NEUTRINOS IN THE PIERRE AUGER EXPERIMENT*

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The origin of extremely high energy cosmic rays is still unknown and is one of most important puzzles in astrophysics. Identifying neutrinos among cosmic rays at the extreme energies would be a major step toward explaining the origin of cosmic rays. In this paper, the cosmic ray research at highest energies is outlined and the role of neutrinos in cosmic ray astrophysics is discussed. The prospects to detect extremely high energy neutrinos in the Pierre Auger Observatory are presented.

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1. Introduction

The energy spectrum of cosmic rays extends to beyond 10^{20} eV, *i.e.* more than eight orders of magnitude higher than the energies attained so far in terrestrial particle accelerators. The highest energy cosmic rays make a challenge to astrophysics: in spite of many decades of cosmic ray research, both the sources and physical processes responsible for emission of particles with so high energies remain unknown. The bulk of cosmic rays at energies below 10^{15} eV are known to come from sources within our Galaxy. On the other hand, particles with energies above 10^{18} eV cannot be confined by galactic magnetic fields. Therefore, it is a common belief that the sources of the highest energy cosmic rays almost certainly must be extragalactic. To remind the distance scale involved: the diameter of our Galaxy is about 30 kpc[1]; the quasars are located at distances larger than 500 Mpc, and the radius of visible Universe is ~ 5 Gpc. In the energy range discussed, a convenient unit is an exaelectronvolt: 1 EeV = 10^{18} eV.

The Pierre Auger Project was designed to study the Extremely High Energy Cosmic Rays (EHECR), *i.e.* those above 10^{19} eV. At a neutrino conference, it may be appropriate to explain first, why neutrinos are important for a cosmic ray experiment, and for cosmic ray research in general. Hence, in this paper the main features of highest energy cosmic ray research will be presented, along with the difficulties in explaining the origin of these cosmic rays. A detection technique and some properties of extensive air showers will be discussed further, and the Auger detectors will be shortly characterized. Finally, the prospects to identify neutrinos as primary cosmic ray particles will be presented.

2. Extremely High Energy Cosmic Rays

The extremely high energy cosmic rays open a new window to study astrophysical objects and processes which result in emission of highest energy particles known. At these energies, above about 5×10^{19} eV, cosmic ray protons interact with photons of cosmic microwave background and produce secondary pions, through process $p\gamma \to p\pi^0$ or $p\gamma \to n\pi^+$. A series of such reactions result in considerable reduction of the proton energy, so that the flux of protons with energies above the photoproduction threshold diminishes very quickly with the distance travelled [1]. This effect is illustrated in figure 1. The energy of a proton after travelling less than 100 Mpc falls below the photoproduction threshold, virtually independently of primary proton energy. Thus, even if there are sources in the Universe capable of emitting protons with energies much exceeding the photoproduction threshold, these

[1] 1 parsec(pc) ≈ 3.26 light years $\approx 3.086 \times 10^{16}$ m.

protons get their energies reduced to below the threshold after travelling distances smaller than 100 Mpc. Conversely, if we do observe cosmic rays with energies exceeding the threshold, the sources must be within 50–100 Mpc. Heavy nuclei undergo a photodisintegration, so that their range is also very limited. Among the known particles which might be cosmic rays, only neutrinos are immune to the GZK process.

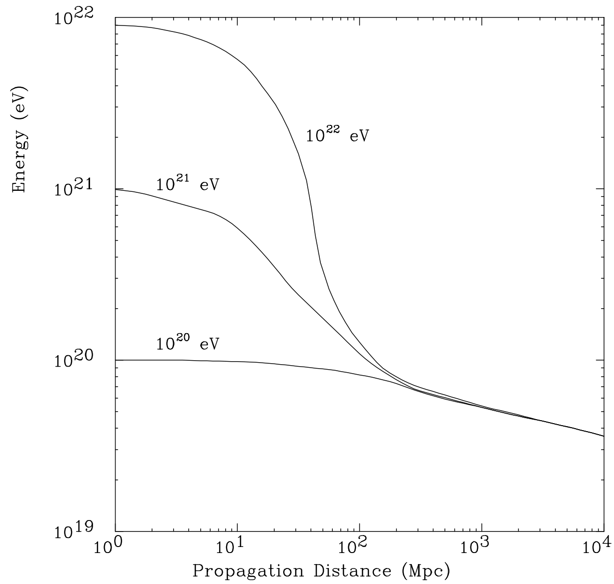

Fig. 1. Energy of protons with various initial energies, as a function of propagation distance in intergalactic space.

