Auger : A large Air Shower Array and Neutrino Telescope

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Detection of Ultra High Energy Neutrinos (UHEN), with energy above 0.1 EeV ($10^{18} \text{ eV}$) is one of the most exciting challenges of high energy astrophysics and particle physics. In this article we show that the Auger Observatory, built to study ultra high energy cosmic rays, is one of the most sensitive neutrino telescopes that will be available during the next decade. Furthermore, we point out that the Waxman-Bahcall upper bound for high energy neutrino flux below 1 EeV turns into a lower bound above a few EeV. In this framework and given the experimental evidences for $\nu_{\mu} \rightarrow \nu_{\tau}$ with large mixing, we conclude that observation of Tau UHEN in the southern Auger observatory should most certainly occur within the next five years.

1. Introduction

The nature and origin of the observed Ultra High Energy Cosmic Rays (UHECR) have been for the past decades the subject of numerous debates and models (for a review see e.g. [1,2,3]). None of those models seemed to be able to fulfill simultaneously the source power requirement, its invisibility and the transport energy losses without requiring either new physics or large magnetic field together with a local over-abundance of transient (power sufficient?) sources. Moreover recent experimental results [4,5] shown at the 27th ICRC conference [6], seemed somewhat contradictory in particular concerning the flux of events above the Greisen Zatsepin and Kuzmin cut-off [7]. Given the lack of statistics the interpretation of the same data has even led some authors to completely contradictory conclusions (see e.g. [8,9]). What are the UHECR sources and their distribution? What is their nature and energy spectra? What is the flux above $10^{20}\text{ eV}$? Those are the few fundamental questions that future experiments need to answer.

In the energy range [$10^{19} - 10^{20}$] eV only stable hadrons (e.g. protons) or nuclei, among the known particles, can travel on distance much larger than a few tens of Mpc. However the maximum distance is still limited to about 50 Mpc (our neighborhood on cosmological scale) above $10^{20}$ eV because of photo-production or photo-dissociation processes against the Cosmic Microwave Background of radiation (CMB). If astrophysical objects such as AGN or GRB are to play a fundamental role in UHECR production then particle spectra from distant sources will be affected by these processes. Resulting fluxes should extinct exponentially above $10^{20}$ eV exhibiting the GZK cutoff. Taking into account additional distortions induced for example by extra galactic magnetic fields we conclude that hadron spectra in this energy range will mix the source characteristics together with the transport distortions. On the other hand neutrinos can travel on cosmological distances essentially unaffected and all astrophysical UHECR hadron sources as well as more exotic ones such as topological defect collapses or heavy relic decays are bound to produce Ultra High Energy Neutrino (UHEN). Their detection would be a very valuable clue to the characteristics of the UHECR sources.

2. Auger

Because of their very low flux UHECR cannot be observed directly from space. Instead one must reconstruct the primary cosmic ray characteristics from the Extended Air Shower (EAS) it produces when interacting with the atmosphere. The Auger Observatories [10] consist of two in-
instrumented sites. One in the southern hemisphere, now under construction in Malargüe (Argentina), and the other one in the northern hemisphere. The detection system combines the two major techniques: a fluorescence detector system to measure the longitudinal profile of the EAS and a surface array of detectors to sample its lateral distribution at the ground. With a detection acceptance larger than 16,000 km$^2$sr per site Auger should observe each year more than 5,000 events above $10^{19}$ eV, 500 above $5 \times 10^{19}$ and more than 100 above $10^{20}$.

The southern Auger site will be composed of 1600 Cherenkov stations (our surface detector units) and 4 fluorescence eyes located at the periphery of the array. Each eye is composed of six $30^\circ \times 30^\circ$ mirror and camera units looking inwards over the surface station network. During year 2001 we accomplished all of our planned objectives: complete the construction of the assembly, central acquisition and office, and first fluorescence detector buildings; construct and deploy 40 Cherenkov stations (31 equipped with electronics) and develop and install two fluorescence mirror/camera prototype units. This mini Auger, called Engineering Array (EA) has been successfully running since then and has shown excellent performances most of them being above our initial specifications. Many events were recorded including about 100 hybrid events seen by both the fluorescence and the surface detectors (see Figure 1). It is however beyond the scope of this paper to report on these data and on the detector performances which will be the subject of a dedicated publication\[11\]. Let us mention however, that the construction of the observatory is going on well. A new fluorescence building is now completed and a pre-production observatory with 2 complete eyes and 140 stations should be running in 2003.

