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A combined approach to study the composition of 1–1000 PeV cosmic rays by EAS direct and reflected Cherenkov light detection

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In this study, we propose an alternative approach to solving the CR composition problem using a newly designed detector that registers the Cherenkov light from extensive air showers (EAS). The new SPHERE-3 telescope will be lifted by an unmanned aerial vehicle above the snow surface to an altitude of up to 1.5 km. The telescope's main detector will record an image of the EAS Cherenkov light reflected from the snow, while an additional detector will record an image of the angular distribution of the EAS Cherenkov light at the level of the telescope. Estimates show that observing both direct and reflected EAS Cherenkov light images will enable us to determine the direction and mass of the primary particle more accurately than existing ground-based detectors can.

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1. Introduction

Despite the significant efforts invested in CR composition studies above 1 PeV, the spectra of individual CR elements remain poorly understood. It is likely that the current approaches to solving the CR composition problem are limited in some way, and it is not possible to significantly improve the separability of the primary nuclei groups with these methods.

This work is based on the method of registering reflected Cherenkov light (CL), as proposed by A. E. Chudakov. This quasi-calorimetric method enables the energy of the primary particle to be estimated with the greatest accuracy for an individual event. The energy range of 1–1000 PeV has been chosen, since the mass composition of cosmic rays (CR) in the knee region of the spectrum is still subject to significant uncertainty.

The SPHERE-2 experiment [1] produced results regarding the composition of nuclei [2], but with significant uncertainty, however for a limited statistics of only about 1 000 EAS events [3]. An original technique for separating the light component and other groups of nuclei was employed [4, 5]. At the same time, SPHERE-2 indicated the potential for registering direct CL. 'Parasitic' flashes of direct CL passing through slits between mirror segments have been recorded [6].

The new SPHERE-3 project builds on this opportunity and its main task will be to precisely measure the mass composition of primary CR in the 'knee region' [7]. Rather than dividing the entire primary CR flux into groups, the aim is to establish a relationship between the primary mass and the immediate measured parameter or group of parameters, in order to attribute mass to each event.

Currently, detector design, CL parameters sensitive to the primary mass and optimisation of measurement processing methods are being sought. The sensitivity of the parameter to mass is being checked by classifying events according to this parameter.

2. SPHERE-3 telescope

The SPHERE-3 detector is being developed to expand and complement the capabilities of the previous detector. The utilisation of EAS reflected CL detection as the primary method for the detection will be complemented by the advantages inherent in direct CL detection. The telescope is to be composed of two detectors: firstly, a downward-looking reflected light detector; and secondly, an upward-facing direct light detector.

The SPHERE-3 telescope is to be elevated into the atmosphere by means of an unmanned aerial vehicle (UAV) to an altitude of 1 500 m above the snow-covered surface, with the objective of registering the reflected CL. Contemporary drones possess the capacity to sustain extended flight duration with high enough payload.

The new telescope, compared to its predecessor, will have an increased light collection area and a large mirror. Silicon photomultipliers (SiPMs) will be utilised as light sensitive elements, thereby facilitating enhanced sensitivity and superior temporal and spatial resolution.

A number of methods have been developed, drawing upon machine learning and neural networks, with a view to offering a complement to conventional approaches to the filtering of noise signals. In particular, the trigger procedure method for the reflected light detector using convolu-

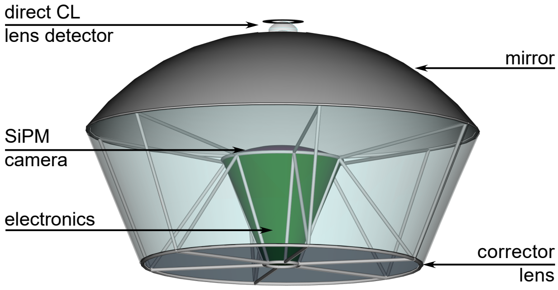

Figure 1: SPEHRE-3 detector general view.

tional neural networks (CNNs) has shown promising results on model data, with the capability to suppress 99% of noise signals [8]. The method is planned to be used for real-time event selection.