The GZK cutoff has important consequences for propagation of cosmic rays. At low energies, cosmic rays are deflected strongly by galactic magnetic fields. Many such deflections result in isotropy of arrival directions of cosmic rays. The situation is very different at extremely high energies. The Larmor radius of a cosmic ray in intergalactic magnetic fields (typically $\sim 10^{-9}$ G) is very large, so that the deflection of a cosmic ray can be expressed by a formula: $\theta \approx 0.3^\circ (L_{\rm Mpc} Z B_{\rm nG})/E_{20}$, where $L_{\rm Mpc}$ is a distance from the source in Mpc, Z is the particle charge, $B_{\rm nG}$ is the magnetic field strength in nG and E_{20} is the particle energy in units of 10^{20} eV. Thus, even a proton with energy 300 EeV, travelling 100 Mpc in intergalactic magnetic fields, gets deflected only by about 10° from its original direction. With the distances limited by the GZK cutoff, this means that at highest energies the arrival directions of cosmic rays should point back to their sources within a few degrees. The experimental data, however, hardly show a correlation of cosmic ray arrival directions with distribution of known astrophysical objects capable of accelerating particles to the observed energies [2]. Even arrival directions of highest energy cosmic rays observed so far (320 EeV Fly's Eye [3] and 200 EeV AGASA [4] events) do not point to known objects which might be sources of particles with such energies.

The cosmic ray energy spectrum obtained by combining data from several experiments: Volcano Ranch, Haverah Park, Fly's Eye, and especially AGASA [5, 6] does not show a sign of the GZK cutoff. Although the data statistics is still very small, the data seem to indicate that the GZK cutoff is not present in the spectrum. This would mean that the cosmic ray sources must be located within the GZK distance, *i.e.* within several tens megaparsecs. If so, pointing to sources should be easy! Therefore, the problem of identifying the sources of EHECR gets even more acute and becomes one of the most important puzzles in present-day astrophysics.

3. Candidate sources of EHECR

Theoretical modelling of highest energy cosmic ray sources is a considerable challenge. There are two broad classes of models of cosmic ray generation at these energies.

A. Acceleration processes (so-called bottom-up scenario). This group of models deals with processes in which particles are accelerated to the observed energies by:

- Diffusive shock acceleration [7]. Particles are accelerated by large-scale shock waves by the first order Fermi process. During the course of acceleration the particles repeatedly cross the front of the shock wave and gain energy at each crossing. The maximum energy attainable in this process is limited by a product of magnetic field strength B and size of the accelerating region L: $E_{\max} < \beta cZBL$, where βc is the shock speed and Z is the particle charge. The diffusive shock acceleration process is known to accelerate the bulk of lower energy cosmic rays (below 10^{15} eV) in supernova remnants. At energies above 10^{20} eV, the feasible candidates are: radio galaxies, active galactic nuclei, collisions of galaxies, *etc.*
- Strong electromagnetic fields in compact objects, *e.g.* pulsars [8]. The strong magnetic fields induce electric fields, which should be capable of accelerating particles in a single step to 10^{20} eV. However, the energy losses expected during this process are large and may exclude pulsars as viable candidates.
- Gamma ray bursts (GRB) [9]. The nature of gamma ray bursts has not been clarified yet, but the energy scale of phenomena producing

GRB is sufficient for accelerating particles to very high energies. Thus the sources of GRB most probably can accelerate particles as well. However, most of these GRB sources are presumably located at cosmological distances, so the GZK cutoff practically excludes any hadrons from these sources being the observed cosmic rays, except from the nearest ones.

