Ultra-High Energy Particles Astronomy with a space-based experiment

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1 Introduction

Ultra-High Energy Cosmic Particles (UHECP) with energies in excess of 10^{19} eV, reach the Earth with a very low flux ($\lesssim 0.01$ particle $\cdot$ year$^{-1} \cdot$ km$^{-2} \cdot$ sr^{-1} for particles with energies $\gtrsim 10^{20}$ eV). The UHECP physics will not be discussed in this paper (see for example [1]). The Pierre Auger Observatory (PAO) will provide, in the next years, a solid understanding of these phenomena [2]. The PAO south site represents for sure the present of the scientific field, while the forthcoming north site is the near future.

However a next-generation space-based experiment might have the capabilities to increase the event statistics with respect to ground-based experiments, aiming at an instantaneous geometrical aperture of the order of 10^6 km$^2 \cdot$ sr. This requires a big experiment, on a medium/long timescale, whose performances demand for a large amount of R&D in order to setup both the technologies and the knowledge to allow an optimal experiment design.

The scientific scenario, which is becoming available thanks to the PAO, will help to tune the scientific objectives and will drive the unavoidable trade-offs on the objectives, the performances and the design choices.

The relevance of a such post-PAO (south and north) experiment is widely recognized by the HE astroparticle physics community. The inclusion of the UHECP physics in the European Space Agency (ESA) Cosmic Vision2015-2025 program [3] provides a suitable framework for the study of future space missions.

2 The required apparatus

The required apparatus is a large aperture, large field-of-view, fast and highly pixelized digital camera detecting with high efficiency near-UV single photons emitted by the Extensive Air Showers (EAS) generated in the interactions between the primary particles and the atmosphere. The instrument looks downward the Earth at night to observe both the EAS scintillation light and the Cherenkov light diffusely reflected by ground, sea or clouds (see Fig. 1).

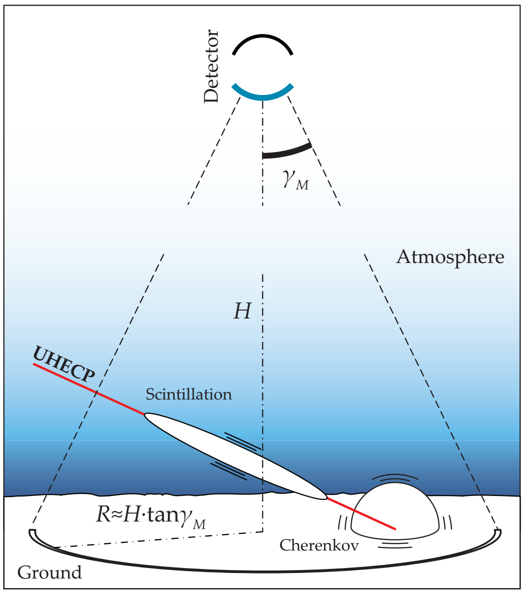

Figure 1: The observational approach of the apparatus.

The detector has to be capable of operating for at least 5-10 years in space. The signal is very small and it is superimposed on a huge background. The continuously changing Field-of-View (FoV) has to be watched by a suitable atmospheric monitoring system, to gather all the information required for the reconstruction of the primary particle.

The main components of the apparatus are:

- a main optics, collecting the light and focusing the EAS image onto a Focal Surface (FS);
- a Photo-Detector (PD) on the FS (photo-sensors, trigger, front-end and back-end electronics, data analysis system), registering the EAS image;
- a calibration system;
- an atmospheric monitoring system;
- other ancillary instrumentation.

Such a challenging experiment needs to exploit novel technologies in order to reach the scientific objectives.

3 The EUSO heritage

The current knowledge relies on the studies already conducted in the framework of the Extreme Universe Space Observatory (EUSO)mission phase A [4, 5]. EUSO was proposed to the ESA as a free-flyer satellite in 1999. In 2000 the ESA recommended to consider the accommodation on the Columbus module of the International Space Station (ISS). This accommodation gave rise to many constraints that limited the final EUSO performances: fixed orbit height (~ 400 km), limits on mass ($\lesssim 1.5$ ton), volume ($\lesssim 2.5 \times 2.5 \times 4.5$ m^3), power consumption ($\lesssim 1$ kW) and telemetry ($\lesssim$ 200 Mbit/orbit). Therefore the maximum optics diameter was ~ 2 m. EUSO has to be considered as a preliminary exercise. The main lesson is that, in designing such an experiment with so many unknowns, one must keep a safe design margin on the expected performances. The second main lesson is that previously unexpected challenges and critical issues were identified during the phase A study. The EUSO efficiency plateau was reached at $E \approx 2 \times 10^{20}$ eV [6]. The current scientific scenario look for an experiment with a magnitude order lower energy threshold, so one needs to gain a factor $10 \div 20$ (at least!) in the threshold.

4 The required performances

The improved scientific objectives, with respect to EUSO, imply improved apparatus requirements. It has to be remarked that an accurate experiment optimization is a complex task and it ca be carried on only with a detailed study. Therefore only preliminary and conservative estimates are given here. These estimates rely on the EUSO Phase A study, based on end-to-end simulations, from the signal generation and transport to the instrument response and data analysis [5, 6]. The EUSO performances are rescaled to the new experiment using simple and approximate, but reasonably accurate, scaling laws and consolidated expectations based on the new technology developments.

