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MULTI-TeV GAMMA-RAY ASTRONOMY

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We review the status of ground-based multi-TeV gamma-ray astronomy. Short descriptions of presently operating and planned detectors in the field are given.

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INTRODUCTION

Cosmic rays were discovered by Austrian physicist Victor Hess in his seminal series of balloon flights which he undertook in 1912 [1] (for more details see reviews [2–4]). Hess eventually got the Nobel Prize for this discovery in 1936. Energy spectrum of cosmic rays spans a huge range exceeding even 10^{20} eV, Fig. 1 [5].

The most energetic event registered in cosmic rays so far is $\sim 3\cdot 10^{21}$ eV [6]. Despite more than one-century history, the origin of cosmic rays is still a mystery, as well as acceleration mechanism of cosmic rays. V. L. Ginzburg and S. I. Syrovatsky in the early 1960s proposed supernova explosions as possible sources of cosmic rays [7, 8]. Supernova explosions with the energy of 10^{51}–10^{53} erg and the rate of 1 explosion per 30–100 yr in the Galaxy could provide the energy density of cosmic rays ($\sim$ 1–2 eV/cm^3). Satellite experiment Fermi-LAT registered gamma-ray emission from supernova remnants (SNR) IC443 and W44 with characteristic features in their energy spectrum confirming definitely for the first time the existence of hadrons accelerated up to several hundreds of MeV, Fig. 2 [9].

But so far there is no unambiguous evidence in favor of hadronic mechanism of cosmic ray acceleration in the high-energy domain. Gamma quanta with energies up to 100 TeV detected by present day Imaging Atmospheric Cherenkov Telescopes (IACT) can be explained by leptonic mechanisms as well, i.e., produced by high-energy electrons via inverse Compton scattering on low-energy ambient photons. Gamma rays with energies higher than 200 TeV cannot be produced by leptonic mechanism. Thus, the detection of gamma rays with energies

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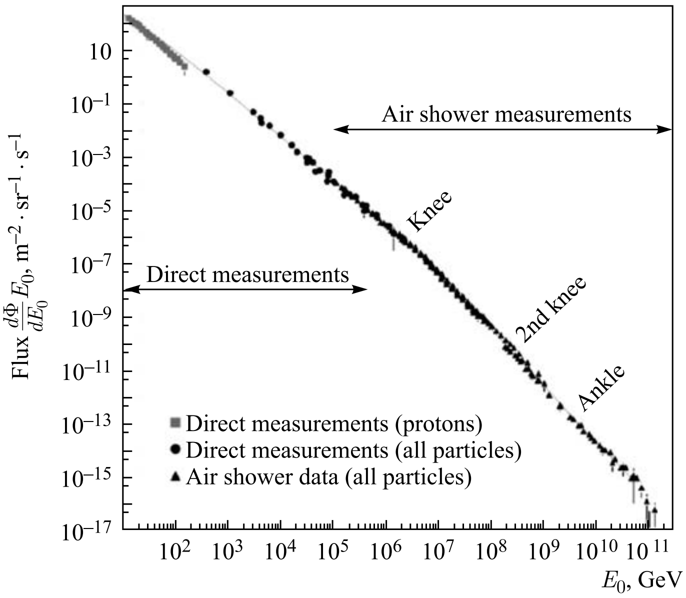

Fig. 1. Energy spectrum of primary cosmic rays [5]

exceeding 200–300 TeV corresponding to parent hadrons with PeV energies from cosmic sources (cosmic PeVatrons) will be the ultimate discovery of cosmic rays origin. Such energetic gamma quanta cannot be detected by satellite experiments due to low flux intensities. So, only ground-based arrays covering large areas are able to detect such gamma rays, identify their sources, and eventually solve more than century-long mystery.