B. The other group of cosmic ray models are those involving non-acceleration processes (so-called top-down models). These include models involving topological defects left after phase transitions in the early universe, in the form of cosmic strings, domain walls, *etc.* [10]. These defects can annihilate by emitting super-heavy X particles with masses at the grand unified theories scale, $M \sim 10^{24}$ eV, which subsequently should decay into quarks and leptons. Hence, particles with energies exceeding 10^{20} eV would be a natural consequence of a defect annihilation, and neutrinos and photons should be present among the final decay products of the X particle. If so, detection of neutrinos at energies above 10^{20} eV would be a strong indication in favour of the topological defect models. Topological defects need not be associated with any visible astrophysical objects, so pointing back to visible sources should not be expected! There are also models postulating heavy relic particles (*e.g.* magnetic monopoles) as primary cosmic ray particles [11], but detailed properties of the relic particle interaction are not known, so these models cannot be tested yet.

4. Neutrinos as cosmic ray particles

Given the above discussion, one can conclude that the origin of EHECR remains a mystery. No conventional source candidates were found within the GZK limit, so it is difficult to explain sources of hadronic primary cosmic ray particles at extreme energies. A question arises whether neutrinos can account for these cosmic rays, especially that neutrinos are immune to the GZK cutoff, and can travel extremely large distances in the Universe. An intriguing observation may be that one can find powerful distant quasars in regions of the sky pointed by arrival directions of highest energy cosmic rays [12]. Although the statistical significance of this observation is small [13], it is interesting to know if quasars can be the sources of these cosmic rays. In particular, this is the case of the highest energy cosmic ray, Fly's Eye 320 EeV event [14]. Very close to the arrival direction there is a powerful quasar 3C 147, which is at a distance about 2.2 Gpc. If objects like this quasar were emitting ultra-high energy neutrinos, then they should also emit comparable numbers of photons with similar energies, since no physical process is known capable of producing high energy neutrinos without photons. These photons would degrade to lower energies in interactions with cosmic microwave background and intergalactic magnetic fields, so that large numbers of lower energy photons should be observed from the direction of the source. The observations exclude this scenario. Also, the longitudinal profile of the observed shower indicates an interaction cross section of the cosmic ray typical for hadrons, not neutrinos. Thus, neither the 3C 147, nor other astronomical object in the vicinity of the 320 EeV cosmic ray arrival direction is a viable candidate for being a source.

There are hypotheses that the particles which propagate over the large cosmological distances are particles so far unknown [15], but there is no experimental evidence to support this hypothesis. In case of the Fly's Eye event, it is worthwhile to note that the shower did not look exotic. On the contrary — as shown in figure 2, the longitudinal profile of this shower very well matches the profile expected for a shower initiated by a proton! If the primary particle indeed was a proton, it certainly must have originated much closer, within some 50 Mpc.

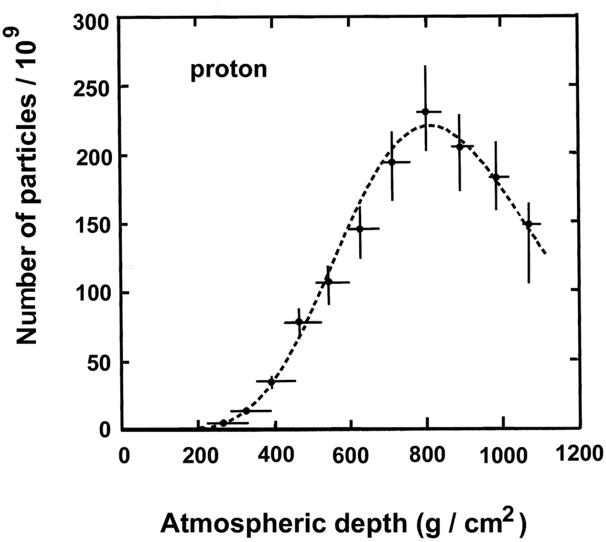

Fig. 2. Longitudinal profile of the Fly's Eye 320 EeV event. The dashed line represents a profile of a proton shower with this energy.

