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UHE neutrino detection from space. Toward a dedicated neutrino observatory

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The upcoming generation of space based fluorescent detectors will measure the flux of charged cosmic rays above the characteristic energy of the GKZ mechanism and will be able also to look for the neutrino component above 30-50 EeV. Here we discuss the feasibility of a subsequent space based detector mainly focused on the neutrino detection. The possibility to lower as much as possible below 10 EeV the energy threshold and the consequent benefit on the neutrino detection is discussed in detail. The main guidelines to achieve such ambitious goal are presented together with some proposal for the optical system.

1. Introduction

Cosmic rays (CR) are highest energy particles present in nature with energies exceeding 10^{20}eV [1]. The sources of such energetic particles are expected to be extra-galactic, such as distant AGNs, powerful radio galaxies etc. These charged CRs interact with cosmic microwave background radiation (CMB) photons during their propagation over cosmological distances, resulting in a rapid loss of energy leading to the so called GZK cutoff in CR energy spectrum [2]. This interaction results in production of ultra high energy (UHE) γ-rays and UHE neutrinos, nicknamed 'cosmogenic neutrinos'.

The upcoming generation of experiments based on the fluorescence light detection from space (EUSO [3], TUS [4], KLYPVE [4]) could at most observe a few UHE neutrinos if the nature favors the most abundant fluxes, but in any case they could not perform a systematic study. It raises naturally the question in what direction should the orbiting fluorescence detectors evolve for conceiving a dedicated neutrino observatory based on this technique. The goal is in effect not far away. In the conclusion of the last October authoritative report of the Neutrino Astrophysics and Cosmology Working Group of the APS [5] it is strongly recommended "the development of experimental techniques that focus on the detection of astrophysical neutrinos, especially in the energy range above 10^{16} eV"; considering the possibilities of the present running (AUGER [6]) or studied (TA [7], and the above quoted from space) experiments, it is claimed in the conclusions that "the technical goal of the next generation detectors should be to increase the sensitivity by factor of 10, which may be adequate to measure the energy spectrum of the expected GKZ neutrinos, produced by the interactions of the ultra-high energy cosmic ray protons with the CMB."

2. Dimensioning of an UHE neutrino observatory from space.

The UHE neutrino flux is strongly model dependent, and for many models ranges on several orders of magnitude. The cosmogenic neutrino flux is the less model dependent basis: the flux of neutrinos accompanying the proton is higher as higher is the proton initial energy and the extrapolation of the proton flux based on the few until now detected events and reasonable hypotheses on the possible distribution and maximum energy of the sources with energy beyond 100 EeV allow evaluating the lower and upper limits of

the expected neutrino flux [8]. The lower and upper numbers of the corresponding neutrino events in an experimental configuration can be used for dimensioning of the UHE neutrino observatory from space.
In order to evaluate the observatory characteristics we relay on the sound basis of the phase A study of the EUSO experiment, where in a work lasted several years it was evaluated the light collection and background and all the parameters of the device and the efficiency of the events reconstruction and identification [9].

The following improving factor and adaptations can be applied:

1. the photoelectric conversion of the fluorescence photons has been assumed in EUSO to be 20%. Presently a robust R&D activity is in progress for increasing this efficiency, and values as high as 45% have already been obtained in prototypes [10]. It is a reasonable assumption that in next few years conversion efficiencies as high as 50% can be reached also for industrial produced detectors. This improvement will increase the signal to background ratio allowing to the decrease the energy threshold for the detection of UHE showers.

2. The optical system of EUSO is based on light transmission through a pair of Fresnel lenses. This choice maximizes the FoV, maximizing the mass of the atmosphere observed from the ISS orbit, but it constitutes a technological limit for the diameter of the pupil by which the light is collected (2 m in the EUSO project), limiting to very high values the corresponding energy threshold. For a neutrino observatory the pupil diameter must be maximized for decreasing as much as possible the energy threshold, in order to match the energy region where the flux of cosmogenic neutrinos is expected to reach its maximum. This is conflicting with the need of maximizing the monitored mass of atmosphere by pushing the FoV beyond 60°. It is therefore necessary to use several large pupil optical systems, what implies the deployment in space of large diameter reflecting systems, each with its own sensor system, possibly (but not necessarily) centralizing the common electronics, data handling and services of the experiment. It must however observed that the maximum FoV cannot be so large to reach the horizon seen from the orbit. Already at 45° from the nadir the signal from the shower is reduced by 50%, and wider angles could not be very useful for a neutrino observatory because of the corresponding increasing of the energy threshold and of the pixel dimension on the ground. It is therefore reasonable to stack to a 90° FoV for the following evaluations.

In order to simplify the multi-parametric task of dimensioning a complex device we stack at some of the assumptions of the EUSO project, such as the location of the device on board of the ISS, which determines the average distance from the ground. The release of this assumption could be used as a handle for a further improvement of the neutrino observatory parameters.

