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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The SPHERE experiment

The method

The SPHERE project studies cosmic rays with energies of 1-1000 PeV. The technique is based on Professor A. Chudakov idea of detecting EAS Cherenkov light (CL) reflected from the Earth's surface by photodetectors elevated above the surface in aircraft (Fig. 1). In contrast to ground-based facilities, where the distance between Cherenkov detectors is rarely less than a hundred metres, the SPHERE telescope's field of view is continuous, and the entire flux of EAS CL is recorded. This reduces systematic errors in the determination of the primary particle energy.

The SPHERE-3 telescopes will measure the spatial and angular distribution of the EAS CL, in particular the light intensity in the axial region, which is a characteristic of the development of the shower that is sensitive to the type of primary particle. Rather than dividing the entire primary CR flux into groups, the aim is to establish a relationship between the primary mass and the directly measurable 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.

Reflected light detector

The detector utilises a Schmidt optical system comprising a composite aspherical mirror itself composed of 7 or 19 elements, with a total diameter of 2200 mm and an aspherical correction lens with a diameter of 1700 mm (in order to enhance the optical resolution of the detector).

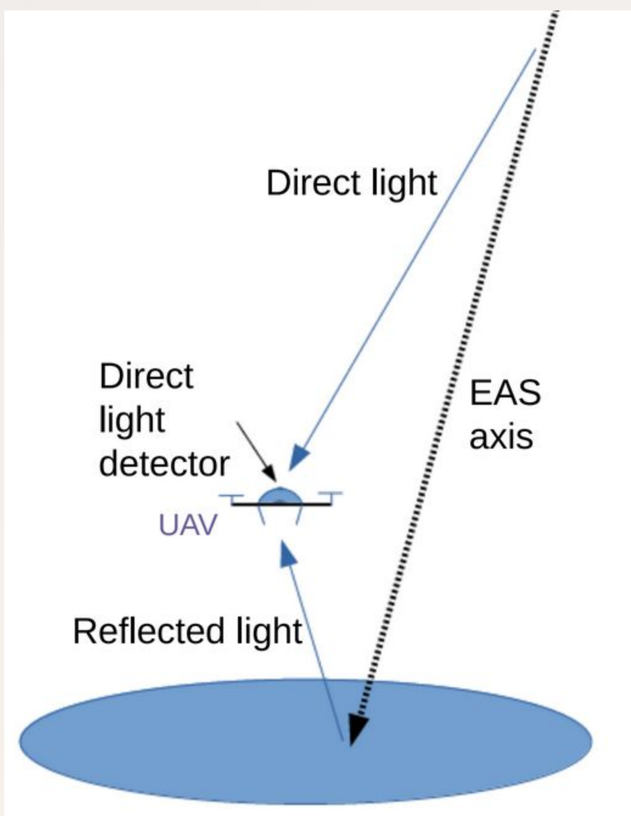

Fig 1: The SPHERE experiment scheme

The detector metal frame is to be composed of lightweight aluminium tubes. A camera of 379 segments, each containing 7 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 the mass of the detector. The equipment is powered by the UAV's power system (Fig. 2).

Direct light detector

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.

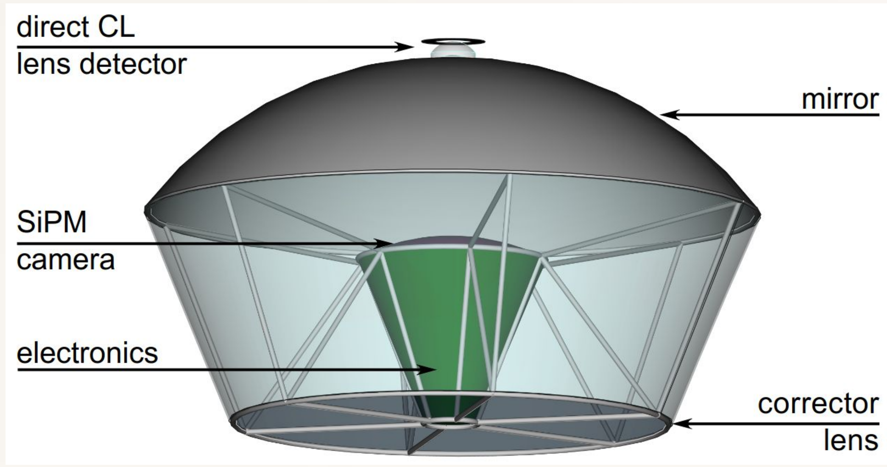

Fig. 2: SPEHRE-3 detector general view.

Estimation of EAS parameters

Methods and Results

Axis location and arrival direction

Reflected light. The arrival direction of the shower can be reconstructed analysing relative delays in reflected photons arrival in different pixels with respect to difference in optical paths length [1]. Depending on the shower energy (and, therefore, number of bright enough pixels) this method allows for 1-2° precision.