3. Neutrino Identification and Acceptance

Previous studies on UHEN interaction in the atmosphere and observation with Auger were reported in \[12\,13\]. UHEN may be detected and distinguished from ordinary hadrons by the shape of the horizontal EAS they produce. Ordinary hadrons have large cross sections and interact very early after entering the atmosphere. At large zenith angles (above 80 deg.) the particles propagation distance along the shower axis between the shower maximum and the ground becomes larger.
Figure 3. Particle time spread with respect to a planar shower front versus distance to the shower axis for 10^{19} eV protons at 80 deg. zenith angle. The primary altitude is given at the interaction point, early interactions (bottom) correspond to high altitude and produce old shower at the ground level, late interactions (top) correspond to penetrating particle and young shower.

than 100 km. At ground level the electromagnetic part of the shower is totally extinguished (more than 6 equivalent vertical atmosphere were gone through) and only high energy muon survive (Figure 2). In addition, the shower front is very flat (radius larger than 100 km) and the particles time spread is very narrow (less than 50 ns).

Unlike hadrons, neutrinos may interact deeply in the atmosphere and can initiate a shower in the volume of air immediately above the detector. These Horizontal Air Shower (HAS) will appear as “normal young” showers with a curved front (radius of curvature of a few km), a large electromagnetic component, and with particles arrival well spread over time (over hundreds of nanoseconds) even at large distances from the axis. These differences are striking when one looks at the ground particles time distribution versus the distance from shower axis. Figure 3 shows this distribution as computed from a Monte Carlo simulation while Figure 4 compares two real events with widely different zenith angle as were recorded by the Auger EA. These plots should only be taken as indicatives. In particular the horizontal shower in Figure 4 has an estimated energy about five times larger than the vertical one, therefore it extends at much larger distance from the shower axis. A fair comparison would require a vertical shower of approximately the same energy whose larger lateral extension would allow to observe the difference in time spread over a wider range. Moreover the time bins in the real data is 25 ns wide (this is not a limitation since our tanks impulse response function is about 50 ns wide) while the Monte Carlo results were plotted with a 1 ns resolution. Nevertheless the difference is still quite clear.

The acceptance to neutrino interactions in the atmosphere above the Auger array has been calculated in [13,14] and reaches about 40 km^3 water equivalent above a neutrino energy of 10^{19} eV. Although quite large this is not sufficient to see a few neutrino events per year except for some very speculative neutrino sources [13,14,15]. Even
at these energies the neutrino interaction length in air is too large compared to the Auger array dimensions and our “target” does not convert enough neutrino into visible HAS above the detector.

4. Tau Neutrino detection

The possibility to detect tau neutrinos in the Auger observatory was first introduced in [10] and was described in detail in a dedicated paper [17]. Unlike electrons which do not escape from the rock [4] or muons that produce a much too faint signal in the atmosphere, taus, produced in the mountains or in the ground around the Auger array, can escape even from deep inside the rock and produce a clear signal if they decay above the detector.

The chain of reactions together with the geometrical configuration that must be met to produce a detectable tau shower are depicted in Figure 5. These conditions are rather severe: the neutrino must be almost perfectly horizontal (within less than 5 deg.) the tau produced by its interaction should escape the earth and then decay over a distance matching the Auger surface array dimension, finally the decay must occur at low altitude. These criteria can be met as a result of a number of favorable numerical coincidences:

- At $10^{18}$ eV the tau decay length is of the order of the Auger array dimension (50 km).
- In earth, the neutrino interaction length at this same energy is a few 100 km.
- For skimming angle below 5° neutrino propagate through a few 100 km of earth a distance corresponding to their interaction length
- A few $10^{18}$ eV is the neutrino energy corresponding to the threshold of pion photo-production by protons on the CMB.

