Enhanced signal of astrophysical tau neutrinos propagating through Earth

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Earth absorbs ν_e and ν_μ of energies above about 100 TeV. As is well-known, although ν_τ will also disappear through charged-current interactions, the ν_τ flux will be regenerated by prompt tau decays. We show that this process also produces relatively large fluxes of secondary $\bar{\nu}_e$ and $\bar{\nu}_\mu$, greatly enhancing the detectability of the initial ν_τ. This is particularly important because at these energies ν_τ is a significant fraction of the expected astrophysical neutrino flux, and only a tiny portion of the atmospheric neutrino flux.

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Introduction.— A variety of astrophysical and exotic sources are expected to produce large fluxes of ultra-high-energy particles, including photons, protons, and neutrinos. Sources such as active galactic nuclei and gamma-ray bursts are at high redshifts, and the photons and protons will be attenuated by scattering on cosmic radiation backgrounds. The protons may also be deflected by magnetic fields. However, neutrinos from distant sources will neither be attenuated nor deflected, thus allowing true neutrino astronomy of the high-redshift universe. Further, it is now known that about one-third of the energy density of the universe is accounted for by particles outside the Standard Model. Among the possibilities are variants of superheavy dark matter, which may produce ultra-high-energy particles from their annihilations or decays. Such signals would be most readily observed from local sources. The existence of cosmic rays with energies up to and above 10^{20} eV is a powerful argument for the existence of ultra-high-energy astrophysical neutrinos. With the upcoming km-scale detectors, a new era of neutrino astronomy will begin, and the energies, directions, and flavors of astrophysical neutrinos will provide important clues to the most violent astrophysical objects and the nature of particle dark matter [1,2].

While these detectors can suppress downgoing atmospheric muons, atmospheric neutrinos are a much more challenging background. Like astrophysical neutrinos, these can pass through Earth and create upgoing muons (for example). They are produced in the decays of secondaries produced by the collisions of cosmic-ray protons with Earth's atmosphere. The decays $\pi^+/K^+ \to \mu^+\nu_\mu$ and $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ and their charge conjugates produce fluxes in the flavor ratio $\nu_e : \nu_\mu : \nu_\tau \simeq 1 : 2 : 0$, where neutrinos and antineutrinos have been combined. These ratios vary with energy and angle when the production of other mesons and their decay lengths relative to the slant depth of the atmosphere are taken into account. In particular, at the highest neutrino energies, there is a tiny relative ν_τ flux from charm decay [3]. The atmospheric neutrino flux falls roughly as E^{-3}, whereas general considerations for astrophysical neutrino fluxes predict shallower slopes, and hence that they will dominate above some energy. For diffuse fluxes, this crossover is thought to be at least 10 TeV (point and/or transient sources can be identified at lower energies) [1,2].

Neutrino oscillations have an important consequence for suppressing the atmospheric neutrino background. The Super-Kamiokande atmospheric neutrino results [4] strongly favor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\sin^2 2\theta \simeq 1$ and $\Delta m^2 \simeq 3 \times 10^{-3}$ eV^2. At the high energies considered here, $\nu_\mu \leftrightarrow \nu_\tau$ oscillations will *never* occur for atmospheric neutrinos, and their flavor ratios will reflect the production mechanism only. In the astrophysical production scenarios, the flavor ratios are also thought to be $1 : 2 : 0$ (again combining neutrinos and antineutrinos), reflecting their production by ultra-high-energy protons. But for the astrophysical sources, $\nu_\mu \leftrightarrow \nu_\tau$ mixing will *always* be complete because of the long path lengths, and so these ratios become $1 : 1 : 1$. In some exotic models [5,6], the initial ν_τ flux is large; in any case, a large ν_τ component in the astrophysical neutrino flux is guaranteed.

This simple fact is very important for the detection of astrophysical neutrinos above the atmospheric neutrino background. This is because ν_e and ν_μ above about 100 TeV will be absorbed by Earth, whereas the absorbed ν_τ flux will be regenerated by prompt tau decays [7]. We point out a new effect: that the regeneration of the ν_τ flux also creates relatively large secondary fluxes of $\bar{\nu}_e$ and $\bar{\nu}_\mu$. These make the detection of astrophysical sources significantly *easier*, and must be accounted for to properly deduce the source spectra and flavor composition.

