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Spatiotemporal Structure of a Reflected Cherenkov Light Signal, as Seen by the Sphere-2 Telescope

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Abstract—SPHERE-2 is a Cherenkov telescope suspended under a tethered balloon and observing the optical Vavilov–Cherenkov radiation of extensive air showers (EAS) reflected from the snowy surface of Lake Baikal. Extended modeling of the SPHERE-2 detector's response is done with a specially developed code. Resulting model events resemble EASes observed during observation runs at Lake Baikal. This work should facilitate event-by-event studies of cosmic ray mass composition in the 10–100 PeV range of energies.

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INTRODUCTION

The aim of the SPHERE project is to study primary cosmic radiation in the energy range above 3×10^{15} eV. The SPHERE-2 Cherenkov telescope observes the Vavilov–Cherenkov radiation of extensive air showers (EAS) from cosmic particles with energies from 10^{16} to 10^{18} eV, reflected from the snow-covered surface of the Earth. Measurements were made in the winter period of 2009–2013 over the snow-covered ice surface of Lake Baikal. The detector was lifted to a height of 900 m above the lake. More than a thousand events classified as being caused by reflected Cherenkov light produced by extensive air showers were observed.

The SPHERE-2 setup is a small optical device lifted above the ground with a tethered balloon. Its optical system consists of a spherical mirror with a diameter of 1.5 m and a 940 mm radius of curvature, a retina of 109 photomultipliers at the focus of the mirror, and a Schmidt restricting diaphragm with an inlet diameter of 930 mm [1]. The setup has a wide viewing angle of 52 degrees, allowing us to observe large snowy surfaces with areas roughly equal to the square of the height of the setup. The data acquisition system with 109 electronic channels allows data to be recorded and saved.

Unlike ground-based Cherenkov arrays, the characteristics of the SPHERE-2 facility exposure depend on the measurement conditions, the most important of which is height H of the telescope above the snowy surface reflecting the EAS Cherenkov radiation. The parameters of exposure must therefore be calculated separately for each position of the setup.

MODELING

To calculate the characteristics of the facility, we performed full Monte Carlo modeling of EAS development from particles of primary cosmic radiation, Cherenkov light reflected from snow, effects of the detector's optical system, the conversion of photons into electrical signals in the detector, and the operation of the detector's triggering system.

The CORSIKA 6.500 software package [2] was used to calculate the spatiotemporal structure of EAS Cherenkov radiation at the level of the reflecting surface with the QGSJET-I/II [3, 4] models of high-energy hadron interactions and the GHEISHA model [5] of hadron interactions at low energies. The calculations were perormed for an level of observation 455 m above sea level, which corresponds to the height of the surface of Lake Baikal. To speed up the calculations, the quantum efficiency of the FEU-83-4 photomultipliers used in the experiment and mirror reflection coefficient $K = 0.9$ were considered at this stage. The propagation of light was assumed to be independent of frequency, and equivalent photoelectrons from EAS Cherenkov photons are traced with the quantum efficiency of the photomultiplier taken into account. Modeling was perfomed for four types of primary nuclei (protons, helium, nitrogen and iron); for three energies (10, 30, and 100 PeV); and two ranges of zenith angles (up to 20 deg and 20 to 40 deg from the normal). A total of more than 1500 different cascades were calculated.

