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The Prototype SPHERE-Antarctica Station and the Possibility of Using Silicon PMTs to Detect the Cherenkov and Fluorescent Light of EASes

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Abstract—The design for a balloon instrument to study the energy spectrum and mass composition of primary cosmic rays at energies exceeding 10^{18} eV is presented. It is planned to conduct the experiment during Antarctica's polar night. The equipment allows the separate registration of fluorescent light (FL) and Cherenkov radiation (CR) in each event. The advantages of the experiment over existing ground-based installations and future orbiting stations are discussed. A way of separating FL from CR with light filters and optical silicon detectors is described.

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INTRODUCTION

The problem of determining the basic characteristics (energy spectrum and mass composition) of primary cosmic rays (PCR) particles at high and ultrahigh energies is highly relevant. The region of ultrahigh energies (10^{18}–10^{20} eV) is of special interest for researchers trying to discover the mechanisms of particle acceleration in sources both in and outside the Galaxy. Research on irregularities in the shape of the energy spectrum and specific features of the mass composition of cosmic rays could provide valuable data regarding the role of extragalactic PCRs. Although several large-scale experiments (the Telescope Array Project [1], the Pierre Auger Observatory [2], Yakutsk [3]) have been performed in recent years, the problem remains unsolved. This is because of the complexity of the problem itself, the complexity of experimental techniques with methodological errors that are often hard to estimate, and the lack of statistics (especially in the region of ultrahigh energies, where accelerator data on the characteristics of interaction are also scarce).

Anisotropy and the grouping of directions of cosmic ray arrival are observed in current experiments at energies higher than 6×10^{19} eV [4, 5]. The interest in this problem stems from the lack of a commonly accepted mechanism of PCR particle acceleration to energies higher than 3×10^{18} eV, the unknown nature of sources of such particles, the discrepancy between results from measuring the PCR spectrum above 5×10^{19} eV in large-scale experiments [6], and the differences between the experimental and model data [7].

THE SPHERE-ANTARCTICA PROJECT

It is hoped that the SPHERE-Antarctica project will help to solve the above problems [8]. A schematic diagram of the proposed experiment is shown in Fig. 1, and it is compared to several existing installations in Table 1. The new station is designed to detect fluorescent tracks of extensive air showers (EASes) in the atmosphere and measure the total integral of Cherenkov radiation (CR) of EASes. This integral is the most accurate measure of the primary particle energy, and the one least sensitive to our choice of the EAS development model. None of the facilities now operating is able to detect the complete CR flux of EASes in the indicated region of energy.

The energy spectrum and the mass composition of cosmic rays at 10^{18}–10^{20} eV are expected to be examined by detecting reflected CR and FL of EASes during the Antarctic polar night with the SPHERE-A balloon station at an altitude of ~30 km. Its geometry factor for CR is $A_{CR} \sim 1300$ km^2 sr, and the factor for CR and FL detection is $A_{CR+FL} \sim 15$–30% A_{CR} (depending on the primary particle energy when at least 50% of an FL track is registered).

The project has several stages of implementation. In the first stage, a tracker probe will be launched in order to determine the probable trajectory of the station's motion and measure the background light. Test measurements with a prototype station will be performed next. The actual SPHERE-A assembly will then be launched. At the last stage, several units will perform regular measurements over 3–10 years. The second phase of implementation (assembling the SPHERE-A prototype) is discussed below.

TASKS OF THE PROTOTYPE

The main tasks of the propotype are to test the technical and engineering design of the equipment, make precise measurements to detect several tens of EAS events, test the procedure for reconstructing EASes and PCR properties using the data on detected events, and to determine experimentally the energy threshold and compare it to simulated data.

The prototype is to take a 30-day flight over Antarctica at an altitude of 30 km during the polar night. As many as 130 EAS events with energies exceeding the energy threshold of the station (5×10^{18} eV) could be detected in this flight. This number was calculated by assuming that the surveyed area would be 600 km^2, the solid angle of event observation would be 4 sr, and the coefficients of the efficiency of observation time utilization are 0.5 (due to the presence of the Moon) and 0.9 (due to cloudy weather).

