole. The zenith angle of the source position varied from 8° to 18° during the observation session.

In this paper, we set a limit to the flux of gamma quanta with energies above 200 TeV at zenith angles up to 20°, which is almost 3 times above the energy threshold of EAS registration from gamma quanta [17]. The variation in the photon flux from EAS of the given energy at variation in the zenith angle from 0° to 20° at a distance of 100 m from the axis is less than 20% [18]. In setting the limit we used the area of 0.45 km^2. This is the area of two clusters of the facility minus a strip of 50 m along the facility's periphery. The efficiency of gamma quanta registration within this area for energies above 200 TeV and zenith angles smaller than 20° is 100%.

The source coordinates were chosen to be Ra = 307.93, Dec = 41.51. This region is close to the pulsar J2032+4127 (with coordinates Ra = 308.00, Dec = 41.46), which rotates about the star MT91 213 (B0Vp) with a period of 50 years and is regarded as the region in which particles can accelerated up to petaelectronvolt energies at collision between the relativistic wind from the pulsar and the star wind from the massive star [10]. These coordinates coincide with the HAWC measurements (Ra = 307.90, Dec = 41.51) [2] and are close to the maximum of observation of LHAASO (Ra = 307.17, Dec = 41.17)

[4] and arrival direction of the neutrino recorded by the IceCube telescope: Ra = 307.53, Dec = 40.77 [5]. In Fig. 2, presented in the galactic coordinates, this direction corresponds to the point $I = 80.3°$ and $b = 1.0°$. The obtained values $N_{\rm ON}$ and $N_{\rm OFF}$ and the excess of events with energies above 200 TeV for each day of observation are depicted in Fig. 5.

The resulting excess of events is computed by the formula (α is the ratio of solid angles)

$$\text{Excess} = N_{\rm ON} - \alpha N_{\rm OFF}, \quad \alpha = \frac{d\Omega_{\rm ON}}{d\Omega_{\rm OFF}}.$$

The estimate of the standard deviation is computed by the formula by Li and Ma [19]:

$$\sigma = \sqrt{N_{\rm ON} + \alpha^2 N_{\rm OFF}}.$$

4. RESULTING FLUX LIMIT

Based on the excess of events from the source obtained during entire 18 h of observation, we estimated the upper limit to the flux:

$$\text{Upper limit} F(E)\,E^2 = \frac{(\text{Excess} + 3.2\sigma)\,E^2}{St} = 6 \times 10^{-11}\,\frac{\text{Tev}}{\text{cm}^2\text{s}},$$

where E is the energy of gamma quantum, S is the facility area (0.45 km^2), and t is the observation time (18 h).

The confidence interval of 3.2σ indicates 90%-probability of signal registration from the source below the given upper limit [20]. The obtained limit to the particle flux is presented in Fig. 1 by the black curve and is a stricter constraint than the result obtained at the Carpet-2 facility.

Taking into account that in the LHAASO experiment and in the HAWC experiment, a wide angular distribution of intensity was observed, we also performed scanning of regions of increased intensity designated in Fig. 2 as regions with a significance above 5σ. Here, we changed the direction of scanning, but the size of the relative regions ON and OFF remained the same as described above. However, the result of the upper flux limit did not change.

5. CONCLUSIONS

By the data of the TAIGA-HiSCORE facility, we attempted to detect an excess of gamma-like EASs with energies above 200 TeV in the direction towards the Cygnus Cocoon source (with coordinates in a circle with a radius of 0.5° relatively to the direction towards the pulsar J2032+4127: Ra = 307.93°, Dec = 41.51°) in October–November 2020. The chosen time of observation and the direction intersect both with the period of increased count rate of events revealed in the Carpet-2 experiment and with the direction and time of the 150-TeV neutrino registered by the IceCube telescope. The obtained upper limit of the flux is estimated as $F(E)\,E^2 < 6 \times 10^{-11}\,\frac{\text{TeV}}{\text{cm}^2\,\text{s}}$, which is an order of magnitude stricter constraint than the result obtained at the Carpet-2 facility. This result does not reject the possibility of a higher flux of gamma quanta from the $p\gamma$ reaction proposed in paper [10], but indicates to the necessity of correcting the model parameters.

The result is obtained by the data of 2020, when the TAIGA-HiSCORE facility occupied an area of approximately 0.5 km^2, whereas, by now, the facility contains 120 detectors over an area of 1.1 km^2. Today, the methods of more efficient suppression of hadron background by the TAIGA-HiSCORE data are intensely developed. Increasing the facility area and new methods of hadron background suppression will allow increasing the sensitivity of the facility to lower fluxes of gamma quanta in the energy range of hundreds of teraelectronvolts.

