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The extreme universe of cosmic rays: Observations from space(*)(**)

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Summary. — The space mission "Extreme Universe Space Observatory—EUSO" is devoted to the investigation of the Extreme Energy Cosmic Rays (EECR with $E > 5 \times 10^{19}$ eV) and of the high energy cosmic neutrino flux. EUSO will observe the streak of UV fluorescence light produced when the particles coming from outer space interact with the Earth's atmosphere, looking downward from space the dark Earth atmosphere under a 60 degrees full field of view. The fluorescence light will be imaged by a large Fresnel lens optics into a finely segmented focal plane detector. The segmentation and the time resolution adopted will consent to reconstruct the shower arrival direction and energy with high precision. EUSO is a collaborating effort of research groups from Europe, USA and Japan and it has been designed to operate for more than 3 years mission life-time; it is expected to detect of the order of 10^3/year EECRs with $E > 10^{20}$ eV and to open a window into the high energy neutrino astronomy. Originally proposed to the European Space Agency as a free-flyer low-earth orbit mission, EUSO has been approved by ESA in March 2000 for an accommodation study on the international space station, with a goal for a flight starting in mid 2006.

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1. – EUSO **science objectives**

The mission "Extreme Universe Space Observatory—EUSO" is devoted to the investigation of the Extreme Energy Cosmic Radiation (EECRs with $E > 5 \times 10^{19}$ eV) and the high energy cosmic neutrino flux. The results obtained will extend our knowledge about the extremes of the physical word and tackle the basic problems still open with a large impact on fundamental physics, astrophysics and cosmology.

A detailed presentation of the EUSO scientific rationale and objectives is given in the original proposal of the mission to ESA as a free flyer in response to the "Announcement of Opportunity (AO) for the F2/F3 missions" in January 2000 [1].

1˙1. *The high energy cosmic radiation.* – Complete and up to date reviews on the general field of the ultrahigh energy cosmic radiation can be found in the proceedings of several recent conferences and workshops like the present one of Chakaltaya/La Paz and that of Metepec/Puebla on August 9-12, 2000.

The cosmic radiation can be considered the "particle channel" complementing the "electromagnetic channel" proper of conventional astronomy. Today substantial progresses have been made in the knowledge of the nature of cosmic rays of relatively modest energy, those reaching up to the "knee" (10^{14}–10^{15} eV); the cosmic radiation on the higher energy side, on the other hand, presents us with the challenge of understanding its origin and its connection with fundamental problems in cosmology and astroparticle physics.

Focal points are represented by

i) The change in the spectral index at $\sim 5 \times 10^{18}$ eV ("Ankle"); this could correspond to

– a change in the primary elemental composition connected with a different source or confinement region in space;

– a change in production mechanism in the original sources;

– a change in the interaction process in the first collision inducing the shower in the atmosphere.

ii) Existence of "cosmic rays" with energy $E > 10^{20}$ eV: (EECR) (fig. 1, bottom panel). A direct question arising is: what is the maximum cosmic ray energy, if there is any limit? Addressing the theoretical issue concerning the production and propagation of 10^{20} eV primary quanta is problematic and involves processes still little known. The energy loss mechanism related to the interaction of hadronic particles with the 2.7 K universal radiation background (Greisen-Zatsepin-Kuzmin effect) conditions the mean free path of cosmic radiation. This effect limits the distance of the sources of primary EECRs to less than 50–100 Mpc, a short distance on a cosmological scale, opening the problems related to the nature of the sources and their distribution in the Universe.

Focusing the attention on the primary sources, two general production mechanisms have been proposed for the EECRs:

1) BOTTOM-UP, with acceleration in rapidly evolving processes occurring in astrophysical objects. The scenario involves astrophysical objects such as, *e.g.*, AGNs and AGN radio lobes. The study of these objects is, besides radio observations, a main goal of X-ray and gamma-ray astrophysics of the late 90s. An extreme case in this class is represented by the gamma-ray bursts, found to be located at cosmological distances. The observation of "direction of arrival and time" coincidences of GRBs and extreme

