ISSN 1063-7842, Technical Physics, 2017, Vol. 62, No. 6, pp. 819–836. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © A.M. Bykov, F.A. Aharonian, A.M. Krassilchtchikov, E.E. Kholupenko, P.N. Aruev, D.A. Baiko, A.A. Bogdanov, G.I. Vasilyev, V.V. Zabrodskii, S.V. Troitsky, Yu.V. Tuboltsev, A.A. Kozhberov, K.P. Levenfish, Yu.V. Chichagov, 2017, published in Zhurnal Tekhnicheskoi Fiziki, 2017, Vol. 87, No. 6, pp. 803–821.

Cherenkov Gamma-Ray Telescopes: Past, Present, Future. The ALEGRO Project

A. M. Bykov[a], F. A. Aharonian[b,c], A. M. Krassilchtchikov[a], E. E. Kholupenko[a,*], P. N. Aruev[a], D. A. Baiko[a], A. A. Bogdanov[a], G. I. Vasilyev[a], V. V. Zabrodskii[a], S. V. Troitsky[d], Yu. V. Tuboltsev[a], A. A. Kozhberov[a], K. P. Levenfish[a], and Yu. V. Chichagov[a]

[a] *Ioffe Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*
[b] *Dublin Institute for Advanced Studies, Dublin, D04 C932 Ireland*
[c] *Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*
[d] *Institute for Nuclear Research, Russian Academy of Sciences, Moscow, 117312 Russia*
**e-mail: eugene@astro.ioffe.ru*

Received November 29, 2016

Abstract—A brief overview of the history of atmospheric Cherenkov gamma-ray telescopes is given. Topical problems of modern astrophysics and fundamental physics to be solved with these instruments are listed. The ALEGRO project of a low-threshold gamma-ray observatory is characterized in detail. The aim of this project is to examine cosmic gamma-ray sources (especially the rapidly variable gamma-ray sources, gamma-ray transients) with high statistics of detected photons in the energy range of 5–50 GeV.

DOI: 10.1134/S106378421706007X

INTRODUCTION

Sharing its place with radio, infrared, optical, and X-ray astronomy, gamma-ray astronomy is one of the major fields of observational astrophysics. Modern methods for observing cosmic gamma quanta cover in the range of 0.1 MeV to several tens of teraelectronvolts [1]. Gamma astronomy provides an opportunity to study the most energetic events in the Galaxy and outside of it. The events in question are associated with stellar explosions at late stages of evolution (see, e.g., [2, 3]), stellar merger, the propagation of shock waves, and intense high-velocity outflows formed in the vicinity of supermassive black holes in active galactic nuclei (see, e.g., [4]). The study of processes in these physical systems is crucial for constructing a coherent theory of evolution of the universe and validating theoretical models of particle physics at energies in excess of 100 TeV, which remain out of the reach of Earth-based accelerators. In addition, modern gamma-ray astronomy is engaged in experimental verification of various hypotheses in fundamental physics (e.g., hypotheses on the nature of dark matter [5], quantum gravity (specifically, Lorentz invariance violation [6]), etc.). These unsolved issues make gamma astronomy one of the most active fields of modern astrophysics and turn gamma-ray observations of cosmic sources into a unique source of data on the nature of these objects.

Both space-based (e.g., INTEGRAL, AGILE, Fermi, etc.) and terrestrial (e.g., H.E.S.S., VERITAS, MAGIC, ARGO-YBJ, TAIGA-HiSCORE, etc.) instruments may now perform observations in the gamma range. Cherenkov gamma-ray telescopes offer the highest sensitivity in the range of 0.1–100 TeV. Such telescopes do not detect cosmic gamma quanta directly; instead, they measure the fluxes of Cherenkov photons. These photons are secondary particles coming from extensive air showers (EASs) initiated by primary cosmic particles (gamma quanta and cosmic-ray (CR) particles with an energy of several gigaelectronvolts or more) that interact with the atmosphere of the Earth. This makes these instruments efficient in detecting gamma radiation of cosmic sources and, along with their relatively low (compared to satellites) cost, contributes to their scientific appeal.

In the present study, a brief overview of the history of Cherenkov gamma-ray telescopes is given, and topical problems of modern astrophysics and fundamental physics to be solved with these instruments are listed. The project of a low-threshold Cherenkov gamma-ray observatory (conception of which was proposed by F. A. Aharonian in [7]) is also characterized in detail.

1. BRIEF OVERVIEW OF THE HISTORY OF CHERENKOV GAMMA-RAY TELESCOPES

A brief overview of the history of Cherenkov gamma-ray telescopes is given below. A more detailed technical review may be found in [8]. Several stages of development of Cherenkov gamma-ray astronomy may be distinguished. The first experiments confirming the possibility of observing EAS Cherenkov radiation from high-energy cosmic-ray particles were performed in the 1950s by Galbraith and Jelley in Great Britain [9] and A. E. Chudakov and N. M. Nesterova in the Soviet Union [10]. The success of these experiments and the idea that both high-energy gamma quanta and CR should initiate atmospheric EASs have encouraged scientists to attempt detecting cosmic gamma radiation using the Cherenkov technique in the 1960s. The first Cherenkov gamma-ray telescopes, which were used in such studies, were installed at the Crimean Observation Station (Lebedev Physical Institute, Soviet Union) [11], Atomic Energy Research Establishment (AERE, Great Britain) [12], and Mount Hopkins Observatory (United States) [13]. However, these instruments did not yield reliable detection of gamma quanta from point sources.

The first observations to reveal high-energy gamma radiation from specific cosmic sources were performed in the late 1960s and the early 1970s. A gamma-ray signal from the Crab nebula was detected by telescopes (two 90-cm reflectors) near Dublin in 1966–1967 [14], although the statistical significance was below 3σ. The Crab nebula was also examined with the first gamma-ray telescope of the Mount Hopkins Observatory [13] and (later) with the Dublin setup (four 90-cm reflectors) modified by A.E.R.E. and University College Dublin working in collaboration [15]. The same instruments were used to observe other potential gamma-ray sources (pulsars CP 1133, HP 1506, and CP 0950; galaxy M87; etc.). Positive excess were detected in some cases (e.g., the gamma flux from HP 1506 was detected with a significance of 2.6σ [15]); however, even the most successful of these observations were performed at the limit of sensitivity and could not provide reliable results with significance well above 3σ. In the Soviet Union, observations of several cosmic gamma-ray sources have been performed since 1969 with the RChV-1 telescope (four reflectors with a diameter of 1.5 m at the Crimean Astrophysical Observatory (CAO)). Some of these sources (e.g., Cas γ-1, which was later identified as pulsar 4U 0115 + 63, and Cas γ-2 [16]) were detected at the limit of sensitivity.

All the above instruments (including the first setups constructed by Chudakov et al. [11] and Jelley and Porter [12]) did only note a Cherenkov flash event and examine the source as it traversed their field of view owing to the rotation of the Earth. The gamma flux from the source was determined as the count rate excess over the background value in the process of source transit within the field of view of a telescope. These instruments belong to the first generation of Cherenkov gamma-ray telescopes. The most comprehensive and adequate version of the technique for analysis of signals from these instruments is found in [17]. The results presented in this paper are used widely in the process of analysis of observational data from modern Cherenkov telescopes. It should be noted that the statistical significance of 3σ does not guarantee the detection of a gamma-ray source with the observation and analysis techniques used prior to the publication of [17]. For example, considerable negative signal excesses over the background (as large as -2.7σ; see [13, 15, 16]) were observed in certain cases. This resulted from inaccuracies of the methods for observational data analysis and complications introduced by various contributing factors, e.g., weather conditions. Thus, although Cherenkov telescopes of the first generation did not manage to detect reliably any source of cosmic gamma radiation, they first established upper limits on gamma-ray flux intensities, which allowed theorists to exclude some models of producing gamma radiation in the studied sources, e.g., [18], and limits on the magnetic field of pulsars, e.g. [19] and, second, provided an opportunity to form a list of potential cosmic gamma-ray sources to be examined with more advanced telescopes.

Relatively complex and efficient Cherenkov gamma-ray telescopes of the second generation were constructed in parallel with observations at telescopes of the first generation. The 10-m Whipple reflector (commissioned in 1968; see, e.g., [20]) at the Mount Hopkins Observatory (now Fred Lawrence Whipple Observatory) and the GT-48 telescope at CAO (this project was conceived in 1973, and the first observations were performed in 1989; see, e.g., [21]) belong to the second generation. These instruments differed from the first-generation ones in that they first allowed one to track the source of gamma radiation continuously and, second, imaging Cherenkov flashes, i.e., bright EAS areas. However, it should be noted that the detector used at Whipple prior to 1978 did not have the capacity to image Cherenkov flashes; just like first-generation telescopes, it only detected the occurrence of these flashes. After 1978, a 19-pixel camera was in use at Whipple, and a 37-pixel camera [22] assembled from separate vacuum photomultiplier tubes (PMTs) was installed in 1983. A new efficient method for observational data analysis (determination of morphological features of imaged Cherenkov flashes with the use of Hillas parameters [23]) provided an opportunity to distinguish events initiated by gamma quanta and CR particles, i.e., separate useful signals from background. The introduction of this method led to a radical increase in the quality of obtained data and a considerable relaxation in the requirements imposed on exposure.

The following additional factors contributed to the increase in efficiency of telescopes of the second generation: a significant increase in the mirror size and application of the stereoscopic method, i.e., Cherenkov flash observations performed by two or more instruments simultaneously at different angles. The introduction of this method resulted in a considerable increase in the efficiency of analysis of morphological features of images, better separation of signals from the background, and an increase in the overall angular resolution. The HEGRA project [24], which was a collaboration of German, Armenian, and Spanish scientists, was among the most successful projects adopting the stereoscopic approach. In 1984, a research group from the Yerevan Physics Institute designed a system of five relatively small (~3 m in diameter) telescopes to be installed near the Byurakan Observatory. The decision was later reconsidered, and the telescopes were eventually installed in the Canaries (at 2200 m above sea level at the Roque de los Muchachos Observatory on the island of La Palma) and formed the basis of the HEGRA system. These five telescopes had the same technical parameters: a mirror area of 8.5 m^2, a field of view of ~4.5°, and 271-pixel (PMT) cameras. Four telescopes formed a square with a side of 100 m, and the fifth telescope was mounted at the center of this square. These parameters allowed HEGRA to detect gamma radiation in the range of primary particle energies above 1 TeV and provided an angular resolution of approximately 0.1° and an energy resolution of ~15%. Several valuable results were obtained at HEGRA. Specifically, the spectrum of gamma emission of the Crab nebula was measured for the first time at a high significance level in the range of 0.5–80 TeV [25]. Teraelectronvolt gamma radiation from several extragalactic objects was also detected reliably [26]. These results were a convincing proof of efficiency of the stereoscopic approach in gamma-ray astronomy. At the same time, the isolated Whipple telescope had the largest mirror (10 m) of all Cherenkov telescopes of the second generation, while stereoscopic observatories had telescopes with smaller mirrors. Therefore, the overall positive effect of the above two additional factors was not as significant as it could be.

In addition to the Cherenkov telescopes mentioned above, several other similar projects were carried out in the 1980s: CAT (France [27]); CANGAROO (Japan, Australia [28]); its considerably more efficient modification CANGAROO II (see, e.g., [29]); TACTIC (India [30]); telescopes Mark 1–6 (Great Britain) located in the United States, Australia, and in the Canaries (see, e.g., [31, 32] and references therein); ShALON (Russia [33]); etc. All of these instruments are also regarded as second-generation Cherenkov telescopes and operated in the teraelectronvolt range of primary particle energies.

It is commonly accepted that second-generation instruments allowed specialists to detect teraelectronvolt gamma radiation from cosmic sources reliably. In 1989, the Whipple telescope detected a signal from the Crab nebula with a significance of 9σ [34]. Another prominent result of observations performed using these telescopes is the detection of teraelectronvolt radiation of extragalactic sources (blazars) [26, 35–37]. However, second-generation Cherenkov gamma-ray telescopes managed to discover only about ten gamma-ray sources in their operational lifetime (through to the middle of 1990s). Some of these sources were detected at the limit of sensitivity. It became apparent that more advanced and sensitive detectors need to be designed, and projects focused on constructing Cherenkov gamma-ray telescopes of the third generation were initiated.

