EUSO : EXTREME UNIVERSE SPACE OBSERVATORY.

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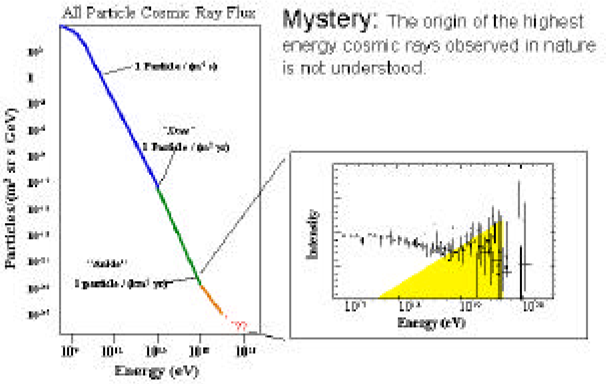
ABSTRACT

Exploiting the Earth Atmosphere as a giant detector for the incoming extraterrestrial flux of High Energy Cosmic Rays and Cosmic Neutrinos , the mission "EUSO-Extreme Universe Space Observatory " is devoted to the exploration of the domain of the highest energy processes occurring in the Universe up to its accessible boundaries. The observable is provided by the Air Nitrogen fluorescence light emitted in the UV band 300 – 400 nm by the Extensive Air Showers produced by the cascading processes of the Primary C.R. Particles interacting with the Atmosphere. The EUSO telescope is based on a double Fresnel lens optics (diameter 2.5 m) coupled to an highly pixelized focal surface composed by multianode PMTs ; the image at the Earth surface is detailed at 1 Km^2 over a total of several hundred thousand of Km^2. EUSO will fly on the International Space Station accommodated as External Payload of the European Space Agency Columbus module . The mission is scheduled to last 3 years , with the start of operations foreseen for 2007/8 . The expectations are of a collection rate of a thousand events / year for Cosmic Rays at $E > 10^{20}$ eV together with tens / hundreds Cosmic Neutrinos at energy above about 4×10^{19} eV. EUSO is the result of the collaborative effort of several Institutions in Europe, Japan and USA and it is conceived within the science program sponsored by various Space Agencies coordinated by ESA.

(°) .This text is largely derived from contributions made by the Author in 2000/2001 to other Workshops and Conferences and from documentation submitted by the EUSO Consortium to the European Space Agency as a part of the proposal EUSO.

The Cosmic Radiation can be considered the "Particle channel" complementing the "Electromagnetic Channel" proper of the conventional Astronomy. The mission "*Extreme Universe Space Observatory – EUSO*" is devoted to the investigation of the Extreme Energy Cosmic Radiation (EECRs with $E > 5\times10^{19}$ eV) and the High Energy Cosmic Neutrino Flux, aiming at the exploration of the highest energy processes present and accessible in the Universe. 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 classic presentation of the Cosmic Ray Energy Spectrum is shown in Fig.1.

Figure 1. Cosmic Ray energy spectrum: evidence for events above the GZK cutoff value are given from the Akeno experiment, in agreement with several other experiments carried out before ; data from the HiRes experiment as reported at the ICRC 2001 , however , apparently do not confirm the picture.

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“ at 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 ~5×10^{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).

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 it involves processes still little known. The energy loss mechanism related to the interaction of hadronic particles with the 2.7 Kelvin 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:

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 90`s. 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 Energy Neutrinos ($E \geq 10^{19}$ eV) in the EUSOmission 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.

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.

Cosmic Neutrinos, not suffering the GZK effect and being immune from magnetic field deflection or from an appreciable time delay caused by Lorentz factor, 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.

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 ($\sim 2\times10^3$ km^2 yr sr) available today for the ground based arrays operational over the world is sufficient only to show the "ankle" feature at $\sim 5\times10^{18}$ 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 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}tonsas 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 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 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° 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.

<u>EUSO General Requirements and Main Goals</u> For a significant observation from a space mission the assumed values are:
a) Effective geometrical exposure of $(5\times10^4\text{-}10^5)$ km^2 sr considering a duty cycle of 0.1-0.15; ***b)*** EAS energy threshold at about 5×10^{19} eV.

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 $\nu_\tau \rightarrow \tau$ interaction, and another, by the τ-decay, can be seen because of the long enough path-length (~ 1000 [$E/10^{20}$ 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 $\nu_\mu \rightarrow \nu_\tau$ 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.

