Physics – Uspekhi **65** (9) 980 – 985 (2022)

CONFERENCES AND SYMPOSIA

PACS numbers: 96.50.S –, 96.50.sd, 98.70.Sa

The LHAASO project: first results and prospects

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DOI: https://doi.org/10.3367/UFNe.2021.06.039213

Contents

Abstract. Recent results of the LHAASO (Large High Altitude Air Shower Observatory) experiment are reviewed. Due to their outstanding characteristics, the facilities incorporated in the project started providing in 2021 the first results in ultra-high energy gamma-astronomy. During a year of operations of only some of the detectors, PeVatrons have been discovered in the Galaxy, many new astrophysical sources of gamma-quanta have been found, and the energy spectra of emitted gamma-quanta have been measured. The most important achievement is that the directions from which the gamma-quanta arrive have been measured with an accuracy as high as 0.05 degrees, implying that their sources can be localized with the same precision. These data enable making certain conclusions regarding the nature of PeVatrons and possible mechanisms of cosmic ray acceleration. Prospects for the further development of the LHAASO experiment are discussed.

Keywords: gamma astronomy, PeVatron, cosmic rays, acceleration mechanisms

1. Introduction

Academician A E Chudakov is known to have been a founder of ultrahigh-energy gamma astronomy. Under his guidance back in the early 1960s in Crimea, the world's first facility for detecting Cherenkov light from extensive air showers (EASs) was created, and it was also the first to yield experimental results in this area [1]. Since then, many such facilities have been created worldwide; technology and especially electronics have made immense progress; telescopes started providing 'images,' and their angular resolution and aperture have been significantly enhanced. Examples include HESS (High Energy Stereoscopic System) [2], MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov telescope) [3], CTA (Cherenkov Telescope Array) [4], and Tunka [5]. Such facilities feature very high angular resolution. Their aperture depends on the area of the mirrors, the total area of which in the planned CTA will be 40,000 m^2. Later, a technique for detecting gamma showers using water Cherenkov detectors was developed, in which a layer of water several meters thick protected from light is viewed by photomultipliers. An example of such a facility is HAWC (High Altitude Water Cherenkov observatory) [6], which consists of 300 water tanks with a diameter of 7.3 m. Despite the impressive dimensions of the facilities listed above, their detecting area is still insufficient for registering very feeble fluxes of gamma-quanta from astrophysical objects at energies $\geqslant 1$ PeV (10^{15} eV).

The year 2021 marks the 100th anniversary of the birthday of my teacher A E Chudakov, and this publication is dedicated to his memory.

2. LHAASO experiment

LHAASO (Large High Altitude Air Shower Observatory), an international high-altitude experiment [7], combines all the methods described above. The experiment is being carried out in China in the east of the Tibetan plateau, in Sichuan province, at an altitude of 4410 m above sea level. An overall view of LHAASO and its components is shown in Fig. 1. The experiment, a project that involves multiple tasks, consists of several independently operating facilities. Two of them were originally intended for the purposes of gamma astronomy: WFCTA (Wide Field-of-view Cherenkov Telescope Array), which consists of 12 wide-angle image telescopes, and WCDA (Water Cherenkov Detector Array), a set of three giant Cherenkov water basins divided into cells with a total area of 300×260 m^2. Construction and installation work was scheduled to be completed only by the end of 2021, but the work was finished ahead of schedule in mid-2021. The facilities were commissioned in stages, and experiments performed with them started in 2019; currently, the existing facilities are being expanded and statistics are being collected.

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Received 16 June 2021
Uspekhi Fizicheskikh Nauk **192** (9) 1048 – 1053 (2022)
Translated by M Zh Shmatikov