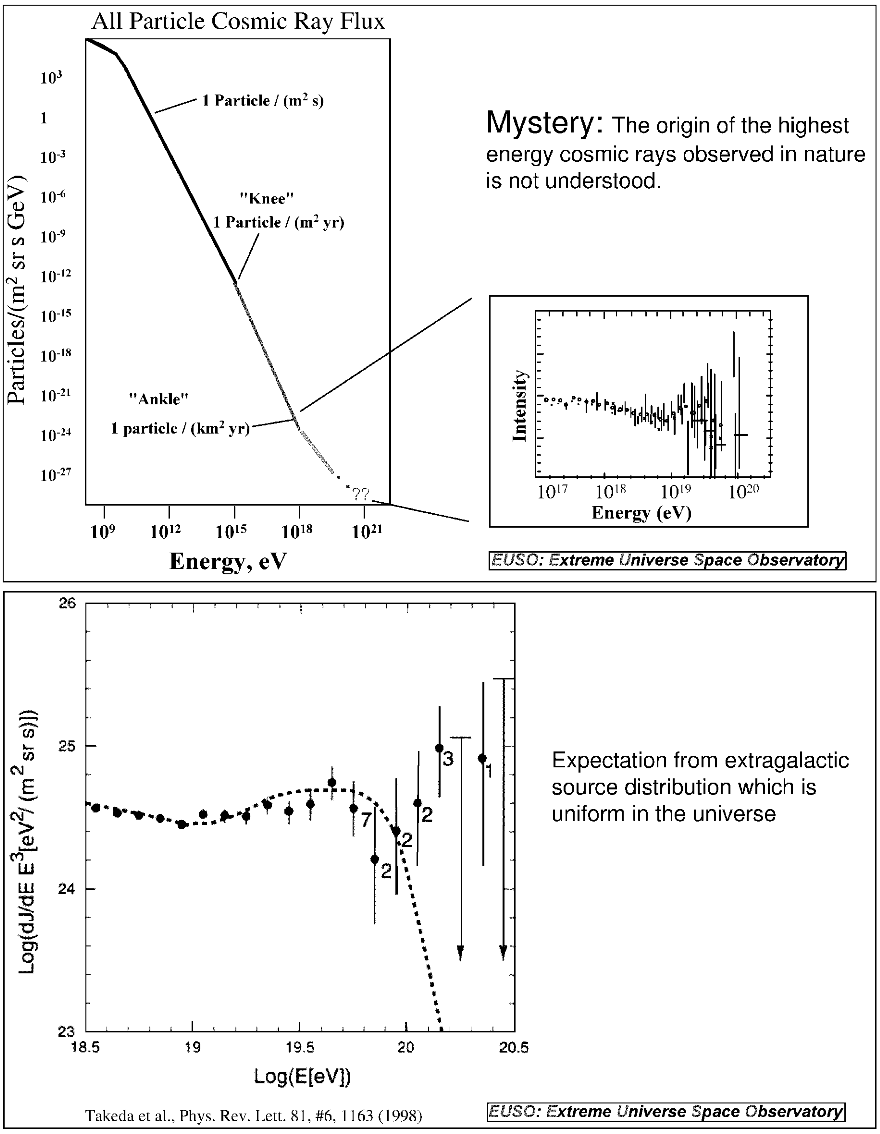


Fig. 1. – Top: The cosmic ray energy spectrum. Bottom: evidence for events above the GZK cutoff value. Recent data from the HiRes experiment confirm the Akeno picture shown in the figure.

energy neutrinos ($E \geq 10^{19}$ eV) in the EUSO mission could provide a crucial test for the identification of the observed GRBs as EECR sources in spite of their location at distances well above the GZK limit.

2) TOP-DOWN processes. This scenario arises from the cascading of ultrahigh energy particles from the decay of topological defects. Cosmic strings would play an essential role for releasing the X-bosons emitting the highest energy quarks and leptons. This process could occur in the nearby Universe. The relics of an early inflationary phase

in the history of the Universe may survive to the present as a part of dark matter and account for those unidentified EECR sources active within the GZK boundary limit. Their decays can give origin to the highest energy cosmic rays, either by emission of hadrons and photons, as through production of EE neutrinos.

From the astroparticle physics point of view, the EECRs have energies only a few decades below the Grand Unification Energy (10^{24}–10^{25} eV), although still far from the Plank mass of 10^{28} eV.

1˙2. *Cosmic neutrinos.* – Not suffering the GZK effect and being immune from magnetic field deflection or from an appreciable time delay caused by Lorentz factor neutrinos are ideal for disentangling source related mechanisms from propagation related effects. The opening of the neutrino astronomy channel will allow to probe the extreme boundaries of the Universe. Astronomy at the highest energies must be performed by neutrinos rather than by photons, because the Universe is opaque to photons at these energies.

