High energy neutrino astrophysics

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I give a brief discussion of possible sources of high energy neutrinos of astrophysical origin over the energy range from $\sim 10^{12}$ eV to $\sim 10^{25}$ eV. In particular I shall review predictions of the diffuse neutrino intensity. Neutrinos from interactions of galactic cosmic rays with interstellar matter are guaranteed, and the intensity can be reliably predicted to within a factor of 2. Somewhat less certain are intensities in the same energy range from cosmic rays escaping from normal galaxies or active galactic nuclei (AGN) and interacting with intracluster gas. At higher energies, neutrinos will definitely be produced by interactions of extragalactic cosmic rays with the microwave background. With the discovery that gamma ray bursts (GRB) are extragalactic, and therefore probably the most energetic phenomena in the Universe, it seems likely that they will be copious sources of high energy neutrinos. Other sources, such as AGN and topological defects, are more speculative. However, searches for neutrinos from all of these potential sources should be made because their detection would have important implications for high energy astrophysics and cosmology.

1. INTRODUCTION

The technique for constructing a large area (in excess of 10^4 m^2) neutrino telescope has been known for more than two decades [1]. The pioneering work of the DUMAND Collaboration led to the development of techniques to instrument a large volume of water in a deep ocean trench with strings of photomultipliers to detect Cherenkov light from neutrino-induced muons [2]. Locations deep in the ocean shield the detectors from cosmic ray muons. The second generation of high energy neutrino telescope such as AMANDA [3] located deep in the polar ice cap at the South Pole, and NT 200 in operation in Lake Baikal, Siberia [4], have demonstrated the feasibility of constructing large area experiments for high energy neutrino astronomy. The next generation telescopes, such as the planned extension of AMANDA, ICECUBE [5], and ANTARES [6], may have effective areas of 0.1 km^3, or larger, and be sufficiently sensitive to detect bursts of neutrinos from extragalactic objects and to map out the spectrum of the diffuse high energy neutrino background. In this paper I focus on possible astrophysical sources of neutrinos contributing to the diffuse high energy neutrino background from ~ 1 TeV to the GUT scale.

2. COSMIC RAY INTERACTIONS WITH MATTER

There will definitely exist a diffuse galactic neutrino background due to interactions of the galactic cosmic rays with interstellar matter. The spectrum of cosmic rays is reasonably well known, as is the matter distribution in our galaxy. Estimates of the neutrino intensity have been made by Silberberg and Shapiro [7], Stecker [8], Domokos et al. [9], Berezinsky et al. [10], and Ingelman and Thunman [11], and the more recent predictions are shown in Fig. 1. The differences of about a factor of 2 between the predictions are accountable in terms of the slightly different models of the interstellar matter density, and cosmic ray spectrum and composition used. Also shown is the atmospheric neutrino background as estimated by Lipari [12]. In addition, there will be a very uncertain background (not plotted) due to charm production (see refs. [13,14] for a survey of predictions).

Somewhat less certain is the flux of neutrinos from clusters of galaxies. This is produced by *pp* interactions of high energy cosmic rays with intracluster gas. Berezinsky et al. [15] have made predictions of this, and I show in Fig. 2 their estimates of the diffuse neutrino intensity due

