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Antarctic balloon-borne detector of high-energy cosmic rays (SPHERE project)

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Abstract

The experiment SPHERE is based on a A.E. Chudakov's suggestion to use a new method for investigations of the energy spectrum of ultrahigh-energy primary cosmic rays. A small device lifted up off a snowed surface of the Earth detects Cherenkov light of an extensive air shower that is reflected from the surface. A contemporary status of the experiment SPHERE, a description of the method, the first measurements of the background night starlight in the region of the Russian Antarctic station Novolazarevskaya are presented. A relatively simple detector SPHERE-2 including a spherical mirror of the diameter 1.5 m and a 100-pixel retina is developed for Antarctic balloon-borne measurements of the cosmic ray spectrum. A long-time winter flight makes it possible to measure the spectrum above 10^{20} eV. A comparison with satellite and ISS projects of the nearest future shows that efficiency of this detector is sufficiently high.

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Keywords: Cosmic rays; Ultra-high-energy particles; Extensive air showers; Balloon; SPHERE project

1. Introduction

Future progress in the field of ultra-high-energy primary cosmic rays is connected with studies of fine details of their energy spectrum. Such studies are possible on the basis of experimental arrays having a higher energy resolution independent of the nature of elementary acts of hadron interaction (calorimetric-type arrays) and a large effective area of detection. The total flux of Cherenkov light from an extensive atmosphere shower (EAS) is proportional to ionization energy loss of charged particles. On the other hand, ionization loss of the shower energy is nearly 70%–80% of the primary particle energy (for the wide energy range of 10^{15}–10^{20} eV). Therefore, the total flux of Cherenkov light of EAS is essentially proportional to the primary particle energy and thus the method of measuring the

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shower energy through a measurement of the Cherenkov light flux is of calorimetric type.

Ground-based experimental arrays are usually employed for Cherenkov light detection. A typical array consists of many detector units and covers an area up to $100\,km^2$ (in existing arrays), or even up to $1000\,km^2$ and more (in projects). But existing ground-based arrays do not directly measure the total Cherenkov-light flux because of large distances between the detectors ($\sim$1 km), so that primary-energy estimates are essentially based on calculations.

The method suggested by Chudakov (1972) makes it possible to really measure the total flux of Cherenkov light. Cherenkov light from EAS forms a light spot on a snow-covered surface. An array lifted up over the snow field during a cloudless and moonless night could monitor and detect such spots. With an array lifted up to the altitude H, one can have a sensitive area $\sim H^2$ (see Fig. 1).

In the energy range of 10^{18}–10^{20} eV, an interesting issue is investigation of the energy spectrum near the so-called knee (at $\sim 5 \cdot 10^{18}$ eV) in more detail. But the most challenging problem here is the Greizen–Zatsepin–Kuzmin (GZK) cutoff in the energy spectrum of cosmic rays. Experimental data of AGASA indicate that the GZK cutoff is absent. If the data are correct, serious difficulties come up for present-day theories. Perhaps, some source that radiates particles of giant energies lies in nearby regions of our Galaxy, or Lorentz invariance is violated at ultra-high energies.

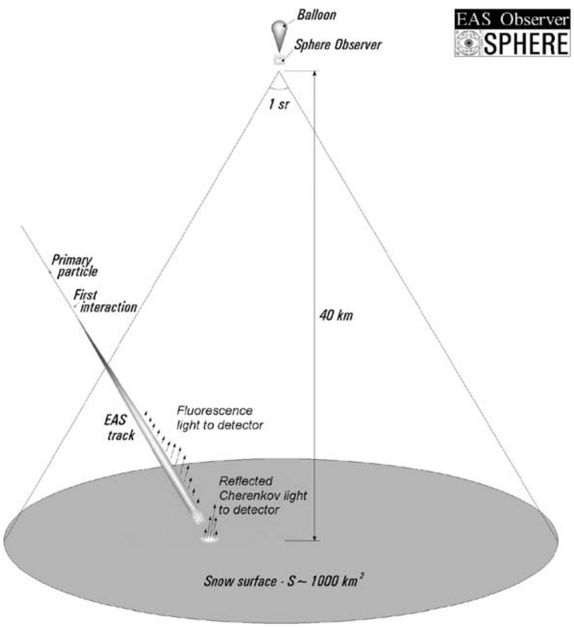

Fig. 1. Configuration of a long-time Antarctic-flight experiment.