2. – Observational problems

The extremely low value for the EECR flux, corresponding to about 1 event per km^2 and century at $E > 10^{20}$ eV, and the extremely low value for the interaction cross-section of neutrinos, make these components difficult to observe if not by using a detector with exceptionally high values for the effective area and target mass. The integrated exposure ($\sim 2 \times 10^3$ km^2 y sr) available today for the ground-based arrays operational over the world is sufficient only to show the "ankle" feature at $\sim 5 \times 10^{18}$ eV in the cosmic ray energy spectrum and the existence of about ten events exceeding 10^{20} eV; the limited statistics excludes the possibility of observing significant structures in the energy spectrum at higher energies. Experiments carried out by means of the new generation ground-based observatories, HiRes (fluorescence) and Auger (hybrid), will still be limited by practical difficulties connected to a relatively small collecting area ($< 10^4$ km^2 sr) and by a modest target mass value for neutrino detection. To overcome these difficulties, a solution is provided by observing from space (fig. 2) the atmosphere UV fluorescence induced by the incoming extraterrestrial radiation, which allows to exploit up to millions km^2 sr for the acceptance area and up to 10^{13} tons as target for neutrino interaction. This is the philosophy of the "AirWatch Programme" and "EUSO" is a space mission developed in the AirWatch framework.

The Earth atmosphere in fact constitutes the ideal detector for the extreme energy cosmic rays and the companion cosmic neutrinos. The EECR particles, interacting with the air nuclei, give rise to propagating Extensive Air Showers (EAS) accompanied by the isotropic emission of ultraviolet fluorescence (300–400 nm) induced in nitrogen by the secondary charged particles in the EAS as a result of a complex relativistic cascade process; an isotropically diffuse optical-UV signal is also emitted following the impact on clouds, land or sea of the Cherenkov beam accompanying the EAS. A shower corresponding to a primary with $E > 10^{19}$ eV forms a significant streak of fluorescence light over 10–100 km along its passage in the atmosphere, depending on the nature of the primary, and on the pitch angle with the vertical. Observation of this fluorescence light with a detector at distance from the shower axis is the best way to control the cascade profile of the EAS. When viewed continuously, the object moves on a straight path with the speed of light. The resulting picture of the event seen by the detector looks like a narrow track in which the recorded amount of light is proportional to the shower size at the various penetration depth in the atmosphere. From a Low Earth Orbit (LEO) space

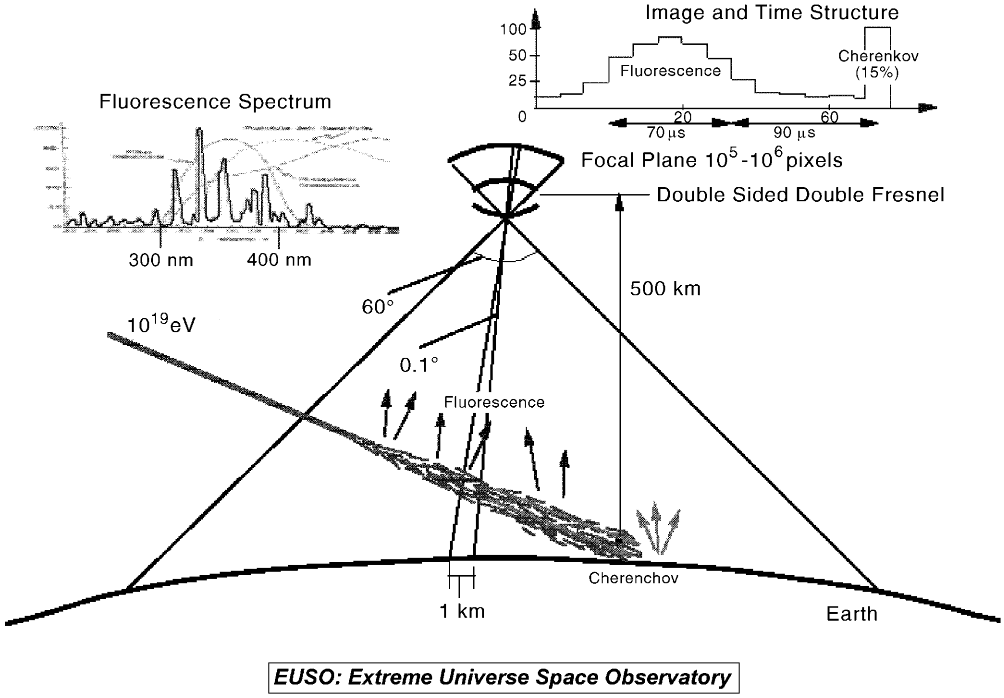
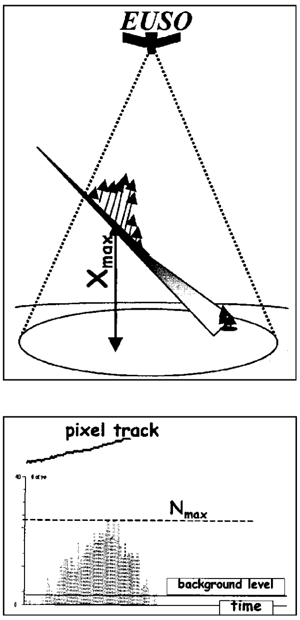