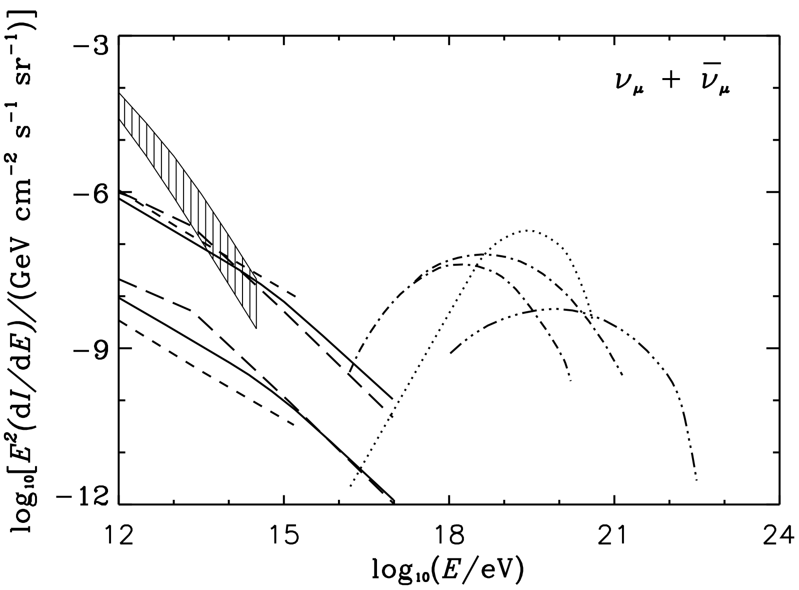

Figure 1. Neutrinos from cosmic ray interactions with the interstellar medium (upper curves for $\ell = 0°$, $b = 0°$, lower curves for $b = 90°$): — — — Domokos et al. [9]; - - - - Berezinsky et al. [10]; —— Ingelman and Thunman [11]. The band with vertical hatching shows the range of atmosheric neutrino background [12] as the zenith angle changes from 90° (highest) to 0° (lowest). Neutrinos from cosmic ray interactions with the microwave background: — · — · — · — Protheroe and Johnson [23] for $E_{\max} = 3 \times 10^{20}$ eV and 3×10^{21} eV; · · · · · · Hill and Schramm [24]; — · · · — · · · — · · · — assuming the highest energy cosmic rays are due to GRB according to Lee [25].

to interactions of cosmic rays produced by normal galaxies and AGN together with an upper limit based on assuming the observed γ-ray background results from π^0 production. Later estimates by Colafrancesco and Blasi [16] are also shown.

3. COSMIC RAY INTERACTIONS WITH RADIATION

Moving to higher energies, cosmic rays above $\sim 10^{20}$ eV will interact with photons of the cosmic microwave background radiation (CMBR) [17,18]. Again, we know that both ingredients exist (the highest energy cosmic ray detected has an energy of 3×10^{20} eV [19], and at least 6 cosmic rays have been detected above 10^{20} eV by the AGASA array [20]), and so pion photoproduction at these energies will occur, resulting in a diffuse neutrino background (Stecker [8]). However, the intensity in this case is model-dependent because it is not certain precisely what the origin of the highest energy cosmic rays is, and whether in fact they are extragalactic, although this seems very probable (see [21] for a discussion of the highest energy cosmic rays). One of the most likely explanations of the highest energy cosmic rays is acceleration in Fanaroff-Riley Class II radio galaxies as suggested by Rachen and Biermann [22]. Protheroe and Johnson [23] have repeated Rachen and Biermann's calculation in order to calculate the flux of diffuse neutrinos and γ-rays which would accompany the UHE cosmic rays, and their result has been added to Fig. 1. Any model in which the cosmic rays above 10^{20} eV are of extragalactic origin will predict a high energy diffuse neutrino intensity probably within an order of magnitude of this at 10^{19} eV. For example, I show an earlier estimate by Hill and Schramm [24]. Also shown is an estimate by Lee [25] of the

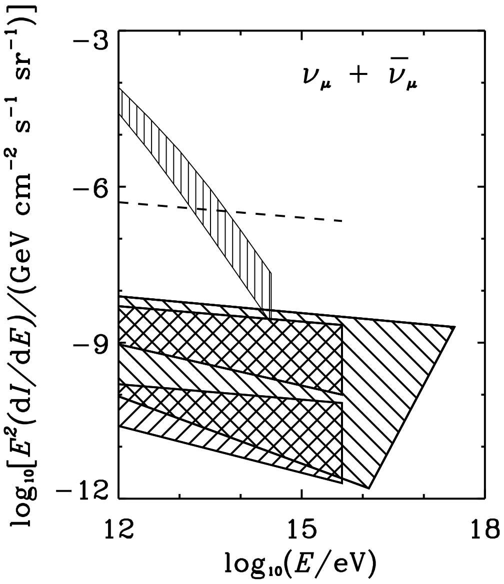

Figure 2. Neutrinos from cosmic ray interactions in clusters of galaxies (Berezinsky et al. [15]): lower hatched area – normal galaxies; upper hatched area – AGN; dashed line – upper bound from γ-ray data. Large hatched region – comic ray interactions with intergalactic medium in clusters of galaxies [16]

diffuse neutrino intensity estimated in a model in which the highest energy cosmic rays have their origin in sources of gamma ray bursts.

4. GAMMA RAY BURSTS

Gamma ray bursts (GRB) are observed to have non-thermal spectra with photon energies extending to MeV energies and above. Recent identification of GRB with galaxies at large redshifts (e.g. GRB 971214 at $z = 3.42$ [26]) show that the energy output in γ-rays alone from these objects can be as high as 3×10^{53} erg if the emission is isotropic, making these the most energetic events in the Universe. GRB 980425 has been identified with an unusual supernova in ESO 184-G82 at a redshift of $z = 0.0085$ implying an energy output of 10^{52} erg [27]. These high energy outputs, combined with the short duration and rapid variability on time-scales of milliseconds, require highly relativistic motion to allow the MeV photons to escape without severe photon-photon pair production losses. The energy sources of GRB may be neutron star mergers with neutron stars or with black holes, collapsars associated with supernova explosions of very massive stars, hyper-accreting black holes, hypernovae, etc. (see [28,29] for references to these models).

