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Extreme energy cosmic rays: Observation of the atmospheric fluorescence from the ISS(*)

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Summary. — From a Low Earth Orbit (LEO: 400–1000 km of altitude) the light due to cosmic rays of extreme energy showering in a huge mass of atmosphere, up to 2–3 $\times 10^{14}$ t, can be registered. This makes it possible to approach fields of Fundamental Research in Cosmology and in Astroparticle Physics up to now out of reach of the experimental observation, making also the vast field of Physics of the Atmosphere available to the exploration.
The full coverage of the whole observable air mass from a LEO requires to cover a Field of View (FoV) of 130°–140° by composing separate modules, each covering a smaller FoV. The ISS is the most suitable vehicle where those modules could be installed, or could be assempled in a co-flying complex. The ISS location also opens the possibility of a gradual realization of the full coverage, and a "technically evolving" approach: the optical system could be regarded as a permanent facility on board (or co-flying with) the ISS for observing the Earth surface in optical and near-optical wavelengths: different sensors could be alternated on their foci to meet the needs of different experiments or services. The missions currently under study can be the starting pieces for a full coverage facility. Besides the EUSO mission, separately described in a dedicated talk, the situation of the ongoing studies will be reported.

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1. – Introduction

From the space it is possible to observe the fluorescence light emitted in the terrestrial atmosphere by the gigantic showers produced by extreme energy cosmic rays. The perspective of installing an adequate observing device on board of the International Space Station (ISS) was suggested several years ago [1] and considered in the framework of the

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Airwatch concept [2]. The potentiality seemed very promising, given the enormous area of the terrestrial surface observable from the ISS. The mass of the air insisting on this surface is 150×10^{12} t, an enormous target not only for the study of extreme energy cosmic rays, but also sufficient for acting as an observatory for extreme energy neutrinos.

At the end of 1999 the call for proposal issued by the European Space Agency (ESA) for the F2/F3 missions gave the occasion of proposing the EUSO experiment [3] on board of a free flier (as required by ESA). When, in February 2000, ESA selected the EUSO experiment for an accommodation study on board of the ISS, it was like a "return to the future", *i.e.* a return to the initial consideration of the ISS as a suitable vehicle for this kind of observations, with the perspective of a promising extension of the EUSO experimental approach in the future.

2. – Expected performance of the EUSO project

Let us now assume EUSO on ISS as a starting point and a "unity" of measurement for discussing the potentiality of a detection system on board of the ISS that could cover the whole Field of View (FoV) from the Nadir up to the horizon observed from the ISS. Assuming the average altitude of the ISS at 400 km, the full coverage FoV is 140.8°, the area of the corresponding observed terrestrial surface 15×10^6 km^2, and the mass of the corresponding volume of air 150×10^{12} t, *i.e.* 90 times the air target observed by EUSO.

In fig. 1 we report the integral counting rate per year of EUSO expected for the charged particle component (that here and in the following will be assumed to be constituted only by protons, for sake of simplicity) and for the ν's $(\nu_e + \nu_\mu)$ coming from the products of the interaction of the protons with the Cosmic Microwave Background (CMB) (the so-called Greisen ν's). This is the "less unprobable" neutrino component expected at the extreme energies. To avoid becoming "model dependent", no other neutrino sources will be considered, even if potentially they could supply much more abundant neutrino fluxes (such as the neutrino's foreseen in the "Top-Down" processes, or those connected in some models to the Gamma Ray Bursts (GRB's)), partly due to the reason that the previsions for their fluxes are much more uncertain.

It is clear from fig. 1 that EUSO, with several hundreds proton-originated events expected per year at $E > 10^{20}$ eV, and several thousands per year in the 10^{19}–10^{20} eV range, is the adequate instrument for exploring the extreme energy region for the proton-initiated showers (or whatever charged hadron primary would be). For the ν-initiated showers EUSO can give a few Greisen ν events, not sufficient for beginning a systematic neutrino astronomy. The high discovery potential of EUSO for what concerns the Top-Down and the GBR ν's must however be underlined.