FUNDING

The work is carried out at the Unique Research Installation Astrophysical Complex Moscow State University–Irkutsk State University and supported by the Ministry of Science and Higher Education of the Russian Federation (agreement no. EB-075-15-2021-675). The work is supported by the state assignments, topic nos. FZZE-2020-0017, FZZE-2020-0024, and FSUS-2020-0039, and by the Russian Science Foundation, project no. 23-72-00019 (Sections 3–5).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. M. Ackermann et al. (Fermi Collab.), Science **334**, 1103 (2011). https://doi.org/10.1126/science.1210311
2. A. U. Abeysekara (HAWC Collab.), Nat. Astron. **5** (6), 465 (2021). https://doi.org/10.1038/s41550-019-0827-7
3. M. Amenomori et al. (Tibet ASγ Collab.), AIP Conf. Proc. **126**, 141101 (2021). https://doi.org/10.1063/1.1370890
4. Zh. Cao et al. (LHAASO Collab), Nature **594**, 33 (2021). https://doi.org/10.1038/s41586-021-03498-z
5. A. M. Bykov, Astron. Astrophys. Rev. **22**, 77 (2014). https://doi.org/10.1007/s00159-014-0077-8

6. E. E. Stüken, S. M. Som, M. Claire, S. Rugheimer, M. Scherf, L. Sproß, N. Tosi, Y. Ueno, and H. Lammer, Space Sci. Rev. **216**, 41 (2020). https://doi.org/10.1007/s11214-020-00652-3
7. F. Aharonian, R. Yang, and E. De Oña Wilhelmi, Nat. Astron. **3**, 561 (2019). https://doi.org/10.1038/s41550-019-0724-0
8. (IceCube Collab.), GRB Coordinates Network (GCN), No. 28927, 1 (2020).
9. D. D. Dzhappuev, Yu. Z. Afashokov, I. M. Dzaparova, T. A. Dzhatdoev, E. A. Gorbacheva, I. S. Karpikov, M. M. Khadzhiev, N. F. Klimenko, A. U. Kudzhaev, A. N. Kurenya, A. S. Lidvansky, O. I. Mikhailova, V. B. Petkov, E. I. Podlesnyi, V. S. Romanenko, G. I. Rubtsov, S. V. Troitsky, I. B. Unatlokov, I. A. Vaiman, A. F. Yanin, Ya. V. Zhezher, and K. V. Zhuravleva, Astrophys. J. Lett. **916**, L22 (2021). https://doi.org/10.3847/2041-8213/ac14b2
10. A. M. Bykov, A. E. Petrov, M. E. Kalyashova, and S. V. Troitsky, Astrophys. J. Lett. **921**, L10 (2021). https://doi.org/10.3847/2041-8213/ac2f3d
11. Zh. Cao et al. (LHAASO Collab.), Phys. Rev. Lett. **131**, 151001 (2023). https://doi.org/10.1103/PhysRevLett.131.151001
12. I. I. Astapov (TAIGA Collab.), J. Exp. Theor. Phys. **134**, 469 (2022). https://doi.org/10.1134/S1063776122040136
13. N. Budnev, I. I. Astapov, P. A. Bezyazeekov, A. Borodin, M. Brückner, D. Chernykh, A. Chiavassa, A. Dyachok, O. Fedorov, A. Gafarov, A. Garmash, V. Grebenyuk, O. Gress, T. Gress, A. Grinyuk, O. Grishin, et al., Nucl. Instrum. Methods Phys. Res., Sect. A **958**, 162113 (2020). https://doi.org/10.1016/j.nima.2019.04.067
14. M. Tluczykont, D. Hampf, D. Horns, D. Spitschan, L. Kuzmichev, V. Prosin, C. Spiering, and R. Wischnewski, Astropart. Phys. **56**, 42 (2014). https://doi.org/10.1016/j.astropartphys.2014.03.004
15. L. G. Sveshnikova, P. A. Volchugov, E. B. Postnikov, I. I. Astapov, P. A. Bezyazeekov, E. A. Bonvech, A. N. Borodin, N. M. Budnev, A. V. Bulan, A. A. Vaidyanathan, N. V. Volkov, D. M. Voronin, A. R. Gafarov, E. O. Gress, O. A. Gress, T. I. Gress, et al., Bull. Russ. Acad. Sci.: Phys **87**, 904 (2023). https://doi.org/10.3103/S1062873823702738
16. A. A. Grinyuk, E. B. Postnikov, and P. A. Volchugov (TAIGA Collab.), Proc. Sci. **ICRC2021**, 713 (2021). https://doi.org/10.22323/1.395.0713
17. A. Sh. M. Elshoukrofy, E. A. Okuneva, and L. G. Sveshnikova (TAIGA Collab.), Proc. Sci. **ICRC2023**, 685 https://doi.org/10.22323/1.444.0685
18. V. V. Prosin (TAIGA Collab.), Bull. Russ. Acad. Sci.: Phys **87**, 1043 (2023). https://doi.org/10.3103/S1062873823702362
19. T.-P. Li and Y.-Q. Ma, Astrophys. J. **272**, 317 (1983). https://doi.org/10.1086/161295
20. G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998). https://doi.org/10.1103/physrevd.57.3873

Translated by E. Oborin