The Extreme Universe Space Observatory (EUSO)

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EUSO is an international mission aimed to measure from space the flux, and investigate the nature and origin of the charged and neutral particles of the Extreme Energy Cosmic Rays (EECR) with energy above the conventional value ($E = 5 \cdot 10^{19}$ eV) of the Greisen Zatsepin and Kuzmin (GZK) effect. EUSO will pioneer the observation from space of EECR-induced Extensive Air Showers (EAS), making measurements of the primary energy, arrival direction and possibly composition of the incoming radiation by using a sensitive area and target volume far greater than that achievable from ground. Such data will shed light on the origin of EECR, on their sources, on the propagation environment from the source to the Earth, and on the particle physics mechanisms at energies well beyond those achievable in man-made accelerators.

1. INTRODUCTION

Cosmic rays have always been at the intersection of astrophysics with particle physics. This is still true in current days where experimenters routinely observe atmospheric showers (EAS) from particles whose energies reach macroscopic values up to about 50 Joules. This dwarfs energies achieved in particle accelerators by about eight orders of magnitude in the detector frame (fixed target experiments) and three orders of magnitude in the centre of mass (collider experiments). Such macroscopic energies in a single particle likely link their origin to the most energetic processes in the Universe and possibly testify physics not yet discovered. Explanations range from conventional shock acceleration to particle physics beyond the Standard Model and processes taking place at the earliest moments of our Universe. After almost 90 years of cosmic rays (CR) research, their origin is still an open question, with a degree of uncertainty increasing with energy. The CR spectrum exhibits little structure, and is approximated by broken power laws $\sim E^{-\gamma}$: at energies $E \sim 4 \cdot 10^{15}$ eV, the so-called “knee”, the flux of particles per unit area, time, solid angle, and energy gets steeper from a power law index $\gamma \sim 2.7$ to one of index ~ 3.0. The bulk of CRs up to at least that energy is believed to originate within our Galaxy. Above the so-called “ankle” at $E \sim 5 \cdot 10^{18}$ eV, the spectrum flattens again to a power law of index $\gamma \sim 2.7$. This latter feature is often interpreted as a cross over from a steeper galactic component, which above the ankle cannot be confined by the galactic magnetic field, to a harder component of extragalactic origin.

Over the last few years, several giant air showers have been detected both in ground detectors measuring the secondary shower particles and in fluorescence telescopes detecting the nitrogen emission induced by the shower in the atmosphere, confirming the arrival of CRs with energies up to a few hundreds EeV (1 EeV = 10^{18} eV), corresponding to about 50 Joules. The existence of such extreme energy cosmic rays (EECRs) poses a serious challenge for conventional theories of CR origin based on acceleration of charged particles in powerful astrophysical objects. In addition, nucleons above ~ 70 EeV loose energy drastically because of photo-pion production by the cosmic microwave background (CMB), the Greisen-Zatsepin-Kuzmin effect (GZK) [Greisen, 1966; Zatsepin and Kuzmin, 1966] which limits the distance to possible sources to less than ~ 100 Mpc. Heavy nuclei at these energies are photo-disintegrated in the CMB within a few Mpc [Stecker and Salomon, 1999 and the references therein]. Unless the sources are strongly clustered in our local cosmic environment, a cut-off in the spectrum above ~ 70 EeV is therefore expected, giving rise to flux suppression above this value.

The experimental situation of the detected flux of EECRs shows a disagreement between the AGASA ground array (11 events detected above 10^{20} eV as opposed to about 2 expected from the GZK effect) and the HiRes fluorescence detector whose measurements seem to be consistent with the presence of a cut-off. The Pierre Auger Observatory may probably solve this discrepancy; however a more sensitive experiment, with a number of events per year increased by at least an order of magnitude, is highly demanded and scientifically meaningful, either to measure the source distribution in the sky or to enlight the spectrum recovery after the energy of the GZK suppression. The EUSO sensitive range, as it is actually proposed and designed, meets this goal with an observational target of the order of 1000 events/year ($E > 10^{20}$ eV) and an energy threshold $E_{th} > 5\times10^{19}$eV.