Direct light. 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. Key points are found to be no more than 2–3° away from the shower arrival direction (Fig.3). This indicates that these points can be utilised as the particle arrival direction.

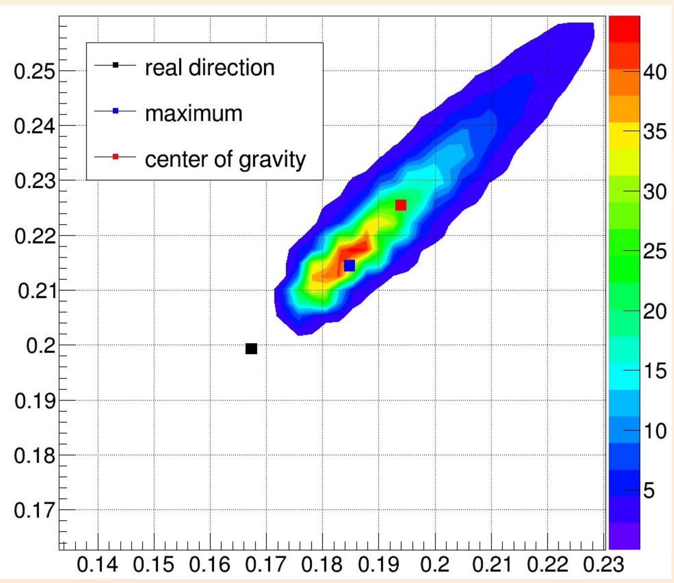

Fig. 3: Angular distribution of CL with key points and real direction

Nevertheless, We noticed that both key points are offset from the actual direction, in a direction coinciding with the major axis of the spot. If this offset is taken into account, the accuracy can be improved to 0.1-0.2°.

Energy

Reflected light only. Energy estimation by means of backward interpolation of the dependence of the full CL flux 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 to build the energy dependence of total flux (Fig. 4). The method is applicable in both scenarios where the mass of the primary particle is unknown and when it is known.

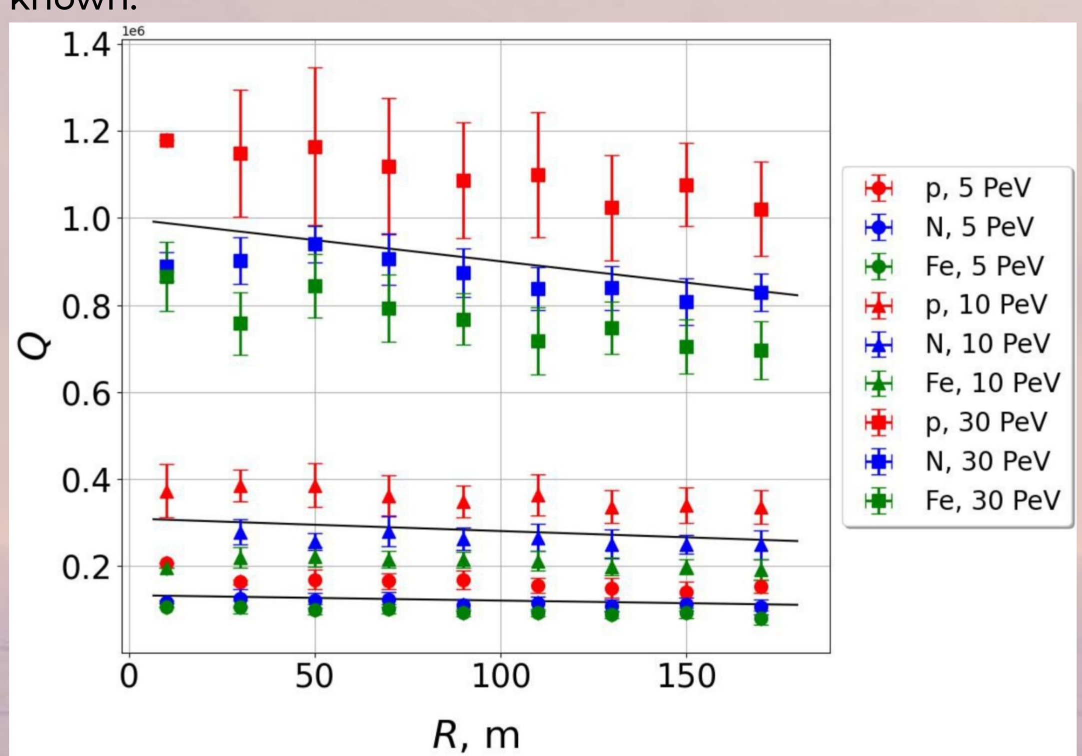

Fig. 4: A set of dependencies of the integral of the approximating function on R

Methods and Results

Mass of primary particle

Reflected light. The determination of the primary particle mass from the image of the reflected CL is based on the use of the Spatial Distribution Function (SDF), obtained by approximating the simulated light images on the detector mosaic. 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. The main measure of the method's accuracy is the type II error when separating events from different primary particle types.