Fig. 2. – Observation of EAS from space.

platform, the UV fluorescence induced in atmospheric nitrogen by the incoming radiation can be monitored and studied. Other phenomena such as meteors, space debris, lightning, atmospheric flashes, can also be observed; the luminescence coming from the EAS produced by the cosmic ray quanta can be on the other hand disentangled from the general background exploiting its fast-timing characteristic feature.

EUSO observes at Nadir from an orbital height of about 400 km. It is equipped with a wide angle Fresnel optics telescope (60 degrees full FoV) and the focal plane segmentation corresponding to about 1 km^2 pixel size on the Earth surface. The area covered on Earth is of about 160000 km^2. Exploiting the high speed of the focal plane detector (10 ns class), EUSO is able to reconstruct the inclination of the shower track by the speed of progression of the projected image on the focal surface and to provide the tri-dimensional reconstruction of the EAS axis with a precision of a degree (or better) depending on the inclination. By measuring the EAS front luminosity with the photoelectrons (PE) detected by the MAPTs covering the focal surface, EUSO registers the longitudinal development of the EAS. In fig. 3 are shown the basic parameters measured and their relation to the physical properties of the incoming EECR or neutrino.

2·1. *EUSO general requirements.* – For a significant observation from a space mission the assumed values are: a) Effective geometrical exposure of $(5 \times 10^4$–$10^5)$ km^2 sr considering a duty cycle of 0.1–0.15; b) EAS energy threshold at about 5×10^{19} eV.



$\#pe \propto$ shower size
UV integral $\propto$ EECR energy
$N_{max} \propto$ EECR energy
$X_{max} \Leftrightarrow$ EECR nature

The measurement of the height X_{max}, where the maximum shower size N_{max} is present, is based on the Cherenkov light, isotropically diffused by clouds, land or sea: the time difference between the arrival of the fluorescence light from the primary track and the back reflected Cherenkov flash localizes the height of the event.
Showers initiated very deep in the atmosphere indicate an origin by neutrinos because of neutrino-air nuclei interaction cross section hundreds times lower than the cross sections for nuclei or photons.

EUSO: Extreme Universe Space Observatory

Fig. 3. – EUSO principle of operation.

3. – Main goals for EUSO

EECR statistics. About 10^3 events/year (an order of magnitude above those expected by the presently planned ground-based experiments) to allow a quantitative energy spectral definition above 10^{20} eV, together with the evidence of possible anisotropy effects and clustering (if any) for the directions of arrival.

Neutrino events. The expected event rate ranges from several events/year (AGN, GRB source) to several events/day according to the effectiveness of the "topological defects" hypothesis. From the observational point of view, the neutrino-induced EAS can be distinguished from background and from other EECR EAS by triggering on horizontal showers initiating deep inside the atmosphere. Moreover neutrinos with energy of about 10^{15}–10^{16} eV interacting in the solid earth and emerging upward in the atmosphere create showers which can be detected by EUSO by means of the Cherenkov beamed signal induced in the atmosphere, extending the capability of EUSO to this lower neutrino astronomy energy band. A horizontal tau-neutrino event at energies greater than 10^{19} eV can be identified by a "double bang" structure. Both the initial shower at the $\nu_\tau \to \tau$ interaction, and another, by the τ-decay, can be seen because of the long enough path-length ($\sim 1000\ (E/10^{20}\ \text{eV})$ km) for τ-decays observable by EUSO. Tau-neutrinos above 10^{15} eV, on the other hand, will be observed and identified as Earth-penetrating "upward" showers (by Cherenkov). High ν_τ flux by the $\nu_\mu \to \nu_\tau$ oscillation and the low detection threshold energy for them allow EUSO to make oscillation experiments in space as well as ν_τ astrophysics of AGN above 10^{15} eV.