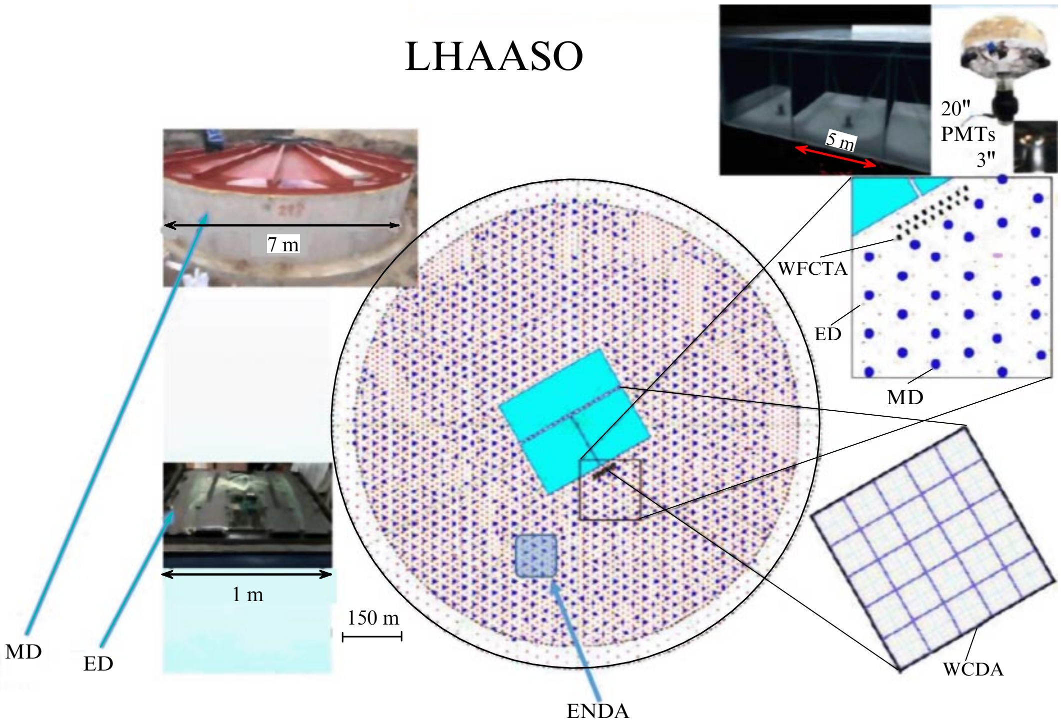

Figure 1. (Color online.) Overall view of the LHAASO experiment and its components (see text). ED — small dots, MD — triangles or circles. Central part and bottom inset show three WCDA water basins; top panel displays location of WFCTA (Wide Field-of-view Cherenkov Telescope Array) imaging telescopes. Photographs of MD (before filling) and ED are shown on left side of the figure; photographs of WCDA cells (before filling with water) and 20-inch and 3-inch photomultiplier tubes (PMTs) used in the cells are shown in upper-right part of the figure.

A team from the Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS) is participating in this experiment. We intend to measure the spectrum and mass composition of cosmic rays in the PeV-energy region by creating the ENDA (Electron–Neutron Detector Array) facility consisting of 400 electron–neutron detectors (en-detectors) developed at INR RAS that detect two EAS components: the main one, which is hadronic (through thermal neutrons) and an electron one [8, 9].

The main part of LHAASO is the Km2A (Km^2 Array), an EAS-facility that consists of 5563 ground-based electron detectors (EDs) with an area of 1 m^2 each and 1221 buried muon detectors (MDs) with an area of 30 m^2 each. The detectors are arranged in the form of a triangular grid: EDs are placed 15 m apart and MDs are spaced 30 m apart. The total area of the facility exceeds 1 km^2. Such an area provides a record high aperture, which is more than an order of magnitude greater than that of WCDA. At the same time, the installation is very dense and saturated, due to which no other facility can compete with it. As a result, it is this facility that was the first to provide unique research information pertaining to gamma astronomy.

3. First results obtained at the Km2A facility

In May 2021, the LHAASO collaboration published a paper on the gamma sources detected using the Km2A facility [10]. The table presents these sources, indicating the statistics at the time of writing of this article (end of 2020) and the astrophysical objects known in the vicinity of each of these

Table. Sources of ultra-high energy gamma quanta discovered in the LHAASO experiment at the Km2A facility [10].

Source	Reliability, σ at $E > 100$ TeV	Observation time, h	$E_{\max}$, PeV	Nearby objects
LHAASO J0534 + 2202	17.8	2236.4	0.88	Crab, PSR
LHAASO J1825–1326	16.4	1149.3	0.42	2 PSR
LHAASO J1839–0545	7.7	1614.5	0.21	2 PSR
LHAASO J1843–0338	8.5	1715.4	0.26	SNR
LHAASO J1849–0003	10.4	1865.3	0.35	PSR, YMC
LHAASO J1908 + 0621	17.2	2058.0	0.44	2 PSR, SNR
LHAASO J1929 + 1745	7.4	2282.6	0.71	2 PSR, SNR
LHAASO J1956 + 2845	7.4	2461.5	0.42	PSR
LHAASO J2018 + 3651	10.4	2610.7	0.27	PSR, YMC
LHAASO J2032 + 4102	10.5	2648.2	1.42	Cygnus OB2, PSR, YMC
LHAASO J2108 + 5157	8.3	2525.8	0.43	—
LHAASO J2226 + 6057	13.6	2401.3	0.57	Boomerang Nebula, PSR, SNR