The relativistic fireball model of GRB (Meszaros and Rees [30]) provides the framework for estimation of neutrino fluxes from GRB. A relativistic fireball sweeps up mass and magnetic field, and electrons are energized by shock acceleration and produce the MeV γ-rays by synchrotron radiation. Protons will also be accelerated, and may interact with the MeV γ-rays producing neutrinos via pion photoproduction and subsequent decay at energies above $\sim 10^{14}$ eV [31,33]. Acceleration of protons may also take place to energies above 10^{19} eV, producing a burst of neutrinos at these energies by the same process [34]. These energetic protons may escape from the host galaxy to become the highest energy cosmic rays [35,36]. Additional neutrinos due to interactions of the highest energy cosmic rays with the CMBR will be produced as discussed in the previous section.

For a sufficiently intense GRB, it may be possible to identify neutrinos from individual GRB. Integrating over all GRB in the Universe, Waxman and Bahcall [31,32] have predicted the diffuse neutrino intensity, and this has been plotted in Fig. 3 with a steepening at 10^{16} eV, and with a continuation to higher energies as suggested by Vietri [34].

5. ACTIVE GALACTIC NUCLEI

The 2nd EGRET catalog of high-energy γ-ray sources [37] contains over 40 high confidence identifications of AGN, and all appear to be blazars (radio-loud AGN having emission from a relativistic jet closely aligned to our line of sight). Since the publication of the 2nd catalog, the number of blazars detected by EGRET has increased to nearly 70 (see refs. [38,39] for reviews). TeV emission has been observed from three blazars, the BL Lac Objects Mrk 421, Mrk 501 and 1ES 2344+514 [40]. Clearly, the γ-ray emission is as-

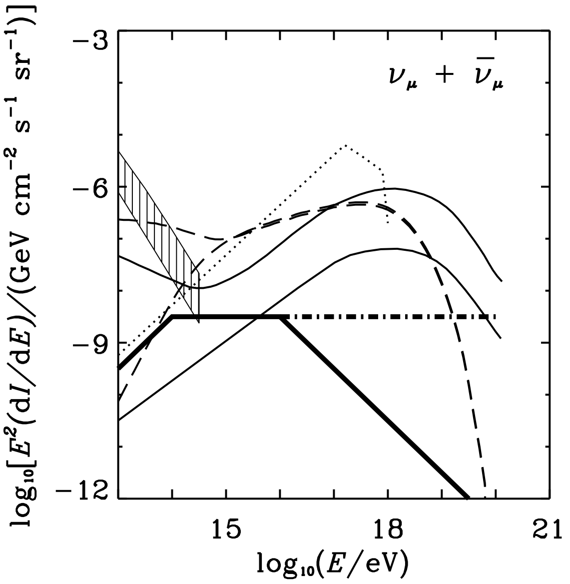

Figure 3. Diffuse neutrinos from GRB: Thick solid line Waxman & Bahcall [31], with extension to higher energies suggested by Vietri [34] (thick chain line). Diffuse $p\gamma$ (lower) and $pp + p\gamma$ (upper) neutrinos from blazars: ——— Mannheim [48] ($p\gamma$) Model A (lower curve), ($p\gamma$+pp) Model B (upper curve); − − − − − Protheroe [46] ×25% – see text; ······ $p\gamma$ Halzen & Zas [49].

sociated with AGN jets. Blazars appear also to be able to explain about 25% of the diffuse γ-ray emission [41], and models where γ-ray emission does not originate in the jet are unlikely to contribute significantly to the diffuse γ-ray (and neutrino) intensity (see Protheroe and Szabo [42] and references therein for predictions for non-blazar AGN). Several of the EGRET AGN show γ-ray variability with time scales of $\sim$ 1 day [43] at GeV energies, and variability on time scales of $\sim$ 1 hour or less [44,45] has been observed at $\sim$ 1 TeV for some BL Lacs. These variability timescales place important constraints on the models, and not all models developed so far are consistent with this. I shall survey the neutrino emission predicted in blazar models irrespective of this, assuming they may be made to accommodate the latest variability measurements.