An instrument package designed to detect both FL of EAS and the flux of CR (reflected from the surface of snow) of EAS at energies ranging from 5×10^{18} to 5×10^{19} eV is being constructed for experiments with the prototype. The equipment having small mass and size that is capable of maintaining an altitude of 25–35 km above Antarctica's surface will be used in this experiment.

INSTRUMENTATION OF THE PROTOTYPE

Performance specifications of the prototype are presented in Table 2.

The optical system of the prototype features a system of lenses with correction for spherical aberration, an input window diameter of 160 mm, and a complete

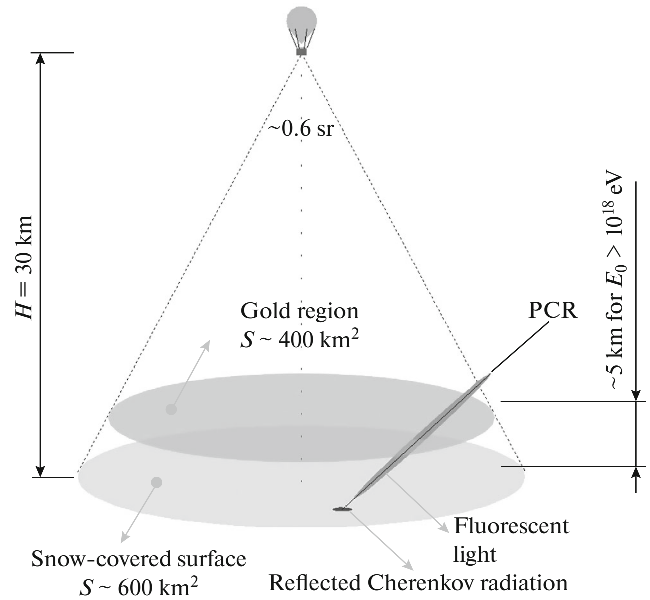

Fig. 1. Schematic diagram of the experiment in Antarctica. The SPHERE-Antarctica station and its prototype have similar geometric parameters, but differ in sensitivity and optical resolution (by a factor of ~10). Events from the gold region simultaneously contain data on CR and FL intensity.

viewing angle of ~0.6 sr (not to be confused with the EAS event observation angle of 4 sr). Optical EAS components are focused onto a matrix of 256 MicroFJ 60035 Series silicon photomultipliers (SiPMs) [9]. Each matrix element is 6 × 6 mm in size. The quantum efficiency of the photocathode in the maximum of its sensitivity at a wavelength of 420 nm is 40–50%. While having a quantum sensitivity comparable to that of common PMTs, SiPMs are more lightweight and compact and do not require high-voltage power. SiPM dark current is comparatively large in a standard laboratory setting, but falls considerably at the low temperatures encountered at an altitude of ~30 km.

All SiPM elements have a differentiating fast output that allows us to use SiPM data in the photoelectron count mode. This eliminates the need to use complex and energy-consuming analog-to-digital convert-

Table 1. Comparison of several current experiments

Setup	Methods			
	EAS particles	Cherenkov radiation	fluorescent light	position
AUGER (PAO)	X		X	Southern Hemisphere
Telescope Array (TA)	X		X	Northern Hemisphere
Yakutsk	X	X		Northern Hemisphere
SPHERE-A		X	X	Southern Hemisphere
JEM-EUSO (K-EUSO)		?	X	Northern and Southern hemispheres

Table 2. Prototype characteristics

General specifications	
Aperture diameter	160 mm
Input window area	0.02 m^2
Weight of instrumentation	Up to 10 kg
Detector and electronic equipment	
SiPM (6 × 6 mm) channels	256
Laser lidar	0.3 W, 405 nm
Positioning system	GPS/GLONASS
Satellite communications system	Iridium or Gonets

ers. The measuring channel operates on the basis of a programmable logic microchip. The presence of a photoelectron at the channel input is checked every 5 ns. This time step excludes the possibility of counting losses or double counting, since the half-amplitude duration of the SiPM signal is also 5 ns.