The other optical atmospheric phenomena represent a very interesting field of research for themselves. Balloon and micro-sat programs to measure the night sky UV background have been initiated.

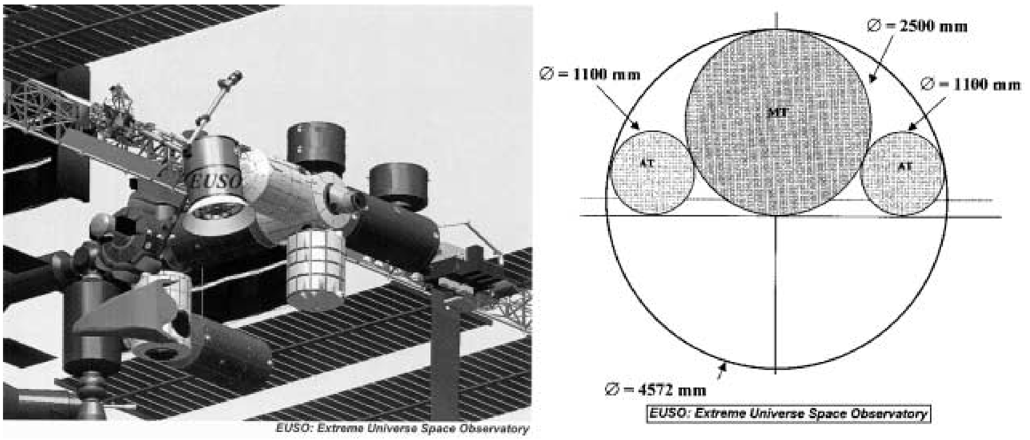


Fig. 4. – Left: EUSO at the COF-EPF (from Alenia Aerospazio Space Division). Right: EUSO on the ICC. Configuration 3 (section across the ICC and the Shuttle bay) [2].

4. – EUSO **schematic outline**

EUSO, originally proposed to ESA for a free-flyer LEO mission, has been approved for the “accommodation study” on the ISS International Space Station. Under the assumption of both a LEO (∼500 km altitude) free-flyer mission or the ISS accommodation (400 km average altitude), the coverage of the observable atmosphere surface at the scale of thousand kilometers across and the measurement of very fast and faint phenomena like those EUSO is interested in, requires

– optical system with large collecting area (because of the faint fluorescence signal) and wide equivalent field of view covering a sizable half opening angle around the local Nadir (to reach geometrical factor of the order of 10^6 km^2 sr),

– focal plane detector with high segmentation (single-photon counting and high pixelization), high resolving time (10 ns), contained values for weight and power,

– trigger and read-out electronics prompt, simple, efficient, modular, capable to handle hundreds of thousands of channels, and comprehensive of a sophisticated on-board image processor acting as a trigger.

Figure 4, left panel, shows an artistic view of ESA “Columbus Orbital Facility” on the ISS with EUSO attached at Columbus. In the undergoing “accommodation study” [2] several options are considered depending on the “transportation system” facility to orbit. Figure 4, right panel, shows the option corresponding to “Configuration 3”, where a section of the ICC (Integrated Cargo Carrier) is given.

In the baseline considered an optimal exploitation of the accommodation volume resource can be obtained by the combination of a central “Main Telescope” with 2.5 m diameter devoted to the observation of the EECRs and neutrino flux with $E > 3 \times 10^{19}$ eV, with two “Auxiliary Telescopes” (diameter 1.2 m) devoted one to the investigation of the neutrino component at energies (10^{15}–10^{16} eV) for which the Earth is not opaque and which can be revealed by observing the Cherenkov light associated with the upward moving EAS induced by the neutrino interaction with the upper crust layers of the solid Earth; the other AT is dedicated to the cloud sounding and other auxiliary observation modes.