1. GROUND-BASED MULTI-TeV GAMMA-ASTRONOMY ARRAYS

High-energy gamma quanta with energies more than 100 GeV cannot reach the Earth's surface and cannot be detected directly; on the other hand, their fluxes are so small that satellite and balloon studies allow to extend up to a few GeV (the most successful telescope is Fermi-LAT telescope which has done dozens of discoveries for a few years of operation). So, studies in the energy range of more than 100 GeV are performed by ground-based arrays which detect secondary particle showers originating after interaction of primary high-energy gamma ray with atomic nuclei of the Earth's atmosphere. The most popular arrays are Cherenkov telescopes registering Cherenkov light pulses produced by particles of electromagnetic cascades. These pulses are observed on the Earth in the visible and UV regions in small solid angle ($\sim 10°$) in the direction of

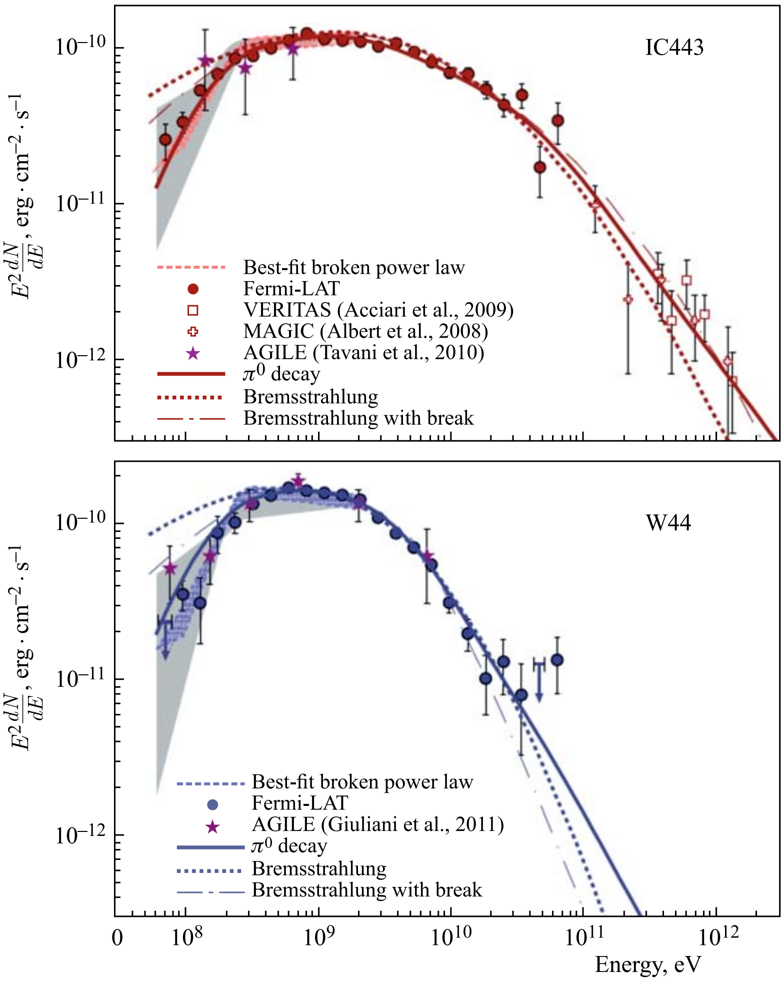

Fig. 2. Energy spectra of SNRs IC443 and W44 detected by Fermi-LAT satellite experiment [9]

primary gamma ray. The main parameters of pulses are: the areas illuminated by such pulses are dozens of thousands of square meters; the pulses brightness is comparable with night sky background, the pulses width is of ~ 10 ns.

The experimental high-energy gamma-ray astronomy was founded by A. E. Chudakov and his team in the early 1960s. They developed and built the first ever Cherenkov telescope to search for high-energy gamma-ray sources, Fig. 3 [10]. The array was located in Crimea, USSR. Since that time Cherenkov

Fig. 3. The first gamma telescope in the world developed by A. E. Chudakov and his team in Crimea, USSR [10]

telescopes underwent half-century impressive development as a method of gamma-ray detection.

Cherenkov telescopes can be divided into four generations:

1. The 1st generation: the Crimean Observatory (Lebedev Institute); Dublin University; Woodstock College; Smithson Observatory; Institute of Physics, Mumbay; University of Sidney.