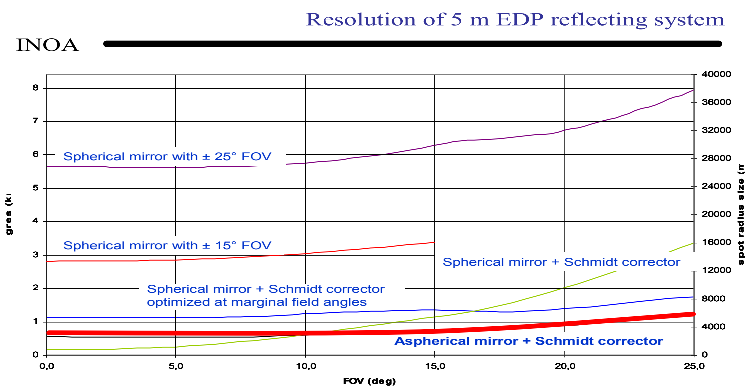

Figure 1. Resolution of 5 m pupil reflecting systems.

The angular resolution of the optical system strongly depends from its FoV. In order to cover the whole 90° useful FoV with a limited number of identical optical subsystems the FoV of each of them must be as large as possible. For a single subsystem the pixel dimensions on ground and the corresponding pixel dimensions on the detector are reported in Figure 1 as a function of the FoV [11].

The best result is given by a Schmidt system with an aspherical mirror. Since a good performance on axis is not crucial, an other optimization can be performed in order to preserve the desired RMS spot radius, and consequently the on ground resolution, even at larger radius. Optimizing the system at 15° from its axis, the dimension of the spot is homogeneous over the entire fields up to about 22°, which allows a RMS of the spot better than 1 cm in diameter, with a corresponding resolution better than 1 km on the ground. These values are very near to those chosen in the EUSO project for assuring optimal image reconstruction and trigger capability. A few (≥4) sub-systems are enough for covering the whole useful FoV of the neutrino observatory. Indeed the Schmidt telescope, one of the best known reflectors, well matches both the large FoV and a large collecting area, and appears as an appropriate solution to solve the problem. Existing Schmidt telescopes do not meet the dimension needed for this kind of space application. Pursuing this way it is therefore also a technology challenge, which may open the way to many new applications for space astrophysics.

In order to evaluate the number of the expected UHE neutrinos detected by a space observatory, besides the light collection and the detector sensitivity it must be considered the capability of the system to identify the shower produced by the neutrino in the flood of the showers produced by UHECRs. The ratio between this two classes of showers is about 10^3 at 10^{20} eV, 10^4 at 10^{19} eV and reaches 10^5 at 10^{18} eV. The effective threshold for the neutrino detection depends from the possibility of its identification, based on the depth inside the atmosphere of the origin of the shower and on the length and shape of its longitudinal development [12], and therefore depends from the quantity of the collected light. Extensive simulations have been made for understanding this parameter [13].

	EUSO like		Multi-mirror		
H (km)	400		400		
Total FoV (°)	60 →		90		
Radius on ground (km)	235		413		
Area on ground (10^3km^2)	173		536		
Pixel on ground (km * km)	0.8 x 0.8		≤1.0 x 1.0		
Φ pixel on detector (cm)	0.6		≤1.2		
Area/pixel (≈n. of pixels)	270k		536k		
Pupil diameter (m)	2.0	2.0 →	5.0	7.5	10.0
Photo detection efficiency	20%	50%	50%	50%	50%
E threshold (EeV)	50	20	5.5	3.2	2.3
Proton events/year,					
GKZ + uniform source distrib.	1200	8000	300k	900k	1800k
with E_p >100 EeV)	100	100	310	310	310
Neutrino events per year (≈ min)	**0.6**	**1.5**	**18**	**30**	**42**
Neutrino events per year (≈ Max)	**12**	**18**	**108**	**120**	**138**

Figure 2. Event rate for different configurations of the observatory. The arrows give prominence to the main changes of the EUSO parameters

The evaluations of the minimum and maximum numbers of neutrino detected and identified events are reported in the table shown in Figure 2 for three values (5, 7.5 and 10 m) of the diameter of the pupil at 400 km of altitude (columns 3-5), compared with the number of events expected in EUSO for two values (20% and 50%) of the photoelectron conversion (columns 1-2).

As a further remark it must be considered that the optical configuration needed for a UHE neutrino observatory from space is considerably large, exceeding the dimensions of the available spacecraft, therefore segmented mirrors be open once in orbit appears to be a suitable solution. The simplest deployment mechanism consists in dividing the mirrors into a fixed center structure, about the same size of the focal plane, surrounded by a "petal" structure holding the remaining mirror. The whole could be closed around the focal plane and the corrector plate, achieving a compact cylindrical structure with a diameter close to that of the entrance pupil. The tolerance involved in the mechanical deployment system is not stringent for the present design, because of the relatively large spot dimensions. The angular tolerance for the mirror surface results to be several mrad, easily achievable with mechanical systems without any in-orbit adjustment.

In conclusion an UHE neutrino observatory from space can be built with large mirrors, and the construction is already possible with the existing technologies, scaling the dimensions in order to get a higher signal, and hence a lower threshold. The orbit can also be higher, increasing the observed area downward. Better performance is obtained with a design including an aspherical primary mirror, yielding either to a possible significant reduction of the total mass of the systemby reducing the size of every single pixel or to a higher limiting FoV by maintaining a greater spot size radius. Several construction techniques may be considered for the manufacturing of the optical telescope, amongst them replication by nickel electroforming is a widely used technique for producing cost effective and light weight optics for space applications.

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