Tau Neutrinos at EeV Energies

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Abstract

Astrophysical sources of ultrahigh energy neutrinos yield tau neutrino fluxes due to neutrino oscillations. At neutrino energies in the EeV range, radio Cherenkov detection methods show promise for detecting these fluxes. We quantify the tau neutrino contributions to the signal in, for example, a detector like the Radio Ice Cherenkov Experiment (RICE) for a Z-burst flux prediction. Tau neutrino regeneration in transit through the Earth, including energy loss, is evaluated.

1. Introduction

The experimental evidence of $\nu_\mu \leftrightarrow \nu_\tau$ neutrino oscillations [5] means that astrophysical sources of muon neutrinos become sources of ν_μ and ν_τ in equal proportions after oscillations over astronomical distances [1,2]. Although ν_μ and ν_τ have identical interaction cross sections, signals from $\nu_\tau \to \tau$ conversions have the potential to contribute differently from ν_μ signals. The τ lepton can decay far from the detector, regenerating ν_τ [7-9]. This also occurs with μ decays, but electromagnetic energy loss coupled with the long muon lifetime make the ν_μ regeneration from muon decays irrelevant for high energies. A second signal of $\nu_\tau \to \tau$ is the tau decay itself [3,4].

In this paper, we investigate the effect of ν_τ regeneration from tau decays in the neutrino energy range between $10^6 - 10^{12}$ GeV. Attenuation shadows most of the upward-going solid angle for neutrinos. Regeneration comes from interaction and decay, so one is necessarily considering incident neutrinos which are nearly horizontal or slightly upward-going in a discussion of tau neutrino regeneration. The Radio Ice Cherenkov Experiment (RICE) [11] has put limits on incident isotropic electron neutrino fluxes which produce downward-going electromagnetic showers. Here, we look at the ν_τ contribution to horizontal or upward-going

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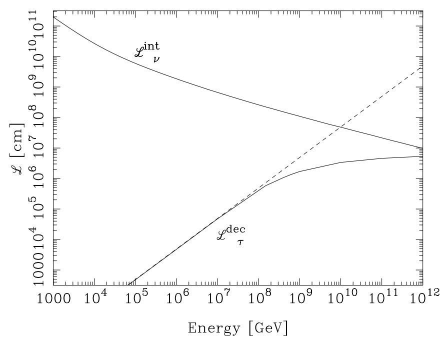

Fig. 1. Neutrino interaction length (solid line) and the tau effective decay length without energy loss (dashed line) and with energy loss in water (solid line).

electromagnetic showers where the shower is produced in 1-4 km of ice. The Antarctic Impulsive Transient Antenna (ANITA) also uses the ice as a neutrino converter [6]. The ANITA balloon missions will monitor the ice sheet for refracted radio frequency signals and require upward-going neutrino interactions.

2. Neutrino Attenuation and Regeneration

Tau neutrino attenuation and regeneration is governed by its interaction length and the tau decay length which is shown in Fig. 1. We also plot the effective decay length with tau electromagnetic energy loss [10]. The neutral current neutrino(antineutrino) cross section contribution to the total is about 1/2 of the charged current cross section. As a comparison of the interaction lengths with physical distances we note that the chord (D) of the earth (in water equivalent distance) as a function of the nadir angle is given as $D = 2R_\oplus\, \rho_{\rm rock}\, \cos\theta = 5.9 \times 10^7$ cm.w.e. for $\theta = 89°$. Here $R_\oplus = 6.4 \times 10^8$ cm, the mean Earth radius and the density of standard rock $\rho_{\rm rock} = 2.65$ g/cm^3. Neutrino attenuation is clearly an important effect for nearly horizontal neutrinos.

The effective decay length of produced taus does not go above 10^7 cm, even for $E_\tau = 10^{12}$ GeV. This is because electromagnetic energy loss over that distance reduces the tau energy to about 10^8 GeV, at which point, the tau is more likely to decay than interact electromagnetically [10].

Attenuation and regeneration is governed by the neutrino transport equations, as in, e.g., Ref. [8]. The coupled differential equations are solved approximately using Euler's method for the neutrinos, which is modified to include continuous tau decay for the taus. Energy loss of the τ is accounted for by shifting $E_{\tau,f} = E_{\tau,i} \exp(-\beta\Delta X)$ for column depth step size ΔX and β from the average high energy loss formula $-dE_\tau/dX \simeq \beta E$. As a first approximation, we use $\beta = 0.8 \times 10^{-6}$ cm^2/g.

