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EUSO - Extreme Universe Space Observatory: Doing astronomy looking downward the Earth atmosphere

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Abstract. *EUSO* - Extreme Universe Space Observatory is a space mission devoted to the investigation of the highest energy processes present and accessible in the Universe. The main objective is the measurement of the energy spectrum beyond 3×10^{19} eV of the EECR (Extreme Energy Cosmic Rays) and the opening of the channel of the High Energy Neutrino Astronomy, to probe the nature and distribution of sources and the boundaries of the extreme Universe. *EUSO* will observe, from space, the track of fluorescence UV light induced by the Extensive Air Showers developed in the atmosphere by the incoming radiation. *EUSO* instrument is a UV telescope based on a wide angle Fresnel optics (2.5 m lens diameter, ±30° FOV), a highly pixelised focal surface (~ 1 km^2 pixel at Earth), an on board electronics capable of triggering on the EAS images. *EUSO* has been approved by the European Space Agency for a Phase A accommodation study as external payload on the International Space Station. Operation is tentatively foreseen for 2008.

1 Introduction

One of the most challenging issues in Astroparticle Physics is represented by the observation in the Cosmic Radiation of sub-atomic particles with energy above 10^{20} eV (Linsley, 1962; for a review: Nagano and Watson, 2000). This fact raises fundamental scientific questions in connection with the origin of the EECRs and their propagation in the intergalactic space.

The Earth atmosphere constitutes the ideal detector for these Cosmic Ray particles and the companion Cosmic Neutrinos; interacting with the atmosphere, they give rise to Extensive Air Showers (EAS) as a result of a complex relativistic cascade process. EAS are accompanied by the isotropic emission of UltraViolet (UV) fluorescence induced in Nitrogen by the propagating secondary charged particles. An isotropically diffuse optical-UV signal is also emitted following the impact of the Čerenkov beam accompanying the EAS on clouds, land or sea. EAS originated by an EECR forms a significant streak of fluorescence light over several kilometres along its passage in the atmosphere, depending on the nature of the primary particle (Proton or Nucleus or Neutrino), and on the arrival direction respect to the vertical.

The extremely low value for the EECR flux, corresponding to ~ 1 event/(km^2 sr century) at energy greater than 10^{20} eV, makes difficult the observations. Even experiments carried out by means of the new generation ground based observatories, like Auger (Pryke, 1998), will still be limited by practical difficulties connected to the relatively small collecting area (< 7000 km^2, Auger case).

To overcome these difficulties, a solution is provided by observing from space the atmospheric UV induced fluorescence, which allows exploiting up to more than 100,000 km^2 acceptance area: this observation approach with a detector at distance from the shower axis is the best way to control the cascade profile of the EAS.

EUSO is the first space mission devoted to the investigation of EECRs and will observe the fluorescence signal looking downwards the dark Earth's atmosphere from ~ 400 km altitude.

EUSO has been approved by the European Space Agency ESA for a Phase A study concerning its accommodation as external payload on the International Space Station (ISS), with a goal for flight in 2008. The instrument consists of a UV telescope with large collecting area and wide field of view (FOV) ±30° based on a double Fresnel lens system, a high segmented focal detector, and a sophisticated on-board image processing acting as a trigger.

EUSO is a collaborating effort of many research groups from Europe, USA and Japan and it has been designed to operate for more than 3 years mission lifetime.

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2 Science objectives

The EECR component with energy $E>10^{19}$ eV can be considered as the appropriate "Particle" channel to complement the "Electromagnetic" one, specific of conventional Astronomy. EECRs present us with the challenge of understanding their origin and propagation in the intergalactic space in connection with problems in Fundamental Physics, Cosmology and Astrophysics.