2. The 2nd generation: CAT, HEGRA, Whipple, GT-48, SHALON.

3. The 3rd generation: H.E.S.S., MAGIC, VERITAS.

4. The 4th generation (projects): CTA.

The real breakthrough in the studies of high-energy cosmic gamma-ray radiation has been done for the last 10 years due to the 3rd generation Cherenkov telescopes H.E.S.S. [11], MAGIC [12], CANGAROO [13], VERITAS [14]. The telescopes are narrow-angle telescopes with FOV of 3–5°. They consist of 10–17 m diameter mirror and a matrix of PMTs in the mirror's focal plane. The mirror collects Cherenkov light, and the image of Cherenkov light pulse is produced in the matrix of PMTs. A method to analyze the image shape proposed by A. M. Hillas in the late 1980s allowed one to separate with reliability (confidence) showers produced by gamma rays from showers produced by hadrons of cosmic ray. Such telescopes are called IACT (Imaging Atmospheric Cherenkov Telescope). An alternative approach to the detection of EAS Cherenkov light without shower's image is used successfully for cosmic ray studies with Tunka-133 array [15] and will be used in the Tunka-HiSCORE observatory [16].

The present-day telescopes (H.E.S.S., MAGIC) consist of 2–4 mirrors and PMT matrixes of each mirror include about 1000 PMTs. The main parameters of telescopes are their sensitivity which is measured in units of Crab Nebula, energy range, energy and angular resolutions. Sensitivity of the telescopes increased by a factor of 100 in comparison with the pioneering Whipple telescope. If 50 h were needed for the Whipple telescope to detect the brightest source Crab Nebula with 5σ confidence level, with present-day telescopes it takes just 25 s.

H.E.S.S. (High Energy Stereoscopic System) [11] is located in the Southern Hemisphere in the Namibian upland Khomas Region (23°16′ S, 16°30′ E). Energy of registered gamma quanta is in the range of 100 GeV – 100 TeV. Sensitivity is 0.002 Crab Nebula. Stereoscopic system of H.E.S.S. consists of four identical telescopes with mirrors of 12 m in diameter located at a distance of 120 m from each other in a square and one, 28 m in diameter, in the centre, Fig. 4.

Fig. 4. H.E.S.S. (High Energy Stereoscopic System) telescope [11] in Namibia

Angular resolution is 0.1° for the energy range of 120 GeV – several TeV. Energy resolution is $\sim$ 15%. H.E.S.S. had been studying the main part of the Galactic disk and discovered $\sim$ 70 Galactic sources belonging to classes of supernova remnants, pulsar nebulae binary star systems, star clusters. Relatively recently gamma rays from molecular clouds in the vicinity of supernova remnants have been registered. About 30 of registered sources are located off the Galactic plane. These sources are largely associated with Active Galactic Nuclei (AGN) and the most part of the sources are BL Lacertae (BL Lac).

VERITAS [14] (Very Energetic Radiation Imaging Telescope Array System) array consists of four identical telescopes located in the southern Arizona, USA, at the altitude of 1.3 km above sea level (31° N), Fig. 5. Each telescope has an optical reflector of 12 m in diameter and 499 PMTs matrix at its focus allowing 3.5° field of view. Angular and energy resolutions of the array are 0.1° and 15%, respectively, at energy of $\sim$ 1 TeV. Presently, the array sensitivity allows one to detect sources with intensity of 100 times less than Crab Nebula for just 25 h. The total observation time is 1000 h per year. The array detected

Fig. 5. The VERITAS telescope in Arizona, USA [14]

39 sources including PWN, SNR, binary systems, pulsars, galaxies with active star production, as well as nonidentified sources.

MAGIC telescope [12] (Major Atmospheric Gamma Imaging Cherenkov telescope). The MAGIC telescope is located on the Canarian island La Palma at the altitude of 2.2 km. The telescope has the lowest energy threshold of $\sim$25 GeV. From 2004 till 2009 the array operated as mono telescope with 17 m diameter mirror, since 2009 with the second identical telescope starting to operate the array functions as stereo system, Fig. 6. The stereo system permitted to increase substantially the sensitivity of the array which is now 1% of Crab Nebula at 1 TeV and 10% — at 10 TeV. The array has energy and angular resolutions of 15% and 0.07°, respectively. The MAGIC telescope detected nine Galactic objects: Crab Nebula, the Galactic Centre, HESS J1813, HESS J1834, the SNRs Cassiopeia A and IC443, the X-ray binary LSI 61+303, the unidentified EGRET source TeV 2032, and the Crab pulsar. Owing to the low threshold, unlike other telescopes MAGIC can detect pulsed gamma radiation from pulsars. Such a radiation with energies higher than 25 GeV from Crab Nebula has been detected by MAGIC.