EUSO Schematic Outline EUSO, originally proposed to ESA for a free-flyer LEO mission , has been approved for an "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. Fig.2 shows an artistic view of EUSO attached at Columbus on the ISS

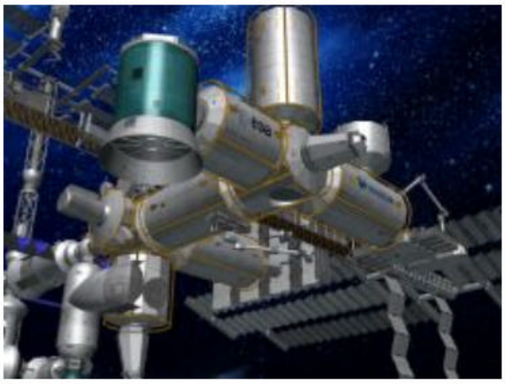


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Figure 2. EUSO at the COF-EPF.

1.1 ***EUSO Payload: The "Main Telescope".*** The EUSO Main telescope is presented schematically in the artistic view of Fig.14. 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°	Event energy threshold $\geq 5\times10^{19}$ eV

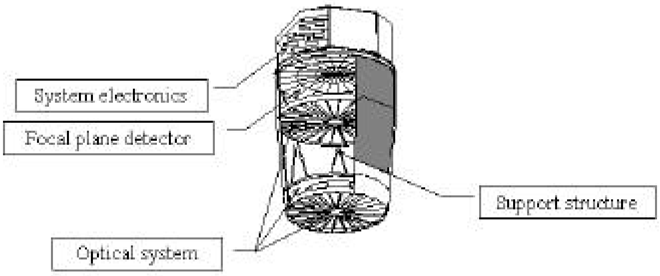

Figure 3. View of the EUSO Main Telescope.

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.

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°) considers two plastic Fresnel lenses with diameter 2.5 m and iris diaphragm 2.0 m diameter.

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 ($\approx2\times10^5$ 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 a very few devices. A suitable off-the-shelf device is the Multi-Anode Photomultiplier Hamamatsu R5900 series. These commercial photomultipliers meet closely the requirements imposed by the project. 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 bi–dimensional array of n×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.

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.

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.

Expected Results Extensive simulations have been elaborated by O. Catalano at IFCAI/CNR.

Fig.4 and Fig.5 report the expected results for EUSO in the ISS version, compared with 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".

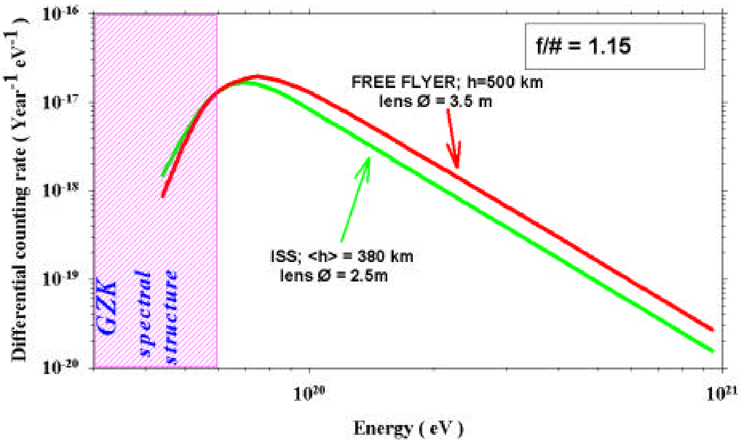

Figure 4 Differential EECR counting rate: comparison between EUSO on the ISS and the original free-flyer proposal. The dashed zone shows the spectral structure induced by the GZK effect.

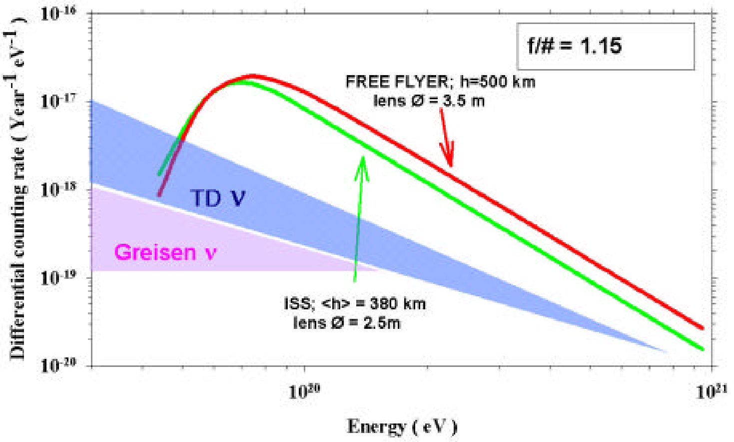

Figure 5. Neutrino expectation: the different shadowed areas refer to Topological Defects (TD) ν and Greisen ν (by interaction of the Primary (CR)