At high energies focal points for the Cosmic Ray (CR) flux are represented by:

- The change in the spectral index at the "Ankle" (the break in the energy spectrum occurring at $\sim 5\times10^{18}$ eV). This could correspond to: a change in the production mechanism in the original sources; a change in the primary elemental composition connected with a different confinement region; intervention of a new component of extragalactic origin superimposing to the general Galactic one.
- How far the Cosmic Ray energy spectrum extends and what is the maximum value observable, if there is any limit? The existence of cosmic rays with $E>10^{20}$ eV is itself problematic: indeed, in this energy range the production mechanisms and propagation of primary quanta involve processes that are poorly understood. The energy loss mechanism related to the interaction of CR particles with the 2.7 K universal background radiation, (GZK effect with photoproduction at Primary energy $E \sim 5\times10^{19}$ eV), (Greisen, 1966; Zatsepin and Kuz'min, 1966), constrains the mean free path of high energy hadrons to be <50-100 Mpc, a short distance on cosmological scales.
- The energy range investigated allows us to test the Theory of Relativity in an extreme domain orders of magnitude above the limit reached with man made particle accelerators (Sato, 1972, 1998; Coleman, 1997; Gonzalez-Mestres, 1998): the observation of the occurrence of the GZK effect at 5×10^{19} eV constitutes in itself a crucial test for the Lorentz transformations at gamma $\sim 10^{11}$ for protons.

Cosmic neutrinos with high enough energy produce detectable EAS. Not suffering of the GZK effect and being immune from magnetic field deflection or from an appreciable time delay caused by Lorentz factors, these particles are ideal for disentangling source related mechanisms from propagation induced effects. The opening of the High Energy Neutrino Astronomy as a new branch of Science will allow probing 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. Astrophysical neutrinos, however, demand for observation a very large detector (10^6 km^2 sr acceptance area and 10^{12} t for the target mass). The orbiting night-sky watcher, *EUSO*, with the large area and target mass of Earth's atmosphere observed, would allow the exploration of the cosmic neutrinos flux (Bottai et al., 2001).

3 Observational approach

In spite of the big efforts lavished in the last 40 years, no more than a handful of EECR events has been reported by the ground based experiments. The Earth atmosphere, viewed from space with an acceptance area of 10^6 km^2 sr and target mass of the order of 10^{12} tons, constitutes an ideal absorber/detector for the EECRs and for Cosmic Neutrinos. EECRs and EE Gamma Rays and Neutrinos, colliding with air nuclei, produce secondaries that in turn collide with the air atoms giving rise to a propagating cascade of particles, the EAS. In the complex hadron-electromagnetic cascade represented by the EAS the most numerous particles are electrons; their number at "shower maximum development" is proportional to the energy of the Primary. Electrons moving through the atmosphere ionise the air and excite metastable energy levels in its atoms and molecules. With a short relaxation time, electrons from those levels return to ground state emitting a characteristic fluorescence light. In air the fluorescence extends from Infrared to Ultraviolet, with peaks at wavelengths from 330 nm to 450 nm. The emitted light is isotropic and proportional to the shower energy at any given depth in the atmosphere. A high energy EAS forms a significant streak of scintillation light over 10-100 km in length along its passage in the atmosphere, depending on the energy of the Primary and the 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 (Fig.1 shows an artist view of the *EUSO* concept). The shower appears as a relatively small disc-shaped luminous object emitting a power of the order of hundreds kW; when viewed continuously, the object moves on a straight path with the speed of light. As it does so, the disc luminosity changes from so faint to be undetectable up to a maximum followed by a gradual fading. The resulting 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 depths in the atmosphere. The integral of light recorded in the track (as well as the light signal at the shower maximum) is proportional to the Primary energy. The cascade shape (especially the position of the shower maximum as a function of the penetration depth) gives an indication about the nature of the Primary. Showers initiated after the traversal of a very deep layer of atmosphere indicate an origin by neutrinos because the neutrino-air nuclei interaction cross-section is several orders the cross section for hadrons or photons (Sacco et al., 2001).

