

DETECTING COSMIC RAYS OF THE HIGHEST ENERGIES

NATO Advanced Research Workshop, Oujda, Marocco, 21-23 March 2001

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1. Introduction

The highest energies are defined, at a given time, by our detector capabilities. Thus the highest energies will be the just measured or soon to be measured energies. To-day, the frontier in cosmic rays reaches 10^{20} eV. This represents a macroscopic energy, namely 16 J, transported by a microscopic object. For charged particles, the highest energy events seem to necessitate some New Physics, beyond the present understanding of astrophysics and particle physics.

Concerning neutrinos, apart from the low energy ones coming from the explosion of SN1987A, only neutrinos of terrestrial origin have been detected so far. It is a challenge to detect neutrinos which may be witnesses of the most violent phenomena in the Universe. With their very small probability of interactions and their neutral nature, they can come unaffected from the most distant parts of the Universe. Theoretical predictions give two regions of interest: from 10^{14} eV to 10^{17} eV for the contribution of AGN's, and from 10^{18} eV to 10^{20} eV for GZK neutrinos, the ones created but the high energy cosmic rays interacting with the CMB.

Moreover, the study of high energy neutrinos may be used, not only to find sources, but also to constrain some properties of these elusive particles. For example, limits on oscillations can be achieved for δm^2 unreachable otherwise, and one can dream of searching for cosmic neutrinos through the Z^0 resonant absorption.

2. Charged cosmic rays

The spectrum of cosmic rays as it is measured to-day, extends over more than 30 orders of magnitude in flux and reaches energies of macroscopic

size.

The highest energy events are at the origin of a puzzle. Protons above $5 \cdot 10^{19}$ eV undergo the GZK (Greisen-Zatsepin-Kuzmin) effect, namely their interaction cross-section with the CMB background is such that one interaction length amounts to about 50 Mpc. This is only 1% of the size of the Universe and there are no known sources energetic enough in this close neighbourhood. The GZK effect should show as a pile-up of events followed by a cut-off at the critical energy. Experimentally, a few events are seen above the cut-off, and there is no unique explanation for their existence. In 'top-down' models, these events are interpreted as traces of topological defects or very high mass remnants of the Big Bang.

In order to shed some light on the problem, it is essential to increase the present statistics. Here comes the difficulty: the flux is extremely low, on the order of 1 cosmic per km^2 and century.

The Auger observatory is instrumenting 3000 km^2 in the Argentinian pampa, thus hoping to collect some 30 events per year in the interesting energy region. The set-up should be operational in a couple of years.

Euso projects to use an optical telescope on the International Space Station. From 380 km altitude, it is able to watch 150000 km^2 of atmosphere and should detect some 800 events par year through the fluorescence light emitted along the showers generated by the passage of the cosmic rays.

3. The problems of neutrino detection

Very ambitious projects also exist for neutrino detection. The aim is to instrument large volumes of up to 1 km^3 under the ice of the South Pole or deep underwater. However this technique is only efficient for the detection of up-going muons produced in the interactions of ν_μ . The energy resolution on the detected muon is based on catastrophic bremsstrahlung and is limited typically to a factor of 5.

The difficulty of detecting neutrinos comes from their very small cross-section necessitating large targets. Even at an energy of 10^{20} eV, the cross-section reaches only 10^{-31} cm^2 . The probability of interacting while traversing the atmosphere is only 10^{-4} . The most optimistic predictions of neutrino fluxes give no hope of seeing events coming down from the sky. Thus it is necessary to use a denser target. The earth is an obvious candidate but here comes another problem. At very high energies the earth becomes opaque to neutrinos. The cut-off happens at 100 TeV. Above this energy, ν_e and ν_μ are absorbed if they cross the earth through its center. The case of the ν_τ is more favorable because of the multibang phenomenon. An effect similar to the GZK one takes place: very high energy ν_τ can cross the earth but their energy is degraded and they all exit with a few 10^{14} eV. Of course,

ν_τ detection is only possible if neutrinos oscillate with maximum mixing since only ν_e and ν_μ are directly produced in known mechanisms, at least in first order.

The Auger observatory will be able to detect a few ν_τ events, by catching some of the products of the interaction in the mountain close to the apparatus. For Euso the possibility of detecting neutrino interactions by up-coming showers in the atmosphere is hampered by the threshold which is too close to the cut-off coming from earth opacity.