Most of the cosmological theories on CR origin, and the GZK effect itself, predict moreover a significant production of astrophysical neutrinos ranging up to energies $\geq 10^{18}$ eV. It is a common taste that astronomy at the highest energies must ultimately be performed by neutrinos because the Universe is transparent to no other known radiation. However, detection of astrophysical neutrinos demands an extraordinarily large volume, and EUSO will significantly increase the target volume compared with ground-based detectors, enabling exploration of the neutrino Universe.

2. THE EUSO OBSERVATIONAL APPROACH

Detecting fluorescence light, induced in the atmosphere by Extensive Air Showers (EAS), is commonly used for studying EECR in ground-based experiments. The new approach of EUSO, which looks at the atmosphere from a space-based UV telescope, contains some peculiarities with respect to the ground-based approach that need to be outlined in view of the different problems/opportunities arising from them.

The EUSO detection method, based on the observation from space of the fluorescence yield of EAS produced by EECR, relies primarily on the demand for a large increase in event statistics compared with that of any ground based experiment. The calculations based on the simulated performance of the EUSO detector in the configuration optimised during the advanced feasibility study lead to the conclusion that more than 10^3 showers per year are expected to be detected with $E > 10^{20}$ eV in the case of super-GZK flux spectrum; the spectral shape above the GZK characteristic energy will be measured with a high degree of confidence level also in the case of the GZK suppression.

The EUSO detection device consists mainly of a large field-of-view telescope, placed aboard the International Space Station ISS and pointing to nadir. The Earth surface viewed by EUSO, according to the preliminary instrument definition, exceeds $2 \cdot 10^5$ km^2, with a total mass for the overlying atmosphere greater than 10^{12} tons. This will allow not only studying the highest energy showers with much higher statistics that any proposed ground-based experiment, but also to search for the possible existence of multiple shower events. Because of the large target mass ν-induced showers could be detected, under favourable conditions of flux and cross section.

The use of a space-based detector has a number of very significant advantages:

- a full sky coverage is obtained in a single experiment, thanks to the ISS orbit inclination (± 51°);
- the non-proximity of the EUSO detector to the EAS, considerably diminishes the severe problems associated with the determination of the solid angle and with the differential attenuation of the atmosphere traversal suffered by the UV light, also within the same EAS;
- the near-constant fluorescence emission at different heights below the stratosphere allows to make simple and justified assumptions on the relationship between the energy and the fluorescence yield at the EAS maximum as well as to the relationship between the time structure of the EAS and the height at which it is produced;
- the observation of the fluorescence light from above allows the method to be much less sensitive to the presence of most aerosols, which are limited to altitudes below the atmosphere boundary layer;
- a further signature of an EECR event can be detected: the shower "footprint" given by the Čerenkov light flash on ground (or on an optically thick surface encountered by the EAS along its path). An intense Čerenkov radiation is in fact produced by the ultrarelativistic particles in the EAS. This Čerenkov light, emitted as the shower progresses through the atmosphere in a broad wavelength band (~ 200 to 500 nm), with a λ^{-2} dependence of the emitted photons per unit length, is highly collimated around the shower axis, and will be only partially scattered by the atmosphere itself. As a result its propagation accompanies the shower front and the resulting light beam is "dumped" on an optically thick surface encountered by the shower, i.e. a dense cloud or the Earth surface (sea, desert, forest, etc).

The fluorescence light from the shower appears as a thin luminous disk - whose intensity is proportional to the number of charged particles in the EAS - with a variable radius of the order of 0.1 km, and a front thickness of the order of a few meters. It moves through the atmosphere approximately at the speed of light. The fluorescence light at the maximum development of the EAS and the total integrated fluorescence light are proportional to the primary particle energy. The additional observation of the impact point on land, sea or cloud top, with measuring the time of the diffusely reflected Čerenkov light provides additional information useful to improve the EAS reconstruction. This light emission is imaged on the focal surface of the EUSO telescope, where the apparent EAS angular size can vary from few to tens of degrees, corresponding to a length from few to tens of km on Earth depending on many parameters, such as the nature of the primary particle, its energy and arrival direction. The image will be sequentially recorded, starting as a faint signal, increasing to a maximum before fading gradually away. A proton induced EAS of energy $E \sim 10^{20}$ eV will be typically imaged by the EUSO instrument as a number of detected photons per pixel per μs, over several aligned pixels during tens to hundreds of μs. This pattern will be followed, in many cases and with a time delay up to hundreds of μs, by the diffusely reflected Čerenkov light spot, peaked within a few pixels and within a time window of a few μs.