Extremely high energy neutrinos can be produced in a number of astrophysical environments. Wherever high energy hadrons have a chance to interact and produce pions, neutrinos are present among the decay products of the pions. Therefore, virtually all the charged particle acceleration sites are potential sources of high energy neutrinos. These include radio galaxies, active galactic nuclei, *etc.* as well as intergalactic matter or galactic disk, in which the high energy cosmic rays can interact. However, if these astrophysical sites were sources of neutrinos of the extreme energies, then they would have to emit much larger numbers of neutrinos (and photons) at lower energies — contrary to observations. Therefore, there are strong arguments that neutrinos cannot account for the bulk of cosmic rays at the extreme energies. Nevertheless, it is possible that some neutrinos are present among the highest energy cosmic rays.

As pointed above, another source of high energy neutrinos can be the topological defects. The superheavy X particles emitted in topological defect annihilation are supposed to decay into quarks and leptons, so that many neutrinos should be expected from the decays of particles created in the quark hadronization. The energy spectrum of neutrinos should thus extend up to 10^{24} eV. There are large uncertainties as to the neutrino flux at these energies. Figure 3 shows predictions of neutrino fluxes from various sources [16]. Three classes of spectra are shown in this figure: 'certain' refers to neutrinos produced by interactions of cosmic rays in the galactic disk (upper and lower heavy lines, for directions within galactic disk and perpendicular to it) and neutrinos produced by the GZK mechanism. Both cosmic rays and microwave background are known to exist — thus the label 'certain'. The 'probable' curves refer to particle production in various models of active galactic nuclei. Finally, the 'speculative' predictions are difficult to assess at present.

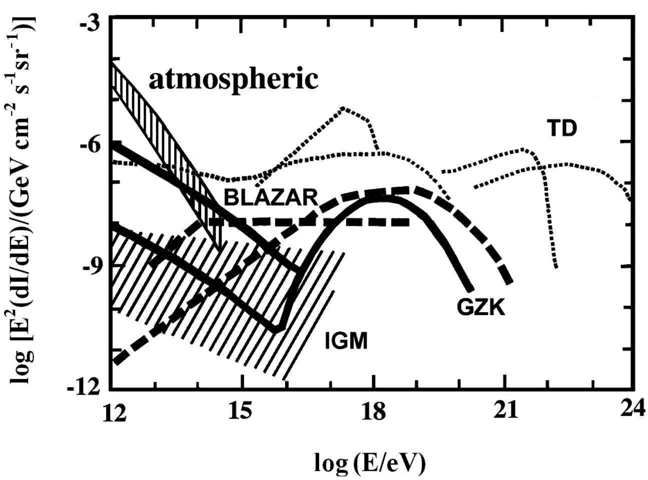

Fig. 3. Predictions of neutrino spectra from various sources [16]. Solid lines denote 'certain' spectra (see text), dashed lines — 'probable', and dotted lines — 'speculative'.

5. Detection of air showers in the Auger experiment

The extremely high energy cosmic rays are so rare that huge detector is necessary in order to collect a sizeable sample of data during the detector lifetime. The only practical approach is to let the cosmic rays interact in the atmosphere and initiate extensive air showers. The showers can be then recorded by detectors located on the ground. As can be seen in figure 2, the number of particles in the shower increases as the shower develops, reaches a maximum at a depth around 800 g/cm^2, and then decreases, as the secondary particles get absorbed in the atmosphere. The thickness of the atmosphere is about 1000 g/cm^2 (depending on altitude), so a vertically incoming shower barely passes over its maximum before it hits the ground. The situation is very different for a shower at large zenith angle, which in the following will be called a 'horizontal shower'. The amount of air encountered by such a shower is much larger than the 'vertical' thickness of the atmosphere. Thus the electromagnetic shower has time to develop fully and eventually get absorbed in the air, before hitting the ground. After some 3 atmospheric thicknesses, only muons, which originated in pion decays, propagate in the air.