2. CURRENT STATE OF CHERENKOV GAMMA-RAY ASTRONOMY

The first Cherenkov gamma-ray telescopes of the third generation (H.E.S.S. [38, 39], MAGIC [40, 41], and VERITAS [42, 43]) were commissioned in 2002–2007. H.E.S.S. and VERITAS are complex stereoscopic systems with larger apertures and high level of image detail. Each system initially contained four telescopes 10–12 m in diameter with cameras that have 10^2–10^3 PMT pixels. MAGIC was an isolated gamma-ray telescope with a mirror diameter of 17 m. At the time of their commissioning, these instruments detected gamma radiation in the range of 0.1–30 TeV. The MAGIC (Roque de los Muchachos Observatory, La Palma, the Canaries) and VERITAS (Fred Lawrence Whipple Observatory, Arizona) observe primarily the northern celestial hemisphere, while H.E.S.S. (Khomas Highland, Namibia) is focused on the Southern Hemisphere. The commissioning of third-generation telescopes was a significant advancement for Cherenkov gamma astronomy: more than 175 cosmic sources of teraelectronvolt radiation have already been discovered.

The projects of third-generation gamma-ray telescopes provided considerable opportunities for enhancement and modification, e.g., H.E.S.S. and VERITAS were expected to include 16 and 7 telescopes, respectively [44]. In recent years, these opportunities are being gradually translated into reality. The MAGIC II telescope [45, 46], which has the same 17-m mirror and a more advanced camera, was commissioned in 2009. This marked the start of stereoscopic observations at the MAGIC observatory. The MAGIC I camera was upgraded in 2012, and the telescopes became technologically identical [47]. This resulted in a considerable increase in sensitivity and a reduction in the threshold observation energy, which is now just 50 GeV [48]. The H.E.S.S. II telescope with an effective mirror diameter of 28 m was commissioned in 2012. As a result, the threshold energy of detection of gamma events was reduced to 20–30 GeV [49].

3. BASIC OBJECTS OF CHERENKOV GAMMA-RAY ASTRONOMY

The following astrophysical objects and phenomena are examined using Cherenkov gamma-ray telescopes.

3.1. Supernova Remnants and Supervoids

Supernova outbursts are associated with the end stages of the evolution of massive stars and the evolution of degenerate dwarf stars in binary stellar systems. The study of supernovae is of fundamental importance for astrophysics, since immense releases of energy, momentum, and synthesized chemical elements have a great effect on stellar formation processes and the evolution of galaxies. The results of observations of type-Ia supernovae have established the accelerated expansion of the universe as fact and contributed to the introduction of hypothetical dark energy into the theory. Supernovae emit electromagnetic radiation in all spectral ranges; the interaction of matter ejected during a supernova outburst with the surrounding interstellar medium may be observed for thousands of years in the form of supernova remnants (SNRs), which are regarded as the most probable sources of galactic cosmic rays. The detection of SNR gamma emission in the megaelectronvolt range by the INTEGRAL space observatory provided an opportunity to estimate the concentration of unstable isotopes (^{44}Ti, ^{56}Co, etc.) in ejected matter. These results were compared to the predictions of current supernova explosion models (see, e.g., [50–52]). The detection of SNR emission with energies in excess of 0.1 GeV by orbital gamma-ray telescopes and with energies higher than 50 GeV by Cherenkov gamma-ray telescopes demonstrated that mechanisms of particle acceleration to energies higher than 10 TeV with an efficiency of conversion of the kinetic ejection energy into CR of ~10% (or higher) are in operation in shell-like SNRs (Tycho's SNR, Cas A, Kepler, etc.). SNRs interacting with molecular clouds (IC 443, W 44, etc.) exhibit high gamma flux densities. In contrast to shell-like SNRs, they are bright in the gigaelectronvolt range, but generally have softer gamma emission spectra. The analysis of emission spectra of these remnants, which were examined at energies lower than 1 GeV by the Fermi and AGILE space telescopes, provided the first conclusive estimate of the role of nucleon gamma emission processes in SNRs. Gamma radiation of the RX J1713-3946 remnant, which was measured by the H.E.S.S. Cherenkov telescope [53] at energies through to 50 TeV, has a spectrum with a photon index of approximately 2. The image of this remnant and its considerably hard index suggest that lepton gamma emission processes (inverse Compton scattering of microwave photons by electrons and positrons, which were accelerated to energies on the order of 100 TeV in the SNR) may play a part here. In order to characterize the contribution of nucleon and lepton SNR emission mechanisms in greater detail, one must accumulate large statistics of detected photons and data regarding the parameters of interstellar medium in the vicinity of the SNR. These data will also provide an opportunity to determine the nature and efficiency of the processes of CR acceleration by shock waves in SNRs (see, e.g., [54–56]).

It was determined in observations that massive progenitors of core-collapse supernovae form in clusters with different stellar densities. Spatial correlation of supernovae is of considerable importance for the evolution of interstellar medium. Supervoids formed by multiple supernova outbursts may serve as sources of relativistic particles and gamma radiation [57–59]. Compact massive stellar clusters, which may turn out to be efficient sources of both gamma radiation and high-energy neutrinos [60, 61], were recently discovered. Observations of these sources with high photon statistics should allow one to determine the nature of nonthermal components in supervoids and compact clusters of young massive stars.

3.2. Gamma-Ray Pulsars

Pulsars are rapidly rotating magnetized neutron stars (compact stellar remnants formed in the process of core collapse of massive stars). Pulsar radiation with its highly stable period originates in the magnetosphere and is observed in all ranges of the electromagnetic spectrum (from radio waves to gamma rays). Even after decades of extensive research, the electrodynamics of pulsar magnetospheres still remains a challenging unsolved problem. This is attributed to the complexity of processes of formation and dynamics of relativistic electron-positron plasma in strong magnetic fields with rapid rotation of a compact star (oblique magnetic rotator) and the effects of general relativity taken into account. The observed pulse shape varies from one energy range to another and may have several peaks. Models of rotation energy conversion and the processes of dissipation of magnetic fields outside the light cylinder, which are associated with effective particle acceleration, may be tested by performing detailed observations of gamma radiation with high photon statistics.

Fermi/LAT observations of gamma radiation of the Crab nebula pulsar in the range of 0.1–20 GeV [62] revealed that the phase-averaged spectrum of this source may be characterized by the following dependence:

$$\frac{dF}{dE} = F_0(E/1\ \mathrm{GeV})^{-\Gamma}\exp(-E/E_\mathrm{c}), \tag{1}$$

where $F_0 = (2.36 \pm 0.06 \pm 0.15) \times 10^{-7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{GeV}^{-1}$, spectral index $\Gamma = 1.97 \pm 0.02 \pm 0.06$, and cutoff energy $E_\mathrm{c} = 5.8 \pm 0.5 \pm 1.2$ GeV. It was found that a large fraction of energy of the detected pulsar gamma radiation is contained in pulse peaks, the overall duration of which may be as large as 20% of the complete pulsar phase.

Cherenkov telescopes may be used to observe these pulsations in the harder part of the gamma-ray spectrum (above 30–50 GeV) [63–68]. Specifically, it follows from the joint analysis of MAGIC [63] and

Fermi/LAT [62] data that the averaged aggregate spectrum of pulses P1 and P2 of the Crab nebula pulsar in the range of 5–100 GeV (in the indicated range, these pulses are found in phase intervals [–0.06; 0.04] and [0.32; 0.43], respectively, where 0 corresponds to the maximum of pulse P1 at the frequency of 1.4 GHz) may be characterized by the following power dependence:

$$\frac{dF}{dE} = F_0(E/10\ \mathrm{GeV})^{-\Gamma}, \tag{2}$$

where $F_0 = (3.0 \pm 0.2) \times 10^{-10}$ cm^{-2} s^{-1} GeV^{-1}, and spectral index $\Gamma = 3.0 \pm 0.1$. In the range of 0.15–1.5 TeV, the spectrum of pulse P2 of the Crab nebula pulsar may also be characterized by a power dependence:

$$\frac{dF}{dE} = F_0(E/150\ \mathrm{GeV})^{-\Gamma}, \tag{3}$$

where $F_0 = (2.0 \pm 0.3) \times 10^{-14}$ cm^{-2} s^{-1} GeV^{-1}, and spectral index $\Gamma = 2.9 \pm 0.2$. The intensity of emission in pulse P2 at 150 GeV is approximately two times higher than that in the primary pulse P1 [67].

3.3. Pulsar Wind Nebulae (Plerions)

Processes that occur in the vicinity of the light cylinder of a rapidly rotating pulsar may result in the acceleration of relativistic wind, which carries away a considerable fraction of the braking energy of a magnetic dipole. Pulsar wind is an anisotropic flux of cold ultrarelativistic particles with Lorentz factors as high as $\sim10^4$–10^6. This flux carries magnetic fields with an energy density exceeding the rest energy density of wind particles. A region of wind dissipation where ultrarelativistic particles undergo acceleration forms in the process of interaction of magnetized pulsar wind with the surrounding medium. The synchrotron radiation of accelerated relativistic electrons and positrons may be detected in a wide range spanning from radio to gamma photons. Inverse Compton scattering of relativistic electrons by various photonic fields (specifically, by the field of microwave and infrared background photons) produces a flux of gamma quanta with energies exceeding 1 GeV. The Crab nebula is the best-known object of this type. At energies below 300 GeV, its emission may be detected both by terrestrial Cherenkov telescopes with a large effective area and by orbital telescopes AGILE and Fermi/LAT. In the range of 0.1–100 GeV, the spectrum of emission of the Crab nebula is characterized well by a combination of two power laws that correspond to the above radiation production mechanisms [62]. Since the Crab nebula is a bright and relatively stable source emitting throughout the entire electromagnetic spectrum, it was used to calibrate the detectors of numerous telescopes. This makes the recent discovery (made by AGILE and Fermi/LAT) of immense gamma-ray flares in the Crab nebula at energies ranging from 100 MeV to several gigaelectronvolts all the more important [69]. No matching variations of the Crab nebula radiation flux in the other spectral ranges have been found yet. This imposes stringent constraints on the models of gamma-ray flares in the Crab nebula and the theories of formation of its emission spectrum. Gamma-ray flares in the Crab nebula may be interpreted as synchrotron radiation of shock-accelerated electrons in strongly fluctuating magnetic fields (see the model proposed by Bykov et al. in [70]).

The systematic search for pulsars and pulsar wind nebulae conducted with terrestrial gamma-ray telescopes has resulted (as of June 2016) in the detection of more than 30 plerions. This is one of the largest populations of observable teraelectronvolt sources in the Galaxy. Modern Cherenkov telescopes are involved in observations of objects of this type at energies higher than several tens of gigaelectronvolts [71–74].

Specifically, H.E.S.S. observations of the Vela X region with the Vela pulsar wind nebula revealed the presence of an extended (more than a degree in size) gamma-ray source, which has a hard spectrum with a photon index of approximately 1.3 at energies below 10 TeV. This spectrum does not get softer toward the source edges [73]. The gamma-ray source is several times larger than the X-ray nebula and resembles much more closely (in its positioning and size) the larger-scale radio nebula around the Vela pulsar. The existing models of emission of this object do not reproduce correctly the spectral and morphological parameters of the Vela X gamma-ray source. New-generation Cherenkov telescopes with increased sensitivity and resolution will provide more accurate data on the observable parameters of teraelectronvolt radiation of pulsar wind nebulae (specifically, it will allow observers to measure spatially resolved gamma-ray spectra, which will be used to refine the models of the production and propagation of accelerated particles within these objects). An increase in sensitivity should also result in the detection of gamma emission of extragalactic pulsar wind nebulae. Only one object of this kind has been discovered to date, i.e., energetic gamma nebula N157B in the Large Magellanic Cloud [74].

3.4. Galactic Microquasars

Microquasars are binary systems with a compact object (black hole or neutron star) accreting matter from its stellar companion. This accretion produces high-velocity outflows (jets). The study of these objects is crucial for understanding the physics of accretion and relativistic outflows. In addition, microquasars may feature prominently in the process of reionization of the universe (ionization of interstellar gas in the epochs that correspond to cosmological redshift $6 < z < 30$). Gigaelectronvolt and teraelectronvolt radiation of several microquasars has already been detected [75–78].

