Neutrino astrophysics with JEM-EUSO

A.D. SUPANITSKY[1,2], G. MEDINA-TANCO[2] FOR THE JEM-EUSO COLLABORATION.
[1]*Instituto de Astronomía y Física del Espacio (IAFE), UBA-CONICET, Argentina.*
[2]*Instituto de Ciencias Nucleares, UNAM, Circuito Exteriror S/N, Ciudad Universitaria, México D. F. 04510, México.*
supanitsky@iafe.uba.ar

Abstract: High energy neutrinos play a fundamental role on the understanding of several astrophysical phenomena and, in particular, on the origin and propagation of extreme energy cosmic rays. JEM-EUSO is a proposed orbital detector to be installed onboard the International Space Station. It is designed to observe the fluorescence light produced by the air showers initiated by the extreme energy component of the cosmic rays, including gamma rays and neutrinos. In this work we study the discrimination capability of the mission between nearly horizontal neutrino and proton showers, at the highest energies, by using the atmospheric depth of maximum development. We propose a new method to discriminate between electron neutrino and tau horizontal showers, developing very deep in the atmosphere, by using the multi-peak structure that they present. We also study the flux of tau leptons emerging from the Earth, including the case of the presence of oceans, produced by the interaction of tau neutrinos inside the Earth for a given model of gamma ray bursts and in the context of the JEM-EUSO mission.

Keywords: Cosmic Rays; High Energy Neutrinos; Space Observation.

1 Introduction

The astrophysical information carried by very high energy neutrinos is very important for the understanding of the origin and propagation of the cosmic rays. Such particles can be produced during the propagation of the cosmic rays in the interstellar medium [1], as by-products of the hadronic interaction in the sources [2] and as the main product of the decay of superheavy relic particles [3, 4].

In this work we study the characteristics of inclined tau and electron neutrino showers and its discrimination from the proton component in the context of the JEM-EUSO mission [5]. The main parameter used to separate the different species is X_{max}, the atmospheric depth of the maximum development of the showers.

Also, an extension of the study presented in Ref. [6] about showers initiated by neutrinos that interact in the central region of the field of view of the JEM-EUSO telescope (in nadir mode) is developed. A possible technique to identify the presence of both tau and electron neutrinos in a given sample is proposed.

Finally, the propagation of tau neutrinos inside the Earth is studied. In particular, neutrinos originated in gamma ray bursts are considered, for which the propagation in the presence of oceans is compared with the one in the mantle of the Earth.

2 Inclined neutrino showers

Neutrinos can initiate atmospheric air showers when they interact with the nucleons of the air molecules. The probability that a neutrino interact in the atmosphere increases with zenith angle because of the increase of the number of target nucleons. High energy neutrinos, propagating through the atmosphere, can suffer charge (CC) and neutral (NC) current interactions. The CC interactions are the most important for the space observations because in the NC interactions most of the energy is take by a secondary neutrino which could produce an observable air shower just in the case it suffers a subsequent CC interaction. The shower produced by the hadronic component resultant from the NC interaction is difficult to observe from the space due to the high energy threshold of the telescope.

As a result of a CC interaction, a very high energy lepton, which takes most of the energy of the incident neutrino, is generated. Typically, it takes $\sim 80\%$ of the neutrino energy at $E_\nu \cong 10^{20}$ eV, the rest of the energy goes into the hadronic component.

Proton and neutrino showers of $E = 10^{20}$ eV and $\theta = 85^\circ$ are simulated in order to study their characteristics and its possible identification. The last version of CONEX [7] (v2r2.3) with QGSJET-II [8] is used to generate the proton and neutrino showers. Electron and tau neutrino showers are considered. The program PYTHIA [9], linked with LHAPDF [10], is used to simulate the electron neutrino-nucleon interactions. The CTEQ6 [11] set of parton distribution functions are used. The air showers are generated injecting the produced particles in CONEX [6]. For the case of tau neutrinos it is just consider the decay of tau leptons of $E = 10^{20}$ eV, for which the simulation program TAUOLA [12] is used.