4. A novel way to look at neutrinos

In order to alleviate these constrains, it is proposed to search for neutrino interactions in a mountain. This allows a detector closer to the shower and a target thin enough. The leptons generated in the process have a chance to come out of the rock and they subsequently develop a shower through the atmosphere of a valley. The shower is detected by its Cerenkov emission in an optical device. Cerenkov emission has the advantage over fluorescence to give collimated light. For example the Euso threshold is a few 10^{19} eV for fluorescence, it is only a few 10^{14} eV for Cerenkov light. But the subtended solid angle in a given set-up reduces to 10^{-3} sr, because of collimation.

The telescope copies the one of Euso. Its optics covers a large field of view of 60 degrees. It could in principle be a 1 m² prototype of the final device (Eusino?). The detector must be fast, it is based on multianode photomultipliers. The background fixes the needed number of pixels. The night-glow is measured equal to 200 photoelectrons per m², ns and sr. In order to get a 10% random occupancy with a 10 ns gate, this requires about 20000 pixels (10% of the full Euso). With a valley 20 km wide, each pixel sees a spot of less than 100 m \times 100 m of the opposite face.

Two such telescopes separated by a few 100 m and observing the same area would allow coincidences and stereoscopic information by TOF, thus reducing drastically the background.

5. Expectations

There are two ways to look for Cerenkov light: direct observation when the detector lies in the illuminated cone, or reflected light. The first method is adapted to point-like sources, the second to a diffuse flux.

For the direct detection of Cerenkov light, one considers neutrinos traversing the mountain ridge in front of the telescope. Cerenkov intensity for a given electromagnetic shower in the atmosphere has been well studied by the high energy photon telescopes (Cat, Whipple...). A shower of 300 GeV initiated about 10 km above earth generates 2 photoelectrons per m² over a full area of half a km². This gives a total of a few 10^5 photoelectrons. Higher

energy showers give a linearly increasing flux of photons. The threshold is dictated by the number of detected photons. If one requires a minimum of 10 photoelectrons over a few adjacent pixels, the energy threshold is $2 \cdot 10^{13}$ eV. At such energy the atmospheric flux starts to die down in front of the predicted AGN contributions. This method is well adapted to search for a neutrino emission coming from our galactic center or from AGN's like the Markarians.

For the indirect Cerenkov light, the idea is to take advantage of the flash of light reflected on the mountain facing the telescope. The albedo is quite large, specially on a snowy surface. The reflection spreads light over 2π sr. The set-up is now sensitive to large solid angles, but the telescopes catch a small fraction, 10^{-10} , of the emitted photons due to reflection. This pushes the threshold to higher values. To collect 10 photoelectrons in a telescope, the initial shower energy must be above 10^{17} eV. This energy range is well adapted to GZK neutrinos.

6. Conclusion

The relatively modest experiment discussed here can explore an effective area of 50 km^2 due to the large field of view of the optical device. The effective target depends on the nature of the considered neutrino.

For ν_μ , the produced μ can cross large distances in the rock before it exits, but the Cerenkov light emitted along its trajectory in the atmosphere may not be intense enough.

For ν_τ the situation is the most favourable. The τ can cross several km in the rock, then comes out of the mountain and decays over the valley giving a high energy shower. The effective target is huge, up to $500 \text{ km}^3 \text{sr}$ at high enough energies. With the technique of the reflected Cerenkov flash, and with the expectations of GZK neutrinos, a calculation gives some 10 events per year.

For ν_e , one can take advantage of the Landau-Pomeranchouk-Migdal effect which suppresses the development of electromagnetic showers in dense materials. At energies of 10^{20} eV, an electron produced by the interaction of a ν_e can cross up to 100 m of rock. When it reaches the air the shower develops immediately. Thus the effective target has a depth of 100 m.

The present idea is essentially adapted to the detection of ν_e and ν_τ interactions. This is complementary to the physics reach of volume detectors like Amanda and Antares which are limited to ν_μ interactions. The angular resolution is quite good reaching 2 mrad. Moreover, this technique allows a decent energy measurement, typically 30%, and, if statistics are large enough, spectra can be measured.

7. References

For more reading:

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