3. – Lowering of the EUSO energy threshold

For expanding EUSO in the direction of the realization of a neutrino observatory we can act in two directions: a) going down in the energy threshold for the observation of the atmospheric showers, thus profiting of the expected increase of the rates in the lower energy region, where the flux is much higher, and/or b) increasing the FoV to include the greatest possible area of the terrestrial surface in the observation.

In order to decrease the energy threshold, we can both increase the diameter of the optical system collecting the fluorescence light, and the efficiency of the sensors in converting this light into an electric signal. In fig. 1 we show the effect on the annual counting rates of increasing the optics diameter by a factor of 5, from the 3 m diameter of

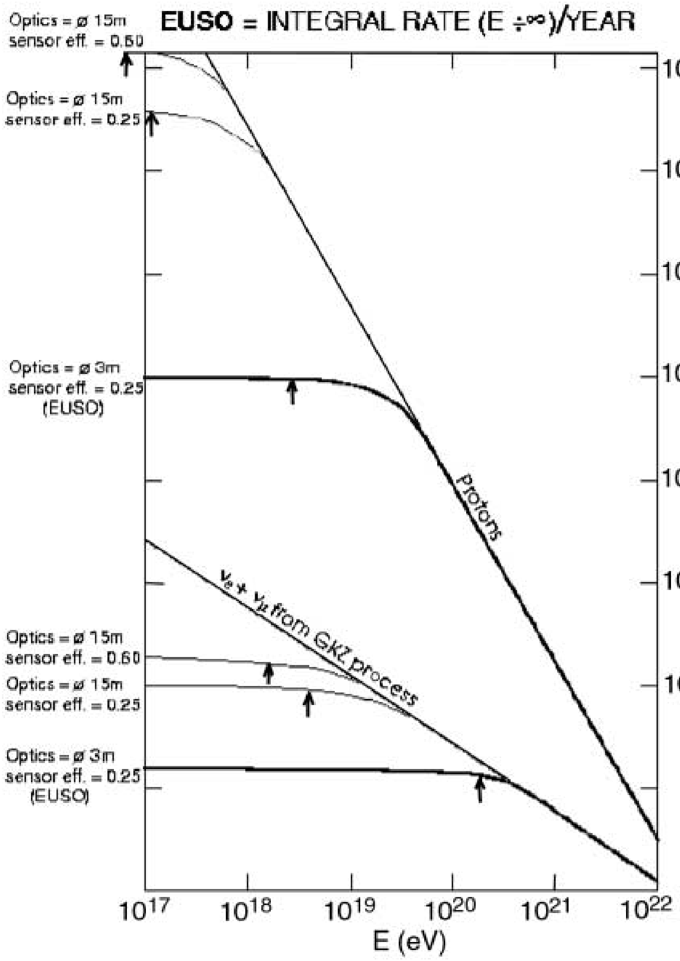

Fig. 1. – Integral counting rate per year of EUSO expected for the charged particle component and for the ν's coming from the products of the interaction of protons with the CMB (see text for details).

EUSO to 15 m. It is also indicated the additional effect obtained by increasing the sensor efficiency from 25% (typical of good photomultiplier photocatodes) to 60% (typical of well matched solid state sensors). Pointing the attention to the annual rate of the Greisen ν's, one can see that it increases by about a factor of 15, up to 22 ν events/year. The arrows reported in fig. 1 indicate the approximate energy thresholds, considered at about 90% of the total integral counting rate.

The approach of increasing the optics diameter, also if at the expense of reducing the area of the observed terrestrial surface, is considered by the Mexican-Russian collaboration for the project KLYPVE, where it is planned of deploying in space an enormous mirror, hung to an arm which is attached to the bottom part of the Russian segment of the ISS [4]. For the sake of an easy comparison with fig. 1, let us suppose that the diameter of the KLYPVE mirror be 15 m: the proton rate is very high in the whole 10^{18}–10^{21} energy range, while the Greisen rate remains insufficient for systematic neu-