sources. The maximum recorded energy of an EAS, identified as a shower from a primary gamma ray, was 1.42 PeV. The source, named LHAASO J2032 + 4102, is located in the so-called Cygnus Cocoon, but does not exactly coincide with any known astrophysical object. The collection of statistics continues, and now several PeVatrons have already been discovered, which most likely testifies in favor of the hadron acceleration mechanism, hadronic PeVatrons, in which the accelerated particles are protons and heavier particles, while gamma quanta are formed from the decay of neutral pions.

An interesting feature of the new sources, noted in the table, is that only one of them (the first line of the table) coincides within the measurement errors with a known astronomical object — a pulsar in the Crab Nebula. A careful study of the table shows that in the vicinity of each of the 12 discovered sources there is one or two pulsars (PSRs), clusters of young stars (Young Massive Cluster, YMCs), while in the vicinity of only four of them there are supernova remnants (SNRs). This observation is very surprising and unexpected, since, according to the acceleration mechanism generally accepted now, it is the remnants (envelopes) of young supernovae that are considered the main source of cosmic rays. However, there are no young supernovae in the vicinity of the discovered gamma sources.

Apparently, an intensive search for new theories and mechanisms that drive the operation of natural particle accelerators, PeVatrons, will now commence. Relatively recently, clusters of young massive stars were proposed as possible 'stationary' PeVatrons [11], since supernovae can only accelerate cosmic rays to PeV energies for a short time after collapse and cannot provide the observed flux. In the vicinity of three of the discovered sources (including the found LHAASO J2032 + 4102 PeVatron), there are indeed such clusters. It is noteworthy that, in the models of particle acceleration on supernova envelopes, obtaining a power-law energy spectrum of cosmic rays and the chemical composition of cosmic rays that would agree with the observational data is a challenging problem.

Regarding the acceleration of cosmic rays by pulsars, the LHAASO data directly indicate their presence in the vicinity of the discovered sources. These objects were also considered earlier as possible sources of cosmic rays (see, for example, [12] and references therein). However, this explanation also encounters difficulties in predicting the energy spectrum (a very hard spectrum is obtained in the calculations), but a heavy composition is predicted at ultrahigh energies, which partly agrees with the experimental results (at least with the experimental data of the Pierre Auger Observatory (PAO)).

Another paper recently published by the LHAASO collaboration [13] is devoted to the result obtained at the Km2A and WCDA facilities, namely, a comprehensive study of the gamma-ray flux from a known source in the Crab Nebula, which is a 'reference candle' in the Galaxy. This object is a remnant of the historical supernova of 1054. Now, there is a pulsar inside the nebula, which is clearly visible in the optical, X-ray, and other ranges of the spectrum. The Km2A experiment 'sees' this source in the energy range of 40–400 TeV at a level above 46 standard deviations.

The spectrum at energies above 1 TeV, measured by the WCDA and Km2A facilities, agrees well in principle with that expected from the scattering of electrons by photons (inverse Compton effect), thus indicating that the lepton acceleration mechanism is definitely operative there. However, this mechanism is expected to only operate at energies below 1 PeV, and the spectrum becomes sharply steeper in the energy range of several hundred TeV. However, gamma rays with energies above 1 PeV from the Crab Nebula have already been registered. As noted in [13], most likely, a proton (hadron) PeVatron is also operative there, generating gamma quanta in the decay of neutral pions. This mechanism implies that pulsars in the Galaxy are sources of cosmic rays with energies up to $\sim$ 10 PeV per nucleon. Actually, most likely, the energies can be even higher, since the collection of statistics is ongoing, and the maximal possible energy of gamma quanta is still unknown, while the energy of the parent protons should be approximately an order of magnitude higher than that of the resulting secondary gamma quanta (first, the energy is distributed between the produced pions; then, the neutral pion generates two gamma quanta, and the energy is halved). The spectrum of gamma rays from the Crab Nebula measured in a wide energy range from 0.3 TeV to 1.6 PeV is approximated well by a power-law spectrum with a differential exponent of 3.12 ± 0.03.