The interaction points of the neutrino showers are simulated by taking at random values of the atmospheric depth from an exponential distribution, $P(X) \propto \exp(-X/\lambda_\nu(E_\nu))$ with $\lambda_\nu(10^{20} eV) = 3.2 \times 10^7$ g cm^{-2}, in the interval $[0, X_{end}]$ where X_{end} is the atmospheric depth from the top of the atmosphere to the core position, which for $\theta = 85°$ is ~ 10573 g cm^{-2}. Note that due to the large mean free path of the neutrinos the exponential distribution can be approximated by the uniform distribution in the interval $[0, X_{end}]$.

Figure 1 shows the profiles for some simulated events. The neutrino showers that develop deeper in the atmosphere can present more than one peak, this is due to the LPM fluctuations suffered by showers dominated by the electromagnetic component. For the case of tau leptons, just in $\sim 18\%$ of the decays a high energy electron or positron is produced, $\tau^\pm \to e^\pm \nu_\tau \nu_e$. The showers produced by this channel that develop deep in the atmosphere can have more than one peak. On the other hand, in every electron neutrino interaction a high energy electron or positron is produced, increasing the probability of finding a shower with more than one peak. This is the reason why 15% of electron neutrino showers present more than on peak whereas the same happens with just 1% of the tau neutrino showers.

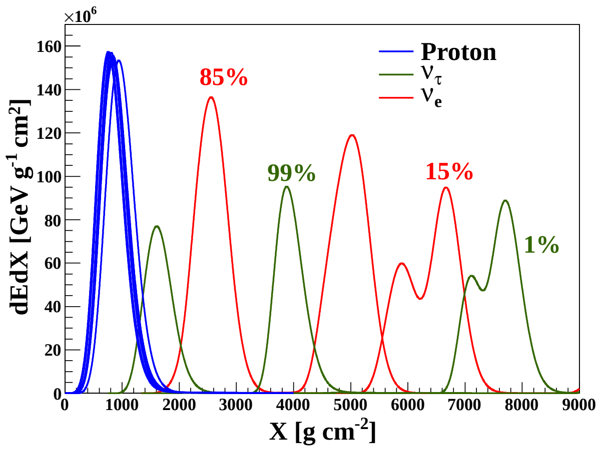

Figure 1: Simulated proton and neutrino showers of $E = 10^{20}$ eV and $\theta = 85°$.

Note that about 17.51% of the taus decay into a muon and two neutrinos, $\tau^\pm \to \mu^\pm \nu_\tau \nu_\mu$. The showers initiated by the muons are quite difficult to observe from the space because the deposited energy of these kind of showers is much smaller than the regular ones. Therefore, these type of showers are excluded from the subsequent analyses.

Figure 2 shows the distributions of the first peak of the simulated showers. Just the events with the first peak above 1 km of altitude are taken into account, which is equivalent to consider the ones whose first peak has an atmospheric depth less than ~ 9000 g cm^{-2}. It can be seen that, above ~ 1600 g cm^{-2} the distributions corresponding to tau and electron neutrinos are flat and extended over a huge interval of atmospheric depth, which allows a very efficient discrimination of the neutrino showers from the proton ones. Note that, as expected, the overlap between the X_{max} distributions of protons and taus is larger than the corresponding one to protons and electron neutrinos.

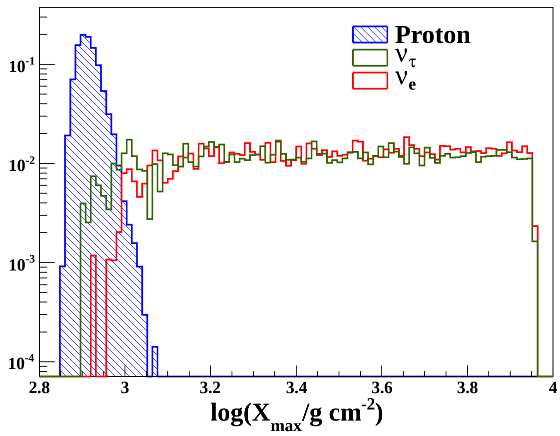

Figure 2: Distribution of the first peak of the profiles for proton and neutrinos of $E_\nu = 10^{20}$ eV and $\theta = 85°$.