3.5. Active Galactic Nuclei

Active galactic nuclei (AGN) are systems associated with supermassive black holes at the centers of galaxies. Enormous energy releases are typical of these objects (see, e.g., [79]). It is assumed that their emission is produced by the accretion of matter to supermassive black holes. Detailed measurements of AGN spectra in the gamma range are needed in order to construct quantitative models of physical processes that occur within these sources. Cherenkov gamma-ray telescopes are actively involved in AGN observations (see, e.g., [80, 81]). Although these observations often provide only the upper limits on radiation fluxes in the range above 0.1 TeV [82], this result is significant in itself, since these limits allow theorists to place constraints on the models of particle acceleration and AGN gamma emission. For example, H.E.S.S. observations demonstrated that the central engine of our Galaxy (supermassive black hole Sagittarius A*) may accelerate particles to energies on the order of 1000 TeV [83]. The origin of these particles, which are observed in the terrestrial atmosphere as galactic CR, is one of the unsolved current problems of high-energy astrophysics.

3.6. Gamma-Ray Bursts

Gamma-ray bursts are gamma-ray flares that are apparently associated with massive supernova explosions or mergers of degenerate stars. Gamma-ray bursts rank among the brightest events in the universe. Their duration varies from 10 ms to several minutes [84]. The initial burst of gamma rays is normally followed by more extended emission at lower frequencies. Although the studies into gamma-ray bursts performed over the last years have advanced considerably our understanding of these objects [85], their nature still remains uncertain. Gamma-ray bursts and their afterglow are observed at all wavelengths from radio waves to the gamma range. However, satellite observations of the hardest part of the spectrum (above 1 GeV) are scarce due to the fact that orbital telescopes do not have the needed sensitivity (the effective area of Fermi/LAT in this range is smaller than 1 m^2 [86]). Modern terrestrial Cherenkov telescopes do not detect gamma-ray bursts, since the observation time is limited to several tens of seconds, and the emission of these events fades considerably at energies higher than several tens of gigaelectronvolts. However, several attempts at detecting gamma-ray bursts (with orbital X-ray and gamma-ray telescopes used as triggers) with Cherenkov telescopes have been made over the last decade. As a result, upper limits on gamma radiation fluxes associated with these bursts were set in the range above several hundred gigaelectronvolts [87–89]. For example, an upper limit (at the 95% confidence level) of 4.2×10^{-12} photons cm^{-2} s^{-1} for the total flux at energies exceeding 380 GeV was obtained in [87] for an exceptionally X-ray-bright gamma-ray burst GRB 100621A. These measurements provided an opportunity to constrain (at the same confidence level) the ratio of GRB 100621A luminosities in the X-ray and gamma ranges: $L_X/L_{VHE} > 0.4$, where L_X is the overall luminosity at 0.3–10 keV, and L_{VHE} is an overall luminosity in the 0.38–100 TeV range. This ratio is crucial for modeling the afterglow of gamma-ray bursts and may constrain models that rely on the assumption that leptons, which produce X-ray emission of a burst, may also be involved in the generation of superhigh-energy gamma radiation. Physical models of gamma-ray bursts are based on the idea of the efficient conversion of power of relativistic flows of magnetized plasma, which is produced in the process of stellar collapse to a rotating black hole, into electromagnetic radiation [90]. It should be noted that observations of the most energetic radiation of gamma-ray bursts are exceptionally important, since they probe directly into the processes of energy conversion in the central engine of a burst and, thus, help define the nature of these sources.

3.7. Search for Dark Matter

The clarification of the nature of dark matter is set to be one of the most important advances in modern physics and astrophysics. Several hypotheses regarding the nature of dark matter may be tested using terrestrial gamma-ray telescopes. For example, these telescopes may detect gamma radiation, which accompanies the decay of hypothetical exotic dark matter particles that were produced in the early universe [91]. Gamma radiation may also be produced in the process of annihilation of weakly interacting massive particles (WIMPs) in the Galaxy halo. Evidence that indicates a connection between diffuse gamma emission in a narrow line toward the center of the galaxy or the Coma cluster and annihilation of light supersymmetric WIMPs was discussed in several papers (see, e.g., [92, 93]). Cherenkov gamma-ray telescopes are now actively searching for gamma radiation from the hypothetical process of the annihilation of dark matter particles in dwarf galaxy haloes [94–96]. These observations were used to set the upper limit on the cross section of this process. For example, H.E.S.S. observations of a number of dwarf galaxies [94] resulted in the determination of the following maximum possible annihilation rate of WIMPs with masses in the range of 1–2 TeV: 3.9×10^{-24} cm^3 s^{-1} (at the 95% confidence level). The upper limits on annihilation rates of WIMPs with masses in the range of 10 GeV to 100 TeV were set for various channels of these reactions after the joint analysis of observational data on 15 dwarf galaxies (examined by Fermi/LAT) and galaxy Segue 1, which was observed by the MAGIC Cherenkov gamma-ray observatory [95]. The typical upper limits (95% confidence) obtained vary from 10^{-26}–10^{-25} cm^3 s^{-1} (depending on the channel) for WIMPs with a mass of 10 GeV to 10^{-22}–10^{-21} $cm^3 s^{-1}$ (depending on the channel) for WIMPs with a mass of ~100 TeV. In addition to dark matter research, observations of gamma radiation of galaxy clusters and upper limits on fluxes of such radiation prove useful in determining the role of nonthermal components in the evolution of these objects [97].

3.8. Determination of Parameters of Extragalactic Infrared Background and the Search for Axion-Like Particles

Gamma radiation from distant sources is absorbed strongly as it propagates through extragalactic background radiation [98]. Infrared background photons are the primary target for gamma photons. Their interaction results in the production of electron–positron pairs, and the energy of gamma radiation decreases, thus falling out of the range of sensitivity of terrestrial Cherenkov telescopes. The systematic contribution of zodiacal light and the emission of our Galaxy makes it rather hard to estimate diffuse extragalactic infrared background directly from observational data. Therefore, the observations of high-energy photons of the teraelectronvolt range from distance sources were used to obtain rough upper estimates for the extragalactic infrared background (see, e.g., [99]). These estimates are inherently based on certain assumptions regarding the nature of radiation in the source; thus, they may be regarded as qualitative estimates, but not as accurate quantitative estimates. It was found that these upper estimates for the diffuse infrared background are almost the same as (or even lower than; see, e.g., [100]) the lower estimates derived from calculations of the radiation density from visible galaxies. This discrepancy between the absorption of gamma radiation and theoretical models of the infrared background initiated the reexamination of theoretical lower limits and was termed the infrared-TeV crisis [101]. However, it follows from an analysis of an ensemble of distant sources [102, 103] that even the minimal models yield nonphysical distance-dependent effects in reconstructed (with absorption factored in) spectra of sources. This suggests that the universe is anomalously transparent to high-energy gamma radiation. Several scenarios [104–106] were proposed in order to explain this effect. In these scenarios, photons mix with axion-like particles, which are hypothetical pseudoscalar particles that interact with photons in the same manner as axions do (see for example, [107]). Further observations of gamma-bright galactic nuclei (blazars), including the most distant sources, in the range of 10–100 GeV [108] are required in order to validate these scenarios and choose the most relevant one. These observations are within the capacity of low-threshold Cherenkov gamma-ray telescopes.

3.9. Galactic Center

Having processed H.E.S.S. observations, the authors of [83] concluded that particles may be accelerated to energies on the order of 10^{15} eV in the vicinity of the Galactic center (central supermassive black hole Sagittarius A*). This is evidenced by the nature of the gamma radiation spectrum, which does not drop through to 100 TeV. The search for galactic sources of CR particles with energies near and above 10^{15} eV, which are observed in the CR spectrum, is one of the current unsolved problems of high-energy astrophysics.

The TeVCat catalogue [109] is the most comprehensive database of galactic and extragalactic sources detected by Cherenkov gamma-ray telescopes at energies above 0.1 TeV. As of June 2016, it contained 176 such sources. In addition to the above-mentioned direct observations of cosmic gamma-ray sources and independent determination of extragalactic background radiation (see, e.g., [110]), Cherenkov gamma-ray telescopes may perform tasks such as determining the intensity of the high-energy electron and CR ion background (see, e.g., [111]), validating quantum gravity models (see, e.g., [66, 112, 113]), etc.

4. PROSPECTS FOR THE FURTHER DEVELOPMENT OF CHERENKOV GAMMA ASTRONOMY

Although gamma-ray astronomy has enjoyed rapid progress in the last decades, certain relevant problems, which seem to be theoretically solvable by observations with Cherenkov gamma-ray telescopes, still remain unsettled. Even the most advanced third-generation systems, such as H.E.S.S. II and MAGIC II, do not have the capacity to solve these problems. Specifically, only the upper limits on gamma radiation fluxes are known for many cosmic sources, while the very presence of a considerable gamma flux coming from them is almost beyond doubt [82, 87–89]. This suggests the need to construct more powerful fourth-generation Cherenkov gamma-ray telescopes.

The insufficient sensitivity of telescopes is the most important problem of Cherenkov gamma astronomy. The international Cherenkov Telescope Array (CTA) project with 32 participating countries [114] is aimed at solving this problem. The current version of this project [114, 115] implies the construction of two gamma-ray observatories, i.e., a southern one in the Atacama desert of Chile and a northern one in La Palma in the Canary Islands, Spain. Three types of telescopes should be designed for CTA, i.e., large (with a mirror diameter of 23 m, a sensitivity range of 20–200 GeV, and a field of view of approximately 4.5°), medium (12 m, 0.1–10 TeV, and ~7°), and small (4 m, 3–300 TeV, and ~10°). The southern observatory will have four large, 24–40 medium, and 72 small telescopes distributed over an area of 4 km^2. The northern observatory will have four large and 15 medium telescopes covering an area of 0.4 km^2. This arrangement of a large number of telescopes distributed over a considerable area will grant record-high values of the effective detection area and sensitivity at primary gamma quanta energies that exceed 100 GeV.

The insufficiently low detection energy threshold is another problem of Cherenkov gamma astronomy. In the ideal case, this energy should be as low as 2–3 GeV, which is the theoretical threshold of Cherenkov telescopes. No instruments for proper observations of cosmic gamma-ray sources in the range of 5–30 GeV are currently available: the apertures of orbital gamma-ray telescopes are too small (~1 m^2), and the existing ground-based telescopes do not have the sensitivity required to detect weak Cherenkov flashes produced by primary quanta with the indicated energy. Thus, the observation ranges of orbital and terrestrial instruments do not overlap securely even in the case of relatively long-term observations of steady sources of cosmic gamma radiation. At the same time, the measurement of spectra of cosmic gamma-ray sources in a wide energy range (0.1–1000 GeV) is crucially important for the reasons stated below.

Certain types of cosmic gamma-ray sources demonstrate considerable variability of spectral properties in the range of 1–30 GeV. Specifically, the results of observations of pulsars suggest that their radiation flux decays exponentially in the range of 1–10 GeV (see, e.g., [62]). This decay may be characterized by formula (1) and agrees with the predictions of models of inner (see, e.g., [116]) and outer (see, e.g., [117]) gaps as the regions of particle acceleration and gamma radiation production in the magnetosphere of the pulsar in the Crab nebula. At the same time, the modeling of data from [62] with a superexponential spectrum [$\sim\exp\{-(E/E_c)^b\}$, $b > 1$] yielded $b = 0.89 \pm 0.12 \pm 0.28$ and excluded the value of $b = 2$ with a statistical significance of 4.9σ, which practically confirms the inapplicability of a superexponentially decaying function proposed in [118] to the observed spectrum.