4. Results and discussion

Summarizing, the first results of the LHAASO experiment already have far-reaching consequences. They herald the beginning of a new stage in studying cosmic rays, their sources, and astrophysics. Until now, gamma astronomy and cosmic-ray physics have existed separately, but now, when the energies of the observed gamma quanta extend to a region above 1 PeV and their source is accurately identified, these branches of research merge. It turns out that both are formed in the same sources and in the same processes. This is especially important for the physics of cosmic rays. Apparently, the model of cosmic ray acceleration in supernova envelopes fails to pass experimental verification, and new models are required. In this connection, it would be relevant to recall that, from the very beginning, this model was not supported by all scientists. Of special importance for this issue of *Physics–Uspekhi* is that it was not supported by A E Chudakov, and he argued about it with V L Ginzburg. For example, paper [1] contains the following assertion: "One cannot exclude the possibility that envelope of supernovae are not so powerful source of cosmic rays as it is assumed at present. If so, the solution of the problem of cosmic rays origin is to be connected with the objects of another nature, perhaps on the earlier stage of our Galaxy development." These words were prophetically written by Chudakov in 1963. In our opinion, the idea pertaining to the early stages of the development of the Universe correlates very well with the hypothesis of F Aharonian et al. [11] if we assume that the processes occurring in the early Universe were identical to those that now occur in clusters of young massive stars or in the center of the Galaxy.

Finally, theorists should look for new mechanisms for the acceleration of cosmic rays by pulsars that could explain the gamma-ray spectra observed in the LHAASO experiment, the close but not complete spatial coincidence of detected sources with pulsars, and other features. The LHAASO results have been highly assessed in a recent paper [14], where they are compared with the detection so far of the 'tip of the iceberg.' The possible mechanisms of cosmic ray acceleration in relation to the discovery of PeVatrons in the Galaxy are also discussed there. The significance of the first LHAASO results is also evidenced by the number of citations

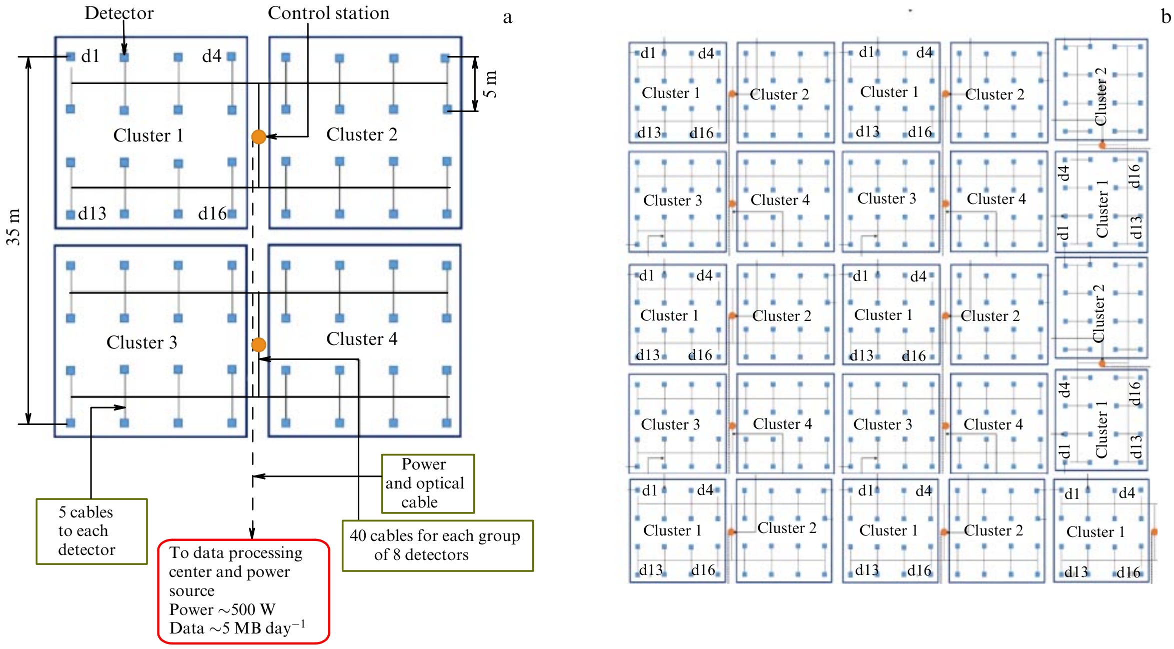

Figure 2. (Color online.) Configuration of two ENDA facility versions: (a) initial ENDA-64; (b) full ENDA-400.

of the above-mentioned studies, which exceeds 100 in six months.

