Frascati Physics Series Vol. XXXVII (2004) pp. 429–436
Frontier Science 2004, Physics and Astrophysics in Space
Frascati, 14-19 June, 2004

EUSO: A SPACE-BORNE EXPERIMENT FOR UHECR OBSERVATION

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Abstract

The *EUSO* experiment is currently under study by ESA for a possible installation on the International Space Station. The experiment is designed to observe, by means of a space-based apparatus, the Extensive Air Showers produced in the atmosphere by Ultra High-Energy Cosmic Rays. The design of a large aperture, large field of view, fast and high granularity, single-photon Photo-Detector, sensitive in the near UV and suitable for a few years of operation in space, is a challenging task. The basic aspects of the current concept of the *EUSO* mission, based on the presently known requirements and constraints will be described.

The *EUSO* experiment can be considered the precursor and pioneer of a new generation of experiments in the UHECR field aiming to go beyond what is practically achievable at the Earth surface.

1 Ultra High Energy Cosmic Rays

The interpretation of the phenomenology of the Ultra High Energy Cosmic Rays (UHECR) is one of the most challenging topics of modern astro-particle physics [1]. UHECR reach the Earth with a low flux (of the order of $F \approx 0.01$ particle year $^{-1}$ km^{-2} sr^{-1} for particle with an energy $E \gtrsim 10^{20}$ eV) and therefore a complex and sophisticated experimental apparatus is required to observe them.

The *EUSO* (Extreme Universe Space Observatory) experiment, proposed to the European Space Agency (ESA) for installation on the International Space Station (ISS), has just finished its phase A study (the feasibility study).

The experiment goal is the study of the Cosmic Rays in ultra high energy part ($E \gtrsim 5 \cdot 10^{19}$ eV) of the energy spectrum, by observing, from Space, the Extensive Air Showers (EAS) produced by the interaction of the primary UHECR with the atmosphere. This is accomplished by installing *EUSO* on the ISS, looking down to nadir during night-time.

The phase A study has demonstrated the technical feasibility, with up-to-date technology, of a scientific apparatus satisfying the *EUSO* scientific objectives.

2 The observational technique

EUSO is an implementation of the *AirWatch concept*, originally proposed by John Linsley more than twenty years ago [2]: to observe EAS from Space, as shown in Figure 1.

An EAS can be detected by observing the air scintillation light, isotropically produced during the EAS development, and proportional, at any point along the EAS development, to the number of charged particles in the EAS. The additional observation of the diffusely reflected Cherenkov light (reflected either by land, sea or clouds) provides additional information. Therefore it is possible to estimate the energy and arrival direction of the primary UHECR, and to gather information about its nature. The atmosphere acts as a calorimeter (passive, continuously changing and outside human control).

Any given EAS will be seen as a point moving with a direction and angular velocity depending on the EAS direction. The peculiar characteristics of the EAS, including the kinematical ones, allow one to distinguish them from the various backgrounds, because those have a typically different space-time development.

Key points of the observational technique are the following.

- A large instantaneous geometrical aperture can be obtained ($\mathcal{A}_{\rm GEO} \gtrsim 2.1 \cdot 10^5$ km^2 sr, at least), thanks to the large distance ($\gtrsim 400$ km) and depending on the Instrument Field of View ($\gamma \gtrsim 20°$). A large mass

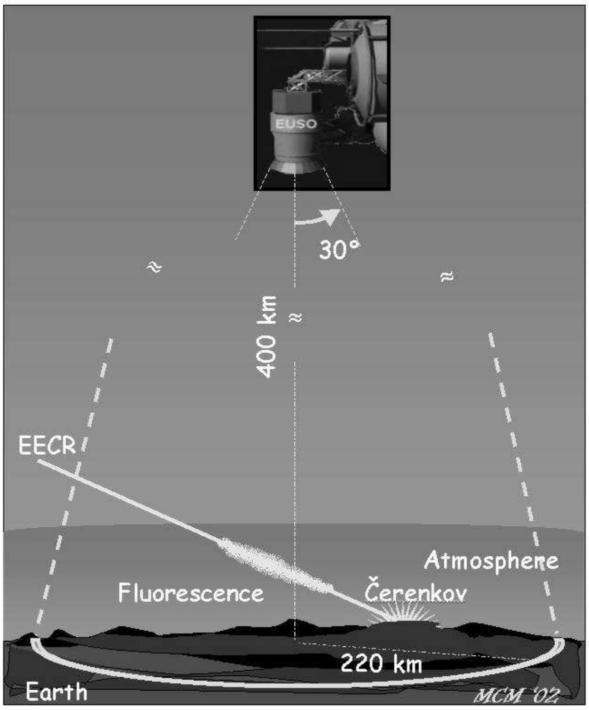

Figure 1: The *EUSO* observational approach.

of atmosphere (the calorimeter medium) can therefore be observed. The estimated duty cycle is in the range $\approx (0.05 \div 0.20)$.