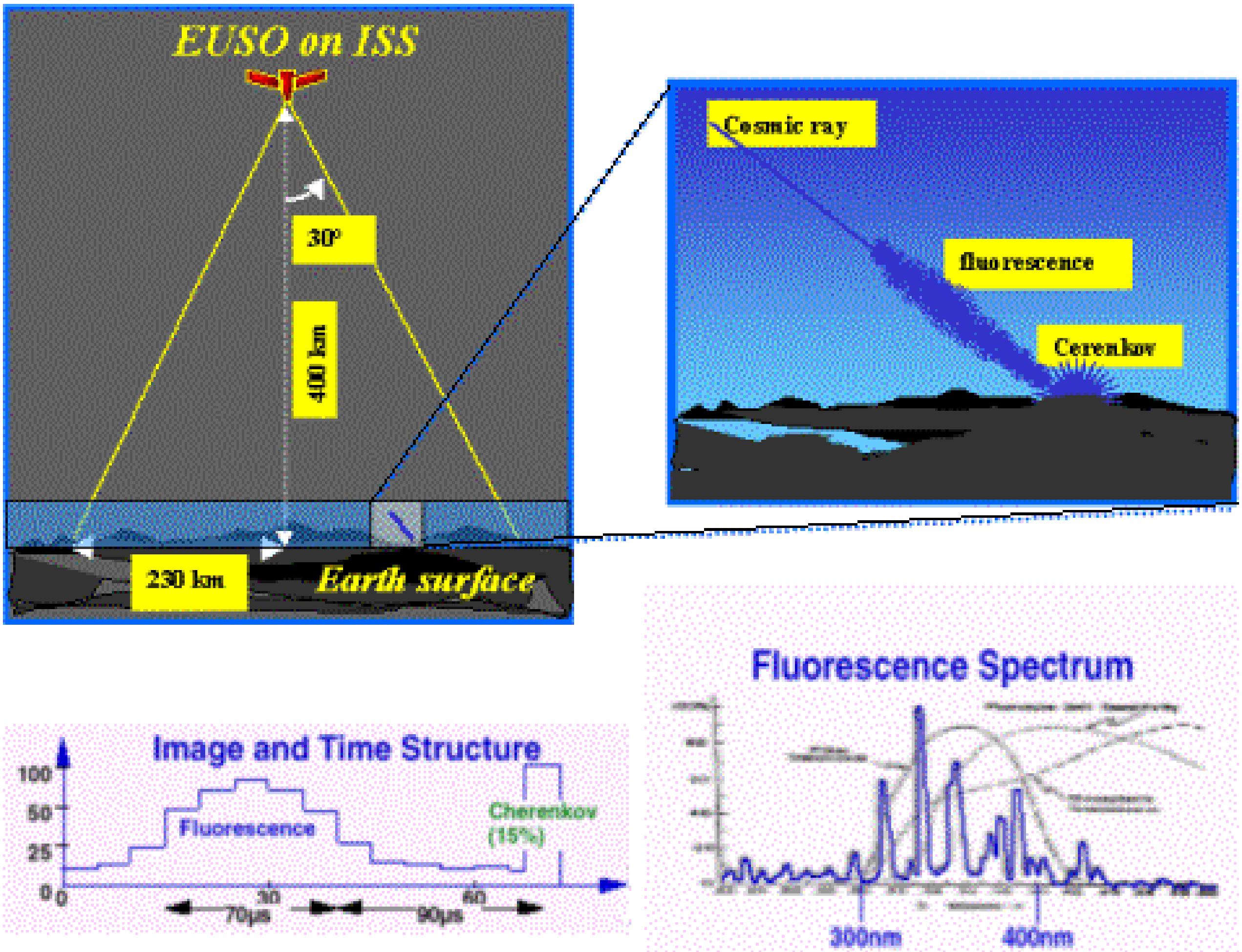

Fig.1. Artist view of the *EUSO* concept. The shower development occurs in the atmosphere layers below 30-40 km a.s.l.; the isotopic fluorescence emission is proportional at any depth to the number of charged particles (mainly electrons) present in the shower front: $N_e \approx E_{eV}/(1.4x10^9)$. The UV yield is ≈ 4 photons per meter of electron track, almost independent from air pressure and temperature. When the shower hits the Earth surface or the top of a cloud, the Čerenkov light (beamed along the shower axis) diffuses and becomes isotropic, and the *EUSO* telescope will detect it. The signal at the *EUSO* altitude is practically free from the "proximity" effect ($1/ r^2$).