Fig. 6. The MAGIC telescope on La Palma Island, Spain [12]

This fact practically excludes a model predicting pulsed radiation nearby pulsar surface, because strong magnetic fields will absorb the radiation via a process of pair production. Due to low threshold and high geographical latitude, the MAGIC telescope studies effectively extragalactic objects along with other scientific tasks including study of upper limits on gamma-ray fluxes from GRBs and Dark Matter annihilation in binary spheroidal galaxies and galaxy clusters.

CTA [17] (Cherenkov Telescope Array) (2016–2017) is a project of the 4th generation of Cherenkov telescopes accumulating all previous experience of imaging telescopes and consisting of the main array in the Southern Hemisphere aimed at studies of Galactic objects and an auxiliary array in the Northern Hemisphere aimed at studies of metagalactic objects basically nuclei of active galaxies. The arrays will consist of dozen of 10–15 m telescopes (like H.E.S.S., VERITAS) fixed at 100 m distance from each other and aimed at studies in the energy range of 100 GeV – 100 TeV and one 20–30 m telescope or two telescopes like H.E.S.S.II dedicated to study low-energy region of less than 100 GeV. To probe gamma radiation with more than 10 TeV, arrays with larger area (a few km^2) are necessary. So, either these are telescopes with relatively small area (a few m^2) spaced by 100–200 m^2 or telescopes like H.E.S.S. with 500 m space. A configuration of telescopes sub-clusters deployed with larger spacing is also possible. The artistic view of the array is shown in Fig. 7.

Goals and advantages of the CTA are the following. The CTA increases sensitivity by one order of magnitude: its sensitivity in the energy range of 100 GeV – several TeV is 10^{-3} of Crab. The CTA increases detecting area and thus frequency which is very important for study of transient phenomena. It improves angular resolution ($\sim$ arc-minutes) for better investigation of nonlocal objects morphology. It improves energy resolution in a very wide energy range

Fig. 7. The artistic view of the CTA array [7]

of dozens GeV – 100 TeV. The CTA can operate in different configurations because it consists of a variety (*multitude*) of telescopes. It can provide also deep studies of unit objects and can do simultaneous monitoring of dozens of objects. The CTA will operate as an open observatory providing free access to data for astrophysicists and astronomers, particle physics scientists, cosmologists, etc. The total number of discovered sources will be increased by a factor of 10 and will reach 1000 objects.

The main competitor of atmospheric Cherenkov telescopes in the field of high-energy gamma-ray detection is shower arrays which register shower of secondary charged particles and restore primary energy. The separation of gamma-induced showers over hadron-induced showers is done by existence of penetrating component and by lateral distribution of particles in the shower. Registration methods can differ. The main advantages of such arrays are the wide field of view (up to 45°), observation period is close to calendar time period in contrary to Cherenkov telescopes where effective dark time period (duty cycle) does not exceed 10%. At the same time, registration threshold is very high — not less than 10 TeV. Thanks to continuous observation time, such telescopes are able to detect transient phenomena like GRBs.

Milagro [18]. Pioneering gamma-observatory of such a kind, Milagro had been operating since 2000. The array was located near Los Alamos at the altitude of 2500 m above sea level. It was water Cherenkov detector of $60 \times 80 \times 8$ m size. Cherenkov light was collected by 723 PMTs put in two layers, bottom layer registered basically the light produced by penetrating component to separate gamma-induced showers from hadron-induced ones, Fig. 8. The array operated in the energy range of 1–100 TeV with maximum efficiency in the range of 10–50 TeV. The Milagro array was first to evaluate Galactic diffused gamma radiation at energy of 10 TeV. The experiment registered dozen Galactic sources with energy of 20 TeV, eight with high confidence level. Out of 34 Galactic sources from BGL (Fermi catalog of sources) being in the Milagro field of view TeV radiation was observed for 14 sources with 3σ confidence level.