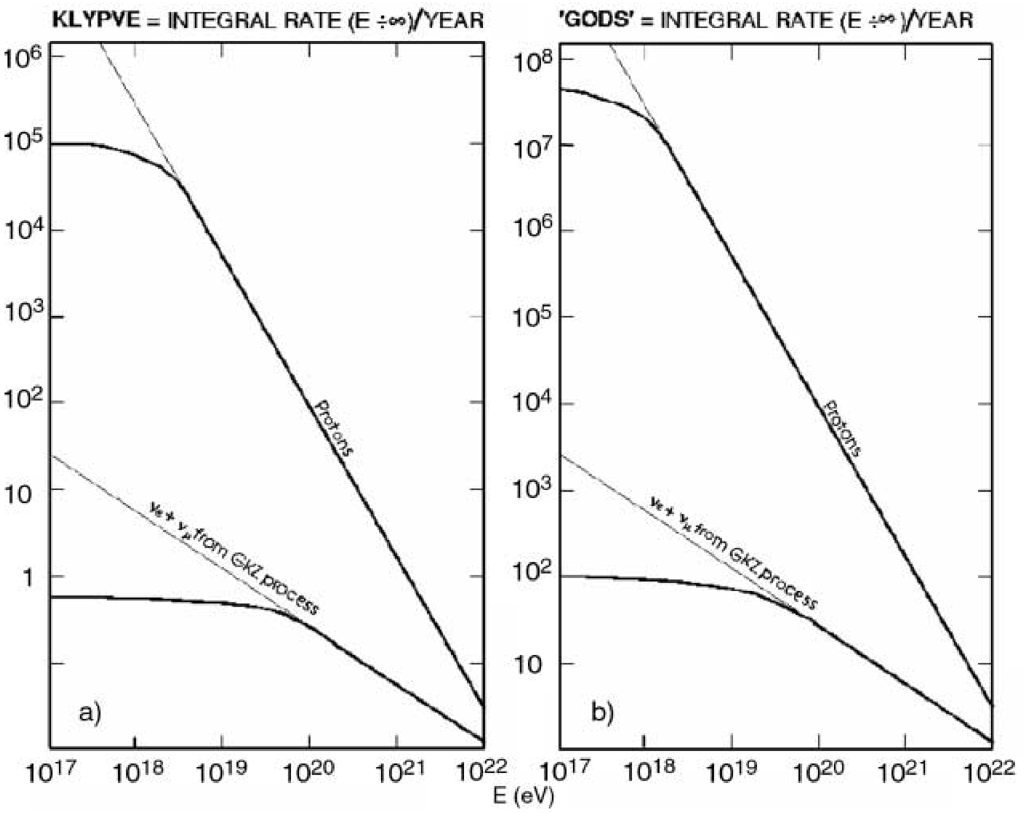

Fig. 2. – As fig. 1 for: a) KLYPVE and b) "GODS". See text for details.

trino observations (see fig. 2a).

4. – Increasing the FoV of the system

The approach of increasing as much as possible the FoV in order to increase the area of the observed terrestrial surface has been considered in the Airwatch/Owl collaboration, by combining seven independent optical systems in one device [6], thus reaching a total FoV of 115°. The expected rates are those reported in fig. 2b, showing that such an approach allows to start the neutrino astronomy at the extreme energies with about 100 ν events/year.

Let us now put the question in general terms, forgetting about the design of a possible detection system.

In fig. 3 the area of the observable terrestrial surface from an altitude of 400 km is reported as a function of the distance of the circumference of this surface from the Nadir direction (the scale is that at the right side, given both in 10^6 km^2 and in "EUSO units"). In order to obtain the corresponding annual counting rates several effects must be taken into account:

1) The attenuation of the light signal due to the distance "*d*" between the emission point and the detector. Since the length of the portion of shower seen in an angular pixel