The aim of the Pierre Auger Project [17] is to make a detailed study of cosmic rays at energies above 10^{19} eV. In order to overcome difficulties with the small cosmic ray flux, the Auger Observatory will have a total area of 6000 km^2, divided into two sites of 3000 km^2 each: one in the southern hemisphere (in Mendoza, Argentina) and the other in the northern (in Utah, USA). A hybrid detection technique will be used. An array of detectors spread on the ground (the so-called surface detector) will consist of 1600 detector stations per site, spaced 1.5 km from each other; each station will be a water Čerenkov detector. In addition, an optical detector similar to Fly's Eye will be used to probe longitudinal development of the shower by recording the fluorescence light emitted by the shower in the air. Fig. 4 shows the principle of the hybrid detection of air showers in the Auger Observatory. Joint use of the two types of detectors will enable calibration cross-checks to minimize systematic errors and will result in unprecedented accuracy of shower measurements: the surface array will measure lateral spread of particles in a shower, with the ability to distinguish signals from electrons and muons (although distinction between individual particles will generally not be possible), and the fluorescence detector will determine the longitudinal profile of the shower and its depth of maximum development, $X_{\max}$. The $X_{\max}$ is one of the best observables for identification of the particle which initiated the shower.

Both types of Auger detectors will be able to independently detect air showers. While the surface array will be active all the time, the fluorescence

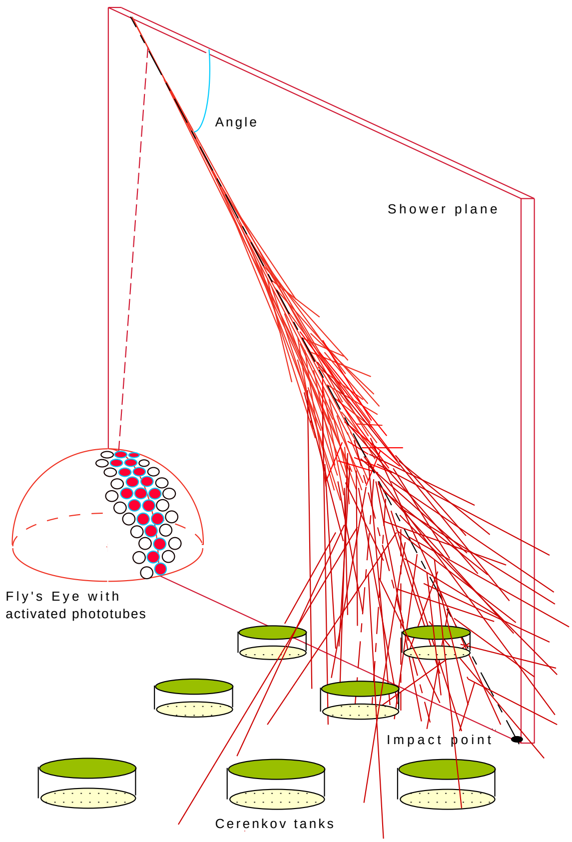

Fig. 4. Hybrid detection of extensive air showers in the Pierre Auger Observatory.

detector can operate only on clear moonless nights, *i.e.* $\sim$ 10–15% of the time. Therefore, for (presumably rare) neutrino detection, the surface array will be much more important and in the following we will focus on the surface detector only.

6. Neutrino detection capability of the Pierre Auger Observatory

Among the horizontal showers it is possible to distinguish showers initiated by high energy neutrinos from those started by hadrons. The thickness of the Earth's atmosphere (about 1000 g/cm^2) corresponds to about 11 proton interaction lengths (even more interaction lengths of heavier nuclei), or $\sim$ 27 radiation lengths. For a horizontal shower, the potential pathlength is up to 36 000 g/cm^2, equivalent to $\sim$ 400 proton interaction lengths, or $\sim$ 970 radiation lengths. Let us focus on horizontal showers in the following. It is clear that no 'ordinary' (*i.e.* hadronic) cosmic ray can reach the ground

— it is sure to interact in the air. Moreover, the resulting electromagnetic shower will develop and die out before reaching the ground, *i.e.* before arriving anywhere near the detector. Neutrino is the only known particle capable of penetrating so deep.