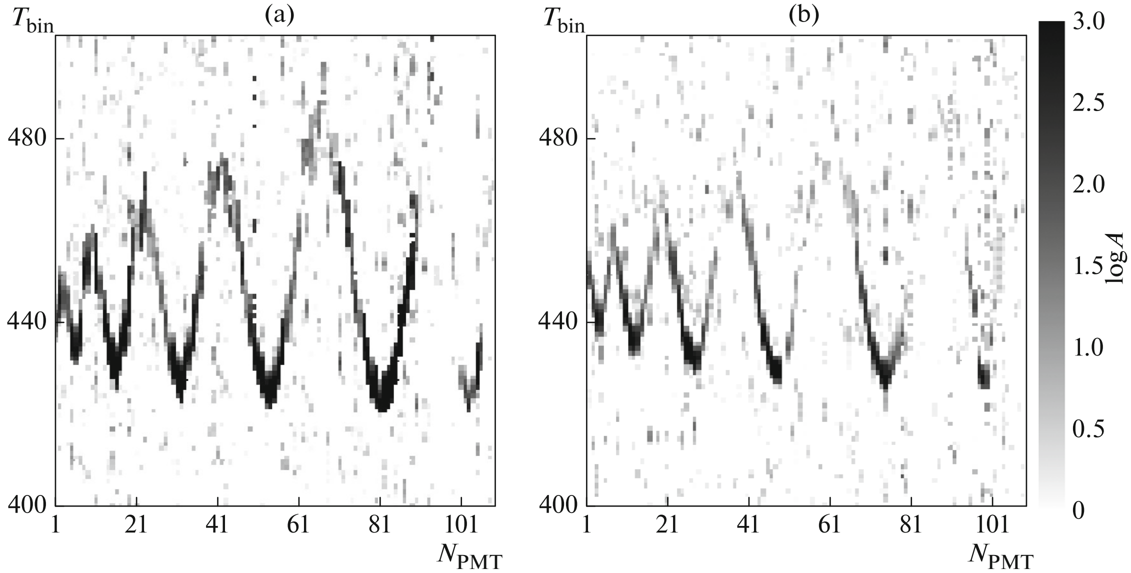

Fig. 1. Examples of the SPHERE-2 detector's response: (a) calculated response of the facility at a height of 580 m above the level of observation for Cherenkov light from an iron nucleus with an energy of 30 PeV; (b) event of the 2013 experiment, recorded by the setup at a height of 589 m.

The result from the first stage of modeling for each primary nucleus is a spatiotemporal three-dimensional array of equivalent photoelectrons at the level of the lake's surface: $F(nx, ny, nt)$ = F[480][480][102], with a spatial step of 2.5 m in two coordinates and 5 ns in time.

Optical and geometric effects of light propagation from the snowy surface to the detector were considered at the next stage of modeling. These included the reflection of light from snow and a model of the detector's optical system. Each photomultiplier of the detector, lifted to height H, observes its own part of the reflecting surface and registers the photons of Cherenkov light that come from it. The reflectance from snow is almost constant in the 300 to 400 nm region of photomultiplier tube (PMT) sensitivity [6], allowing us to operate already at the previous stage of calculation in terms of effective photoelectrons.

The GEANT4 program code was used to model the passage of photons through the optical system of the detector at height H above the level of the lake's snowy surface [7]. Calculations were performed for heights of 400, 500, 580, 700, and 900 m, corresponding to the detector's locations in the experiment. For each primary nucleus from the first stage of modeling, the array of photons that reached the photocathodes of the PMT detector when the installation was at all five specified heights was calculated for 100 possible locations of the shower axis in the facility's field of view. Five hundred different versions of the detector's points of view were calculated for each shower, producing an array of effective photoelectrons that reached the PMT retina. The time of arrival, the PMT number, the distance to the center of the photocathode, and the angle of incidence on it were recorded for each effective photoelectron.

At the third stage, the electronic part of the setup with a resolution of 1 ns was modeled. The absolute calibration factor of installation [8] was allowed for to normalize the output signal. The background light and electronics noise was considered by adding part of a channel-by-channel sweep of experimental data from a region far from that of the registration of the Cherenkov signal to the calculated data. The resulting model responses were stored in a format similar to that of the SPHERE-2 detector's experimental data: the signal amplitudes from 109 measuring channels with a resolution of 12.5 ns and a total duration of 1.2 μs. This allowed us to process the modeled and experimental data using the same programs.