Direct light. The angular distribution of CL also holds the information on the particle type and can be studied with the aim of identifying a primary mass-sensitive characteristic. Two criteria were developed. One of them is based on the length of the major axis of the spot, and the other is contingent on the ratio of integrals over two rectangular regions of the angular distribution (Fig. 5). Since we know axis location and arrival direction, we can construct a grid of criteria based on relative azimuths and on the distance to the shower axis.

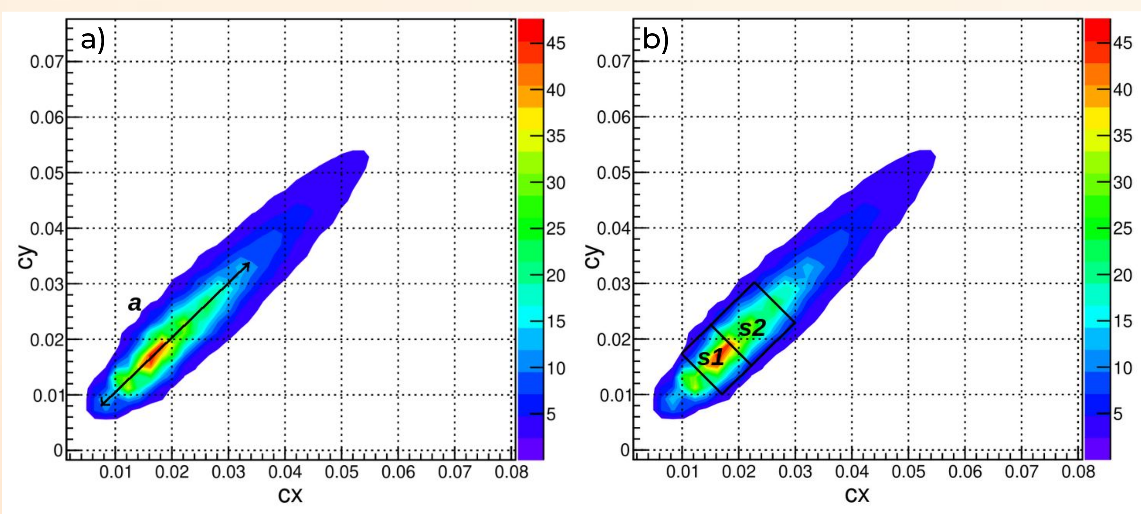

Fig. 5: a) the length of the major axis of the spot and b) integration areas

Dual detection

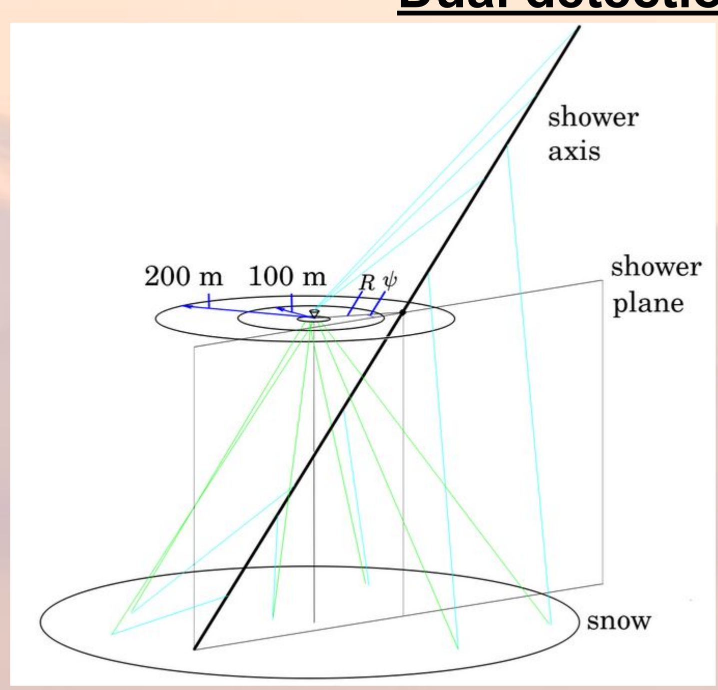

Fig. 6: EAS detection at two levels. Reflected light (green) is collected by the lower detector of the SPHERE-3, direct light (blue) is accepted by the upper one.

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 (Fig. 6).

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 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.1.

Conclusions and informations

Conclusions

Tab. 1	p-N separation		N-Fe separation	
	error p	error N	error N	error 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

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.

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.

Acknowledgments

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References

[1] Approaches to Optimisation of Experimental Design for Cosmic Ray Mass Composition Studies in the 1-1000 PeV Energy Range / Chernov D.V., Azra C.G., Bonvech E.A. et. al. // Physics of Atomic Nuclei, том 87 (Suppl 2), S319–S338 (2024).

Read more about the SPHERE experiment