2.1 Reflected Cherenkov light telescope design

The detector utilises a Schmidt optical system comprising a composite aspherical mirror itself composed of 7 or 19 elements (depending in technical limitations of manufacturing), with a total diameter of 2 200 mm and an aspherical correction lens with a diameter of 1 700 mm (in order to enhance the optical resolution of the detector). The detector metal frame is to be composed of lightweight aluminium tubes 1. A camera of 379 segments, each containing seven SiPMs with light collector lenses, is installed near the focus of the mirror. The electronic systems are mounted directly beneath the photosensitive camera. This eases the assembly process and reduces cable lengths and the mass of the detector. The equipment is powered by the UAV's power system.

2.2 Direct Cherenkov light telescope design

The utilisation of angular images of direct CL is proposed as a means of enhancing the sensitivity to the mass composition. In order to achieve this a separate detector with its own matrix and lens will be used. We determined that a detector with 400 cm^2 aperture is sufficient for our task. The requirements for the matrix and the final design of this detector is not yet finalized. In case a blue-sensitive CCD chip with a very large cell is not available, the detector can be implemented using SiPMs with a segmented lens. However, the size of such a detector and the structure of its photosensitive camera will be comparable to those of a reflected light detector.

3. Primary particle parameters reconstruction

In order to determine the primary particle parameters (e.g. energy, arrival direction and mass) with the least possible uncertainty, a self-consistent procedure for their evaluation is required. However, it is first necessary to estimate the parameters as a preliminary approximation. Special procedures are employed for this purpose. The energy, the position of the EAS axis on the snow, the arrival direction, and the mass can be estimated using reflected light telescope data. It is evident that more accurate estimates of the direction and mass can be obtained from direct light detector data. The mass estimate can be further refined by combining data from both detectors.

The primary objective of the data analysis is to identify features that can be physically interpreted and that allow us to determine the parameters of the primary particle with understandable and physically meaningful characteristics. The development of these features will facilitate the control of the quality of the telescope design's automatic optimisation, incorporating machine and deep learning methodologies. The methods described below have now been developed.

The data of a reflected CL detector allows reconstruction of all characteristics of the primary particle. These characteristics include the arrival direction and energy. Furthermore, the classification of the particle by mass is achievable. The development and application of these methods was undertaken in the experiment with the SPHERE-2 detector [1, 5], and they are now being adapted for the new telescope. The data obtained from a direct CL detector facilitates the reconstruction of the particles' arrival direction and its mass. It is imperative to note that the estimation of energy cannot be conducted in the absence of external knowledge regarding the distance from the shower core to the detector. Nevertheless, the most promising approach is a combined data analysis that utilises data from both detectors for the same shower.

3.1 Axis location and arrival direction

The arrival direction of the shower can be reconstructed analysing relative delays in reflected photons arrival in different pixels [1]. Depending on the shower energy (and, therefore, number of bright enough pixels) this method allows for 1–2° precision.

The utilisation of direct CL detector data, which itself comprises angular information on EAS CL flux, facilitates the implementation of more sophisticated methodologies. In this case the determination of the particle arrival direction is achieved through the utilisation of key points, namely the maximum and centre of gravity of the angular distribution. The maximum and centre of gravity are found to be no more than 2–3° away from the shower arrival direction. This indicates that these points can be utilised as the particle arrival direction.

Nevertheless, it is possible to enhance the precision of the results by observing that both key points are offset from the actual direction, in a direction coinciding with the major axis of the spot. The magnitude of the offset is contingent on the distance between the detector and the axis of the shower, a measurement that can be obtained using the reflected light telescope. Subsequent to the subtraction of the magnitude of the offset from the coordinates of the key points, a result that is a fraction of a degree away from the true direction is obtained. The mean error is 0.10° (for the maximum) and 0.22° (for the centre of gravity) at a distance of 100 m from the axis.