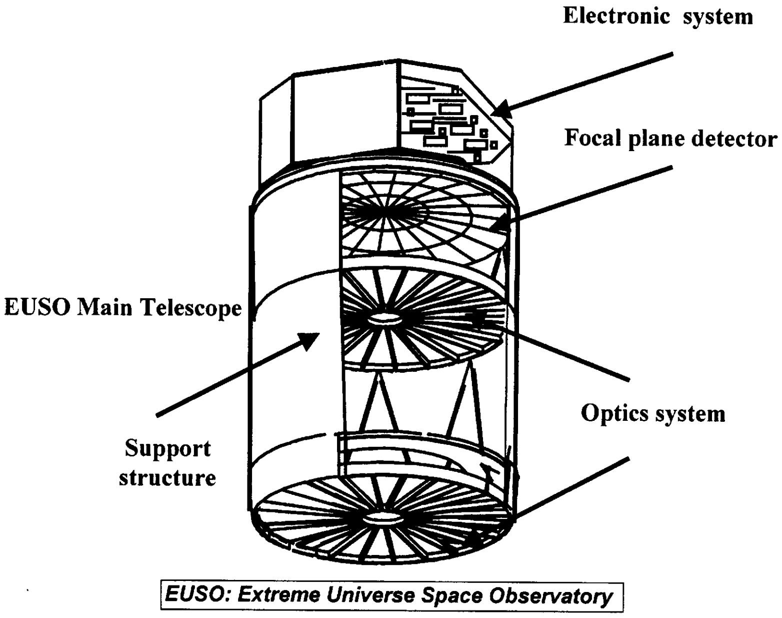


Fig. 5. – View of the EUSO main telescope.

4·1. *EUSO payload: The main telescope.* – The EUSO main telescope is presented schematically in the artistic view of fig. 5. The instrument consists of three main parts: optics, focal surface detector, trigger and electronics system. An effective synergy between the parts constituting the instrument is of fundamental importance for achieving the EUSO scientific objectives. Optics, detector elements, system and trigger electronics have to be matched and interfaced coherently to obtain a correct response from the instrument. Scientific requirements have been of guidance for the conceptual design of the apparatus and in the choice among various possible technical solutions. The design criteria are based on the following assumptions: 380 km orbit; pixel size at ground: 1 km^2; FOV of ± 30 degrees; event energy threshold $\geq 5 \times 10^{19}$ eV.

The observation from space calls for an approach different from that of the conventional ground-based fluorescence experiments. For space application the instrument has to be compact as much as possible, highly efficient, and with a built-in modularity in its detection and electronics parts. For what concerns the detection method, the single-photon counting technique has been preferred to the charge integration alternative, because of a better statistical response in the presence of the very few photoelectrons expected by the faint UV fluorescence signal.

4·1.1. The optics. The optical system required for EUSO aims at finding the best compromise in the optical design, taking into account the suitability for space application in terms of weight, dimensions and resistance to the strains in launch and orbital conditions. The optical system views a circle of radius ~ 220 km on the Earth and resolves 0.8×0.8 km^2 ground pixels: this determines the detector size to be adopted to observe the events. The forgiving resolution requirements of EUSO suggest the consideration of unconventional solutions, identified in the Fresnel lens technology. Fresnel lenses provide large-aperture and wide-field with drastically reduced mass and absorption. The use of a broader range of optical materials (including lightweight polymers) is possible for reducing the overall weight. The present Fresnel optical camera configuration study (FoV 60 degrees) considers two plastic Fresnel lenses with diameter 2.5 m; all the wide field optical camera elements will be integrated onto the payload module mechanical structure.

4˙1.2. The focal surface detector. Due to the large FOV and large collecting area of the optics, the focal surface detector is constituted by several hundreds of thousands of active sensors ($\approx 2 \times 10^5$ pixels). The detector requirements of low power consumption, low weight, small dimension, fast response time, high quantum efficiency in UV wavelength (300–400 nm), single photoelectron sensitivity, limit the field of the possible choices to few devices: a suitable off-the-shelf device is the multi-anode (64 channels) photomultiplier Hamamatsu R5900 series. Pixel size, weight, fast time response and single photoelectron resolution are well adaptable to the EUSO focal surface detector. The organization in macrocells of the focal surface (a macrocell is a bidimensional array of $n \times n$ pixels) offers many advantages as easy planning and implementation, flexibility and redundancy. Moreover, modularity is ideal for space application. The multi-anode photomultipliers represent, in this contest, a workable solution. The focal surface detector will be based on modules with geometrical shape that allows fitting the optical focal surface and reducing the complexity of assembly and testing.