At the next stage, the calculated detector responses passed through the trigger system operation model of the setup for each experimental measurement session. In the measuring channels of the discriminators, thresholds were set equal to the experimental ones. The setup's efficiency of registration was then determined for each measuring session.

Figure 1a shows an example of the calculated response of the SPHERE-2 detector at an altitude of 580 m above the snowy surface to a primary iron nucleus with an energy of 30 PeV and a zenith angle of 27.5 deg. Experimental noises are superimposed on the calculated signal of the measuring channels. This event passed trigger selection in the trigger model. The abscissa axis in this figure shows the number of the measuring channel; the ordinate, the time bin number 12.5 ns long. The measuring channels are numbered

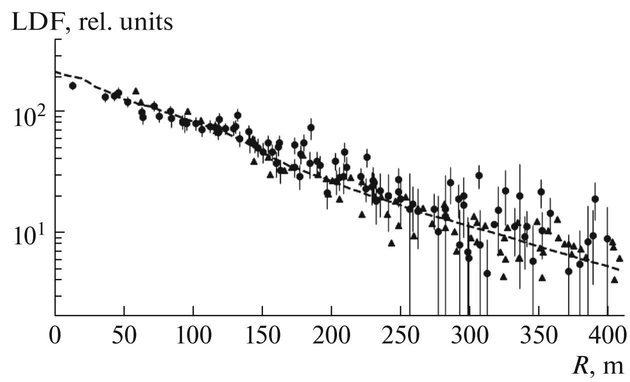

Fig. 2. Cherenkov light LDF according to the model (triangles) and experimental (circles) detector responses, shown in Fig. 1. The dashed line shows the composite LDF for the same event when modeled.

according to their location in the PMT mosaic in a diverging spiral, starting with the central PMT with number 1 [1]. For comparison, Fig. 1b shows event 2013-1-11228, registered in 2013 by SPHERE-2 setup at a height of 589 m above Lake Baikal. The distance from the center of the field of view of the optical part of the facility to the shower axis was around 145 m for both events.

The simulated and experimental responses of the detector are processed by the same algorithms. The lateral distribution function (LDF) of EAS Cherenkov light in particular can be obtained from detector responses. For a set of the calculated responses of a detector at a certain height, a composite model quantity is plotted from one primary shower: $F(nx, ny, nt)$, the spatial distribution function of the EAS Cherenkov light from this particle. It is found by averaging the LDF, plotted using trigger-tested detector responses calculated on the basis of spatiotemporal array $F(nx, ny, nt)$ of photoelectrons of the same primary particle. The composite LDF registered by the detector at a certain height thus corresponds to the LDF image of an extensive air shower, averaged over different locations of the shower axis within the detector's field of view. The fluctuations of registered photoelectrons are averaged in the composite LDF, but the information about the fluctuations in the evolution of the initial EAS is preserved.

The triangles in Fig. 2 show the LDF for the same model response of the detector as in Fig. 1a. In obtaining a composite LDF, this model function was averaged along with other LDFs plotted from the responses of the SPHERE-2 detector at a height of 580 m above the snowy surface. It corresponds to the effect from a primary iron nucleus with an energy of 30 PeV and a zenith angle of 27.5 deg. The resulting composite LDF for this shower is shown in Fig. 2 by a dashed line. The dots in this figure represent the LDF, normalized to the model function. The same experimental data from the detector at an altitude of 589 m were used in this case (see Fig. 1b).

CONCLUSIONS

The SPHERE-2 detector is the only one by which an appreciable number of EAS were recorded by registering reflected Cherenkov light, and the spatial distribution functions of the Cherenkov light were plotted for all these events. Detailed Monte Carlo modeling of the detector's response was performed using a special modular code. The calculation results were virtually independent of the proposed model of the optical properties of snow. The results allowed us to study the mass composition in the event-by-event mode. Work is now under way to further improve the modeling procedures and determine the particle mass of primary cosmic radiation.

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