The main physics performance parameter are the instantaneous geometrical aperture, the energy threshold, the energy and angular resolutions and the duty cycle. From the current scientific scenario, the energy threshold has to be of the order of $\sim 10^{19}$ eV.

The instantaneous geometrical aperture has to be very large and the operational time has to be long enough to get a big exposure providing a number of UHECP larger than it is possible from the Earth. In order to increase the aperture one needs to put the detector in a very high orbit. This weakens the signal, which scales with the square of the distance from the EAS. Therefore the orbital parameters have to be tuned in order to improve the expected performances. Varying the orbital height, for instance using an elliptic orbit, actually extends the observational energy range.

With a free-flyer satellite one has many more degrees of freedom in the choice of orbit than from the ISS.

¿From the instrumental point of view, the basic performance parameter is the photon collection capability, which strongly affects the main physics performances: the threshold, the energy and angular resolutions and the geometrical aperture, since that with a better photon collection capability one can put the detector on an higher orbit maintaining the same threshold The photon collection capability depends on the entrance pupil size and on the photon collection efficiency. The latter is affected by the optics efficiency (OE), the photo-detector efficiency (PDE) and many other efficiency factors, which are typically very close to one. So the only parameters capable, a priori, to provide a significant improvement are the OE and the PDE. The optics aperture is the only sizable parameter, within the external constraints. Since this is the only parameter affecting the performances that can be dimensioned, the instrument should to be designed to have the largest dimensions compatible with a non-deployable photo-detector. Indeed, while large deployable optical systems are currently under development [8], at this moment the developing a deployable photo-detector seems to be a too challenging task.

Provided that suitable technologies are successfully developed, the following goals can be accomplished:

- observed area (at apogee) $\approx 8 \times 10^5$ km^2;
- instantaneous geometrical aperture at apogee $\approx 2 \times 10^6$ km$^2 \cdot$ sr
- the duty cycle is a delicate parameter and a precise value can be only measured; with a guess-estimate we can say that it is of the order of 10%-20%;
- angular granularity corresponding to ~ 1 km at Earth;
- with an entrance pupil diameter of ~ 8 m and a PDE doubled with respect to EUSO ($\sim 25\%$) one can think to reach a threshold $\lesssim 10^{19}$ eV with a statistical uncertainty of $\sim 10\%$;
- angular resolution of few degrees (limited by the EAS visible track length and the number of FS channels).

Some technological developments should be carried on:

- a deployable catadioptric optics;
- high PDE sensors; for example the Geiger-mode Avalanche Photo-Diode (GAPD), provided that the current limitations are successfully overcome [9, 10];
- micro-electronic technologies.

5 The Super-EUSO mission

The Super-Extreme Universe Space Observatory (S-EUSO) [7] is an international multi-agency mission, led by ESA. The S-EUSO proposal is based on the technological and mission studies already carried on in the Phase A of the EUSO mission. S-EUSO will observe the EAS from space, shedding light on the origin and sources of UHECP, on their propagation environment and on particle physics at energies well beyond the man-made accelerators. In this sense, such a mission will develop the particle astronomy field, already opened by the PAO. A further scientific fall-out of the mission will be the systematic monitoring of the electromagnetic atmospheric phenomena (e.g. lightnings). In the Table 1 the main parameter of the mission and the experimental apparatus current design are reported.

ORBIT			
perigee radius	~ 800 km	ground velocity	7.5 km/s
apogee radius	~ 1000 km	pointing accuracy	~ 3 deg
inclination	50 deg $\div$ 60 deg	lifetime	$5 - 10$ years
period	~ 100 min		
OPTICS		FOCAL SURFACE	
mirror diameter	11 m	diameter	4 m
pupil diameter	7 m	number of channels	$\sim 10^6$
f/#	0.7	pixel size	~ 4 mm
granularity at ground	~ 0.7 km	sensor PDE	$\gtrsim 0.25$
field of view	25 deg	power per channel	$\lesssim 2$ mW
throughput	> 0.7		

Table 1: Main parameters of the S-EUSO mission (to be optimized).

The required dimensions and the use in space require the optics to be lightweight and deployable. The most versatile configuration is a catadioptric one, e.g. a Schmidt telescope. The focal surface is made by an array of photo-sensors. High PDE is required. The front-end electronics will be a custom ASIC fully integrated with the photo-sensor. Due to the very large span of the energy range (almost three order of magnitudes), two complementary approaches are required: the single photon counting technique at low energies and the charge measurement technique at high energies. The trigger has to be fast and selective in order to tag the EAS signal while rejecting the background in an efficient way.

The observation of the atmosphere inside the FoV (using for instance an infrared camera and/or a LIDAR) will provide key parameters for the EAS reconstruction.

5.1 The preparatory program

A careful mission design optimization is required. This implies collecting as many as possible preliminary informations. Therefore it is necessary to follow some preliminary steps: improving the fluorescence yield and Cherenkov albedo measurements through dedicated experiments and characterizing in detail the background via a micro-satellite mission (which can also test some technological issues) [11]. The space approach has to be validated through some preliminary small mission. In this sense the russian TUS [12] and the japanese JEM-EUSO [13] pathfinders are under study.

6 Conclusions

A space-based experiment for UHECP detection is very challenging. It is mandatory to clarify the scientific goals for such a post-PAO experiment. The experimental design will require many trade-offs and some preliminary steps (background characterization, etc.) are mandatory.

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