Study of the energy spectrum and nuclear composition of the primary cosmic rays in the wide region of 10^{15}–10^{20} eV is the main aim of the experiment SPHERE. Two detectors, SPHERE-1 and SPHERE-2, were elaborated for these purposes. The first measurements with SPHERE-1 have been done in 1975–2000 (Antonov et al., 1975, 1986, 1997, 1999, 2001a). At this stage of the experiment, the detector was lifted up to 1 km above a snow field by a tethered balloon. Now a more precise detector SPHERE-2 in under development (Antonov et al., 2001b,c,d; Nikolsky et al., 2002).

2. Detector SPHERE-1

Fig. 2 shows a scheme of the detector SPHERE-1. Optical part of the array consists of a spherical mirror (diameter 1.2 m), a mosaic of 19 photomultipliers (PMT), and a Schmidt diaphragm for image correction. From the altitude of 1 km, each PMT observes an area of $\sim$200 m in diameter. Inside a 2 μs strobe, the number of photons and the pulse form is recorded with the step of 30 ns. Electronic control was automatically performed by means of an on-board computer. High voltage for PMTs and thresholds were adjusted (also automatically) according to PMT currents and the event rate. The thresholds, the PMT currents, the battery voltage, and a temperature inside a container with electronics were periodically checked. Stability of PMT amplifications was controlled by using standard light pulses delivered to every PMT with optical fibers. Data were stored at the hard disk of the computer.

Using the detector SPHERE-1 situated at the ground and directed to zenith, measurements of the starlight background have been performed in the region of the Russian Antarctic station Novolazarevskaya during the Antarctic winter of 2003 (Antonov et al., 2004).

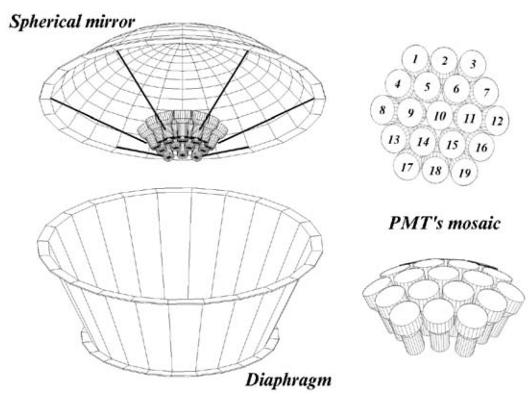

Fig. 2. Optical scheme of the detector SPHERE-1.

3. Detector SPHERE-2

Optical scheme of the detector SPHERE-2 is the same as that of SPHERE-1. The light image of EAS is viewed by 100 photomultipliers situated at the focal surface of a spherical mirror having the diameter 1.5 m. A full angle of view is ~1 sr. Fig. 3 shows a calculated image of a parallel light beam at the PMT retina. Practically all the beam energy is concentrated in a circle of the diameter ~4 cm as shown in Fig. 4.

The detector lifted up to the altitude of 30–40 km makes it possible to have a sensitive area of $\sim 1000\,\mathrm{km}^2$. After a primary cosmic-ray particle produces an extensive air shower of secondary particles, ionization (fluorescent) light generated by the particles creates a light track of EAS in the atmosphere. Every pixel of the PMT array observes an area of $\sim 3 \times 3\,\mathrm{km}^2$ at the ground level and $\sim 1.5 \times 1.5\,\mathrm{km}^2$ for part of the EAS track at the level of 15 km. A light image of the EAS track is collected to 1–5 pixels depending on the zenith angle of the track. Amplitudes and shapes of pulses in PMTs situated along the EAS track reflect the EAS cascade curve in the Earth's atmosphere. Measurements of the PMT pulse forms with the step of 100 ns enable one to determine the EAS track direction, the primary energy, and the form of the EAS cascade curve in the atmosphere. So, the detector SPHERE-2 will allow to detect both Cherenkov and fluorescent light of EAS.