The neutrinos at low energies have very small interaction cross section, so they easily can penetrate the whole Earth without interacting. Their cross section increases with energy, however, so that a neutrino with energy 10^{19} eV has interaction probability $\sim 10^{-5}$ per 1000 g/cm^2 travelled. Thus its interaction probability in the air is not negligible and the high energy cosmic neutrino can interact anywhere along its path — in contrast to a proton cosmic ray which must interact in the atmosphere high above the ground — and far from the detector, in case of horizontal showers. We note here that neutrino interaction cross section at 10^{19} eV is so large that the Earth becomes opaque to neutrinos. Therefore, no upward-going neutrinos at this energy can be detected in underground detectors! Only neutrinos coming from above the ground can be detected.

The main difficulty is to distinguish the showers which were started by high energy neutrinos from those (presumably much more numerous) due to protons (or electrons/photons, if they are among the cosmic rays at these energies). As pointed above, the horizontal showers provide a means to select neutrino showers [18,19]. A neutrino-induced shower can start very deep in the atmosphere, relatively low above the ground (and close to the detector). Such a 'young' shower contains an electromagnetic component, including very soft electrons and muons, so that the shower front is rather thick and curved ($R_{\rm curv} \sim 10$ km). The thickness of the shower front changes considerably with the distance from the shower axis. As illustrated in figure 5, the time spread of particles passing through a detector located near the shower axis is much narrower than the spread of particles at large distances. This means that the thickness of the shower front increases with the distance from the axis.

On the other hand, a horizontal shower initiated by a hadron must start high above the ground. In the following, such shower will be called a 'far shower'. The most of electromagnetic component gets absorbed in the atmosphere before reaching the ground, and only hard muons (with typical energies of several tens GeV), plus an admixture of radiative products and decay electrons from muons, reach the ground. The shower front, when it eventually reaches the ground, is a thin, relatively flat disk, with radius of curvature on the order of 100 km. The time during which the shower front passes through the detectors is very short (much less than 100 ns), resulting in short-duration signals, order of the detector response time of 100 ns, even at large distances from the shower axis (see figure 5).

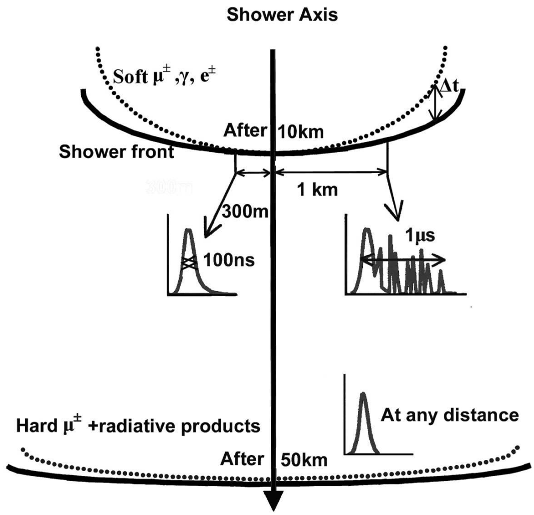

Fig. 5. Shower front profile at different distances from the primary interaction [27]. The small plots show time distributions of signals in the ground detectors.