3 Horizontal neutrino showers

In this section the showers generated by horizontal neutrinos that interact in the central region of the field of view of the JEM-EUSO telescope, in nadir mode, are considered. For the case of electron neutrinos, this showers are dominated by the LPM effect and can present more than one peak [6]. As mentioned before, just $\sim 18\%$ of the tau showers are initiated by electrons or positrons, diminishing in this way the probability to find showers with more than one peak. Figure 3 shows the distributions of the first peak for tau and electron neutrino showers of $E = 10^{20}$ eV and $\theta = 90°$ injected in the center of the field of view (fov) of JEM-EUSO at sea level. These distributions present two populations. The population with smaller values of X^1_{max} corresponds to showers dominated by the hadronic component and the other one corresponds to showers dominated by the electromagnetic component. As expected, the hadronic population is more important for tau showers.

Figure 4 shows the probability to find showers with exactly $N_{X^i_{max}}$ peaks for electron neutrino and tau showers. At sea level, the probability to find a tau shower with just one peak is $\sim 98\%$ whereas for electron neutrinos is $\sim 65\%$. At an altitude of 5 km, the probability to find a tau shower with just one peak is $\sim 99\%$ whereas for electron neutrinos is $\sim 76\%$. The reduction of the probability to find more than one peak with increasing altitudes has to do with the fact

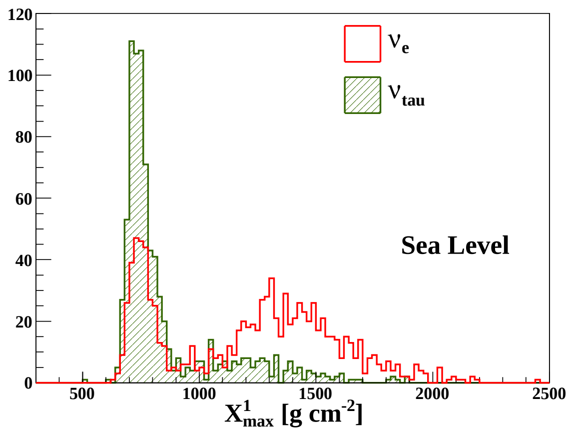

Figure 3: Horizontal tau and electron neutrino showers of $E = 10^{20}$ eV injected in the center of the field of view of the JEM-EUSO telescope and at sea level.

that the development of the showers takes place in regions with smaller values of air density, therefore, the influence of the LPM effect is also reduced.

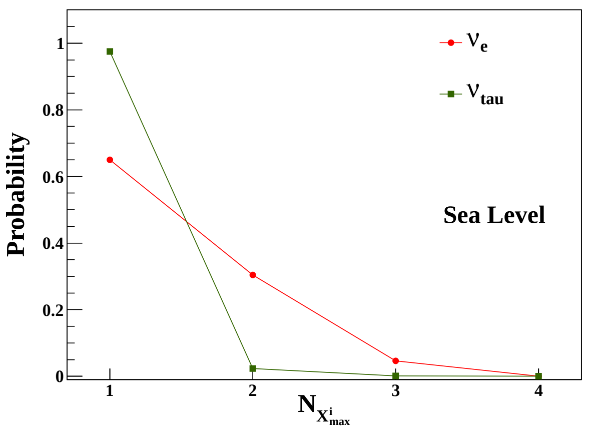

Figure 4: Probability to find showers with exactly $N_{X^i_{max}}$ peaks for horizontal tau and electron neutrino showers of $E = 10^{20}$ eV, injected in the center of the field of view of the JEM-EUSO telescope in nadir mode.

The difference between the number of showers with just one peak can be used to study the relative abundance of tau and electron neutrino showers. Due to the large decay length of the taus at 10^{20} eV ($\sim$ 5000 km), the ratio between the number of tau neutrino and electron neutrino horizontal showers (starting in the center of the fov of the telescope) is of order of $N_{sh}(\nu_\tau)/N_{sh}(\nu_e) \cong 0.07$, assuming that the relative abundances of the incident flux are equal to one. Upper panel of figure 5 shows the region (in blue) of 95% of probability to find a fraction of n_1/N showers with just one peak, as a function of the sample size N, obtained from simulations, for a mixture of equal number of incident tau and electron neutrinos. Note that showers corresponding to the muonic decay channel of the tau are not included in the analysis. Observed values of n_1/N smaller than the black solid line reject the hypothesis that the sample is composed by tau showers alone, with probability of rejection larger or equal to 0.95, depending of the particular value of n_1/N. Also, observed values of n_1/N larger than the red solid line reject the hypothesis that the sample is composed by just electron neutrino showers with probability of rejection larger or equal to 0.95, again depending on the particular value of n_1/N. From the figure it can be seen that for 95% of the cases, samples of more than 15 showers are needed to be able to reject the hypothesis of having tau showers alone. Although not shown in the figure, the number of events needed to reject the hypothesis of having a sample with electron neutrinos alone has to be grater than $\sim$ 9300.

