Neutrino Flux Bounds, Event Rates, and their Implications for an Inner Earth Tomography

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1 Introduction

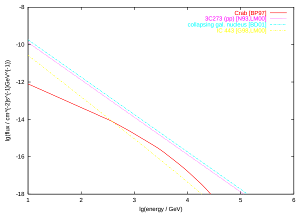

Fig. 1: Muon neutrino fluxes from various proposed point-like sources.

High-energy protons hitting proton or photon targets produce electron and muon neutrinos so that astrophysical objects such as AGNs and GRBs are good candidates for neutrino sources. Some examples of postulated fluxes are given in Figs. 1 and 2 (cf. Learned and Mannheim 2000). We assume that due to the large distances covered, neutrino flavor oscillations result in an equipartition among the flavors, and a significant number of tauon neutrinos is to be expected (Learned and Pakvasa 1995, Husain 2000). Here and in the following, no distinction between particles and antiparticles is made.

As the production of neutrinos, protons, and γ-rays is correlated, one may use the observational upper bounds on cosmic-ray protons and the diffuse γ-ray flux in order to obtain upper bounds for the possible neutrino fluxes. In this work we consider the bounds proposed by Waxman and Bahcall (1999, WB) and by Mannheim et al. (2001, MPR)

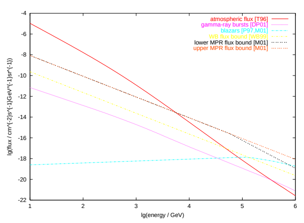

Fig. 2: Various postulated isotropic muon neutrino fluxes and upper flux bounds.

2 Crossing the Earth

Neutrino interactions during the propagation through the inner Earth lead to the set

$$\frac{d\phi_{\nu_l}(E,x)}{dx} = -\frac{\rho(x)}{m_p}\sigma_{\mathrm{tot},l}(E) + \sum_k \int_E^\infty dE' \frac{\rho(x)}{m_p}\frac{d\sigma_{k\to l}}{dE}(E',E) + \text{tauon decay} \qquad (1)$$

of integro-differential equations for the time-development of the neutrino fluxes ϕ_i of the various flavors i (cf. Gandhi 1996, Becattini and Bottai 2000, Hettlage and Mannheim 2001). Here, the cross sections σ comprise charged-current, neutral-current, and neutrino-electron interactions. x, E, and $P_{\mathrm{dec,l}}$ denote the distance traveled, the energy and the tauon decay probability (Pasquali and Reno 1999), respectively. We use the CTEQ5DIS parton distributions (Lai et al. 2000). For the approximation of a discretized grid, the solution of Eq. 1 may be obtained analytically (t is the column number density):

$$N_k(t) = \sum_{i=0}^{k} N_k^{(i)} e^{-A_i t},\ N_k^{(i)}(t) \equiv \begin{cases} N_k(t=0) - \sum_{l=0}^{k-1}\sum_{r=0}^{k-1}\frac{B_{rk}}{A_k - A_l}N_r^l(t) & ,\ i=k \\ \sum_{r=0}^{k-1}\frac{B_{rk}}{A_k - A_i}\phi_r^{(i)}(t) & ,\ i<k \\ 0 & ,\ i>k \end{cases}$$

The A_k and B_{ki} follow from the discretized equations.

3 Neutrino detection

High-energy neutrinos can be detected by means of water-based Čerenkov detectors such as BAIKAL and AMANDA, which look for the Čerenkov radiation of leptons produced in charged-current neutrino-nucleon interactions. The event rate corresponding to leptons originating inside the detector is given by

$$\dot{N}_{l,\mathrm{in}}(E_l) = \int_{E_l}^{\infty} dE' \phi_{\nu_l}(E') \frac{d\sigma_{\mathrm{CC},\nu_l}}{dE}(E', E_l) \frac{\rho}{m_p} A_{\mathrm{eff}} h,$$

where for the height and effective area of the detector we assume $h = 1\ \mathrm{km}$ and $A_{\mathrm{eff}} = 1\ \mathrm{km}^2$, respectively. For the events due to interactions outside the detector we get $\dot{N}_e \equiv \dot{N}_\tau \equiv 0$ and

$$\dot{N}_{\mu,\mathrm{out}}(E_\mu) = \int_0^\infty dx \int_{E_\mu^{\mathrm{init}}(E_\mu,x)} dE' \phi_{\nu_l}(E') \rho A_{\mathrm{eff}} \frac{d\sigma_{\mathrm{CC},\nu_\mu}}{dE}(E', E_\mu^{\mathrm{init}}(E_\mu, x)),$$

where E_μ^{init} denotes the initial muon energy which results in the energy E_μ after traveling a distance x. For simplicity we take the muon energy loss to be continuous. In addition, the muons arising from tauon decays have to (and have been) included in the computation of the event rate.