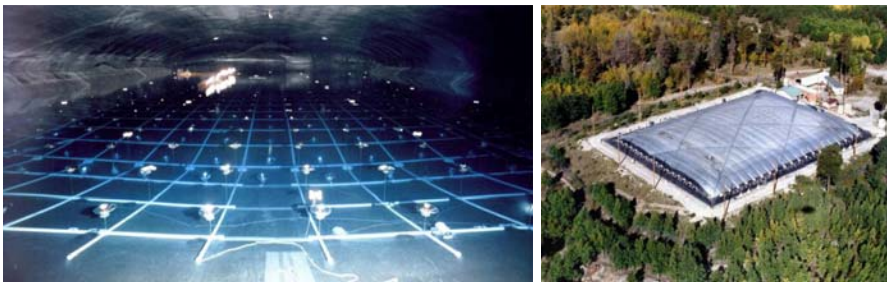

Fig. 8. The Milagro detector in New Mexico, USA [18]

HAWC [19] (High-Altitude Water Cherenkov Gamma-Ray Observatory). This observatory is further development of the Milagro telescope. It is also located in the high mountains of Sierra Negra (4100 m a.s.l.) in the circus between two extinct volcanoes in the Pico de Orizaba National Park near Puebla, Mexico.

It will consist of ~ 300 big opaque water tanks (4 m high and 7.3 m in diameter). Each tank will be equipped with three peripheral and one central PMTs to collect Cherenkov light produced by charged particles in water. The array's total area is 150×150 m. The layout of the array is shown in Fig. 9. The observatory is aimed to study gamma radiation in the wide energy range of 100 GeV – 100 TeV with a very wide field of view which is almost 15% of the whole sky. Separation of gamma-induced showers from high background of hadron-induced events will be done using lateral distribution of hit detectors. The physics program is extremely wide covering Galactic sources, Galactic diffused radiation, extreme accelerators in the Galaxy, metagalactic sources, GRBs, etc.

Fig. 9. The HAWC experiment in Sierra Negra, Mexico [19]

LHAASO [20] (Large High Altitude Air Shower Observatory). Development of a giant complex array LHAASO started in the Chinese Sichuan province at altitude of 4100 m a.s.l., Fig. 10.

The new array will incorporate 5000 scintillator detectors of electrons and 1200 muon detectors with total area of 4000 m^2. Scintillator detectors of EAS electromagnetic and muon components will be deployed over the area of 1 km^2. Besides the detailed studies of energy spectrum and mass composition of cosmic rays with energies up to 10^{18} eV, the array will allow one to perform searches for local sources of gamma quanta with energies higher than 30 TeV with unprecedented level of sensitivity. For search of gamma-quanta sources in lower energy region (~ 100 GeV) the water Cherenkov detectors with total area of 90 000 m^2 will be inserted into the array. In addition to the wide-angle detectors it is as-

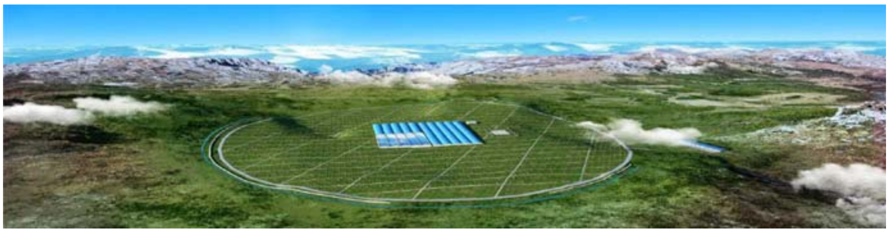

Fig. 10. The LHAASO project in Sichuan, China [20]

sumed to have two narrow-angle gamma telescopes (IACT) registering showers images with energy threshold of 30 GeV.

TAIGA [21] (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy). The same hybrid approach as in LHAASO project is pursued in the TAIGA experiment which is now under development in the Tunka Valley in the Republic of Buryatia in Russia. The idea of the experiment is to combine a wide-angle EAS Cherenkov array of large area and a net of relatively small IACTs. Moreover, a system of surface and underground scintillator detectors is planned to be installed too for registration of electromagnetic and muon components of EAS, respectively. The wide-angle Cherenkov array named Tunka-HiSCORE will consist of a distributed array of optical stations with the spacing between them of the order of 100 m. The optical station of the array consists of four PMTs each equipped with its own Winston cone which increases the light collection area by a factor of 4. The net of IACTs (Tunka-IACT) will consist of the order of 10 small area (~ 10 m^2) HEGRA-like telescopes. The scintillation detector system (Tunka-Grande) will very helpful in gamma/hadron separation too. The layout of the experiment is shown in Fig. 11. The filled rectangles are optical stations of the Tunka-HiSCORE array already installed in the framework of the Tunka-133 EAS Cherenkov array [22] which has been operating since 2009 (filled circles in the figure). The optical station of the Tunka-HiSCORE array and its electronics layout are shown in Fig. 12, from left to right, respectively.