3.2 Energy

The energy of a primary particle can be estimated using the approach from SPHERE-2 [5], but other approaches can also be probed using available higher computational power. It was found that energy estimation by means of backward interpolation of the dependence of the full CL flux (integral over the approximating function) on the energy and distance from the telescope axis to the axis of the snow shower yielded superior results in certain cases. A set of total CL flux dependences for varying energies and distances is derived from the model data. The energy dependence of total flux is derived from the points of this set, using known axis location from reflected CL data.

The method is applicable in both scenarios where the mass of the primary particle is unknown and when it is known. In scenarios involving unknown mass, the set of total flux dependences is

Table 1: Classification errors for long axis length method. p and Fe — misclassification probability for proton and iron, correspondingly, p-N and N-Fe — probability to classify proton as nitrogen and nitrogen as iron.

Energy	10 PeV		30 PeV	
zenith angle	15°	20°	15°	20°
p	0.25	0.27	0.31	0.30
p-N	0.26	0.28	0.26	0.28
N-Fe	0.23	0.23	0.23	0.28
Fe	0.24	0.24	0.23	0.28

regarded as a composition of groups of varying energies, each group corresponding to a specific mass. Else, the set of dependences for the considered mass is taken.

3.3 Mass

The determination of the primary particle mass from the reflected CL data is based on the use of the Spatial Distribution Function (SDF), obtained by approximating the light distribution on the detector camera.

Owing to the continuity of the SDF, it is possible to compute total number of CL photons in the camera and use it a normalization factor (and energy estimation parameter). Since there is a correlation between the shape of the distribution and the type of particle, the method relies on calculating two integrals: one over a central circle of the image on the mosaic, and the other over a surrounding ring. Based on these integrals, a criterion is constructed that allows for the classification of events by particle type, ranging from protons to iron nuclei.

The main measure of the method's accuracy is the type II error when separating events from different primary particle types. Currently, separation is performed between p-N and N-Fe groups, with the present error rate being about 38%.

The angular distribution of CL also hold the information on the particle type and can be studied with the aim of identifying a primary mass-sensitive characteristic. The first criterion developed is based on the length of the major axis of the spot. Optimal thresholds were selected, with these depending on the distance to the shower axis. A grid of criteria was constructed based on relative azimuths and on the distance to the shower axis, allowing the primary particles to be classified into three groups: protons, nitrogen, and iron. The classification errors a give in Tab. 1.

The second criterion is contingent on the ratio of integrals over two rectangular regions of the angular distribution, a methodology that aligns with that outlined in [9]. Moreover, for each distance under consideration, the optimal absolute threshold at which to minimise mass separation errors is selected. These errors are presented in Tab. 2.

At the moment, the position and size of the integration regions are being optimised. After that, it is planned to build a similar criterion grid and then to develop a criterion based on the approximation parameters of the angular distribution.

Table 2: Best classification errors for rectangles method for different distances from shower axis. Corresponding thresholds are given in brackets.

100 m (9 ph.e.)		140 m (11 ph.e.)		200 m (3 ph.e.)	
p-N	N-Fe	p-N	N-Fe	p-N	N-Fe
0.06	0.02	0.12	0.11	0.16	0.11

3.4 Dual detection

The utilisation of data from two detectors has been demonstrated to assist in the reduction of classification errors. In order to achieve this, it is necessary for the shower axis to be within the field of view of both detectors (see Fig. 2). At 500 m altitude, the axis should be positioned between 100 and 200 m from the detector. In case the shower axis being too close, the image becomes excessively small and difficult to analyse. In case the shower axis being distant, there is insufficient light. Furthermore, the intersection of the shower axis with the snow should be within a 175 m circle. The reciprocal position of the detector and the axis of the shower during dual registration is illustrated in Fig. 2.