It seemed that the authors of [62] had resolved the issue of the shape of the spectrum f the pulsar in the Crab nebula. However, recent observations of this pulsar with the MAGIC Cherenkov gamma-ray telescope [63] suggest the presence of a considerable radiation flux at energies in the range of 25 GeV to ~1.5 TeV [67]. This was not predicted by any model available at the time and baffled theorists. As a result, standard pulsar emission models were modified [63]. It should be noted that Fermi/LAT and MAGIC observations of even a bright object like the Crab nebula pulsar contain relatively large experimental errors in the range of 10–30 GeV, which is attributed to the reduction in sensitivity of both instruments in this range. For example, these errors manifest in the fact that the spectral index ($\Gamma_{25} = 3.4 \pm 0.5 \pm 0.3$) of the overall spectrum (P1 + P2) determined by MAGIC in the range of 25–100 GeV differs somewhat from spectral index $\Gamma_{10} = 3.0 \pm 0.1$, which was determined by the joint analysis of Fermi/LAT and MAGIC data and was used in formula (2).

It was demonstrated in [62, 63] that detailed and accurate measurements of pulsar spectra in the range of 5–30 GeV are critical for choosing the right model of particle acceleration and pulsar emission generation. These measurements require expanding the technical capabilities of gamma astronomy in the indicated range (specifically, commissioning new terrestrial Cherenkov gamma-ray observatories with low observation energy thresholds).

Other issues related to pulsars may also be resolved using Cherenkov gamma-ray observatories with low observation energy thresholds. It is expected that pulsar radiation beams in the gamma range are considerably wider than those in the radio range, and these beams do not necessarily overlap [119]. Therefore, the chances of detection of rapidly rotating neutron stars in the gamma range are higher. This may also explain the presence of unidentified gamma-ray sources in the EGRET and Fermi catalogues; it is assumed that a considerable fraction of these sources are radio-quiet neutron stars (see, e.g., [120]). The observation of pulsed emission of these objects at energies above 5 GeV by Cherenkov telescopes with their increased detection area will be a direct and indisputable proof of the validity of this hypothesis [121]. It should be noted that the model of polar caps and the outer gap model predict substantially different fractions of radio-quiet neutron stars [122]. Thus, if Cherenkov gamma-ray observatories with low observation energy thresholds could conduct a sufficiently accurate measurement of the fraction of these objects in the entire sample of observed pulsars, the result would be an additional argument in choosing the right model of generation of radiation by rapidly rotating neutron stars [121].

Further complications arise in observations of rapidly variable and burst gamma-ray sources, e.g., gamma-ray bursts [87–89]. The time of observation of these sources is limited not only by the technical capabilities of a gamma-ray observatory, but also by the specifics of emission mechanisms. The gamma radiation fluxes from such sources decrease considerably as the detected photon energy increases; therefore, it is reasonable to examine them in the range of 5–30 GeV, where the expected gamma radiation fluxes are much higher than those in the range of 30–50 GeV, which is accessible for current Cherenkov telescopes.

Gamma radiation from several microquasars has been detected both in gigaelectronvolt and teraelectronvolt ranges [123]. However, since the intermediate range of 10–100 GeV has not been examined, the mechanism of generation of this radiation remains unclear.

Cherenkov telescope systems with large mirrors (25–30 m in diameter) located at a considerable altitude above the sea level (at least 4 km) are needed in order to detect the above-mentioned sources efficiently in the range of 5–30 GeV (see, e.g., [7]). The detectors of these telescopes should have a higher photon detection efficiency than the detectors of current telescopes, which use traditional vacuum PMTs. This enhancement of parameters of Cherenkov telescopes will be aimed not so much at raising their sensitivity in the range of 0.1–100 TeV, which is the typical range for high-energy gamma astronomy, as at reducing the threshold observation energy to 3–5 GeV.

The MACE project, which consists of constructing a telescope with a 21-m mirror at an altitude of 4200 m [124–126] at the Indian Astronomical Observatory site at Hanle (Ladakh, India), is one of the projects aimed at reducing the threshold observation energy. The telescope has been operational since 2016. At the second stage of this project, another telescope with similar characteristics will be installed (presumably in 2018) at the same site. However, even if this stereoscopic gamma-ray observatory will indeed become operational, its threshold energy will be no lower than 20 GeV. Therefore, MACE will not reach energies close to the theoretical limit of 2–3 GeV.

It should be noted that attempts to construct a low-threshold (~10 GeV) Cherenkov telescope have already been made by the Solar One Gamma Ray Observatory project team [127]. This project was renamed CACTUS and carried out later at the Solar Two power plant site, but the threshold energy was reduced to just ~50 GeV [128].

5. ALEGRO GAMMA-RAY OBSERVATORY PROJECT

The ALEGRO (Atmospheric Low Energy Gamma-Ray Observatory) project developed at the Ioffe Institute is aimed at examining the important and insufficiently studied gamma range of 5–30 GeV. The energy threshold of this instrument (~5 GeV) will be much lower than that of the existing Cherenkov telescopes. This should help reveal several significant spectral features of stationary gamma-ray sources (specifically, the exponential drop in pulsar spectra in the range of 1–10 GeV) and investigate rapidly variable gamma radiation of GRB sources and active galactic nuclei with a sensitivity and time resolution that considerably exceed the parameters of existing gamma-ray observatories. The following approaches are planned for achieving these goals.

1. The ALEGRO observatory will be located at an altitude of 4–5 km above sea level. Two potential sites are now under consideration. The first site (Fig. 1a) is in the Atacama desert (Chile, Argentina) at an altitude of 4.7–5.3 km. This region has a unique astronomical climate. Due to the recent construction of the LLAMA radio telescope, it also offers well-developed infrastructure, which provides an opportunity to save funds. The second scenario (Elbrus Gamma-ray Observatory, EGO), which was developed in collaboration with the Institute for Nuclear Research, involves constructing telescopes at an altitude of 3.7 km in the vicinity of Mt. Elbrus (10 km away from Terskol; see Fig. 1b). The most important thing is that the surface density of Cherenkov photons (SDCP) at such altitudes is approximately two times higher than the corresponding density at an altitude of ~2 km (Fig. 2) where H.E.S.S. and MAGIC telescopes are located. Under otherwise equal conditions, this alone makes the detection of EASs at an altitude of approximately 5 km significantly more efficient.

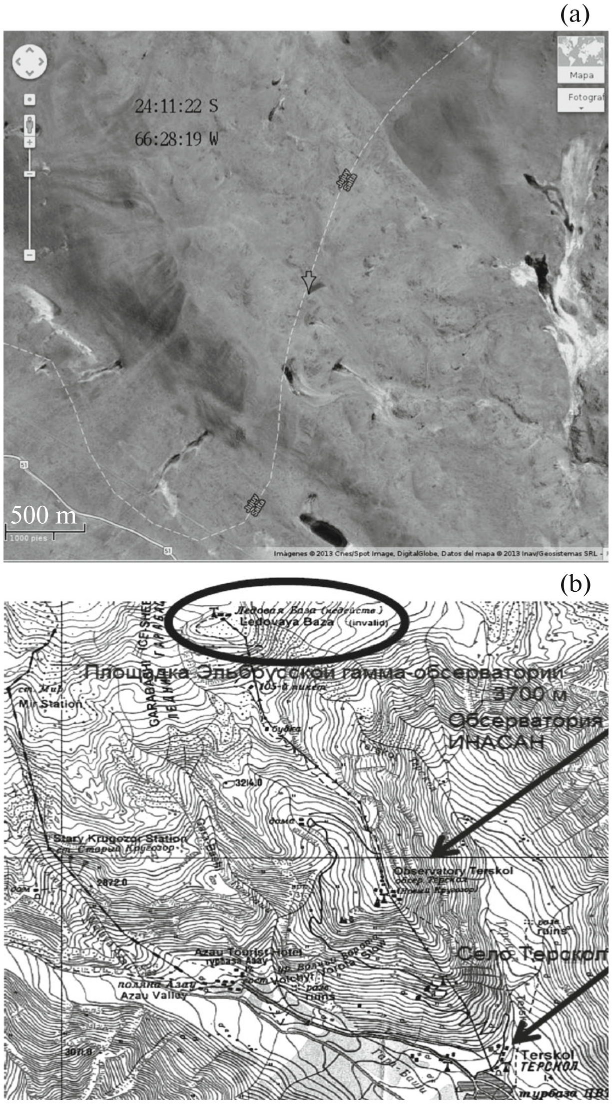

Fig. 1. Maps of potential sites for the ALEGRO Cherenkov gamma-ray observatory: (a) site in the Atacama desert (Argentina) and (b) site in the vicinity of Mt. Elbrus.

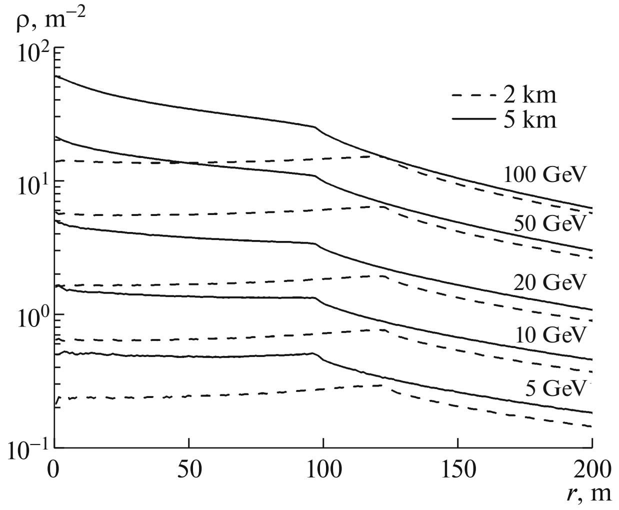

Fig. 2. Dependences of the average surface density of Cherenkov photons (SDCP) on the distance to the axis of an extensive air shower (EAS) for different energies of primary gamma quanta (indicated next to the curves) and observation altitudes.

2. Multipixel Geiger-mode avalanche photodiodes (MGAPDs), which are also known as silicon photomultipliers (see, e.g., [129]), will be used in the ALEGRO telescopes instead of traditional high-voltage PMTs. Internal noise-free signal amplification by several orders of magnitude, which is induced by an electron-hole avalanche initiated by an optical photon entering a detector, makes MGAPDs capable of efficient detection of individual Cherenkov photons. A multipixel detector is basically a large set of microcells connected in parallel; if several photons hit the detector simultaneously, each photon produces an avalanche in just a single cell, and the electric signal at the output is proportional to the number of triggered cells. Numerical modeling allows one to estimate the SDCP at a primary gamma quanta energy of approximately 5 GeV (see, e.g., [7, 130]). The obtained estimate demonstrates that MGAPDs used as Cherenkov radiation detectors may indeed guarantee efficient operation of terrestrial gamma-ray telescopes at the indicated low energies of primary particles. The major advantage of MGAPDs over traditional vacuum PMTs is their capacity to perform observations during moonlit nights, which translates into an increase in the exposure time, and high quantum efficiency (30–40% instead of 10–20%; see, e.g., [131, 132]). In addition, MGAPDs are easier to use and require much lower electric voltage and power. This translates into a considerable reduction in the detector weight and relaxes the requirements imposed on mechanical systems that secure the detector in the mirror focus and rotate the entire structure (detector and mirror). The only significant drawback of silicon photomultipliers is the temperature sensitivity of operating voltage, which necessitates the use of a feedback system with thermal sensors. It should be noted that this feedback technology has been tested already at the prototype Cherenkov FACT telescope [133] and was proven efficient.

3. In order to detect as many Cherenkov photons as possible, mirrors of the 30-m class made from separate segments will be used in the ALEGRO telescopes (see, e.g., [7]). Although this complex will have a considerable size, the time needed to point it at the studied region of the sky will remain in the range of 20–40 s. The majority of existing Cherenkov telescopes are fitted with 12–17-m mirrors, which detect three to six times fewer photons.

4. Four ALEGRO telescopes will be set up on railroad mounts (in much the same fashion as the VLA telescopes [134]). If it is found that local topography makes it impossible to construct railroad tracks, all (or several) telescopes may be mounted on automobile chassis; BELAZ series 7530–7560 with a payload capacity of 220–360 t is a candidate drive truck in this case. A major advantage of the simultaneous use of several telescopes is the capacity to observe the same atmospheric avalanche from several directions. This allows one to reconstruct accurately the avalanche geometry and distinguish atmospheric showers caused by gamma quanta from background events induced by cosmic rays. The sensitivity of an array of Cherenkov telescopes is an order of magnitude higher than that of a single telescope; in addition, an array features a lower energy threshold and better angular and energy resolutions. The H.E.S.S. and VERITAS gamma-ray telescopes have a similar array structure, but fixed observation positions. Railroad or automobile chassis will grant the ALEGRO observatory the possibility to alter is spatial configuration and adapt to specific tasks. The accuracy of mutual positioning will be guaranteed by local distance sensors. Proprietary software will be developed for processing and analyzing the ALEGRO observational data. In the process of development, special attention will be paid to the accuracy and efficiency of analyzing algorithms in the range of primary particle energies of 5–50 GeV.