A measurement of the shower front curvature is also very useful to distinguish a far shower from a deep one. Figure 6 shows simulated densities of muons and electrons in a deep horizontal shower, as seen in the Auger ground array [18]. Triggered detector stations are marked by circles with a letter T inside. The timing information from the many detectors will enable determination of both the direction and curvature of the shower front. The bottom panel shows muon arrival times with respect to an ideally planar shower front. A curvature of the shower front manifests itself in delays increasing with the distance from the axis. For comparison, corresponding plots of a far shower are shown in figure 7. The electromagnetic component is absent, so muon densities are shown for two different directions relative to the geomagnetic field, with local components 0.3 Gauss (vertical) and 0.4 Gauss (horizontal). The muon delays (bottom panel) are much smaller in this case, indicating a flatter shower front.

Thus, among the horizontal showers, the distinction between far and deep showers is possible in the Auger detector. A far shower can be initiated by any kind of primary cosmic ray particle, while a deep shower can be started practically only by a neutrino. A possible background among the deep showers can be due to a shower initiated by decay of a tau lepton which was produced in an upstream far shower, or to large γ bremsstrahlung of a muon. In such a case, the shower front at the ground would consist of a thick, curved front and a flat, thin one, superposed on each other. The distinction deep/far shower is somewhat less clear in this case, but still possible. This background, however, is estimated to be very small [20].

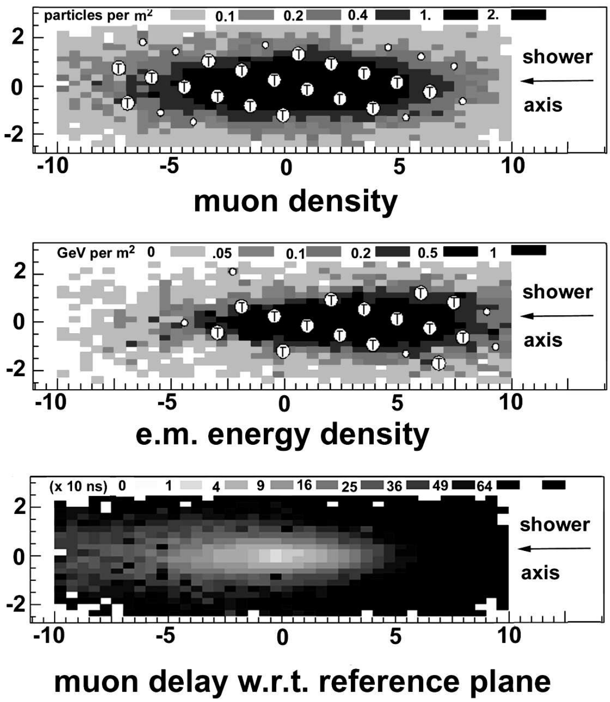

Fig. 6. Distribution of muon density, electromagnetic energy density and muon delays with respect to a planar shower front, for a deep horizontal shower initiated by a 10 EeV proton at 3 km above the ground and 80° zenith angle [18]. The x and y axes are coordinates in km on the ground. The circles with a T show positions of triggered ground detector stations.

The question now is, what is the expected flux of extremely high energy neutrinos, and whether it is large enough for detection of any neutrinos in the Auger detectors. The neutrino acceptance of Auger will be on the order of 15 km^3 sr water equivalent (increasing with energy) [19,21] — comparable to largest proposed neutrino detectors, like the ICECUBE, but Auger will detect neutrinos at much higher energy range. The flux predictions of topological defect models are very uncertain and differ much in different models. The photoproduction models are understood much better. The flux limits from these sources are shown in figure 8 [22]. The leftmost hatched region indicates atmospheric neutrinos together with an experimental upper limit from the Fréjus experiment [23]. The dotted and dashed curves indicate fluxes from blazars [24] and gamma ray bursts [25]. The straight line labelled W&B indicates the upper limit determined by Waxman and Bahcall [26] on the basis of observed cosmic ray flux and diffuse γ ray background. The