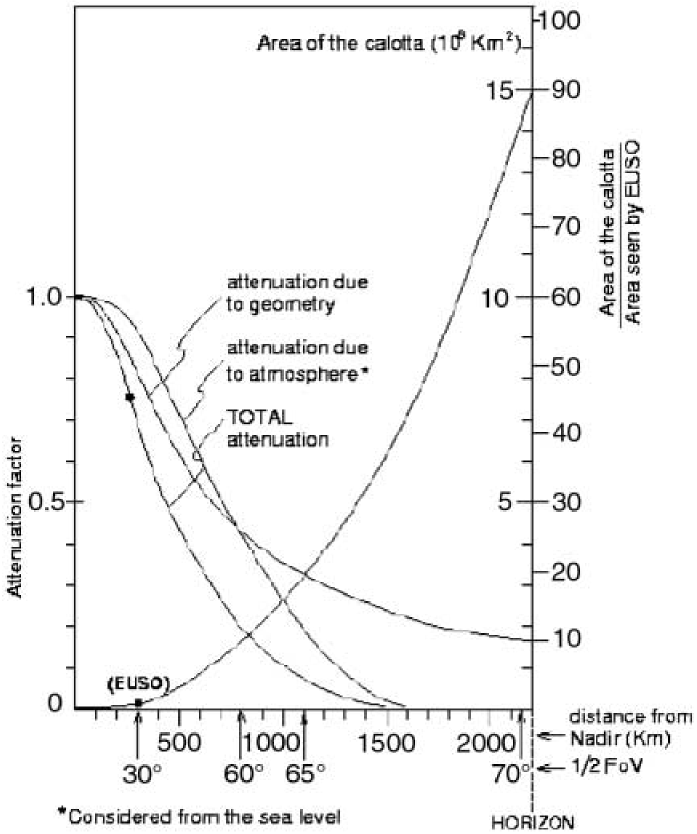

Fig. 3. – Area of the observable terrestrial surface from an altitude of 400 km as a function of the distance of the circumference of this surface from the Nadir direction (see text for details).

of the detector increases as d, while the signal attenuates as d^{-2}, the signal diminishes as d^{-1} (see in fig. 3 the curve of the signal amplitude normalized to the amplitude at Nadir, the scale is that on the left side).

2) The absorption of the light by the atmosphere. At the Nadir the atmosphere transparency is about 0.56. By increasing the angle of view from the Nadir direction the thickness of the air to be crossed by the light increases. Due to the Earth curvature it increases much faster than for the observation of a flat surface. Furthermore, since it appears as the power in an exponential function, the corresponding transparency of the atmosphere rapidly falls to zero. It is less than 2% already halfway between the Nadir and the horizon (the curve in fig. 3 is normalized to the Nadir transparency; the scale is on the left side).

The total transparency normalized to the Nadir is given by the product of the two above effects, and is reported in fig. 3 on the same left-side scale.

There are several other effects that should be taken into account and could further worsen the experimental situation with increasing distance from the Nadir direction. The most relevant are the signal/noise ratio, worsening as d^{-1}, and the increase of the terrestrial surface observed in a single angular pixel (it reaches 4×180 km^2 at the

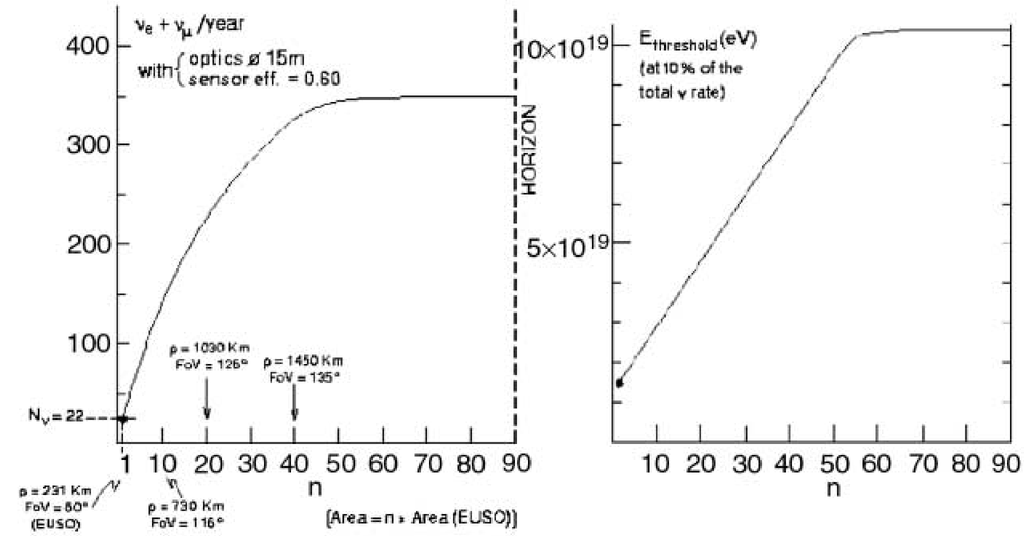

Fig. 4. – a) Annual rate of detectable Greisen ν's as a function of the area of the covered terrestrial surface; b) energy threshold of the system. See text for details.