It should be noted that the estimated cost of the ALEGRO project in the above configuration is more than an order of magnitude lower than the cost of the Fermi orbital gamma-ray telescope (approximately 700 million in 2008 dollars; see, e.g., [135]).

6. MODELING THE PARAMETERS OF THE ALEGRO GAMMA-RAY OBSERVATORY

Cherenkov flashes in extensive air showers induced by cosmic gamma quanta are being modeled at the Ioffe Institute since 2012. Flash images produced by telescopes are modeled, algorithms for fast image processing are developed, and accompanying atmospheric events influencing the process of observations are studied. A specialized software package

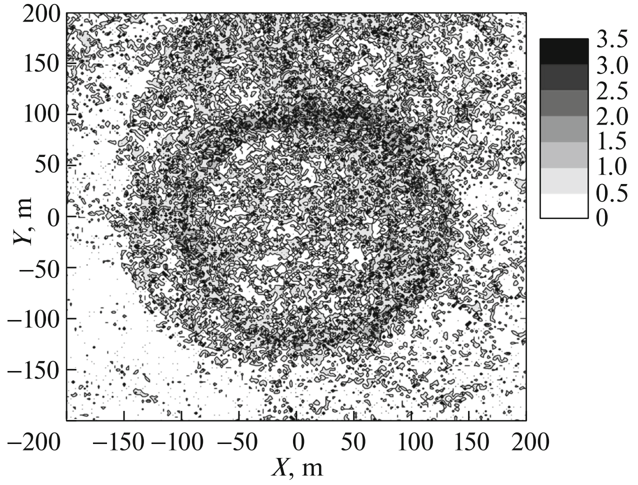

Fig. 3. Distribution of the surface density (integrated over the spectrum) of photons of a Cherenkov flash, which was induced by a gamma quantum with an energy of 5 GeV, at an observation altitude of 5 km. Color scale represents SDCP values expressed in photons/m^2.

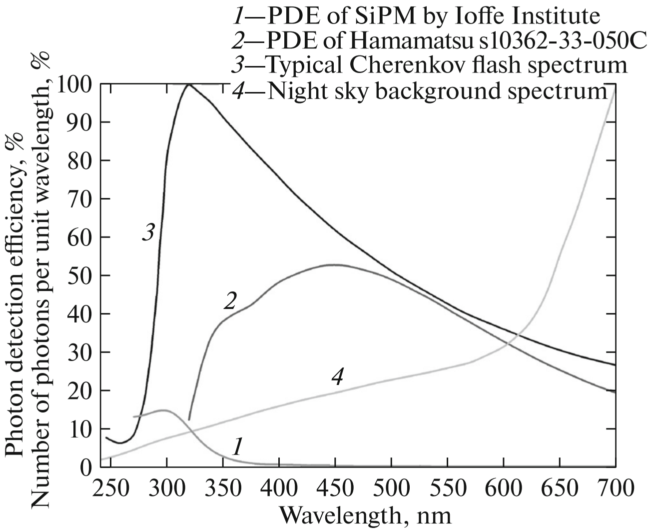

Fig. 4. Model spectrum of Cherenkov radiation of an extensive air shower (normalized to 100% at the maximum at a wavelength of 320 nm), which was induced by a gamma-ray event in the atmosphere of the Earth, at an altitude of 5 km above sea level (curve *3*); background night sky spectrum normalized to 100% at a wavelength of 700 nm (curve *4*; calculations are based on the data from [138, 139]); sensitivity curves of MGAPDs produced by Hamamatsu (curve *2*, [140]) and the Ioffe Institute (curve *1*).

(ALEGRO Soft) to analyze the observational data of the future observatory is under development. The following results have already been obtained.

1. A proprietary code for EAS modeling was developed using the GEANT library package for simulating elementary nuclear-physical processes [136]. It should be noted that this new software package has several advantages over the CORSIKA code [137], which is the one used most often to model EASs. For example, ALEGRO Soft allows a user without detailed knowledge of the code to modify calculations and set different atmospheric parameters (temperature, density, ozone and pollutant concentrations, magnitude and direction of the magnetic field of the Earth, etc.), is based on state-of-the-art models of nuclear interactions (as a part of the GEANT project, they are updated regularly), etc. One of the most significant differences between ALEGRO Soft and CORSIKA consists of the fact that photons with close wave vectors are not grouped into bunches for joint processing in ALEGRO Soft: trajectories are calculated individually for each photon. This is important, since photon bunching results in a considerable distortion of images of the modeled Cherenkov flashes at primary particle energies below 30 GeV. The indicated advantages make it possible to use ALEGRO Soft calculations to justify the relevance and feasibility of a fourth-generation terrestrial gamma-ray observatory and outline a plan for it. Since CORSIKA is the code used most often to model EASs and the results of CORSIKA calculations are recognized by the scientific community and used to analyze observational data provided by terrestrial gamma-ray telescopes of the second and third generations, the results of modeling a set of test problems with ALEGRO Soft were compared to those obtained with CORSIKA. It was found that the maximum difference between the obtained average SDCP values does not exceed 0.5 standard deviations. In view of the difference in the used numerical methods, this provides evidence of a fine agreement between ALEGRO Soft and CORSIKA applied to test problems at energies above 30–50 GeV.

The results of applying ALEGRO Soft are presented in Fig. 3, where the surface density of Cherenkov photons from an EAS, which was induced by a vertically incident gamma quantum with an energy of 5 GeV, is shown as a function of coordinates at an observation altitude of 5 km. The model spectrum of a Cherenkov flash is shown in Fig. 4 alongside the background spectrum of night sky and the sensitivity curves of MGAPDs produced by Hamamatsu and the Ioffe Institute.

2. A proprietary code for modeling the optical system of the ALEGRO telescope (with the specifics of telescope positioning at the site taken into account) was developed. This code allows one to alter the telescope parameters (mirror diameter, focal distance, etc.).

3. An algorithm and a numerical code for removing optical photons of the night sky background from the images formed at the focal planes of the ALEGRO telescopes were developed. Figure 5 presents the results of modeling and processing model observational data. For illustrative purposes, the focal-plane image of the initial Cherenkov flash from Fig. 3 with-

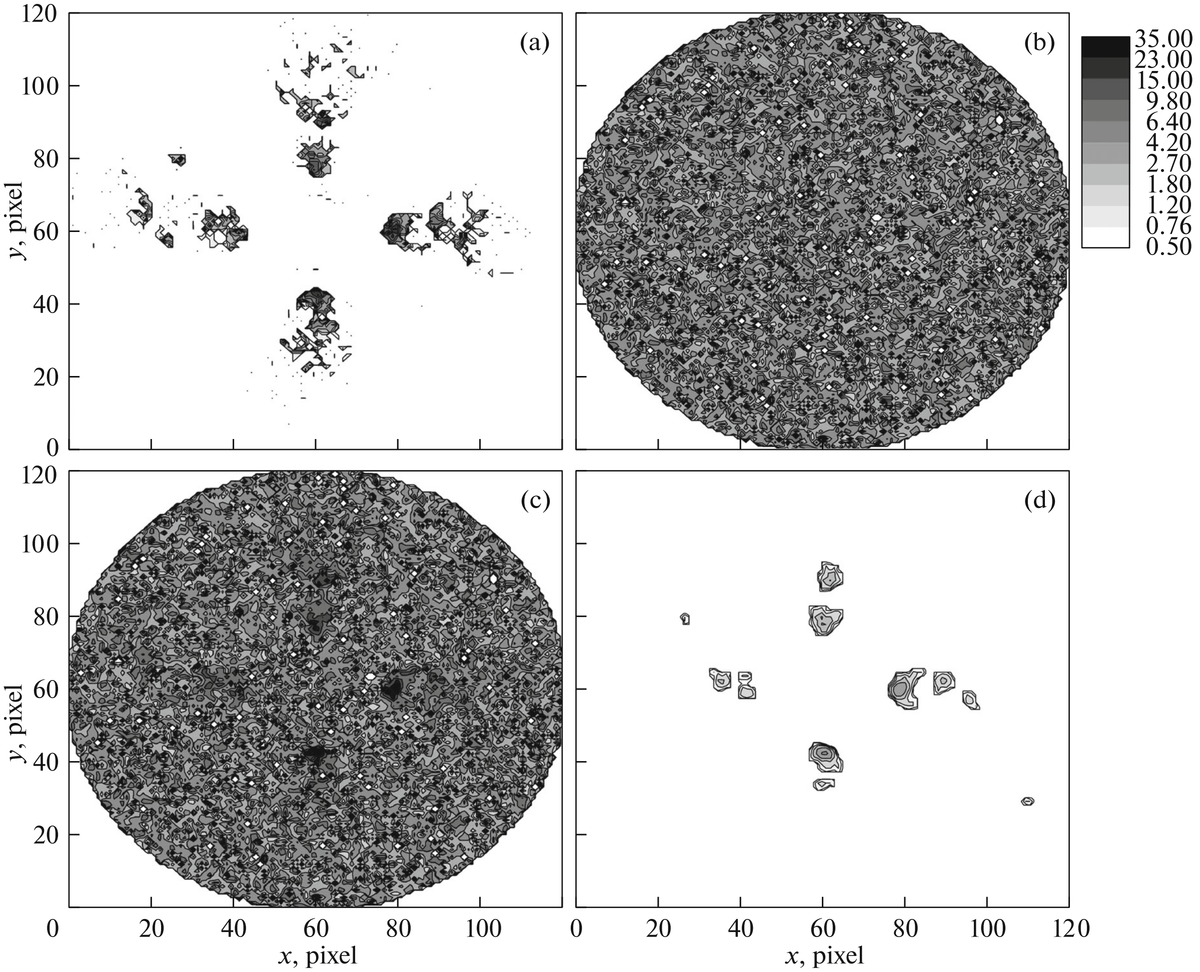

Fig. 5. Images at focal planes of telescopes (for convenience, the focal planes of all telescopes are shown in one image): (a) Cherenkov flash produced in the interaction of a 5-GeV gamma quantum with the atmosphere; (b) optical night sky background; (c) images (a) and (b) combined; (d) image (c) after filtering. Maximum intensities are (a) 30 photons/pixel, (b) 18 photons/pixel, (c) 35 photons/pixel, and (d) 5 units/pixel. Color scale to the right of image (b) is valid for all images.

out any optical background is shown in Fig. 5a. Figure 5b presents the optical night sky background imaged with an exposure of 10 ns for a flux of 4.6 × 10^{12} photons m^{-2} s^{-1} $ster^{-1}$ [138]. The combined image, i.e., a model of an actual optical signal arriving at the photodetector unit, is shown in Fig. 5c. Figure 5d presents the end result of processing simulated noisy data. The modeled detecting system was formed by four identical telescopes with parabolic mirrors with a diameter of 30 m, a focal distance of 46.9 m, and a field of view of 2.9°. These telescopes were assumed to be located at points with coordinates (100 m, 0 m); (0 m, 100 m); (–100 m, 0 m); (0 m, –100 m) at an altitude of 5 km above sea level. The surface of the optical detector unit was modeled as a circular region 1.2 m in diameter that is broken down into 11 310 pixels (a single pixel is a square with a side of 1 cm).

The pixel illumination intensity, which defines the brightness of pixels in Figs. 5a–5c, is the positive whole number of photons striking a pixel within a time interval with a typical duration of 10 ns. The photon detection efficiency was modeled as a random variable with a normal distribution with its parameters being 0.30 ± 0.07 electrons/photon. The difference in dimension and magnitude of values in Figs. 5c and 5d is attributed to the inclusion of photon detection efficiency and the specifics of mathematical signal processing in accordance with the developed algorithm. Thus, Fig. 5 illustrates the feasibility of reliable detection of gamma quanta with an energy of ~5 GeV by terrestrial Cherenkov gamma-ray observatories. The expected angular resolution at 5 GeV is 0.3°–0.4° (depending on the event selection criteria; see Fig. 6). This value is sufficient to resolve variable gamma-ray sources in the range of ~5 GeV. The measurement of light curves of variable gamma-ray sources in this range is one of the major goals of ALEGRO.