5. Prospects

5.1 Background information

Further development and the possible extension of the LHAASO project facilities will be determined by the logic of the development of the experiment and the results obtained. The use of the created infrastructure — roads, high-speed communication lines, proximity to the airport — will undoubtedly continue in the long term. As new tasks arise, new projects will appear. For example, in the future, it is planned to extend research to the field of gamma-ray astronomy: the detection and study of gamma-ray bursts (GRBs) and exploration of potential sources of cosmic rays, including active galactic nuclei (AGNs), pulsars, supernovae, clusters of young massive stars, and the Galaxy center. Astrophysical research will be complemented by the search for dark matter and any new phenomena that go beyond standard models.

One of the most important areas of LHAASO research is the measurement of the energy spectrum and mass composition of cosmic rays. It is specifically this area that is explored by the INR RAS research team. To this end, as part of the project, a special facility, ENDA, is being developed at INR, which will also be used to conduct geophysical surveys by analyzing variations in the natural flux of thermal neutrons.

5.2 ENDA project

The ENDA project is a development of the earlier PRISMA (PRImary Spectrum Measurement Array) project proposed by us [15] in 2008. The main idea of the project is to detect the EAS hadron component over the entire area of the facility using specially designed electron–neutron detectors placed on Earth's surface in the form of a uniform grid with a spacing of 5 m. The original LHAASO project did not provide for hadron detectors. At the INR's suggestion, the project was complemented with the ENDA facility, which consists of 400 en-detectors developed by INR (electron–neutron detectors that detect both the electron and the hadron components over the entire area of the facility). The facility inside the LHAASO with a total dimension of 100×100 m^2, within which the detectors are installed with a 5-meter spacing, will enable a more accurate determination of the mass composition and energy spectrum of cosmic rays in the PeV energy region. In fact, the central part of the facility will become a huge hadron calorimeter with an area of 1 hectare with an option of unlimited expansion in the future. Figure 2 shows two versions of the ENDA deployment: the initial version consists of four clusters of 16 detectors, and the final one, of 25 clusters. Currently, one cluster of the future ENDA facility is operating in test mode on the LHAASO site [9].

5.3 Motivation

Why should the hadronic component of an EAS be studied? It would be relevant to recall that, as was shown in Zatsepin's work in the mid-20th century, an EAS is a hadron cascade, and it is the hadron component that is its main element, while all the other components are secondary. Nevertheless, experimenters have measured and continue measuring primarily the electromagnetic component, explained by the fact that, as previously thought, an EAS is a purely electromagnetic cascade in the atmosphere. Finally, the electromagnetic component, as the most prolific, produces the main ionization, which is measured by conventional charged particle detectors. Hadrons make up a small additive at the level of 1–2% in terms of quantity and contribution to the total ionization, and, as a rule, they are not separated in registering EASs.

The mathematical apparatus of the EAS method, developed many years ago, only uses the electron component: the age of the shower, which determines the function of the spatial distribution of electrons, and the parameter N_e, which specifies the number of particles in the shower. However, if the EAS phenomenology and its properties at the observational level are explored, a comprehensive study of hadrons in EASs, which determine its properties, is a must. This refers to the measurement of hadrons over the entire area of the facility with a low detection threshold and the use of the measured parameters to reconstruct the energy and mass of the primary particle. Hence, it is clear that attempts to provide a solution to this problem using neutron monitors or hadron calorimeters with a small area and high threshold energy as in the KASCADE (KArlsruhe Shower Core and Array DEtector) experiment (the area of the largest hadron calorimeter in the experiment was 320 m^2 at a threshold energy of 50 GeV) could not be successful.