4 Inner Earth tomography

As the density ρ is the inverse Radon transform of the column density X, one can show that (cf. Deans 1993, Jain et al. 1999)

$$\rho(r) = -\frac{1}{2\pi r}\frac{d\check{\rho}^{(2)}(r)}{dr},\ \check{\rho}^{(2)}(r) \equiv \int_{-\sqrt{R^2-p^2}}^{+\sqrt{R^2-p^2}} X(\sqrt{r^2+q^2})dq,$$

where R is the Earth radius and X is assumed to be a function of the distance from the center of the Earth. Under the assumption that the initial neutrino spectrum is known, the event rate as a function of the nadir angle allows us to obtain X, so that a tomography of the inner Earth might be possible.

The plots of Fig. 3 show the results of simulating such a tomography for five years of data-taking with a cubic kilometer telescope. They clearly illustrate that even under the rather optimistic conditions assumed, any tomography will prove difficult.

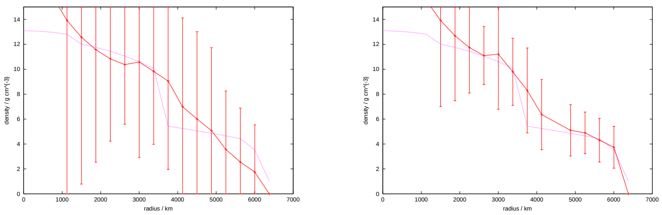

Fig. 3: Results of a (simulated) inner Earth tomography by means of high-energy muon neutrinos, together with the error bars to be expected. The pink line shows the Preliminary Reference Earth Model (Dziewonski and Anderson 1981). *Left:* Tomography for the WB flux bound. *Right:* Tomography for the MPR flux bound corresponding to optically thick sources.

5 Event rates for candidate neutrino sources

In Fig. 4 and Table 1 various proposed neutrino sources are investigated. Here, only neutrinos entering the detector at a nadir angle less equal 90° are considered.

While the number of muon neutrinos is diminished by charged-current interactions, the number of tauon neutrinos is not. Nonetheless one can see from the results that the tauon event rates are smaller, as only tauons produced inside the detector contribute to the event rate, which means that the effective detector volume is considerably smaller.

point-like source	reference	$\dot{N}_\mu^{\mathrm{ICE}}$	$\dot{N}_\tau^{\mathrm{ICE}}$	$\dot{N}_\mu^{\mathrm{ANT}}$	$\dot{N}_\tau^{\mathrm{ANT}}$
Crab Nebula	[BP97]	3	0.7	1	0.3
3C 273 (core, pp-interactions)	[N93,LM00]	41	7	17	3
collapsing gal. nucleus 1 GeV away[a]	[BD01]	0	0	33	8
supernova remnant IC 443	[G98,LM00]	1	0.3	0.4	0.1

isotropic flux	reference	$\dot{N}_\mu$	$\dot{N}_\tau$
atmospheric flux above 100 GeV	[T96]	78114	117524
gamma-ray bursts	[DP01]	25	5
blazars	[P97,M01]	769	47
WB flux bound	[WB99]	442	76
lower MPR flux bound ($\tau_{n\gamma} < 1$)	[M01]	12883	2570
upper MPR flux bound ($\tau_{n\gamma} \gg 1$)	[MPR01]	16293	2796

Table 1: Muon and tauon events $\dot{N}$ per year for various proposed neutrino sources. $E_\nu \geqslant 100\ \mathrm{GeV}$ is assumed. In the case of point-like sources, cubic kilometer telescopes at the sites of both ICECUBE (ICE) and ANTARES (ANT) are considered. ([a] assumed to have a declination of -90°)

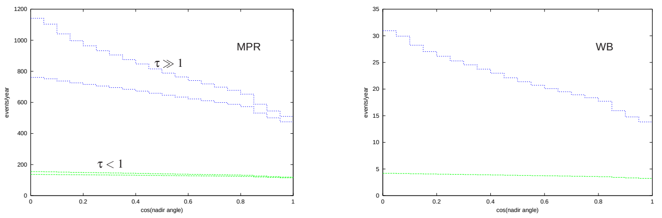

Fig. 4: Muon *(blue)* and tauon neutrino events per year *(green curves)* compatible with the neutrino flux bounds of Fig. 2, if a lower energy cutoff of 100 GeV is assumed. The rates are computed for the angular bins shown, which all correspond to the same solid angle size. *Left:* Rates for the MPR bounds for low and high source opacities. *Right:* Rates for the Waxman-Bahcall bound with source evolution.

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