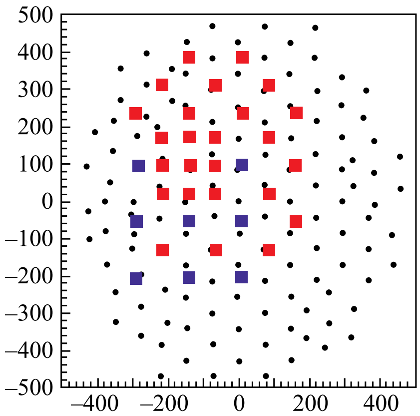

Fig. 11. The layout of the Tunka-HiSCORE array optical stations already installed (filled rectangles) along with the Tunka-133 EAS Cherenkov array optical stations (filled circles) [21]

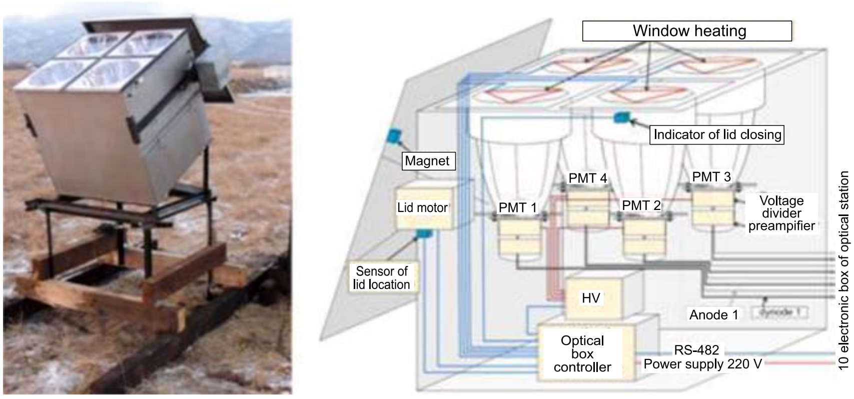

Fig. 12. The optical station (left) of the Tunka-HiSCORE and its electronics layout (right) [21]

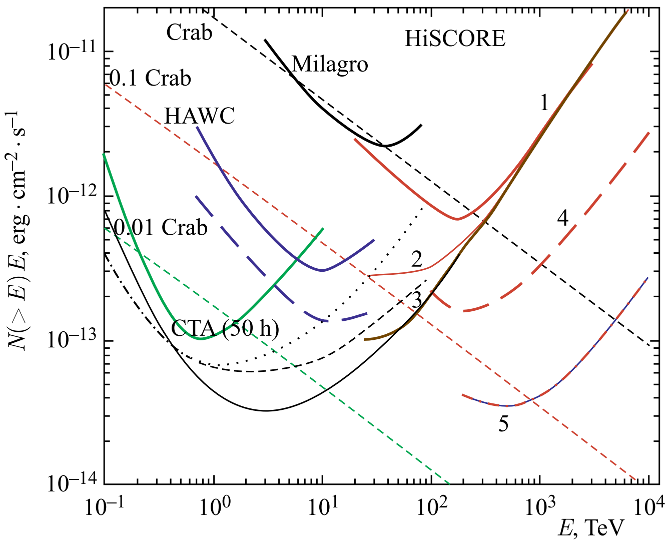

Fig. 13. Sensitivity of the TAIGA experiment to gamma rays. The numbers 1–5 correspond to different stages of the experiment development [21–23]

The complex of the TAIGA experiment including the Tunka-HiSCORE, Tunka-IACT, and Tunka-Grande arrays will be implemented in several stages. The complex will be a powerful tool for studies in multi-TeV gamma-ray astronomy. The sensitivity of the experiment to gamma rays for its different stages is presented in Fig. 13 along with sensitivities of other experiments.

CONCLUSIONS

Experimental multi-TeV gamma-ray astronomy develops rapidly for the last decade. Presently, several large-scale Cherenkov arrays are under construction around the world. They have very diverse physics goals, including the most ambitious goal — registration of gamma rays with energies higher than 100–200 TeV and discovery of PeVatrons in our Galaxy, and therein solution of century-long mystery of cosmic rays origin. Construction of the TAIGA gamma-ray observatory in the Tunka Valley in Siberia will allow Russia to reentry the field of gamma-ray astronomy at a new level.

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