Neutrino propagation in Earth.— Above about 100 TeV, all neutrino flavors have a high probability of interacting in Earth via neutrino-nucleon scattering, with a total cross section $\sigma \propto E^{0.5}$ [8]. Except for $\bar{\nu}_e + e^- \to W^-$ at the Glashow resonance (6.3 PeV), neutrino-electron scattering is irrelevant. Charged-current (CC) and neutral-current (NC) interactions on nucleons occur in the ratio 0.71 : 0.29, and in both cases, the surviving lepton carries about 75% of the initial neutrino energy [8]. The cross sections for neutrinos and antineutrinos are approximately equal. The neutrino interaction length is shown in Fig. 1; it is the same for all flavors since even tau mass threshold effects are negligible.

In the more likely CC interaction, the critical question is the subsequent fate of the charged lepton. An initial ν_e will be removed from the beam and the resulting electron very quickly brought to rest. With an initial ν_μ, the produced muon will eventually decay. However, the laboratory-frame decay length for the muon is always much longer than its range, the distance over which its electromagnetic energy losses bring it to rest. Thus the neutrinos from its decay will be below 50 MeV, and of no further interest here. The decay length and range for muons are shown in Fig. 1.

As first noted by Ritz and Seckel [9], the situation is very different for ν_τ, since at all but the highest energies, the tau decay length is less than its range, so that the tau will decay in flight without significant energy loss; see Fig. 1. Tau decays occur by many branches, but all contain a ν_τ. This regenerated ν_τ carries a fraction about $0.75 \times 0.4 \simeq 1/3$ of the initial ν_τ energy, where 0.4 is for ν_τ from tau decay [10,11]. Ritz and Seckel considered WIMP annihilation in the sun, and the propagation of the produced neutrinos. The utility of this regeneration effect for the detection of astrophysical neutrinos was not noted until a decade later, by Halzen and Saltzberg [7].

The regeneration process will continue (along with the less frequent NC scatterings) until the ν_τ energy has been moderated to the energy such that the neutrino interaction length is comparable to the remaining distance in Earth. At nadir angle $\psi = 0°$, such that the neutrino will cross the full diameter of Earth, the transparency energy is about 40 TeV (at larger nadir angles, neutrinos at higher energies can pass through without scattering). The distribution of ν_τ energies around the transparency energy is characteristically lognormal, with a one-sigma width of approximately one decade. Thus all of the initial ν_τ will emerge at relatively high energies.

Future km-scale astrophysical neutrino detectors are designed for the detection of ν_e (via an electromagnetic shower) or ν_μ (via the track of a penetrating muon). The detection of ν_τ is much more difficult. Learned and Pakvasa [12] have shown that ν_τ may be detected by a "double-bang" signature, if the tau lepton production and decay, each accompanied by a large shower, are well-separated but both occur in the detector. The double-bang events will be observable only in a narrow range around several PeV, and only at large nadir angles, so other techniques for ν_τ detection are needed.

This is precisely the point of the signal proposed by Halzen and Saltzberg [7]. In their scheme, the ν_τ interacts outside the detector and the tau created decays as