The trigger board allows us to select events from the light background and generate an event number to form an event frame from the data files. The trigger is based on a single programmable logic microchip with 256 inputs. The algorithm generates a trigger signal when two, three, or four neighboring cells send a query for generating a trigger confirmation signal.

Measurements performed by stratospheric detectors and orbital stations are subject to errors introduced by EAS CR scattered in the atmosphere. The reliable separation of Cherenkov radiation from fluorescent light in the atmosphere is therefore crucial to enhancing the accuracy of experiments involving cosmic rays of super- and ultrahigh energies. The effect scattered CR has on the results of FL measurements was noted in the JEM-EUSO project [10]. This effect

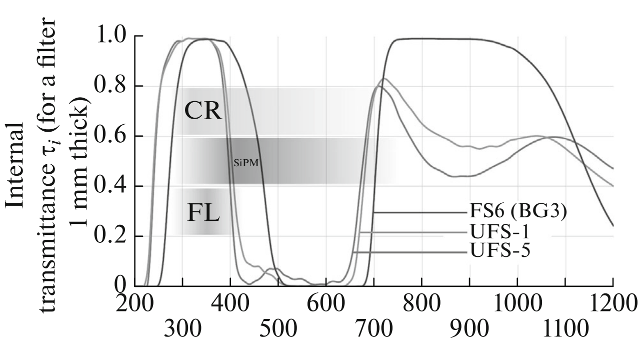

Fig. 2. Spectral characteristics of the FS6 (BG3), UFS-1, and UFS-5 optical filters. Horizontal bands denote the spectral regions of CR and FL and the region of SiPM sensitivity. The darker areas of the bands correspond to the radiation (sensitivity) maxima.

will be allowed for by separating CR from FL. The procedure for this is based on the detection of radiation by two (or more) photoreceivers with light arriving at them either directly from the collecting lens or after passing through an additional optical filter (installed on every other photoreceiver). If the sensitivity parameters of photoreceivers, the absorbing characteristics of filter elements, and the spectra of Cherenkov and fluorescent light are known, the fraction of each component in the overall luminous flux can be calculated. For example, a UFS-1 filter transmits up to 80% of FL in the region of 250–370 nm (see Fig. 2), but blocks more than 90% of the CR tail in the region of 420–650 nm. UFS-5 and FS6 (equivalent to BG3) filters have similar characteristics. In other words, the method is based on the CR spectrum being broader than that of FL one, and a carefully chosen filter allows us to isolate these components.

The station's light-sensitive detector is expected to be calibrated in flight with a laser beam (i.e., laser lidar). The lidar consists of a control unit, a mechanical system for angular positioning, and an FVLD-300S-405 semiconductor laser diode with a radiation wavelength of 405 nm and an optical radiation power of 0.3 W; this corresponds to $\approx 9 \times 10^{-19}$ J/photon and $\approx 3.5 \times 10^{17}$ photon/s. To isolate the reflected light reliably, the duration of a laser pulse directed at the surface of the Earth should be ≈1 ms, which corresponds to $\approx 9 \times 10^{14}$ photons. The number of albedo photons from snow is then ≈1000, which corresponds to ~400 photoelectrons at an altitude of 30 km with the reflection coefficient of snow (0.9) and the cosine of the angle of light arrival to the detector allowed for. The background fluctuation in a cell is 100 photons (≈40 photoelectrons) in 1 ms. The corresponding signal-to-background ratio is approximately 10. The accuracy of calibration can be enhanced by repeating the procedure.

A standard GPS/GLONASS receiver module will be used to determine the position of the measuring equipment. The module provides the geographical coordinates and altitude of the detector.

The Iridium [11] or Gonets [12] satellite communications systems will be used to establish command reception and measurement data transmission. The area of coverage (Antarctica) and the limit on the power consumption of the transmitting and receiving equipment are the primary factors influencing our choice of a satellite system for data transmission.

Since the experiment is to be conducted during the polar night, solar batteries would be useless. Lithium cells will provide power for electronic components. Li/SOCl2 elements have a specific energy as high as 600 W h kg^{-1}. Common commercial batteries are designed to be used at temperatures as low as −60°C.