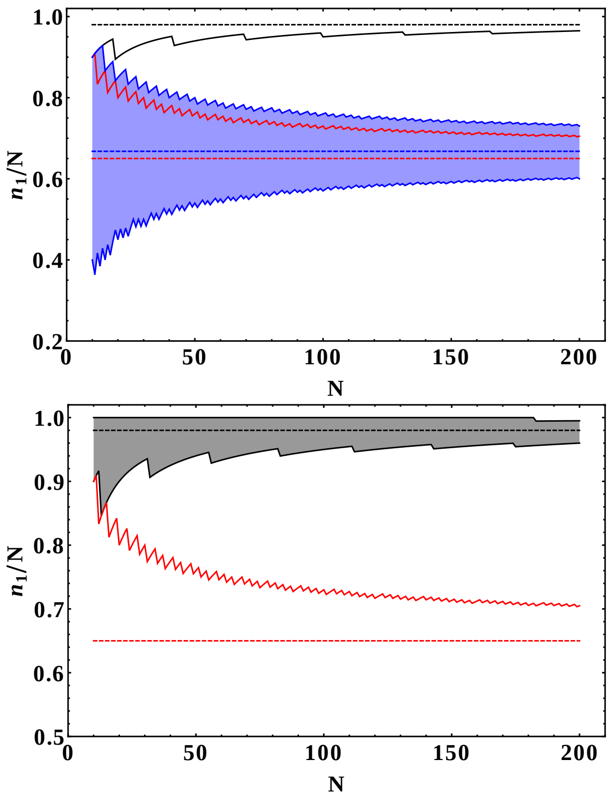

Figure 5: Shadowed region corresponds to 95% of probability to find a fraction n_1/N of showers with just one peak, for a mixture of equal number of incident tau and electron neutrinos (upper panel) and for the case in which the incident flux contains just tau neutrinos (bottom panel), as a function of the sample size N.

Bottom panel of figure 5 shows the region of 95% of probability to find a fraction of n_1/N showers with just one peak obtained from a binomial distribution, for the case in which the samples have just tau showers, as a function of the sample size N. It can be seen that for 95% of the cases, samples of more than $\sim$ 17 events are needed to be able to reject the hypothesis of having electron neutrino showers alone.

It is important to note that as the energy decreases the ratio $N_{sh}(\nu_\tau)/N_{sh}(\nu_e)$ goes to one, as a consequence the number of events needed to reject the hypothesis of having a sample with electron neutrinos alone decreases drastically.

4 Earth skimming tau neutrinos

Gamma ray bursts are potential sources of high energy cosmic rays [13, 14]. If the cosmic rays are efficiently accelerated in GRBs a neutrino flux is expected as a result of the photo-hadronic interactions of protons with the photons present in the acceleration site [15]. The detection of high energy neutrinos in coincidence with GRBs should be a proof of the acceleration of cosmic rays in this kind of events.

Depending on the redshift of the GRB, the JEM-EUSO telescope will be able to observe Earth skimming tau neutrinos, detecting the Cherenkov flashes originated by the showers produced by the decay of the taus after propagation inside the Earth [16].

A modified version of the ANIS [17] program is used to propagate tau neutrinos inside of the Earth. We have improved the propagation and energy lose of the taus in order to study the case in which the taus traverse interfaces between rock and water which is the case of taus emerging from or entering to the oceans.

Two cases are considered, for the first one, the last or external layer of the Earth, of 3 km of thickness, is composed by standard rock of density 2.6 g cm^{-3}. For the second case, this last layer is composed by water, i.e. of density 1 g cm^{-3}. Following Ref. [16] tau neutrinos of 70° of nadir angle are considered. The energy spectrum of the tau neutrinos, used in the simulations, is the one corresponding to figure 2 of Ref. [16].