- Detection of EAS produced by weakly interacting primary particles, starting to shower deeply in the atmosphere, is possible, by the direct observation of the EAS development and starting point.
- All sky coverage is possible with one single apparatus.
- The approach is complementary to the ground-based one. In fact the Space experiments are best suited for the observation of higher energy cosmic rays with respect to ground-based experiments. However an overlap of the observed energy spectrum with the one known from ground-based experiments is required for a better comparison. A larger geometrical

aperture is obtained from Space experiments with respect to ground-based experiments. The systematic effects are different in the two approaches.

2.1 The signal

The scintillation light, mainly emitted in the $330\,\text{nm} \div 400\,\text{nm}$ wavelength range, is isotropic and proportional, at any point, to the number of charged particles in the EAS, largely dominated by electrons and positrons. The total amount of light produced is proportional to the primary particle energy and the shape of the EAS profile (in particular the atmospheric depth of the EAS maximum) contains information about the primary particle identity. In this wavelength range the atmosphere is relatively transparent, down to $\lambda \approx 330$ nm where the ozone absorption becomes strong. However the scintillation signal turns out to be rather weak, due to the large distance, making the task a challenging one. The typical number of detected photons from a proton EAS with $E \approx 10^{20}$ eV, for an *EUSO*-like apparatus, is of the order of $10^2 \div 10^3$ depending on the EAS inclination with respect to ground. The time duration of the signal spans the range from tens to hundreds of μs, again depending on the EAS inclination with respect to ground.

The possible observation of the Cherenkov light diffusely reflected by the Earth (by land, sea or clouds) will help the determination of the EAS parameters. While the amount of observed Cherenkov photons depends on the reflectance and geometry of the impact surface, the directionality of the Cherenkov beam provides a precise extrapolation of the EAS direction to the first reflecting surface.

2.2 The main background contributions

A selective and efficient trigger is required to distinguish the EAS from the background. Many different kind of backgrounds are expected including: the night-glow, man-made lights, auroras, natural photo-chemical effects (in atmosphere, sea and land), low-energy cosmic rays, reflected moon-light and star-light. However the typical characteristics of EAS are quite different from the background ones, in particular the kinematic characteristics. The backgrounds, for instance, typically have a time-scale of the order of ms. Another type of background is the random night-glow, currently estimated, for *EUSO*, in the range $B \approx (3 \div 9) \cdot 10^{11}$ photons $\text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$, in the wavelength range $330\,\text{nm} \leq \lambda \leq 400\,\text{nm}$ at $h \approx 400$ km height, depending on various factors. The random night-glow background in *EUSO* is estimated to be $30 \div 100$ GHz over the full FoV.

3 The *EUSO* Instrument

The design of an Instrument to look from Space to the EAS produced in the atmosphere by UHECR is a challenging task mainly because the UHECR flux reaching the Earth is very small, the observable signal is very faint and the apparatus has to operate in Space [3]. The engineering is very complex and the engineering design has a strong and critical impact on the scientific performance of the Instrument. This is caused by the tight Instrument requirements deriving from the Science requirements.

The *EUSO* Instrument is basically a fast digital camera, operating in the near-UV wavelength range, with large aperture and FoV. The main Instrument requirements are the following.

- The Instrument must collect as many photons as possible, in order to be able to detect the faint signal from the less energetic EAS and to discriminate it from the background. As a consequence a large aperture is required, as well as a good transmission of the optical elements and good photon detection efficiency in the 330 nm $\div$ 400 nm wavelength range. In fact a sufficiently low lower energy threshold is mandatory to connect the energy spectrum observed by *EUSO* with the observations by ground-based experiments, operating in a lower energy range.
- A large Field of View (FoV) is required to be able to observe a mass of atmosphere as large as possible, thus increasing the expected event rates.
- The physics requirements can be satisfied with a system having an angular granularity sufficient to ensure an angular resolution on the EAS direction of $\Delta\alpha \approx 1^\circ$.
- A single-photon detector is required, fast enough to be able to follow the space-time development of the EAS (sampling time below $\approx 0.1\ \mu$s) and reconstruct the EAS kinematical parameters from one single observation point.
- A low noise and good signal to noise ratio are required to detect the faint signal produced by the less energetic EAS and discriminate it from the background. Small cross-talk and after-pulse rate are required to avoid degradation of the energy and angular resolution.
- An efficient and reliable trigger system, capable of a good background rejection, is required to cope with the limited data storage, data transfer and computing capabilities available on-board.
- All the constraints and requirements related to the Space mission have to be accounted for. Mandatory characteristics are therefore: a compact and robust system with low mass, volume and power consumption, good reliability and time stability, radiation hardness and low sensitivity to magnetic fields of the order of the gauss.
- A system is required to protect the Instrument from possibly dangerous

environmental factors, including intense light.

3.1 The main Instrument parameters

The *EUSO* Instrument is made of a main optics, to collect and focus the incoming light, and a photo-detector, on the Focal Surface (FS), to detect the photons collected by the optics. The present provisional *EUSO* parameters and design goals are summarized in Table 3.1.