4. An original code for determining the Hillas parameters of a Cherenkov flash was developed. It allows one to determine the direction of arrival of the

primary particle in each specific case and estimate the parameters of the gamma-ray observatory (angular and energy resolution) by conducting a series of numerical experiments on reconstructing the characteristics of primary particles.

The developed modules of the ALEGRO Soft package for EAS modeling and observational data processing were used to clarify several issues that have arisen in the design of the new-generation terrestrial gamma-ray observatory with a 5-GeV threshold; the presence of a heavy tail in the SDCP distribution, i.e., the lack of a finite SDCP mean-square deviation in the region of the EAS axis, at low energies of primary gamma quanta [130] was demonstrated; the effect of the optical night sky background on the capacity of a fourth-generation Cherenkov telescope to detect cosmic gamma quanta with energies below 10 GeV and observed gamma-ray flares [141] was estimated; and the feasibility of this detection was demonstrated.

The efficiency of the developed technique for determining the characteristics of primary particles (and the ALEGRO Soft package based on this technique) was estimated by numerical modeling of the extensive air showers produced by particles with set parameters. This modeling was performed using the simulating part of the package, and the characteristics of primary particles (particle type, energy, and direction of arrival) were the reconstructed using the analytical part. More than 70 000 numerical experiments were conducted in the range of 5–100 GeV. The obtained results demonstrate that the developed technique and the code package on its basis should be an efficient instrument for processing the observational data of terrestrial Cherenkov gamma-ray observatories and be on par with (or, at low energies in the range of 5–30 GeV, even better than) other known methods and codes designed for processing these data. An example that illustrates observational data processing with ALEGRO Soft is presented in Fig. 7. The obtained results suggest that an angular resolution of approximately 0.16° may be achieved in observations of fairly bright cosmic gamma-ray sources at energies near 20 GeV (if the design of the terrestrial Cherenkov gamma-ray telescope itself is adequate). This resolution is approximately 1.5 times better than the values determined by modeling in other planned projects. For example, the expected resolution of CTA is worse than 0.25° at energies below 25 GeV [114], and the resolution of 5@5 is approximately 0.24° at an energy of 20 GeV [7]. The indicated ALEGRO resolution may be achieved if fairly stringent image selection criteria are set: in the case under consideration, only about 8% of images were selected for analysis. Although the majority of images are then disregarded in the process of mapping the studied celestial sphere region and determining the angular coordinates of the source, the absolute number of processed events from gamma quanta with an energy of 20 GeV will be greater than, e.g., the overall number of events from gamma quanta with an energy of 100 GeV. This suggests that a considerable statistical significance may be achieved within a reasonable observation time even when stringent selection criteria (with more than 90% of images rejected) are used. It should be noted that different selection criteria may be set for measuring other parameters (specifically spectral ones) of the gamma-ray source. As a result, the fraction of images used in analysis may be increased (even to 100%). Model curves of the angular resolution of the ALEGRO observatory for different observation conditions are shown in Fig. 6. The CTA angular resolution curve [114] corresponding to observations of weak sources (i.e., the case of sensitivity optimization) is shown in the same figure for comparison.

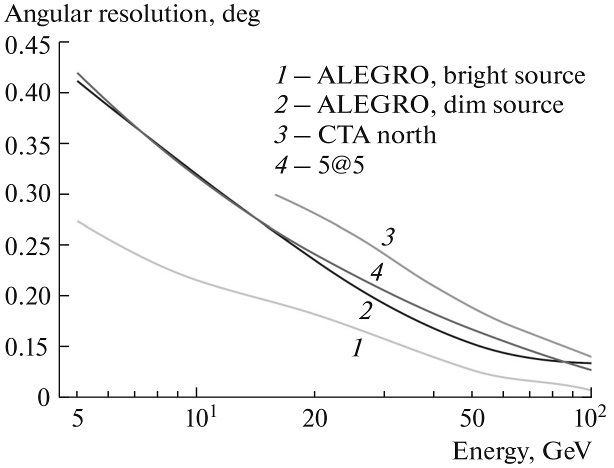

Fig. 6. Model angular resolution of the ALEGRO, CTA, and 5@5 observatories. Curve *2* corresponds to the ALEGRO resolution in observations of weak sources (calculations were performed with the parameters used in [7] for 5@5), while curve *1* represents the resolution in observations of relatively bright sources, which may be isolated by applying stringent event selection criteria (rejection of up to 85% of events with an energy of 10 GeV).

The results of numerical calculations (specifically, the data from [130]) provide an opportunity to estimate the energy resolution of ALEGRO in the general case (i.e., after averaging over the impact parameter values of incident gamma quanta): $\Delta E/E$ ~ 0.8 at an energy of 5 GeV and $\Delta E/E$ ~ 0.2 at an energy of 100 GeV. These values are on par with the expected energy resolution of CTA North [114]. Figure 8 shows the model curve representing the upper (conservative) limit of energy resolution of ALEGRO, which corresponds to observations of gamma quanta with impact parameter $r = 0$ m with respect to the center of the observatory. The curve of CTA energy resolution in the general case (averaged over the impact parameter) [114] is shown in the same figure for comparison. It should be noted that these parameters of the ALEGRO observatory may be enhanced by developing more advanced data

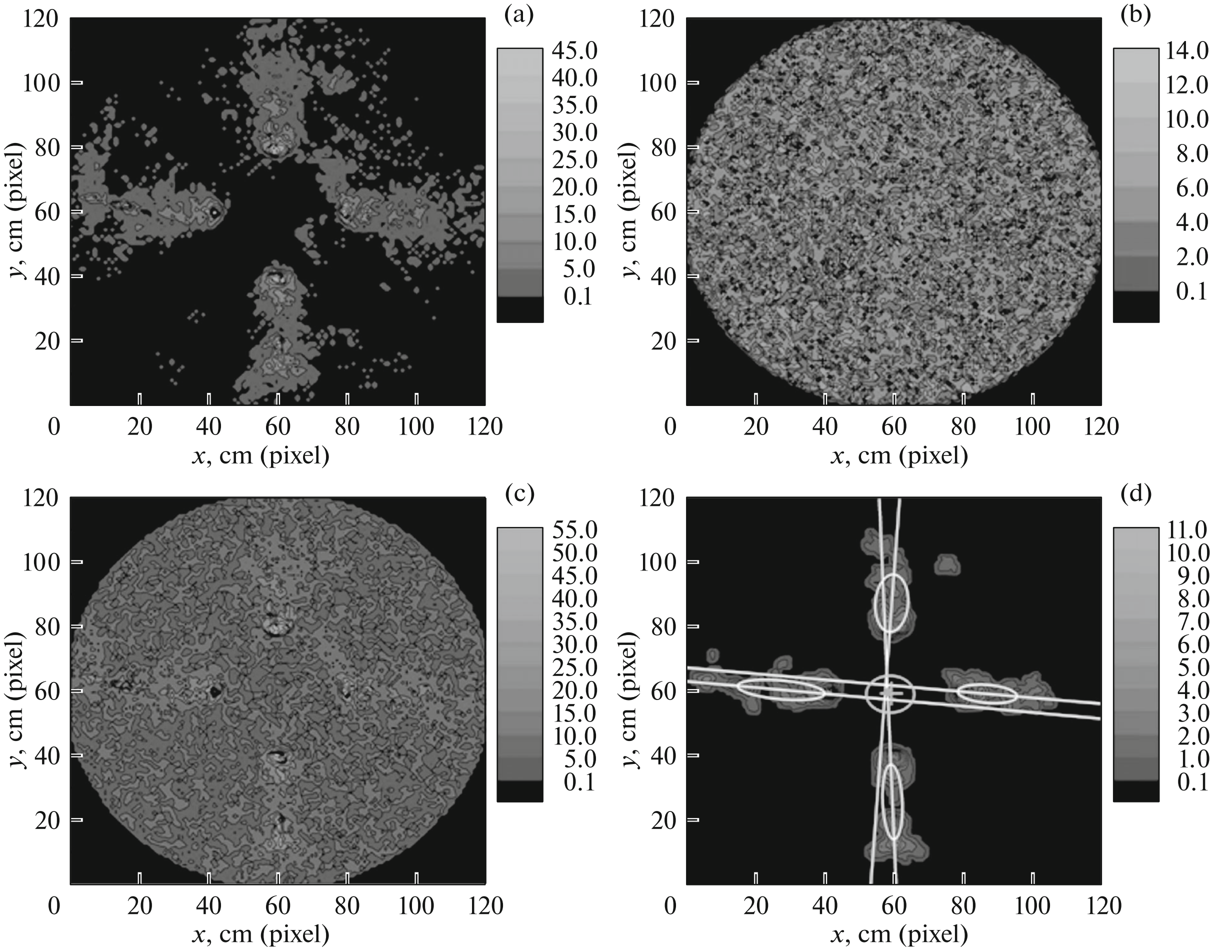

Fig. 7. (a) Focal-plane images of a Cherenkov flash produced in the interaction between a vertically incident gamma quantum with an energy of 20 GeV and the atmosphere (obtained by EAS modeling with the simulating part of ALEGRO Soft). For illustrative purposes, the images at focal planes of all telescopes are shown in the same figure. (b) Image formed by the optical night sky background at the focal plane in 10 ns (obtained using the optical night sky background simulator from ALEGRO Soft). (c) Combined images of a Cherenkov flash and optical background (model of actual signal detected by the gamma-ray observatory). (d) Image obtained after processing (denoising and analyzing the Hillas parameters for to determine direction ofarrival of primary particle) with analytical part of ALEGRO Soft. Major axes of fitting Hillas ellipses (straight lines) indicate direction of EAS development in atmosphere. Point at center of the image denotes the reconstructed arrival direction of the primary gamma quantum, which was calculated as the averaged value of line intersection coordinates. The cross at the center denotes the coordinates of the real arrival direction of the primary gamma quantum. The ellipse at the center is the confidence contour (1σ) of determining the direction of the arrival of the primary particle. This contour defines the angular resolution of the telescope with the given processing algorithm. Length of the major axis of the ellipse at the center corresponds to approximately 0.16°. Complete field of view of ALEGRO telescopes (2.9°) corresponds to 120 pixels.

processing methods based on both massive modeling and analysis of real observational data in the process of operation.

The ALEGRO sensitivity to fluxes from point gamma-ray sources is estimated at 10^{-11}–10^{-12} TeV cm^{-2} s^{-1} in the primary range of 5–50 GeV (Fig. 9). At short exposures, the ALEGRO sensitivity will be higher than (in the range of 20–50 GeV) or be comparable to (at 5–20 and 80–100 GeV) the sensitivity of Fermi/LAT and CTA.

7. ENGINEERING DEVELOPMENT OF THE ALEGRO PROJECT

A series of exploratory and design studies have already been conducted as a part of the ALEGRO project.

A prototype Cherenkov detector subunit containing 64 pixels based on Hamamatsu Photonics s10362-33 avalanche photodiodes has been constructed at the Ioffe Institute and St. Petersburg Polytechnic University. It can be expected that the detector of a single

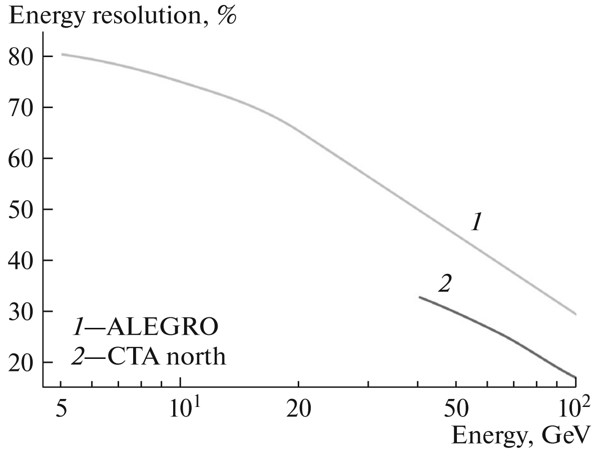

Fig. 8. Model energy resolution of ALEGRO and CTA.

telescope from the ALEGRO array will have approximately 10 000 pixels (photodiodes) produced by Hamamatsu Photonics, SensL, and/or Ioffe Institute. The optical detector subunit is designed for use in Cherenkov gamma-ray telescopes and is a complete functional assembly for a multielement optical detector. The data acquisition and recording system was designed for processing the data from the subunit (the number of incident photons and the coordinates (addresses) of triggered cells). This system detects signals from avalanche photodiodes, amplifies and preprocesses them, and retrieves and transmits data for subsequent software processing in real time.