It is believed that the hadron and electron components are in dynamic equilibrium. This is true, however, only for fairly powerful showers, where the number of cascading high-energy hadrons N_h is sufficiently large. However, as the shower attenuates while passing through the atmosphere, a moment inevitably comes when the number of remaining hadrons is small. Since the number of particles is an integer, at some point the last of the cascading hadrons loses its energy and either decays or is captured, and N_h becomes equal to zero. It is of interest that Greisen [16] drew attention to this circumstance as early as 1960, noting that N_h can be small, down to $N_h = 1$, and this explains the observed large fluctuations in the EAS development. However, Greisen, unfortunately, failed to make the next logical step: 1 is followed by 0! This is a special type of EAS, or more precisely, the stage of development of any shower, which we referred to as coreless [17]. Such showers are drastically different from conventional EASs and are essentially electromagnetic cascades with an admixture of muons and low-energy hadrons (for example, neutrons) at the periphery. These showers have no core, are very loose, have an anomalously large age of ≈ 2, and cannot be described using the usual Nishimura–Kamata–Greisen (NKG) function. As a result, the reconstruction of the parameters of the primary particle of such showers using the standard procedure turns out to be invalid and gives an erroneous result. Data on coreless showers should be either processed using a separate procedure or discarded during processing, which sets a lower limit for using the EAS method that, unfortunately, was not established at the time. This limit depends on the altitude of observation above sea level. Calculations show that this shower power limit is $N_e \sim 10^{6.0} - 10^{6.5}$, which corresponds to the energies of primary particles in the PeV region.

To correctly process EAS data in the PeV energy range, which is transitional from coreless EASs to ordinary ones, a full-fledged measurement of the hadronic component is required. This requirement was the motivation and goal of the PRISMA project, and later the ENDA project, in which it was proposed to register thermal neutrons over the entire facility area using en-detectors developed for this purpose. Our proposal was accepted by the leadership of the LHAASO experiment, as a result of which, in 2019, the creation of the ENDA facility and its deployment began.

As a result of the operation of en-detectors, another area of their application was discovered, namely, the study of various geophysical phenomena by registering and analyzing the natural flux of thermal neutrons. The high stability and sensitivity of the en-detectors to weak fluxes of thermal neutrons in dynamic equilibrium with the environment have already enabled us to discover a number of new geophysical effects [18–21]. These studies will be continued at the ENDA facility.

5.4 En-detector and ENDA facility design

To enable detection of hadrons over the entire area of the facility, a dedicated detector had to have been developed, since conventional EAS detectors are not suitable for this purpose. As a result, a large-area scintillation detector, an en-detector, was developed that is capable of concurrently detecting two EAS components: the electron (e) and neutron (n). The design of this detector is identical to that of a conventional EAS detector, with only one difference. Instead of the standard, usually plastic, scintillator, it uses a very thin layer (50 mg cm^{-2}) of a specialized inorganic scintillator, a luminescent compound consisting of silver-activated zinc sulfide (ZnS(Ag)) and the boron-containing substance B_2O_3, which is an alloy of these substances. Natural boron contains 19% of the ^{10}B isotope, which has a large thermal neutron capture cross section (3800 b), which provides the efficiency of thermal neutron detection at a level of 20%, even without isotope enrichment and even for such a thin layer.

The scintillator is viewed with one 4-inch CR165 photomultiplier tube (Beijing Hamamatsu). A standard 200-liter polyethylene water tank is used as the detector housing. To enhance light collection, a light-collecting cone made of an elastic material with good light reflection, EVA (ethylene vinyl acetate), is used. The employed scintillator features several glow times, due to which it has a very strong advantage: signals from heavy products of slow neutron capture and from relativistic charged particles can be separated based on the pulse shape. All pulses are digitized using a direct conversion analog-to-digital converter (flash ADC), and their shape is analyzed by an online program. This feature makes it possible to also use en-detectors to study variations in natural fluxes of thermal neutrons and their correlations with various geophysical phenomena. As a result, an inexpensive, reliable, and stable detector is now available, which has already been tested in operation on several prototypes, including in high altitude conditions.

6. Conclusions

The international high-altitude experiment LHAASO, which is now in the process of development, has already yielded research results of uttermost importance. Owing to the immense effective area of the Km2A setup, the high density of detectors, an efficient and reliable data acquisition system, and high altitude, this experiment will be unrivaled in the next decade. During the first year of operation of only part of the facility, 12 new sources, including PeVatrons, have already been discovered. The 'reference candle,' the Crab Nebula, which, as it turns out, also contains an operative PeVatron and possibly even two of them — a lepton and a hadron — has been comprehensively studied. The energy spectra of the gamma rays emitted by them have been measured; at least for some sources, they are described well by a power law with a differential exponent close to three. In the next few years, as the area of already operating facilities expands, new facilities (ENDA) are added, and statistics from the LHAASO experiment are accumulated, one can confidently expect new outstanding discoveries, in gamma astronomy and astrophysics, the physics of ultrahigh-energy cosmic rays, and even geophysics. The LHAASO research program and details of the experiment are reported in more detail in the *LHAASO Science Book* [22].

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