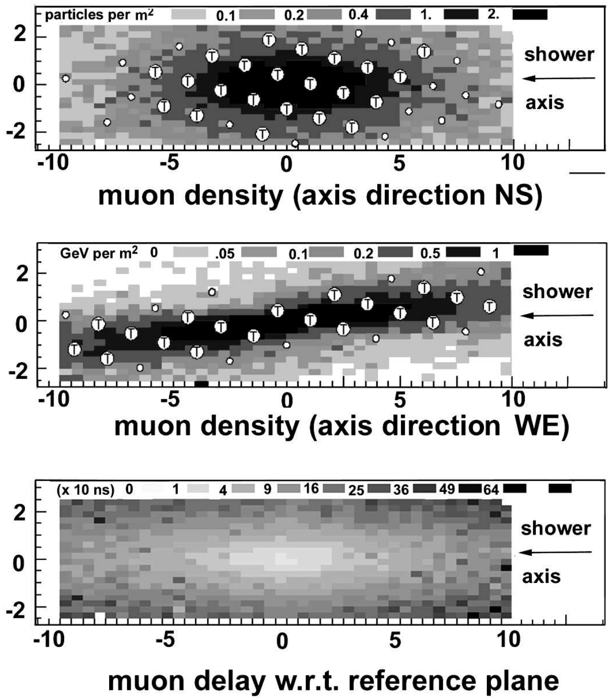

Fig. 7. Distributions of muon density and time delays (as in figure 6) in a far horizontal shower initiated by a 100 EeV proton at altitude 100 km above the ground [18]. The symbols used are as in the previous figure.

line labelled MP&R and the rightmost hatched region indicate predictions by Mannheim, Protheroe and Rachen [22] for optically thick and thin photoproduction sources. The heavy dashed line shows a sensitivity limit of the Auger Observatory, with the sensitivity threshold set at 0.3 events/year per decade of energy [27]. With the expected period of data taking by Auger of about 20 years this sensitivity will be sufficient to set at least a meaningful experimental upper limit on neutrino flux. If the flux is in fact larger than the W&B limit, and near the MP&R prediction, a significant number of extremely high energy neutrinos should be detected by Auger experiment.

7. Conclusion

The sources of extremely high energy cosmic rays have not been identified yet; the experimental data available so far are not sufficient for identification of the sources nor the underlying physical process. There are hypotheses that extremely high energy neutrinos may be present among the cosmic ray particles, originating both from ‘conventional’ photoproduction processes

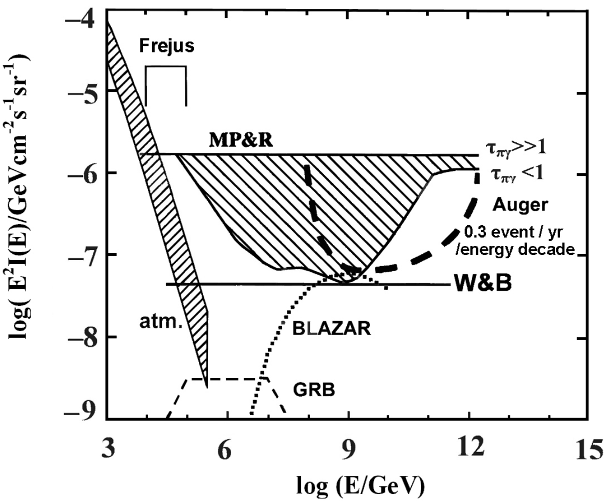

Fig. 8. Fluxes of neutrinos from pion photoproduction sources, along with a limit of Auger sensitivity. See the text for explanation of the curves.

and from hypothetical topological defects which are supposed to be present in the Universe.

The Pierre Auger Observatory, now under construction, will be able to detect the EHE neutrinos through horizontal showers originating deep in the atmosphere. Although the sensitivity of Auger to neutrinos will be on the edge of most conservative predictions for photoproduction sources, there is still a possibility that the neutrino fluxes are in fact higher and Auger will unambiguously detect them. In any case, Auger will be able to place stringent experimental limits on various models. This is especially important for topological defect models. Finally, the neutrino detection capability of Auger is truly complementary to that of existing experiments, like Amanda or the proposed ICECUBE detector. The pioneering data from the Pierre Auger Observatory will be very important for both particle physics and astrophysics.

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