From the ISS low Earth orbit the UV fluorescence induced in the atmospheric nitrogen by the incoming radiation can be monitored and studied; the luminescence coming from EAS produced by the Cosmic Ray quanta (protons, nuclei, gamma rays, neutrinos) can be disentangled from the general background and measured exploiting, as a discriminating factor, the "fast (nanosecond level)" timing characteristics. Other phenomena such as meteoroids, space-debris, lightning, atmospheric flashes, distribution of minor components in the atmosphere, can also be observed. For this aspect *EUSO* is an interesting example of multi-disciplinarity in a space mission (Maccarone and Mineo, 2001).

4 Payload concept

The coverage from a low Earth orbit of the observable atmosphere surface at the scale of thousands kilometres across and the measurement of very fast and faint optical-UV phenomena, requires (Catalano, 2001a):

- optics systems with large collecting areas and wide equivalent FOV;
- high segmentation and high speed (well below the microsecond level) of the focal plane detector;
- a dedicated on-board track recorder acting as a trigger.

An exploded artistic view of the *EUSO* telescope is shown in Fig.2.

The requirement of an “in situ / real time” knowledge of the properties of the atmosphere at the EAS occurrence (presence and nature of clouds, atmosphere transparency) to correct for systematic errors in the measurement of the EAS parameters is fulfilled by a “Lidar sounding” carried out with appropriate instrumentation on *EUSO*.

4.1 Optics and filters

The resolution requirements of 10^4 times more forgiving than the diffraction limit suggest the consideration of unconventional solutions for *EUSO*, identified in the multiple Fresnel lens technology. Fresnel lenses provide large-aperture, wide-field systems with drastically reduced mass and absorption. The use of a broad range of optical materials (including lightweight polymers) is possible for reducing the overall weight.

A two Fresnel lenses system (2.5 m diameter each) has been designed to meet the *EUSO* specifications.

An optical filter will be needed to limit the band-pass of the optics in the 330÷400 nm band where most of N_2 fluorescence lines and Čerenkov radiation are emitted. Bulk absorption filters, dielectric coatings or combinations can be used for this purpose.

4.2 Focal surface

Due to the large FOV and the large collecting area of the optics, the focal surface detector (Ameri et al., 2001) must allocate $\sim 2\times 10^5$ pixels. The demanding detector requirements of low power consumption and weight, small dimensions, fast response time, high detection efficiency in the near UV region (300–400 nm), and single photoelectron sensitivity, limit the possible choices to a few devices. A suitable off-the-shelf device is the multi-anode photomultiplier Hamamatsu MAPMT-R7600 series. The pixel size, the gain, the fast response time, the low weight and dimensions of this MAPMT, and its single photoelectron resolution are well suited to the *EUSO* focal surface detector.

4.3 System electronics: trigger and OBDH

Special attention has been given to the trigger scheme (Catalano, 2001b) where the implementation of hardware-firmware special functions is foreseen.

The trigger module named OUST (On-board Unit System Trigger) 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 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.

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.

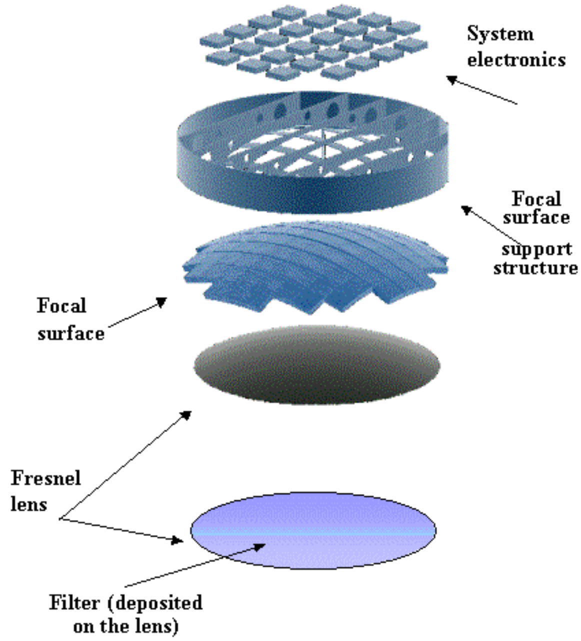

Fig.2. Exploded artistic view of the *EUSO* telescope.

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