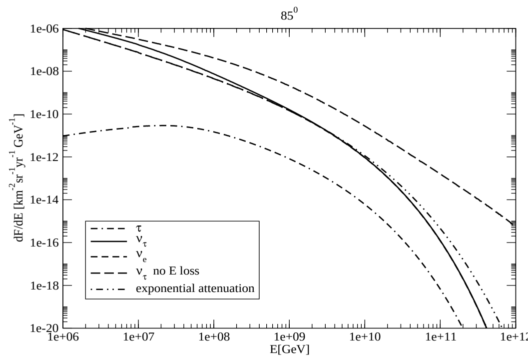

Fig. 2. Electron neutrino, tau neutrino and tau fluxes for an initial Z-burst flux at a nadir angle of 85°.

3. Results

Fig. 2 shows the attenuated/regenerated ν_e and ν_τ fluxes as well as the τ flux for the Z-burst [12] model of Ref. [13], approximated by

$$\frac{dF_\nu}{dE}\,[\mathrm{km}^{-2}\mathrm{yr}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}] = \begin{cases} 1/(E/\mathrm{GeV}) & E < 2.5\times 10^{12}\ \mathrm{GeV} \\ 6.24\times 10^{24}/(E/\mathrm{GeV})^3 & E \geq 2.5\times 10^{12}\ \mathrm{GeV} \end{cases} \tag{1}$$

and we use a nadir angle $\theta = 85°$. We approximate the Earth density over the course of the trajectory to be ρ_{rock} [$D = 2.9\times 10^8$ cm.w.e.]. Little $\nu_\tau \to \tau \to \nu_\tau$ regeneration occurs, as can be seen by comparing the ν_τ flux (solid line) with the ν_e flux (dashed line just below solid curve). The dot-dot-dashed line shows the result of simple attenuation with $\exp(-D/\mathcal{L}^{\nu}_{CC}(E))$, which agrees with the ν_e flux for $E \lesssim 10^{10}$ GeV. The uppermost dashed line corresponds to the tau neutrino flux without the energy loss. The tau flux (dot-dash-dashed line) at the end of the neutrino trajectory through the Earth is a factor of $\sim 10^{-5} - 10^{-3}$ of the attenuated tau neutrino flux for the energy $E = 10^6 - 10^{11}$ GeV.

In Fig. 3, we show the electron fluxes from ν_e charged current (CC) interactions and from $\tau \to e$ for the Z-burst model, again at $\theta = 85°$, for two different column depths in water: $D = 1$ km and 4 km. In evaluating the fluxes, we have integrated over energy distributions of the tau decay or the neutrino interaction cross section. The most important contributions of $\tau \to e$ to the electromagnetic signal occur below 10^8 GeV. For taus, electromagnetic energy loss and the falling probability to decay in depth D suppress $\tau \to e$ high energy contributions. For ν_e, the rising cross section works in the opposite direction.

We conclude that the electron contribution to the electromagnetic signal from τ decay from nearly horizontal incident ν_τ is a small portion of the $\nu_e \to e$ CC signal, except in the energy range of $\sim 10^6 - 10^8$ GeV, for the Z-burst flux model. For the RICE experiment, this is in the energy range where their effective

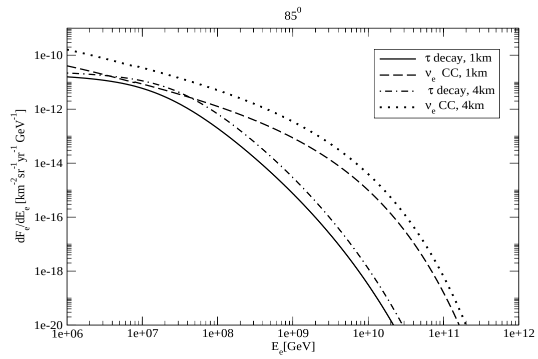

Fig. 3. Electron fluxes from $\tau \to e$ and $\nu \to e$ given an initial Z-burst flux for $\theta = 85°$.

detection volume is smallest, making the τ signal from Z-burst tau neutrinos difficult to extract.

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