A Monte-Carlo technique has been used to simulate the tau neutrino or charged lepton interaction and propagation inside the Earth. The lepton may interact several times through deep inelastic scattering, changing charge in most cases, or eventually decay, but, in all cases, a tau neutrino or charged lepton is present in the final state. Some energy is lost at each interaction, as well as continuously along the paths. However, in our energy range, the initial direction of the incoming neutrino is always conserved (Figure 5).

We computed that most of the detectable signal (90%) comes from upward going $\nu_\tau$ where the interactions occur in the ground all around the array and only 10% from downward going $\nu_\tau$ coming from interactions in the mountains surrounding the array.

The results that we obtained are summarized in Figure 5 and in Table 1 and are very encouraging, even in the case of the highest contribution of Deep Inelastic Scattering (DIS-high) to the tau interaction length (reducing the length over which the tau can escape from inside the earth). In case of a null result (although unexpected!) Auger could set after five years a limit as low as $5 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at 90% CL assuming an $E^{-2}$ energy dependent flux in the range [0.3,3] EeV.

5. The WB upper bound as a lower limit

In 1998, Waxman and Bahcall have calculated a neutrino flux upper limit from astrophysical transparent source, now referred to as the WB limit (or WB bound) [18]. Some authors [19] have argued that this limit was too restrictive in particular because of the spectral properties of the sources. In this section we do not wish to enter this debate but rather follow Waxman and Bah-
call’s argument to conclude that even for those sources a detectable neutrino signal should be visible in Auger.

In their paper the authors suppose that UHECR are protons produced by astrophysical sources. The source flux is then normalized to the observed cosmic ray flux assuming that those protons do not loose most of their energy at the production point against the local photon background. This is the transparency condition which is deduced from the fact that those sources are visible in gamma rays. At this stage a neutrino flux upper limit is obtained assuming that all the proton energy gets converted into neutrino.

Table 1

Expected number of events after five years for the source models presented in Fig. 6 and various DIS contributions to continuous energy losses.

| DIS      | AGN-1 | TD | GRB | GZK | AGN-2 |
|----------|-------|----|-----|-----|-------|
| none     | 135   | 11.5| 2.5 | 8.5 | 14.5  |
| low      | 120   | 9.0 | 2.0 | 7.5 | 12.5  |
| high     | 50.0  | 4.0 | 1.0 | 3.0 | 5.5   |

Below the pion photo-production threshold against the CMB background (around $7 \times 10^{19}$ eV) the computed neutrino fluxes are, by construction, upper limits for those sources. However, for protons with energy above the threshold the situation is quite different: they will effectively convert their energy into neutrino on distances of the order of a few tens of Mpc. Therefore, if those sources are the dominant contribution to the observed cosmic rays in the range [10,100] EeV and since most of them should lie outside our GZK sphere they will produce a neutrino flux of the order of the WB bound.

Since it is generally admitted that any other non transparent astrophysical source would directly produce more neutrinos and since in all top down models the neutrino flux at the production point is much larger then the proton flux, we can conclude that for neutrino energy above a few $10^{18}$ eV the neutrino flux should be above the WB bound.

The WB bound, as given in reference [18], is $1.5 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for a strong z-evolution of the sources. Only half of those neutrino may convert into $\nu_e$ on their way to Earth given a flux of $7.5 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This flux is fifty percent larger than the Auger $\nu_e$ null result limit and within our sensitivity (Figure 6). An example of cosmogenic neutrinos produced by protons from astrophysical source (taken from [19]) is shown under the GZK label in Figure 6 with the corresponding number of events in Table 1.

$^2$The exact location in energy depends on the source distribution dependence to red-shift.
6. Conclusions

The Auger observatory is a very sensitive neutrino telescope reaching for a null result a limit in $\nu_\tau$ flux as low as $5 \times 10^{-9}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$ at 90% CL. Moreover, given the observation of UHECR in the range [10,100] EeV, given the lower limit on neutrino flux which can be derived from the WB bound and given the strong experimental evidence for $\nu_\mu \leftrightarrow \nu_\tau$ with large mixing the expectations for a positive result in the next five years are very high. Beside its excellent performances for the study of UHECR Auger may very well be the first experiment to observe $\nu_\tau$ appearance from a $\nu_\mu/\nu_e$ source.

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