Simulations show that energy threshold of the detector SPHERE-2 will be about 10^{18} eV under considered conditions. The expected number of ultra-high energy events with $E > 10^{20}$ eV during one 100 day flight is 20 to 30 provided the GZK cutoff is absent.

The reflection coefficient of snow will be controlled using an on-board flash lamp. The total power consumed by the SPHERE-2 apparatus is about 50 W.

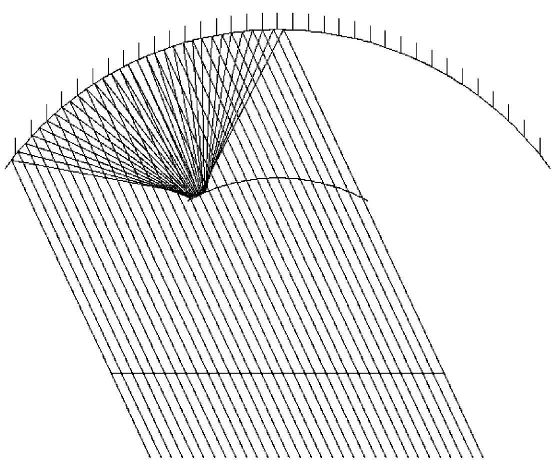

Fig. 3. Image of a parallel light beam at the PMT retina.

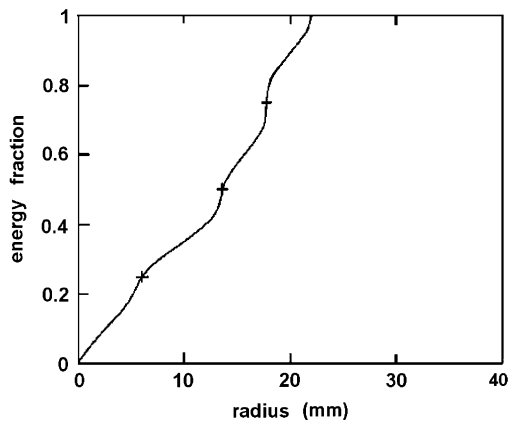

Fig. 4. Energy fraction of a parallel beam inside a circular spot of a given radius at the PMT retina surface (simulations).

The weight of the array without an electric battery is ~80 kg. The battery will add another 200–300 kg.

4. Conclusion

Like SPHERE, many experimental projects (Auger, EUSO, AIRWATCH, etc.) are aimed at solving one of the most interesting problems in ultra-high energy cosmic-ray physics: Does the GZK cutoff exist? Despite such a serious competition, the balloon-borne experiment SPHERE in Antarctica has several advantages.

First, it is possible to perform long-time (up to 100 days) balloon flights around the South Pole at the altitude of 35–40 km and have a satisfactory count rate. The amount of ultra-high energy cosmic particles detected in such a flight will not differ too much from that to be obtained in a orbital experiment during 1 year.

Besides, Antarctic conditions are quite stable and convenient for such kind of experiments. There are no clouds and aerosols during winter nights, so almost 100% of time can be used for measurements which is much better than for orbital experiments. Conditions of light reflection from snow are also permanently stable.

The SPHERE-2 optical system having a rather large angle of view, ~60°, can be very simple because the same area resolution as in orbital experiments is achieved with the number of pixels for viewing the EAS image that is by the factor of 100 less.

For the same primary particle energy, amplitudes of the EAS light pulses in the balloon experiment are by the factor of 100 higher than those in an orbital experiment. Accordingly, energy threshold of $\sim 10^{18}$ eV can be achieved. It will be possible to measure the energy spectrum in the energy range up the GZK cutoff and beyond just in one experiment.

Two different methods of primary-particle energy measurements can be used. They are a detection of the

EAS fluorescence light and a detection of Cherenkov light reflected from snow. This feature provides a way for a cross check that improves a methodical accuracy of determination of the primary particle energy.

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