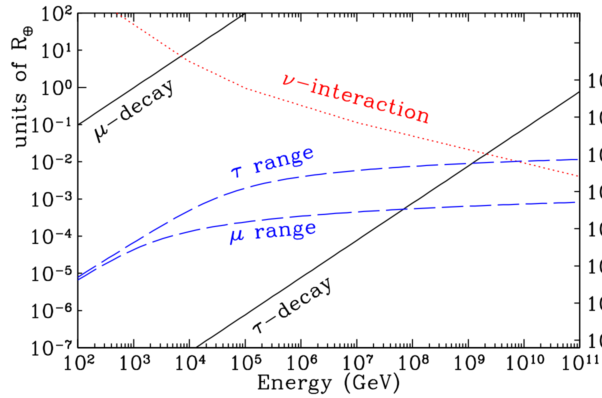

FIG. 1. Some important length scales, in units of Earth radii and km, versus the energy in GeV for the neutrino or charged lepton. *Solid lines:* the μ and τ decay lengths, i.e., the distances over which a fraction e^{-1} of the the initial fluxes would survive (ignoring energy loss). *Dashed lines:* the μ and τ ranges, i.e., the distances in standard rock (22 g mol^{-1}) at a density 8 g cm^{-3} over which the which they would be *fully* stopped by their electromagnetic interactions (ignoring decays). *Dotted line:* the neutrino interaction length (the same for all flavors), i.e., the distance at a density 8 g cm^{-3} over which a fraction e^{-1} of the initial flux would survive. With the exception of the Glashow resonance for $\bar{\nu}_e$ at 6.3 PeV, this figure is the same for antiparticles. While the density varies significantly with nadir angle, 8 g cm^{-3} is representative.

$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$, where the muon, which has a long range, is seen in the detector. These ν_τ events can be separated from ν_μ CC events (which also produce a muon) on a statistical basis, using the fact that the ν_τ nadir angle distribution will be unchanged by passage through Earth, whereas that for ν_μ will show exponential absorption (as will ν_e). Additionally, if the incoming neutrino spectrum is shallower than about E^{-2}, the pileup near the transparency energy may be visible [7,10]. However, it should be noted that the above tau branching ratio of 18% reduces the detectability of the ν_τ flux compared to a ν_μ flux at the same energy, both taken just below the detector. While the muon in the ν_τ-induced case will have an energy roughly 0.4 of that in the ν_μ-induced case because of the tau decay [10,11], the muon range and hence detectability varies only slowly with energy (see Fig 1).

Secondary antineutrinos.— While expected to be a significant component of the astrophysical neutrino flux, and the only component which is not attenuated in Earth, ν_τ are not easily detected. However, we point out a new effect that significantly improves their detectability. In each step of the regeneration process $\nu_\tau \to \tau \to \nu_\tau$ described above, the tau lepton decay will always produce a ν_τ. Additionally, 18% of decays are $\tau \to \nu_\tau \mu \bar{\nu}_\mu$ and 18% are $\tau \to \nu_\tau e \bar{\nu}_e$. In the laboratory frame, on average ν_τ and μ each carry a fraction 0.4 of the tau energy and $\bar{\nu}_\mu$ carries a fraction 0.2 [10,11]. Secondary ν_μ and ν_e are also produced by initial $\bar{\nu}_\tau$ (expected to have a flux comparable to the initial ν_τ). These secondary antineutrinos ($\bar{\nu}_e, \bar{\nu}_\mu$) and neutrinos ($\nu_e, \nu_\mu$) have not been taken into account before, but they have a surprisingly large effect on the detectability of ν_τ and $\bar{\nu}_\tau$.

The number of regeneration steps for ν_τ is approximately $N = \log(E_i/E_T)/\log 3$, where E_i is the initial energy and E_T is the transparency energy. With more steps, there are more opportunities to create secondary $\bar{\nu}_\mu$ and $\bar{\nu}_e$. However, those created farther from the detector have a greater chance of being absorbed. On each step the secondary antineutrinos will carry about 1/6 of the initial ν_τ energy, reflecting the energy lost in the CC scattering and the tau decay.

It is generally assumed that all scatterings and decays are collinear. However, as the number of regeneration steps increases, the cumulative non-collinearity could be large enough to blur astrophysical point sources. If the initial neutrino has energy E_ν, simple considerations indicate that for $\nu_\tau \rightarrow \tau$, the scattering angle is about $1^\circ/\sqrt{E_\nu/\text{ TeV}}$, and for $\tau \rightarrow \nu_\tau$, the decay angle is about $0.2^\circ/(E_\nu/\text{ TeV})$. The decay angle can thus be neglected compared to the scattering angle. In order for the number of scatterings to be nonzero, E_ν must be above about 100 TeV, so that on the last step the angular deviation is about 0.1°. Taking previous regeneration steps into account gives a maximum deviation of about 0.3°. This is below the expected 1° reconstruction resolution of the proposed detectors [2], and so astrophysical point sources should not be blurred by ν_τ regeneration.