EUSO basically operates as a Time Projection Chamber (TPC) to reconstruct the properties of EECR-induced EAS by measuring both the fluorescence and the Čerenkov photons generated by the EAS itself: a two dimensional projection of an EAS is reconstructed from the distribution of the light signals imaged onto the focal surface. The third projection, the distance along the line of sight, is measured from time delays of the arriving photons. The absolute altitude of the EAS can be evaluated from the diffusely reflected Čerenkov light in a delayed coincidence with the fluorescence one. The ionization of nitrogen atoms in the atmosphere by the charged particles of the EAS leads to an isotropic emission of fluorescence light along the EAS path length. Fast charged particles emit Čerenkov light within a small aperture cone along the EAS direction, and this

Čerenkov light can be detected directly for EAS pointing to the telescope or by diffuse reflection from ground, sea or clouds for EAS pointing to the Earth.

The scientific requirements to define the detector are:

- obtain a EECR rate of 10^3 events/year in the energy range $E > 10^{20}$ eV;
- have an energy threshold able to perform an absolute flux calibration with the largest ground-based experiment (AUGER), i.e. at least half a decade overlap in the energy spectrum ($E_{th} \leq 5 \cdot 10^{19}$ eV)
- have a pointing accuracy better than 1° and an energy resolution $\Delta E/E \leq 20\%$ in the energy range $E > 10^{20}$ eV.

The EUSO instrument is conceptually very simple: it basically consists of the EECR and ν telescope assisted by an Atmosphere Sounding Device. The EECR/ν telescope is basically a fast, high-granularity, large-aperture and large Field-of-View camera, working in the near-UV (330÷400 nm) with single photon counting capability. It allows observation of the Earth atmosphere making possible the detection of EECRs and neutrinos of energy $E \geq 5 \times 10^{19}$ eV through the fluorescence signal produced by EAS, and the diffusely reflected Čerenkov light associated with the EAS.

The instrument is made of a collecting optics, focusing the EAS image onto a photo-detector assembly located at the focal surface (FS). A double Fresnel lenses module with 2.5 m external diameter is the baseline optics for the EUSO telescope. Fresnel lenses (made of radiation hard light-weight plastic material) can provide a large-aperture, wide Field of View system with reduced mass and low absorption. The UV light, focused by the large collecting area of the optics, is imaged onto the focal surface. The FS photo-detector is made of highly pixelized single photon sensitive sensors and it is based on a modular structure made of modules with a geometrical shape that allows a good fitting to the FS while reducing the complexity of assembly and testing. The trigger part provides all the functions required for trigger, read-out and storing of the scientific observational data, whereas the control part is in charge of managing the operations of the Instrument, including data telemetry preparation and transmission and thermal control. The EECR/ν signal is extracted from the background and processed on-board, before raw data are sent to ground-stations. An atmospheric sounding device provides useful information on the atmosphere profile, helping the EECR event reconstruction.

Even if a telescope aiming to watch from Space the EAS produced in the atmosphere by EECR is conceptually simple, its design is a challenging task, mainly because:

- the EECR flux reaching the Earth is very small, thus demanding a large FoV and/or a high altitude orbit to increase the aperture;
- the observable signal is faint (isotropic fluorescence emission means a r^{-2} reduction of the collected photons for a distance r of the detector from the fluorescence source), and therefore only very energetic showers can be detected, resulting in a very high energy threshold;
- the apparatus has to operate in space within all the constraints and resource limitations imposed.