horizon) that could delocalize the position of the signal on the terrestrial surface and make it difficult to apply the corrections at the local atmospheric and light emission conditions. However, because these effects strongly depend on the detail of the detection system, they will not be considered in the following, leaving to the real project how to take care of them.

We can now obtain the annual rate of detectable Greisen ν's as a function of the area of the covered terrestrial surface, under the hypothesis of having considered all possible initiatives for minimizing the energy threshold, *i.e.* increase of the optics diameter up to 15 m and of the sensor efficiency up to 60%.

The result is reported in fig. 4a, while in fig. 4b the energy threshold of the system is reported, considered at 90% of the total integral counting rate.

In order to reach a conclusion, it is necessary to add a further consideration.

To the total number of detectable Greisen ν's per year one should apply the efficiency factor for recognizing the ν-originated showers in the huge sea of the p-originated showers. Not taking into account the experimental difficulties in the observations, such as the local atmospheric conditions that can blind portion of the shower (and of which it could be taken into account in a careful analysis), about two third of the ν-originated showers can be distinguished by their deeper origin in the atmosphere, with a neglegible contamination from the p-originated showers. Of the remaining one third, about half should be originated by ν_e and should show a maximum at the depth typical of hadronic showers, and another maximum (in general more intense) at a depth two times deeper, due to the LPM effect that expands the length of the very high energy electromagnetic shower originated by the electron produced in the ν_e interaction. The other half of the not deeply originated ν showers are due to ν_μ interactions, originating a high energy μ and a hadronic shower indistinguishable from a p-originated shower. The total efficiency for distinguishing a ν-originated shower is therefore not greater than 0.8. Correspondly, the number of Greisen ν's detectable from the ISS is not higher than 280, 170 of them being recognized as originated by ν_e interactions and 110 by ν_μ interactions.

However, it must be noted that a further reduction factor could be introduced, by considering the different efficiency of the instrument for detecting ν-induced showers with respect to p-induced ones. This difference is being evaluated by the EUSO collaboration, and it mainly depends on the shorter path available to deeply originated ν showers [7].

5. – Conclusions

It cannot be *a priori* decided if the about 300 Greisen ν's per year could be considered an adequate figure for a possible neutrino observatory, and it will strongly depend on the results of the EUSO observations and of other similar devices and of their possible extensions.

Here I limit myself to two considerations:

1) The area of the total observed terrestrial surface can be increased by increasing the altitude of the detection system. This can be still obtained starting from the ISS, by assembling on board the whole system, and launching it from the ISS equipped by a suitable free flier module. Afterward it would be possible to raise the altitude of the orbit: in fact the mass of the fuel needed for increasing the height of the orbit is not enormous, about 30 kg per t of mass for doubling the height of the orbit from 400 km up to 800 km. However for the same FoV, from a 800 km altitude the total rate of detectable Greisen ν's increases much less than the 4 geometric factors with respect to the ISS orbit, *i.e.* only by a 1.6 factor, because of the increase of the energy threshold due to the light attenuation for the longer distance.

2) A number of identical wide FoV systems could be assembled on board of the ISS and launched on its same orbit, which could present several advantages:

a) the results from the first detection system will teach about the opportunity of increasing the gatering of ν events by launching other devices;

b) the following-on devices could have general structure (optics + mechanics) identical to the first one, greatly decreasing the needed work, the realization time and possibly the prices;

c) since the temporal distance between two subsequent launches could not be in any case short, the sensor and trigger efficiency could be improved from one launch to the following;

d) the attitude of two sufficiently near systems (*e.g.*, less than 1000 km distant) could be adjusted for looking for some time at the same portion of the terrestrial surface, allowing the inter-calibration of the systems.

With N systems, the rate should therefore be at least N times larger than that obtainable by the first system alone.

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