A stratospheric balloon will be used to lift the prototype station. The tentative volume of this balloon is 2000–3000 m^3, and its initial volume at sea level is 20–30 m^3. Small balloons of this type (e.g., the one used in the BARREL experiment [13]) require no complex infrastructure to be launched. A balloon filled with helium is easily held down by two men.

EXPERIMENTAL CONDITIONS IN ANTARCTICA

According to the data from long-term meteorological observations, the cloud cover in Antarctica in the period from May to September is 0–10% in the circumpolar regions and as high as 40–50% at a latitude of ~70 degrees. It is preferable to perform measurements in cloud-free conditions. However, since it is not possible to work in circumpolar regions with average temperatures as low as −60°C, the actual launches are expected to take place at coastal Russian Antarctic stations (Novolazarevskaya and Progress), where the average temperatures in June and July range from −15 to −20°C. Although strong winds predominate during these months, they normally drop to 1–2 m s^{-1} for several days. This is long enough to launch small balloon stations with their deployment and launch cycle extending for less than 12 h.

A constant anticyclone blows over the Antarctic polar region in June–August [14]. A low-pressure region that establishes a stable air funnel near the South Pole forms at an altitude of approximately 30 km. According to meteorological data accumulated over the years, balloons launched from coastal stations drift at an altitude of 15–30 km in the circumpolar regions of Antarctica. Turbulence and centrifugal flows predominate at lower altitudes. The temperature at an altitude of ~30 km varies from –15 to –80°C. The pressure at an altitude of 25–30 km is approximately 10 hPa (0.01 atm). The velocity of the wind varies from 0 to 470 km h^{-1}.

CONCLUSIONS

Measurements with the prototype SPHERE-A station constitute the initial stage of implementing the SPHERE-Antarctica project. The major advantages of the proposed technique are the capacity to measure FL and reflected CR of EASes simultaneously, the potential for multiple launches, and the ease and low cost of project implementation. Measurements in Antarctica allow us to observe PCR sources of the southern celestial hemisphere with high efficiency in terms of exposure time during the polar night, and provide (owing to the clear atmosphere) highly accurate values of CR and FL intensity. The existing infrastructure and logistical routes for delivering equipment to Russian polar stations considerably simplify the management of expeditions.

ACKNOWLEDGMENTS

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REFERENCES

1. http://www.telescopearray.org.
2. https://www.auger.org.
3. http://eas.ysn.ru.
4. Abbasi, R.U., et al. (Telescope Array Collab.), *Astrophys. J.*, 2015, vol. 804, p. 133.
5. Aab, A., et al. (Pierre Auger Collab.), *Astrophys. J.*, 2015, vol. 804, p. 15. doi 10.1088/0004-637X/804/1/15
6. Aab, A., et al. (Pierre Auger Collab.), *J. Cosmol. Astropart. Phys.*, 2015, vol. 2015, p. 49. doi 10.1088/1475-7516/2015/08/049
7. Aab, A., et al. (Pierre Auger Collab.), *Phys. Rev. D*, 2015, vol. 91. p. 032003. doi 10.1103/PhysRevD.91.032003
8. Antonov, R.A., Chernov, D.V., and Stozhkov, Yu.I., *Bull. Lebedev Phys. Inst.*, 2016, vol. 43, no. 2, p. 80.
9. http://sensl.com/products/j-series/.
10. Andreas, H., et al. (JEM-EUSO Collab.), *J. Phys.: Conf. Ser.*, 2015, vol. 632, p. 012092. doi 10.1088/1742-6596/632/1/012092
11. http://www.iridium.com.
12. http://www.gonets.ru.
13. Halford, A.J., McGregor, S.L., Murphy, K.R., et al., *J. Geophys. Res. Space Phys.*, 2015, vol. 120, p. 2557. doi 10.1002/2014JA020873
14. http://earth.nullschool.net/#2015/08/15/0900Z/wind/isobaric/10hPa/orthographic=30,-90,360.

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