We can estimate the secondary $\bar{\nu}_e$ and $\bar{\nu}_\mu$ number flux produced by a ν_τ beam by making the following crude assumptions: (i) ν_τ do not lose energy in their CC or NC interactions; (ii) $\bar{\nu}_e$ or $\bar{\nu}_\mu$ which interact are removed from the beam; and (iii) $\bar{\nu}_e$ or $\bar{\nu}_\mu$ from tau decay are produced with the same energy as the initial ν_τ. Consider a beam of astrophysical neutrinos in the expected ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, each with a flux F_0, and all at an energy E_0. Define f as the fraction of ν_τ interactions that produce a a $\bar{\nu}_e$ or $\bar{\nu}_\mu$: $f = 0.71 \times 0.18 = 0.13$, where the first factor is the CC/NC fraction, and the second factor is the relevant tau-decay branching ratio. The secondary $\bar{\nu}_\mu$ flux from tau decay obeys the equation

$$\frac{d}{dx} F_{\bar{\nu}_\mu}(x) = \frac{f}{\lambda} F_0 - \frac{1}{\lambda} F_{\bar{\nu}_\mu}(x)\,,$$

where x is the distance through Earth at the chosen nadir angle. The first term represents the creation of $\bar{\nu}_\mu$ from the ν_τ flux, and the second represents their subsequent absorption. Note that the interaction length λ is the same for both flavors. Thus, in this simple estimate, the fluxes after propagation through Earth are

$$F_{\nu_e}/F_0 = F_{\nu_\mu}/F_0 = e^{-x/\lambda}\,;\ F_{\nu_\tau}/F_0 = 1$$
$$F_{\bar{\nu}_e}/F_0 = F_{\bar{\nu}_\mu}/F_0 = f\left(1 - e^{-x/\lambda}\right)\,;\ F_{\bar{\nu}_\tau}/F_0 = 0\,.$$

The initial ν_e and ν_μ fluxes are exponentially depleted. However, the flux associated with the initial ν_τ is increased due to the secondary $\bar{\nu}_e$ and $\bar{\nu}_\mu$. For large x, corresponding to more ν_τ regeneration steps, the increased production of $\bar{\nu}_e$ and $\bar{\nu}_\mu$ is balanced by their increased absorption. For the expected initial antineutrinos (with the same fluxes and flavor ratios as for neutrinos), similar results obtain for the production of secondary neutrinos, and they must be added to the above. For small x, the initial ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ fluxes will survive, whereas for large x, they will be absorbed but replaced by the approximately constant secondary fluxes created by ν_τ and $\bar{\nu}_\tau$. Thus even for large energies and/or small nadir angles, the fluxes of ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ *never vanish*, contrary to previous predictions.

We have calculated the secondary $\bar{\nu}_e$ and $\bar{\nu}_\mu$ production with a Monte Carlo code that simulates the passage of high-energy neutrinos through Earth. We assume collinear propagation for all particles followed, as justified above. The code starts with an initial neutrino and randomly samples its interaction probability at each step in distance, using the CC and NC total cross sections from Gandhi, Quigg, Reno, and Sarcevic [8]. In each interaction, we sample the outgoing charged lepton or neutrino energy around the average inelasticity values $\langle y \rangle$ given in Ref. [8]. At these energies, $\langle y \rangle$ is the same for CC or NC interactions, and the same for neutrinos or antineutrinos. Accordingly, for the distributions about $\langle y \rangle$ we use the $d\sigma/dy$ distribution given in Ref. [8] for neutrino-nucleon CC scattering.

After a NC interaction, the neutrino is followed until the next interaction. After a CC interaction, if a muon or tau is created, it is followed. For their energy loss, we use the results of Ref. [13], and for their decays we use the laboratory-frame decay probability distributions. Any electrons created are assumed stopped. For the laboratory-frame ν_τ distribution from tau decays, summed over all branches and including the tau polarization, we use the distributions given in Ref. [10,11]. In tau decays leading to $\bar{\nu}_e$ or $\bar{\nu}_\mu$, we use the distributions for those branches [10,11]. There are many tau decay branches that yield charged pions or kaons. However, these mesons will be stopped before they decay, so that the produced neutrinos are at low energies and hence ignored. For all particles, we impose a low-energy cutoff at 100 GeV, though the results are insensitive to the cutoff as long as it is well below the transparency energy.