4˙1.3. Trigger and electronics system. Special attention has been given to the trigger scheme where the implementation of hardware/firmware special functions is foreseen. The trigger module has been studied to provide different levels of triggers such that the physics phenomena in terms of fast, normal and slow in time-scale events can be detected. Particular emphasis has been introduced in the possibility of triggering upward showers (emerging from the earth, "neutrino candidate") by means of a dedicated trigger logic. The FIRE (Fluorescence Image Read-out Electronics) system has been designed to obtain an effective reduction of channels and data to read-out, developing a method that reduces the number of the channels without penalizing the performance of the detection system. Rows wired-or and columns wired-or routing connections have been adopted inside every single "macrocell" ($n \times n$ pixels unit; ≈ 100 macrocells constitute the focal surface detector) for diminishing the number of channels to read-out. A "free running" method has been adopted to store temporarily the information, coming from the detector, in cyclic memories and recuperate them at the time that a trigger signal occurs. The front-end pixel electronics design has been formalized and computer simulations have proven the validity of the approach we are going to use. A prerogative of the front-end pixel electronics is the reduction of the background when, as in our case, "single photoelectron counting" technique with fast response detector is used. The advantage of such a scheme is to treat macrocells as independent units from one another thus simplifying the design of the entire system, making it simply consisting of a repetition of equal blocks.

4˙1.4. Control electronics. The control electronics is in charge of managing the operations of the instrument. In particular its main functions are

– collection of the scientific data coming from the array detectors (macrocells) consisting of the position and arrival time of detected photoelectrons,

– collection of the housekeeping monitors to check the correct configuration of the instrument,

- preparation of telemetry source packets (scientific, housekeeping, etc.) and transmission of them to the ISS suitable module via On-Board Data Handling (OBDH) bus,

– to receive, validate and distribute the tele-commands coming from the OBDH,

– to control the operative modes during observation and during diagnostic and calibration; these modes include also the autonomous maintenance of the detector safe conditions,

– to provide the data patch and dump capability for S/W reprogramming,

– management of time information,

– conversion of the primary bus provided by the ISS into the secondary regulated voltages necessary for the instrument operation.

A payload (P/L) data handling computer connected by a standard data bus to the spacecraft module on-board computer will manage the P/L module function, the scientific and housekeeping telemetry and the command from ground.

5. – Expected results

Extensive simulations have been elaborated by O. Catalano and reported in his contribution to the Metepec/Puebla Workshop [3].

Figure 6 reports the expected results for EUSO in the ISS version, compared with

Table I. – *EUSO counting rate (events/year).*

Primary energy range (eV)	ISS accommodation (ICC constrained) EOD = 2 m, EED = 2.5 m $f\# = 1.15$	Free-flyer accommodation (original proposal) EOD = 2.6 m, EED = 3.5 m $f\# = 1.15$
5×10^{19}–6×10^{19}	250	250
6×10^{19}–7×10^{19}	650	650
7×10^{19}–8×10^{19}	750	900
8×10^{19}–9×10^{19}	700	900
9×10^{19}–1×10^{20}	550	800
1×10^{20}–5×10^{20}	700	1200
5×10^{20}–1×10^{21}	80	130
$> 10^{21}$	5	10

Table II. – *EUSO time profile.*

Phase	Main outputs	From	To
A	study report, conceptual design	January 2001	June 2001
B	specifications, preliminary design, work-bench test	July 2001	June 2002
C	detailed design, STM development and test	July 2002	December 2003
D	PFM development qualification and test	January 2004	December 2005
D	integration	January 2006	May 2006
E	Launch - start of orbital operations	June 2006	