Avalanche photodiodes of an original design, which are tailored for Cherenkov gamma astronomy, are being constructed [142, 143] at the Ioffe Institute. These photodiodes provide an opportunity to determine the primary particle type by observing the UV component of Cherenkov radiation (see, e.g., [144]) and extend the capabilities of an observatory (e.g., perform observations on moonlit nights [145]). A detection efficiency of ~2% in the far UV range has already been demonstrated [142]. The work on increasing this efficiency and extending the sensitivity range to the visible part of the spectrum is in progress.

CONCLUSIONS

Cherenkov gamma-ray astronomy provides valuable data on the emission of extreme cosmic objects that are needed to solve certain relevant problems of modern astrophysics and fundamental physics. The sensitivity of the planned ALEGRO gamma-ray observatory of the fourth generation will extend to the important and insufficiently studied energy range of 5–50 GeV.

The following results, which define the basic parameters of the future observatory, have already been obtained.

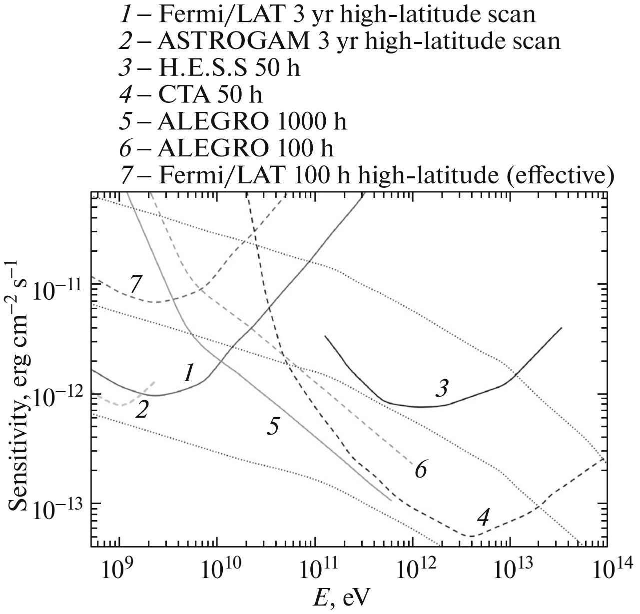

Fig. 9. Sensitivity of existing and future instruments to gamma radiation fluxes from point cosmic sources. ALEGRO exposures are longer than those of other Cherenkov gamma-ray telescopes due to the fact that this observatory is planned to be operated on moonlit nights.

1. Cosmic gamma quanta with energies of 5 GeV can be detected using a system of optical telescopes with 30-m mirrors located at an altitude of 4–5 km above sea level. Under otherwise equal conditions, the threshold observation energy of a gamma-ray observatory at an altitude of 5 km is at least 1.5 times lower than that of an observatory at an altitude of 2 km.

2. The influence of the optical night sky background is significant for detection of cosmic gamma quanta in the range of 1–10 GeV, but is not an insurmountable natural obstacle to observations of cosmic gamma-ray sources. Specifically, the probability of detection of a gamma quantum with an energy of 3 GeV (without preserving the data on the energy and arrival direction, which is sufficient for measurements of light curves of gamma-ray bursts) is approximately 50% at small zenith angles of observation (<10°) and small impact parameters (<100 m with respect to the geometric center of the observatory in the square configuration with a side of 140 m (see also [141])).

3. The expected energy resolution of ALEGRO is $\Delta E/E \sim 0.8$ at 5 GeV (see also [130]) and $\Delta E/E \sim 0.2$ 100 GeV.

4. An angular resolution of 0.16° at 20 GeV may be achieved at small zenith angles of observation by setting specific selection criteria for images to be analyzed.

5. The sensitivity of ALEGRO in the range of 5–100 GeV may be as high as 10^{-11}–10^{-12} TeV cm^{-2} s^{-1}.

Thus, the results of modeling and hardware development demonstrate that the ALEGRO observatory will be an efficient instrument for observing cosmic gamma-ray sources in the energy range of 5–50 GeV. This observatory will allow specialists to resolve a number of important problems of experimental gamma-ray astronomy and high-energy astrophysics.

ACKNOWLEDGMENTS

The work of E.E. Kholupenko, A.M. Krassilchtchikov, and P.N. Aruev was supported in part by the Russian Foundation for Basic Research (grant OFI-m 16-29-13009).

REFERENCES

1. F. Aharonian, *Very High Energy Cosmic Gamma Radiation: a Crucial Window on the Extreme Universe* (World Scientific, 2004).
2. K. T. S. Brazier, A. Carraminana, P. M. Chadwick, et al., Nucl. Phys. B. Proc. Suppl. **14**, 188 (1990).
3. A. D. Zych, F. Ait-Ouamer, A. D. Kerrick, et al., Bull. Am. Astron. Soc. **22**, 1222 (1990).
4. M. L. Ahnen, S. Ansoldi, L. A. Antonelli, et al., Astrophys. J. Lett. **815**, L23 (2015).
5. A. Abramowski, F. Acero, F. Aharonian, et al., Phys. Rev. Lett. **106**, 161301 (2011).
6. G. Amelino-Camelia, J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, and S. Sarkar, Nature **393**, 763 (1998).
7. F. A. Aharonian, A. K. Konopelko, H. J. Volk, and H. Quintana, Astropart. Phys. **15**, 335 (2001).
8. A. M. Hillas, Astropart. Phys. **43**, 19 (2013).
9. W. Galbraith and J. V. Jelley, Nature **171**, 349 (1953).
10. N. M. Nesterova and A. E. Chudakov, J. Exp. Theor. Phys. **28**, 388 (1955).
11. A. E. Chudakov, V. L. Dadykin, V. I. Zatsepin, and N. M. Nesterova, in *Proc. 8th Int. Cosmic Ray Conf., Jaipur, India, 1963*, Vol. 4, p. 199.
12. J. V. Jelley and N. A. Porter, Q. J. R. Astron. Soc. **4**, 275 (1963).
13. G. G. Fazio, H. F. Helmken, G. H. Rieke, and T. C. Weekes, Astrophys. J. lett. **154**, L83 (1968).
14. D. J. Fegan, B. McBreen, E. P. O'Mongain, N. A. Porter, and P. J. Slevin, Can. J. Phys. **46**, S433 (1968).
15. W. N. Charman, J. H. Fruin, J. V. Jelley, D. J. Fegan, et al., in *Proc. 11th Int. Cosmic Ray Conf., Budapest, Hungary, 1970*, p. 59.
16. A. A. Stepanian, B. M. Vladimirskii, Iu. I. Neshpor, and V. P. Fomin, Astrophys. Space Sci. **38**, 267 (1975).
17. T.-P. Li and Y.-Q. Ma, Astrophys. J. **272**, 317 (1983).
18. R. J. Gould and G. R. Burbidge, Ann. Astrophys. **28**, 171 (1965).
19. M. V. Krishna Apparao, Nature **223**, 385 (1969).
20. G. G. Fazio, H. F. Helmken, G. H. Rieke, and T. C. Weekes, in *Proc. 11th Int. Cosmic Ray Conf., Budapest, Hungary, 1970*, p. 115.
21. B. M. Vladimirsky, Yu. L. Zyskin, Yu. I. Neshpor, A. A. Stepanian, V. P. Fomin, and V. G. Shitov, in *Proc. Very High Energy Gamma-Ray Astron. Conf., Crimea, 1991*, p. 21.
22. M. F. Cawley, D. J. Fegan, K. Gibbs, et al., in *Proc. 19th Int. Cosmic Ray Conf., La Jolla, United States, 1985*, Vol. 3, p. 453.
23. A. M. Hillas, in *Proc. 19th Int. Cosmic Ray Conf., La Jolla, United States, 1985*, Vol. 3, p. 445.
24. F. A. Aharonian, A. G. Akhperjanian, A. S. Kankanian, et al., in *Proc. 22nd Int. Cosmic Ray Conf., Dublin, Ireland, 1991*, Vol. 2, p. 615.
25. F. Aharonian, A. Akhperjanian, M. Beilicke, et al., Astrophys. J. **614**, 897 (2004).
26. F. Aharonian, A. Akhperjanian, J. Barrio, et al., Astron. Astrophys. **327**, L5 (1997).
27. A. Barrau, R. Bazer-Bachi, E. Beyer, et al., Nucl. Instrum. Methods Phys. Res., Sect. A **416**, 278 (1998).
28. S. Ebisuzaki, P. G. Edwards, H. Fujii, et al., in *Proc. 22nd Int. Cosmic Ray Conf., Dublin, Ireland, 1991*, Vol. 2, p. 607.
29. K. Tsuchiya, R. Enomoto, L. T. Ksenofontov, et al., Astrophys. J. Lett. **606**, L115 (2004).
30. N. Bhatt, N. K. Agarwal, C. K. Bhat, et al., in *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City, United States, 1999*, Vol. 4, p. 104.
31. P. M. Chadwick, N. A. Dipper, J. C. Dowthwaite, et al., in *Proc. 19th Int. Cosmic Ray Conf., La Jolla, United States, 1985*, Vol. 3, p. 406.
32. P. Armstrong, P. M. Chadwick, P. J. Cottle, et al., Exp. Astron. **9**, 51 (1999).
33. V. G. Sinitsyna, S. I. Nikolsky, A. Y. Alaverdian, et al., in *Proc. 24th Int. Cosmic Ray Conf., Rome, Italy, 1995*, p. 334.
34. T. C. Weekes, M. F. Cawley, D. J. Fegan, et al., Astrophys. J. **342**, 379 (1989).
35. M. Punch, C. W. Akerlof, M. F. Cawley, et al., Nature **358**, 477 (1992).
36. F. Piron, in *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City, United States, 1999*, Vol. 3, p. 326.
37. N. A. Andreeva, Yu. L. Zyskin, O. R. Kalekin, Yu. I. Neshpor, A. A. Stepanyan, V. P. Fomin, N. N. Chalenko, and V. G. Shitov, Astron. Lett. **26**, 199 (2000).
38. W. Hofmann, in *Proc. 28th Int. Cosmic Ray Conf., Tsukuba, Japan, 2003*, p. 2811.
39. F. Aharonian, A. G. Akhperjanian, K.-M. Aye, et al., Astron. Astrophys. **425**, L13 (2004).
40. C. Baixeras, Nucl. Phys. B. Proc. Suppl. **114**, 247 (2003).
41. J. Cortina, Astrophys. Space Sci. **297**, 245 (2005).
42. J. Holder, in *Proc. 29th Int. Cosmic Ray Conf, Pune, India, 2005*, Vol. 5, p. 379.
43. J. Holder, V. A. Acciari, E. Aliu, et al., AIP Conf. Proc. **1085**, 657 (2008).
44. T. C. Weekes, H. Badran, S. D. Biller, et al., Astropart. Phys. **17**, 221 (2002).
45. J. Cortina, F. Goebel, and T. Schweizer, arXiv:0907.1211 [astro-ph.IM].
46. A. Moralejo, arXiv:0912.3673 [astro-ph.IM].