In the context of the experimental setup, each event detected by the two detectors was assigned a point in the two-dimensional feature space. The length of the major axis for direct light was used as the metric, while the ratio of the integrals over the inner circle and outer ring for reflected light

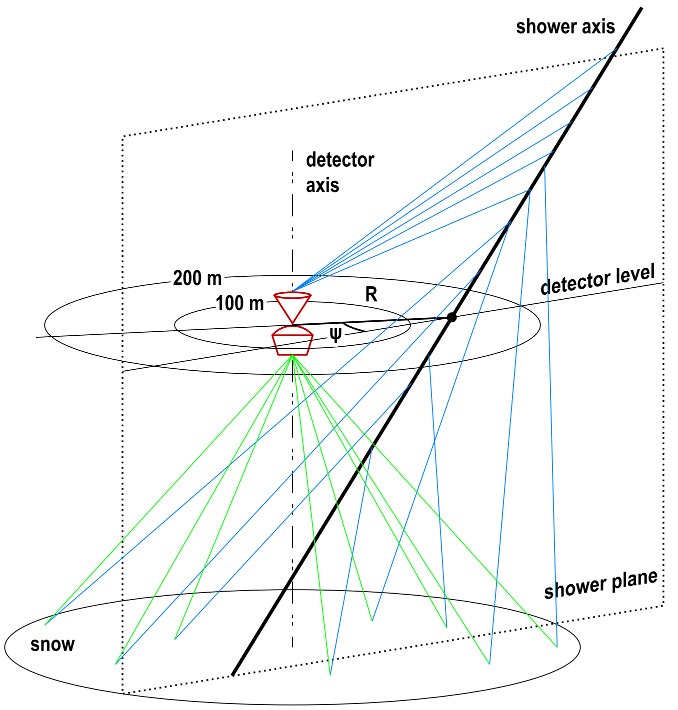

Figure 2: EAS detection at two levels. Reflected light (green) is collected by the lower detector of the SPHERE-3, direct light (blue) is accepted by the upper one.

Table 3: A comparison of mass classification errors for the reflected CL data, the direct light CL data, and the joint classification; p and Fe — misclassification probability for proton and iron, correspondingly, p-N and N-Fe — probability to classify proton as nitrogen and nitrogen as iron.

	p	p-N	N-Fe	Fe
reflected CL	0.32	0.32	0.31	0.31
direct CL	0.25	0.26	0.23	0.24
combined analysis	0.22	0.15	0.19	0.14

served as the secondary metric. Subsequently, lines were constructed in order to separate the points in a manner that would minimise separation errors. The method was employed to reduce the errors to the values given in Tab. 3.

4. Discussion

Presently, SPHERE stands as the sole experiment successfully implementing the registration of reflected CL from EAS. In the context of this series of experiments, a new mobile Cherenkov telescope, SPHERE-3, is under development. This telescope is equipped with two detectors: one for reflected CL and the other for direct CL. The primary purpose of this instrument is to facilitate a detailed study of the mass composition of CR. This fact renders the SPHERE-3 project under development unique, as the techniques proposed are entirely novel. It has been determined that the analysis of the angular distribution of the CL of EAS holds considerable promise for the successful completion of this task. Conducting such an experiment will facilitate the elucidation of the composition of high-energy primary CR, a subject of paramount importance in the contemporary field of CR physics.

Two methods for estimating the mass of a primary particle from the characteristics of direct light have been established, which demonstrates the value of the information obtained. The potential for dual detection by direct and reflected light was validated, and a methodology for particle mass classification utilising the combined data from both detectors was proposed. This demonstrates the capabilities of the SPHERE-3 detector.

In order to further reduce the separation errors, it is planned to improve the method of primary particle mass estimation from the ratio of integrals, for example, to select optimal integration regions and thresholds. It is also possible to search for other criteria, for example, among the approximation parameters of the angular distribution.

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