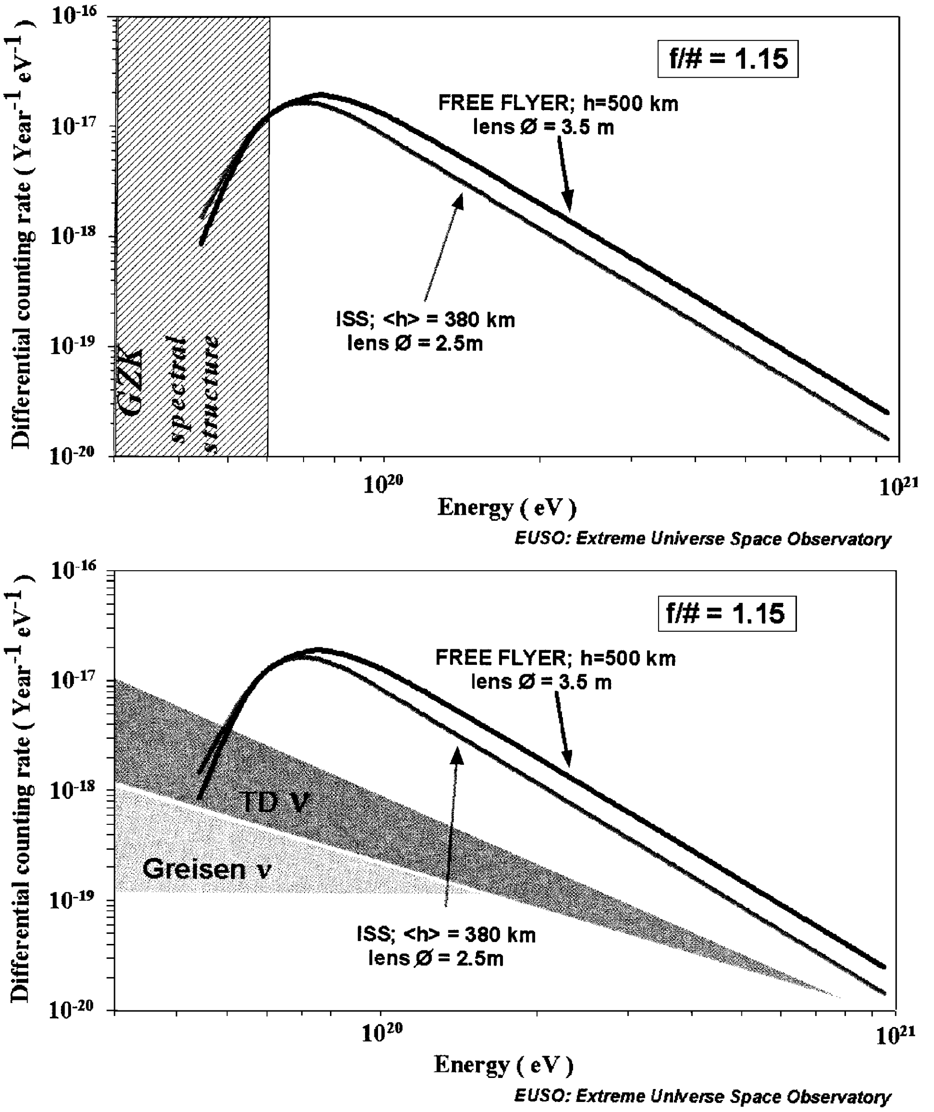


Fig. 6. – Top: differential EECR counting rate: comparison between EUSO on the ISS and the original free-flyer proposal. The dashed zone shows the spectral structure induced by the GZK effect. Bottom: neutrino expectation: the different shadowed areas refer to Topological Defects (TD) ν and Greisen ν (by interaction of the primary (CR).

those referred to the free-flyer version of the original proposal to ESA: in the two versions the results appear almost identical, with the lower altitude for the ISS compensating the reduced dimensions of the optics for what concerns the threshold. Table I shows the numerical values for the expected EECR counting rate. For the neutrino component the values expected are conditioned by the large indetermination existing in the theoretical prediction. Table II gives the time profile presently envisaged for the mission.

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This presentation is made on behalf of the EUSO Collaboration. The determinant contribution of O. Catalano, M.C. Maccarone and B. Sacco is deeply acknowledged; Y. Takahashi has always been present with his essential interventions providing fundamental ideas and criticisms.

REFERENCES

[1] Scarsi L. *et al.*, *Proposal for the ESA F2/F3 Mission*, January 2000, `http://www.ifcai.pa.cnr.it/EUSO/docs/EUSOproposal.pdf`, and references therein.
[2] ESA-ESTEC, *EUSO Accommodation Study for ISS*, in progress (2000).
[3] Scarsi L., *EUSO: Using high energy cosmic rays and neutrinos as messengers from the unknown universe*, in *Proceedings of the International Workshop on "Observing Ultra High Energy Cosmic Rays from Space and Earth", Metepec, Puebla, Mexico, August 9-12, 2000*, edited by H. Salazer *et al.*, *AIP Conf. Proc.*, Vol. **566** (American Institute of Physics, New York) 2001.