The main *EUSO* parameters and design goals	
ISS average orbit height	$H \approx 430$ km (at year 2010)
ISS orbit inclination	$i = 51.6°$
Orbital period	$T_0 \simeq 90$ min
Operating wavelength range (WR)	$\{330 \text{ nm} \leq \lambda \leq 400 \text{ nm}\}$
Observation duty cycle	$\eta \simeq (0.10 \div 0.20)$
Operational lifetime	at least three full years
Instrument field of view (half-angle)	$FoV \simeq 30° \equiv \gamma$
Effective aperture at high-energy	$\simeq (6 \div 9) \cdot 10^4$ km^{2}sr
Angular granularity	$\Delta\alpha \simeq 0.1°$
Optics maximum diameter	$D_M \simeq 2.5$ m
Optics aperture (entrance pupil diameter)	$D \simeq 2$ m
Optics $f/\#$	$f/\# \leq 1.25$
Optics spot size diameter on the FS	3 mm $\div$ 6 mm
Average transmission of the optics	$K_{opt} \approx 0.5$
Average photo-detector detection efficiency	$\varepsilon_{det} \approx 0.1$
Pixel dimensions	$\approx 3 \div 6$ mm
Number of channels	$\approx 1 \cdot 10^5 \div 4 \cdot 10^5$
Average atmospheric transmission (in WR)	$K_{atm} \gtrsim 0.4$
Background (in WR at ≈ 400 km height)	$(3 \div 9) \cdot 10^{11}$ m^{-2} s^{-1} sr^{-1}

3.2 The Atmospheric Sounding

The knowledge of the atmospheric properties on a event by event basis is important in order to improve the data quality, energy resolution and primary particle identification, in particular. For this reason a LIDAR to perform atmospheric properties sounding has been added to the current experimental apparatus. This will allow to determine the atmospheric properties relevant to the reconstruction of the triggered events, thus greatly improving the data quality.

4 Scientific activities to support the development of a Space-based observatory

A number of activities are required to provide information necessary/useful for a better design and optimization of a space-based experiment and to help the data-set interpretation such as:

- measurement of the fluorescence yield (many efforts are on-going);
- measurement of the Cherenkov light albedo from land, water and clouds under different relevant conditions (efforts are on-going: the ULTRA experiment [4]);
- a dedicated measurement of the diffuse background from space, to improve the current knowledge is probably necessary.

5 Conclusions

After the Pierre Auger project (both south and north Observatories) and Telescope Array will have clarified the UHECR properties around the GZK-cutoff region a different approach is probably needed to explore the higher energies.

The full understanding of the space-based approach, proposed more than 20 years ago, is now reaching its maturity, and it is now ready to pass into the implementation Phase.

The *EUSO* project has just finishing its phase A study. During phase A a preliminary conceptual design of the Instrument has been developed, capable to fulfill the Scientific requirements. The positive outcome of the *EUSO* phase A study from the scientific and technical point of view has demonstrated that the construction of an *EUSO*-like apparatus is a technically achievable goal with up-to-date technology. The Cosmic Rays physics community started to learn how to do such a kind of Experiment/Mission, thanks to the opportunity provided by the *EUSO* phase A.

EUSO is an energy range which makes it an experiment complementary to present and forthcoming ground-based experiments, the Pierre Auger Observatory and Telescope Array in particular. The Observational Approach implemented by *EUSO* makes it the precursor and pioneer of a new generation of experiments in the UHECR field.

The design of an *EUSO*-like Instrument is a real challenge due to the many (scientific and technical) requirements and constraints. Unconventional solutions might be required under many respects.

UHECR observation from space is a challenging task, requiring a huge and well-coordinated effort by the whole Cosmic Rays physics community.

6 Acknowledgements

The support from ESA and from the many national funding agencies (in particular from Italy, France, Portugal, US and Japan) is gratefully acknowledged. The author wishes to thank, in particular, the Istituto Nazionale di Fisica Nucleare (INFN), as well as the Agenzia Spaziale Italiana (ASI), for continuing support.

References

[1] A. Watson, these proceedings;
V. Berezinsky, these proceedings;
P. Blasi, these proceedings.

[2] J. Linsley, *Call for Projects and Ideas in High Energy Astrophysics*, 1979.

[3] The AirWatch Collaboration, Workshop on Observing Giant Cosmic Ray Air Showers, AIP Conf. Proc., 433, 353-357, (1998); The AirWatch Collaboration, Proc. SPIE 3445, 486, (1998); R. Stalio et al., Proc. 26th ICRC 2, 403 (1999); K. Arisaka, *Optimization of OWL-AirWatch Optics and Photo-Detectors*, 28/12/1999, available at `http://www.physics.ucla.edu/ arisaka/`; M. Ameri et al., *Study report on the EUSO photo-detector design*, Report INFN/AE-01/04, April 2001; O. Catalano, Il Nuovo Cimento 24C, n. 3, (2001), pag. 445; M. Ameri et al., Proc. 27th ICRC (2001), Hamburg, August 2001; A. Petrolini, Nucl. Phys. Proc. Suppl. 113 (2002) 329.

[4] O. Catalano et al., *ULTRA: UV Light Transmission and Reflection in the Atmosphere*, funded by INFN.