47. D. Nakajima, D. Fink, J. Hose, et al., in *Proc. 33rd Int. Cosmic Ray Conf., Rio de Janeiro, Brazil, 2013*, p. L0787.
48. J. Aleksić, E. A. Alvarez, L. A. Antonelli, et al., Astropart. Phys. **35**, 435 (2012).
49. Y. Becherini and M. Punch, AIP Conf. Proc. **1505**, 741 (2012).
50. M. Renaud, J. Vink, and A. Decourchelle, Astrophys. J. Lett. **647**, L41 (2006).
51. N. Prantzos, C. Boehm, A. M. Bykov, et al., Rev. Mod. Phys. **83**, 1001 (2011).
52. E. Churazov, R. Sunyaev, J. Isern, et al., Nature **512**, 406 (2014).
53. F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, et al., Astron. Astrophys. **464**, 235 (2007).
54. A. M. Bykov, R. A. Chevalier, D. C. Ellison, and Yu. A. Uvarov, Astrophys. J. **538**, 203 (2000).
55. D. C. Ellison, P. Slane, D. J. Patnaude, and A. M. Bykov, Astrophys. J. **744**, 39 (2012).
56. P. Slane, A. M. Bykov, D. C. Ellison, G. Dubner, and D. Castro, Space Sci. Rev. **188**, 187 (2015).
57. A. M. Bykov, Space Sci. Rev. **99**, 317 (2001).
58. M. Ackermann, M. Ajello, A. Allafort, et al., Science, **334**, 1103 (2011).
59. A. M. Bykov, Astron. Astrophys. Rev. **22**, 77 (2014).
60. A. Abramowski, F. Acero, F. Aharonian, et al., Astron. Astrophys. **537**, A114 (2012).
61. A. M. Bykov, D. C. Ellison, P. E. Gladilin, and S. M. Osipov, Mon. Not. R. Astron. Soc. **453**, 113 (2015).
62. A. A. Abdo, M. Ackermann, M. Ajello, et al., Astrophys. J. **708**, 1254 (2010).
63. J. Aleksic, E. A. Alvarez, L. A. Antonelli, et al., Astrophys. J. **742**, 43 (2011).
64. A. Abramowski, F. Aharonian, F. Ait Benkhali, et al., Astron. Astrophys. **562**, L4 (2014).
65. C. Stegmann, presented at *Astroparticle Physics 2014 – A Joint TeVPA / iDM Conf., Amsterdam, the Netherlands, 2014.* https://www.mpi-hd.mpg.de/hfm/HESS/201406-TeVPA-Amsterdam-nofilm.pdf.
66. M. Chrétien, J. Bolmont, and A. Jacholkowska, arXiv:1509.03545 [astro-ph.HE].
67. S. Ansoldi, L. A. Antonelli, P. Antoranz, et al., Astron. Astrophys. **585**, A133 (2016).
68. G. T. Richards, arXiv:1508.06969 [astro-ph.HE].
69. A. A. Abdo, M. Ackermann, M. Ajello, et al., Science **331**, 739 (2011).
70. A. M. Bykov, G. G. Pavlov, A. V. Artemyev, and Yu. A. Uvarov, Mon. Not. R. Astron. Soc. Lett. **421**, L67 (2012).
71. J. Aleksić, S. Ansoldi, L. A. Antonelli, et al., Astron. Astrophys. **567**, L8 (2014).
72. E. Aliu, S. Archambault, T. Arlen, et al., Astrophys. J. **764**, 38 (2013).
73. A. Abramowski, F. Acero, F. Aharonian, et al., Astron. Astrophys. **548**, A38 (2012).
74. A. Abramowski, F. Acero, F. Aharonian, et al., Astron. Astrophys. **545**, L2 (2012).
75. J. Albert, E. Aliu, H. Anderhub, et al., Science **312**, 1771 (2006).
76. F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, et al., Astron. Astrophys. **460**, 743 (2006).
77. V. A. Acciari, M. Beilicke, G. Blaylock, et al., Astrophys. J. **679**, 1427 (2008).
78. J. Rico, M. Rissi, P. Bordas, et al., in *Proc. 30th Int. Cosmic Ray Conf., Merida, Mexico, 2007*, Vol. 2, p. 699.
79. D. M. Worrall, M. Birkinshaw, R. A. Remillard, et al., Astrophys. J. **516**, 163 (1999).
80. E. Lindfors, J. Phys.: Conf. Ser. **355**, 012003 (2012).
81. W. Benbow, arXiv:1508.07251 [astro-ph.HE].
82. A. Abramowski, F. Aharonian, F. Ait Benkhali, et al., Astron. Astrophys. **564**, A9 (2014).
83. A. Abramowski, F. Aharonian, F. Ait Benkhali, et al., Nature **531**, 476 (2016).
84. K. Toma, R. Yamazaki, and T. Nakamura, Astrophys. J. **620**, 835 (2005).
85. D. S. Svinkin, D. D. Frederiks, R. L. Aptekar, et al., Astrophys. J., Suppl. Ser. **224**, 10 (2016).
86. W. B. Atwood, A. A. Abdo, M. Ackermann, et al., Astrophys. J. **697**, 1071 (2009).
87. A. Abramowski, F. Aharonian, F. Ait Benkhali, et al., Astron. Astrophys. **565**, A16 (2014).
88. J. Aleksic, S. Ansoldi, L. A. Antonelli, et al., Mon. Not. R. Astron. Soc. **437**, 3103 (2014).
89. E. Aliu, T. Aune, A. Barnacka, et al., Astrophys. J. Lett. **795**, L3 (2014).
90. A. Bykov, N. Gehrels, H. Krawczynski, M. Lemoine, G. Pelletier, and M. Pohl, Space Sci. Rev. **173**, 309 (2012).
91. K. N. Abazajian, P. Agrawal, Z. Chacko, and C. Kilic, Phys. Rev. D **85**, 123543 (2012).
92. E. Tempel, A. Hektor, and M. Raidal, J. Cosmol. Astropart. Phys., No. 09, **032** (2012).
93. T. Arlen, T. Aune, and M. Beilicke, Astrophys. J. **757**, 123 (2012).
94. A. Abramowski, F. Aharonian, F. Ait Benkhali, et al., Phys. Rev. D **90**, 112012 (2014).
95. M. L. Ahnen, S. Ansoldi, L. A. Antonelli, et al., J. Cosmol. Astropart. Phys., No. 02, **039** (2016).
96. B. Zitzer, arXiv:1509.01105 [astro-ph.HE].
97. M. Bröggen, A. Bykov, D. Ryu, and H. Röttgering, Space Sci. Rev. **166**, 187 (2012).
98. A. I. Nikishov, J. Exp. Theor. Phys. **14**, 393 (1962).
99. L. Costamante, Int. J. Mod. Phys. **22**, 1330025 (2013).
100. F. Krennrich, E. Dwek, and A. Imran, Astrophys. J. Lett. **689**, L93 (2008).
101. R. J. Protheroe and H. Meyer, Phys. Lett. B **493**, 1 (2000).
102. D. Horns and M. Meyer, J. Cosmol. Astropart. Phys., No. 02, **033** (2012).
103. G. I. Rubtsov and S. V. Troitsky, JETP Lett. **100**, 355 (2014).
104. A. De Angelis, O. Mansutti, and M. Roncadelli, Phys. Lett. **659**, 847 (2008).
105. M. Simet, D. Hooper, and P. Serpico, Phys. Rev. D **77**, 063001 (2008).

106. M. Fairbairn, T. Rashba, and S. Troitsky, Phys. Rev. D **84**, 125019 (2011).
107. J. Jaeckel and A. Ringwald, Annu. Rev. Nucl. Part. Sci. **60**, 405 (2010).
108. S. Troitsky, Phys. Rev. D **93**, 045014 (2016).
109. TeVCat. http://tevcat.uchicago.edu.
110. D. Mazin, AIP Conf. Proc. **1112**, 111 (2009).
111. F. Aharonian, A. G. Akhperjanian, U. Barres de Almeida, et al., Phys. Rev. Lett. **101**, 261104 (2008).
112. B. Zitzer, arXiv:1307.8382 [astro-ph.HE].
113. J. Albert, E. Aliu, H. Anderhub, et al., Phys. Lett. B **668**, 253 (2008).
114. Cherenkov Telescope Array. https://portal.cta-observatory.org/Pages/Home.aspx.
115. U. Barres de Almeida, Astron. Nachr. **336**, 795 (2015).
116. J. Arons, Astrophys. J. **266**, 215 (1983).
117. J. Chiang and R. W. Romani, Astrophys. J. **436**, 754 (1994).
118. M. Ruderman, in *Pulsars: 13 Years of Research on Neutron Stars*, Ed. by W. Sieber and R. Wielebinski (Springer, Dordrecht, 1981), p. 87.
119. I. A. Yadigaroglu and R. W. Romani, Astrophys. J. **449**, 211 (1995).
120. I. A. Grenier, Astron. Astrophys. **364**, L93 (2000).
121. F. A. Aharonian and S. V. Bogovalov, New Astron. **8**, 85 (2003).
122. A. Harding, AIP Conf. Proc. **558**, 115 (2001).
123. V. Bosch-Ramon, Mem. Soc. Astron. Ital. **83**, 194 (2012).
124. R. Koul, R. C. Rannot, A. Mitra, et al., in *Proc. 32nd Int. Cosmic Ray Conf., Beijing, China, 2011*, Vol. 9, p. 107.
125. K. Yadav, presented at *48th Rencontres de Moriond on Very High Energy Phenomena in the Universe, La Thuile, Italy, 2013.* http://moriond.in2p3.fr/J13/transparencies/yadav.pdf.
126. Major Atmospheric Cherenkov Telescope Experiment. http://www.barc.gov.in/pg/nrl-harl/mace.html.
127. O. T. Tümer, A. D. Kerrick, T. J. O'Neill, R. S. White, and A. D. Zych, in *Proc. 22nd Int. Cosmic Ray Conf., Dublin, Ireland, 1991*, Vol. 2, p. 634.
128. S. Profumo and M. Kamionkowski, J. Cosmol. Astropart. Phys., No. 03, **003** (2003).
129. T. Frach, J. Instrum. **7**, C01112 (2012).
130. G. I. Vasilyev, E. E. Kholupenko, D. A. Baiko, et al., Nauchno-Tekh. Vedomosti S.-Peterb. Gos. Politekh. Univ. Fiz.-Mat. Nauki, No. **4**, 79 (2011).
131. S. Korpar, I. Adachi, H. Chagani, et al., Nucl. Phys. B: Proc. Suppl., **197**, 283 (2009).
132. P. K. Lightfoot, G. J. Barker, K. Mavrokoridis, et al., J. Instrum. **10** (10), 001 (2008).
133. T. Bretz, H. Anderhub, M. Backes, et al., arXiv:1403.3573 [astro-ph.IM].
134. J. Spargo, Natl. Radio Astron. Obs. Obs. **21**, 39 (1980).
135. http://www.spacedaily.com/reports/New_space_telescope_begins_to_comb_the_cosmos_999.html.
136. S. Agostinelli, J. Allison, K. Amako, et al., Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
137. CORSIKA. https://www.ikp.kit.edu/corsika.
138. E. Oña-Wilhelmi, J. Cortina, O. C. de Jager, and V. Fonseca, Astropart. Phys. **22**, 95 (2004).
139. Ch. Leinert, S. Bowyer, L. K. Haikala, et al., Astron. Astrophys. Suppl. Ser. **127**, 1 (1998).
140. HAMAMATSU Photonics. http://www.datasheetlib.com/datasheet/707358/s10362-33_hamamatsu-photonics.html.
141. G. I. Vasilyev, E. E. Kholupenko, S. N. Yablokov, D. A. Baiko, A. M. Bykov, A. M. Krassilchtchikov, and G. G. Pavlov, Nauchno-Tekh. Vedomosti S.-Peterb. Gos. Politekh. Univ. Fiz.-Mat. Nauki, No. 3, 191 (2012).
142. V. V. Zabrodskii, P. N. Aruev, V. P. Belik, B. Ya. Ber, S. V. Bobashev, M. V. Petrenko, N. A. Sobolev, V. V. Filimonov, and M. Z. Shvarts, Tech. Phys. Lett. **40**, 330 (2014).
143. V. Zabrodskii, P. Aruev, V. Belik, et al., Nucl. Instrum. Methods Phys. Res., Sect. A **787**, 348 (2015).
144. O. R. Kalekin, Yu. I. Neshpor, A. A. Stepanyan, et al., Astron. Lett. **21**, 163 (1995).
145. M. C. Chantell, X. Sarazin, P. Fleury, et al., in *Proc. 24th Int. Cosmic Ray Conf., Rome, Italy, 1995*, Vol. 2, p. 560.

Translated by D. Safin