3. EXPECTED RESULTS

The key parameter to fully exploit the potential physics of EUSO, as far as EECR/ν is concerned is the aperture of $6 \cdot 10^5$ km^2 sr. This figure, folded with the acceptance and the duty cycle, enables to predict the expected event statistics, according to the incoming flux of primary Cosmic Rays.

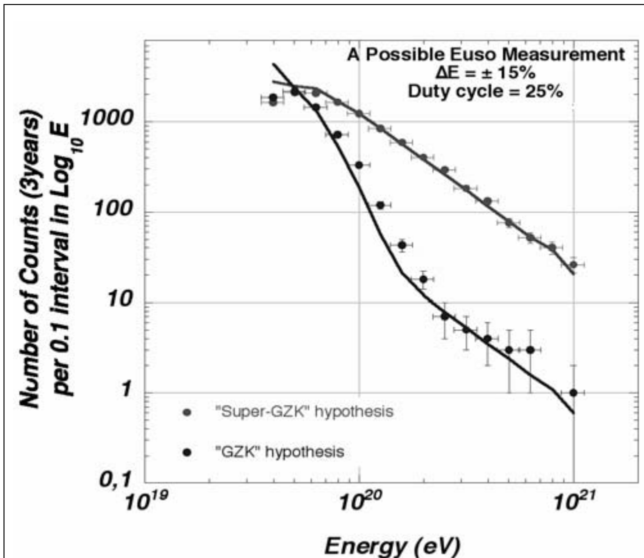

Fig. 1 - EUSO counting rates expected after three years

Energy		SGZK	GZK	SGZK	GZK
Log(E(eV))	eV×10^{19}			#of events>E	
19.7	5.0	1900	1787,7	7832	3434,9
19.8	6.3	1763	1006,5	5932	1647,2
19.9	7.9	1293	414,0	4169	640,7
20.0	10	942	142,5	2876	226,7
20.1	12	640	42	1934	84,2
20.2	15	433	16,2	1294	42,2
20.3	20	293	9,0	861	26
20.4	25	200	6,0	568	17
20.5	31	135	4,0	368	11
20.6	39	87	2,7	233	7,0
20.7	50	60	1,8	155	4,3
20.8	63	40	1,2	85	2,5
20.9	79	29	0,8	45	1,3
21	100	16	0,5	16	0,5

Table 1 – EUSO EECR event rate (in 3 year of operation)

Fig. 1 and Table 1 (where the number of events have been computed with a 19% duty cycle) show the result in terms of number of events, assuming two hypotheses for the energy spectrum:

- a Super-GZK spectrum is observed corresponding to a $E^{-2.7}$ spectrum (extrapolated from the AGASA results) with no GZK suppression and normalized to a value of $3.6 \cdot 10^{-33}$ (events per eV·m^2· sr· s) for E = 10^{19} eV (SGZK);
- a GZK spectrum: the energy profile of this GZK is taken from the work of Berezinsky et al., 1990.

In 3 year lifetime, in the case of Super-GZK ~ 8000 showers are expected to be observed by EUSO above E ~ $4 \cdot 10^{19}$ eV, with an average efficiency of 50%, not including the recovery by using an atmospheric sounding device. The number of expected events above 10^{20} eV is of order of 3000. In the case of a GZK cutoff, under the same assumptions, the number of events observed for energies above 10^{20} eV is ~ 250, and of order of 3500 for energies E > $5 \cdot 10^{19}$ eV. This implies that the GZK decrease can be precisely measured as well as the GZK recovery. If EECR are accelerated in astrophysical sources that extend in space on angular scales smaller than the angular resolution of the detector, one expects that clusters of events should come from the direction of these point sources. A first indication of clustering appears in the AGASA data, where several doublets and one triplet of events have been identified.

Particular attention has been dedicated to investigate the energy region below 10^{20} eV, where the cross calibration with AUGER data will be required as a cross check and absolute intercalibration of the EECR flux. These data lie at the border of the EUSO energy range, i.e. where the efficiency is changing with a steep slope. An error in the energy attribution will therefore turn into a very large error in the flux estimate. The study of the EUSO acceptance shows however that at low energy, the large zenith angle region is highly enhanced. Moreover the throughput of the EUSO optical system is maximised in the central region of the FoV, which can be therefore defined as a bright area for EECR detection.