In Fig. 2 (cf. Fig. 2 of Ref. [7]), we plot the numerical results for the emergent ν_μ and $\nu_\tau + \bar{\nu}_\mu$ fluxes using several initial energies. A very small fraction (about 1%) of ν_τ either downscatter to very low energies by repeated NC interactions, or the tau lepton emerges from Earth; these are neglected in Fig. 2. The results are in general agreement with the analytic estimates, though the $\bar{\nu}_\mu$ flux is about twice as large as the analytic estimate. The principal reason for this is the fact that the secondary

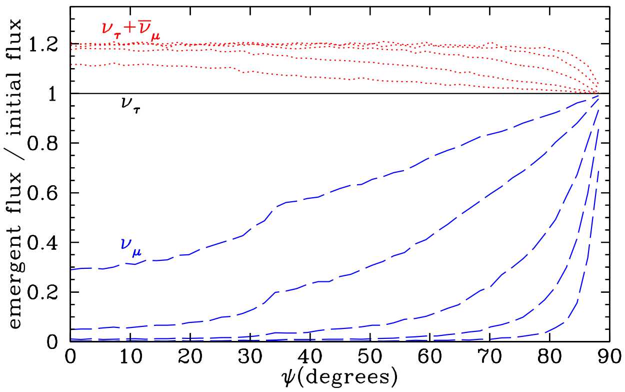

FIG. 2. The surviving fluxes associated with the initial ν_τ and ν_μ fluxes versus nadir angle, for a variety of energies. The results were calculated with our Monte Carlo code, and the slight jaggedness in the curves is due to statistical fluctuations. The initial ν_μ flux is depleted (ν_e would be the same), and the flux associated with the initial ν_τ is increased due to the secondary $\bar{\nu}_\mu$ (and the equal $\bar{\nu}_e$ component, not shown). The initial energies are 10^5, 10^6, 10^7, 10^8, and 10^9 GeV, going from top to bottom for the ν_μ fluxes and bottom to top for the $\nu_\tau + \bar{\nu}_\mu$ fluxes. The emergent ν_τ flux is unity for all energies. We use the density profile given in the Preliminary Reference Earth Model described in, e.g., Ref. [8]. Note the mantle-core transition at $\psi \simeq 33^\circ$, corresponding to a radial distance of 3480 km.

$\bar{\nu}_\mu$ are about 1/2 as energetic as the regenerated ν_τ, and so have a longer interaction length than assumed in the analytic estimate. They are created in the last few interaction lengths of the ν_τ. We find that the ν_τ and $\bar{\nu}_\mu$ are distributed around the transparency energy, as expected. The surviving ν_μ have the initial energy E_0, at least until their flux is greatly suppressed. A very small fraction will be moderated down to the transparency energy by repeated NC interactions; this is why the ν_μ flux in Fig. 2 never completely vanishes.

Conclusions.— Earth absorbs high-energy ν_e and ν_μ. In fact, high-energy ν_τ are absorbed too, but the ν_τ flux is regenerated by prompt tau decays, thus moderating the ν_τ energies down to near the transparency energy. As a function of the nadir angle, the ν_e and ν_μ fluxes are exponentially absorbed, while the ν_τ flux remains unchanged by passage through Earth. Halzen and Saltzberg have proposed that these ν_τ can be detected by CC interactions after which the tau decays to a muon below the detector, and that they can be separated from ν_μ CC interactions by their characteristic nadir-angle dependence [7]. A difficulty with this technique is the 18% branching fraction for the tau decay into a muon.

We have pointed out a new effect, that the $\nu_\tau \to \tau \to \nu_\tau$ regeneration process creates a secondary $\bar{\nu}_\mu$ flux. Though their flux is at most 0.2 of the ν_τ flux, they are as detectable by the production of muons as the entire ν_τ flux. Similarly, a secondary $\bar{\nu}_e$ flux is created that doubles the detectability of ν_τ by the production of electrons and their associated showers. The detectability of ν_τ by neutral-current channels will be about 40% larger. For astrophysical antineutrinos, the secondary neutrinos created have the same effect, again doubling the detectability of the $\bar{\nu}_\tau$ flux. Taking these secondary fluxes into account in the energy and nadir-angle distributions (e.g., in studies like Refs. [10,14]) will be essential for understanding the spectra and flavor composition of astrophysical neutrinos.

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