Figure 6 shows the energy distributions of the tau neutrinos injected into the simulation (black lines), the ones that produced an emerging tau lepton (blue lines), the emerging taus (green lines) and the energy that effectively goes to the shower (magenta lines). This last distribution is obtained by simulating the tau decay with TAUOLA and summing the energy of the particles that contribute to the shower, i.e. all particles excepting neutrinos.

In the case of rock the probability of a tau to emerge from the Earth is $P_R(\nu_\tau \to \tau) = 5.7 \times 10^{-4}$ and the median of the energy distribution of the taus is $med(E_\tau^R) \cong 4 \times 10^{16}$ eV. For the case in which the last layer of the Earth is composed by water $P_W(\nu_\tau \to \tau) = 2.9 \times 10^{-4}$ and $med(E_\tau^W) \cong 6 \times 10^{16}$ eV. Therefore, the number of emerging taus for the case where the last layer of the Earth is made of water is about a factor two smaller than the corresponding to rock, whereas, on average, the energy of the emerging taus is larger for the case of water. This is due to the fact that the energy lose of taus is smaller in the presence of water because the density of water is smaller. In principle, the presence of oceans could deteriorate the detectability of tau showers because of the reduction of the number of emerging taus.

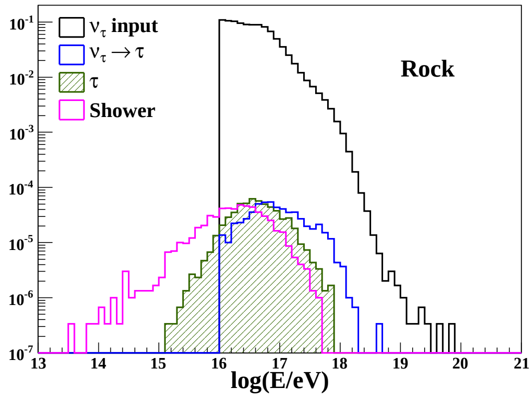

Figure 6: Energy distributions corresponding to the propagation of tau neutrinos of 70° of nadir angle following the energy spectrum of the GRB model of figure 2 of Ref. [16]. Black lines: input spectra; blue lines: neutrinos that produced an emerging tau; green lines: emerging taus; magenta lines: energy that goes to the showers (see the text for details).

The simulation of the Cherenkov photons that reach the JEM-EUSO telescope is the last step to complete the simulation chain for Earth skimming tau neutrinos (without considering the detector which is simulated with the ESAF [18] software). These simulations are under development and will allow us to study in detail the influence of the presence of oceans on the detectability of tau neutrinos from GRBs.

References

[1] V. Berezinsky et al., Phys. Lett., 1969, **28B**: 423.
[2] M. Kachelriess et al., New J. Phys., 2009, **11**: 065017.
[3] R. Aloisio et al., Phys. Rev., 2004, **D69**: 094023.
[4] P. Battacharjee et al., Phys. Rept., 2000, **327**: 109.
[5] Y. Takahashi, New J. Phys., 2009, **11**:065009.
[6] A. D. Supanitsky et al., Astropart. Phys., 2011, **35**: 8.
[7] T. Bergmann et al., Astropart. Phys., 2007, **26**: 420.
[8] S. Ostapchenko, Nucl. Phys. Proc. Suppl., 2006, **B151**: 143.
[9] T. Sjostrand et al., JHEP, 2006, **0605**: 026.
[10] M. Whalley et al., http://hepforge.cedar.ac.uk/lhapdf/.
[11] P. Nadolsky et al., Phys. Rev., 2008, **D78**: 013004.
[12] N. Davidson et al., arXiv:1002.0543.
[13] E. Waxman, Phys. Rev. Lett., 1995, **75**: 386.
[14] M. Vietri, Astrophys. J., 1995, **453**: 883.
[15] E. Waxman et al., Phys. Rev. Lett., 1997, **78**: 2292.
[16] K. Asano et al., Proc. 31st ICRC, 2009, #692.
[17] A. Gazizov and M. Kowalski, Comput. Phys. Comm., 2005, **172**: 203.
[18] C. Berat et al., Astropart. Phys., 2010, **33**: 221.