Because of the large mass (~ 10^{12} tons) of atmosphere in its FoV, EUSO candidates itself as a very powerful detector of ultra high energy cosmic neutrinos, above the energy threshold E > $5 \cdot 10^{19}$eV. The presence of neutrino-induced showers will in fact have a clear signature in EUSO. A ν_e primary entering the atmosphere will produce an electromagnetic shower and hence an EAS as well, if it has the chance to interact through CC interaction in the atmosphere, and will be observed by EUSO, whenever the interaction occurs within the volume limited by its FoV. Since the expected EAS statistics is of the order of 10^3 events/year above 10^{20} eV, as far as the hadronic EECR are concerned, neutrino induced EAS must then be recognized and selected out from those induced by hadrons or photons, with a rejection power of 10^{-4}.

The capability of EUSO to discriminate neutrino-induced showers from “ordinary” cosmic ray showers turns the low neutrino interaction cross section into an advantage: the ν-flux is not attenuated while traversing the atmosphere and neutrino events will be identified by the larger slant depth in the atmosphere where the shower takes place. As a consequence, the neutrino signature in EUSO is completely different from the signature of charged particles, allowing a clear discrimination of the two events. The signature of a neutrino interaction is even further discriminated from that of a charged cosmic ray by detecting the Čerenkov light associated to the shower: because of the different cross-sections the neutrino signature implies the development of the shower much closer to the ground and, as a result, a much shorter time delay between the fluorescence and the Čerenkov light signals of neutrinos as compared with that of charged cosmic rays.

Due to the weakness of neutrino cross sections the neutrino flux is not significantly attenuated while traversing the atmosphere (even at extremely high energy and for horizontal directions). As a consequence the probability distribution for the altitude of neutrino interactions inside the atmosphere follows its density profile and the main signature which identifies neutrino showers from hadron/photon showers is the slant depth at which the first interaction takes place and hence the shower develops. A selection based on the slant depth of the shower maximum appears as the cleanest signature to reach the desired rejection power.

4. CONCLUSIONS

EUSO will address basic problems of fundamental physics and high energy astrophysics, namely:

- investigation of the highest energy processes present in the Universe through the detection and investigation of the Extreme Energy Component of the Cosmic Radiation.
- investigation of the highest energy processes present in the Universe through the detection and investigation of the Extreme Energy Component of the Cosmic Radiation.
- detection of the arrival directions and small-scale clustering of the EECRs will provide information on their origin and on the inter-galactic magnetic fields.
- open the channel of high energy neutrino astronomy to probe the boundaries of the extreme universe and to investigate the nature and distribution of the EECR sources.

From the scientific and technical point of view, the conclusions which can be drawn are that EUSO is a pioneering experiment for studying EAS from space. An instantaneous aperture of $6 \cdot 10^5$ km^{2}sr with a duty cycle ~20% is a technically achievable goal with up-to-date technology. The acceptance reduction due to cloud effect has been evaluated to be ~1/3. EUSO, with its dynamical range ($E > 5\times10^{19}$ eV) is a "beyond-GZK experiment". At $E > 10^{20}$ eV its expected performances are:

- about 10^{3} events/year according to AGASA findings;
- about 10^{2} events/year according to GZK spectrum due to uniform source distribution. In both cases EUSO will complement the AUGER findings;
- study the source spectra will be possible in case that AUGER will confirm a robust incoming flux beyond the GZK suppression range as indicated by AGASA data;
- the spectrum recovery beyond the GZK cutoff and the related source distribution will be studied also in case of GZK suppression that will prevent AUGER to measure any statistically significant flux beyond $E \sim 10^{20}$eV.
- Finally EUSO will be highly sensitive to neutrino astronomy at $E > 5\cdot10^{19}$ eV and will have the chance to open the research field of Extreme Energy neutrino astrophysics (EEν).
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