Most theoretical work on γ-ray emission in AGN jets involved electron acceleration and inverse Compton scattering, and these models will predict no neutrinos. In proton blazar models, protons are accelerated instead of, or as well as, electrons. In this case interactions of protons with matter or radiation would lead to neutrino production. In some of the proton blazar models energetic protons interact with radiation via pion photoproduction (see e.g. [21] for references and a discussion of $p\gamma$ interactions). This radiation may be reprocessed or direct accretion disk radiation [46], or may be produced locally, for example, by synchrotron radiation by electrons accelerated along with the protons [47,48]. Pair synchrotron cascades initiated by photons and electrons resulting from pion decay give rise to the emerging spectra, and this also leads to quite acceptable fits to the observed spectra. These models can produce neutrinos and also higher energy radiation than electron models because protons have a much lower synchrotron energy loss rate than electrons for a given magnetic environment. In both classes of model, shock acceleration has been suggested as the likely acceleration mechanism (see [21] for references).

By appropriately integrating over redshift and luminosity in an expanding universe, using a luminosity function (number density of objects per unit of luminosity) appropriate to blazars, and using the proton blazar models to model the γ ray and neutrino spectra one can estimate the diffuse neutrino background expected from blazars. In Fig. 3 I have added intensities of ($\nu_\mu + \bar{\nu}_\mu$) predicted in proton blazar models by Mannheim [48], Protheroe [46] (×0.25 as only ∼25% of γ-ray background is due to AGN [41] – original calculation assumed 100%) and Halzen and Zas [49]. For some of these models expected muon rates have been calculated [50–52].

6. TOPOLOGICAL DEFECTS

Finally, I discuss perhaps the most uncertain of the components of the diffuse high energy neutrino background, that due to topological defects (TD). In a series of papers [53–56], TD have been suggested as an alternative explanation of

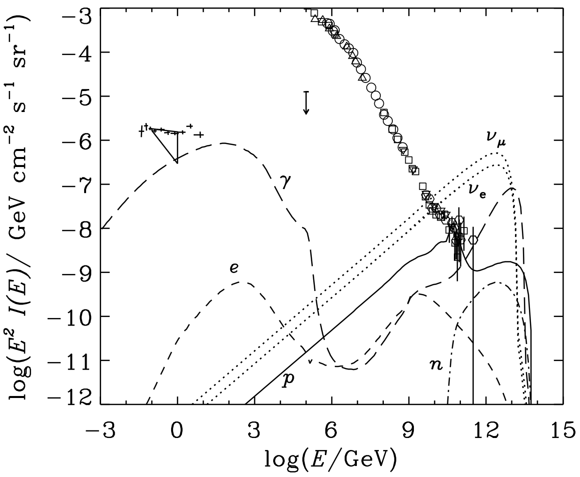

Figure 4. The result of [58] for $M_X c^2 = 10^{14.1}$ GeV, a magnetic field of 10^{-9} gauss, and $p = 2$, normalized the spectrum of "observable particles" (nucleons, photons, electrons) to the 3×10^{11} GeV data [19]). $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ are assumed.

the highest energy cosmic rays. In this scenario, the observed cosmic rays are a result of top-down cascading, from somewhat below (depending on theory) the GUT scale energy of $\sim 10^{16}$ GeV [57], down to 10^{11} GeV and lower energies. These models put out much of the energy in a very flat spectrum of neutrinos, photons and electrons extending up to the mass of the "X–particles" emitted.

Protheroe and Stanev [58] argue that these models appear to be ruled out by the GeV γ-ray intensity produced in cascades initiated by X-particle decay for GUT scale X-particle masses. The γ-rays result primarily from synchrotron radiation of cascade electrons in the extragalactic magnetic field. Fig. 4, taken from ref. [58], shows the neutrino emission for a set of TD model parameters just ruled out according to Protheroe and Stanev [58] for a magnetic field of 10^{-9} G and X-particle mass of 1.3×10^{14} GeV. Clearly for such magnetic fields and higher X-particle masses (e.g. GUT scale), TD cannot explain the highest energy cosmic rays. Indeed there is evidence to suggest that magnetic fields between galaxies in clusters could be as high as 10^{-6} G [59]. However, for lower magnetic fields and/or lower X-particle masses the TD models might explain the highest energy cosmic rays without exceeding the GeV γ-ray limit. For example, Sigl et al. [60] show that a TD origin is not ruled out if the extragalactic field is as low as 10^{-12} G, and Birkel & Sarkar [61] adopt an X-particle mass of 10^{12} GeV. Yoshida et al. [62] investigate various TD scenarios with GUT scale masses, and their predicted neutrino fluxes are generally higher than those of Sigl et al. [60], but such high neutrino intensities are likely to be excluded because the γ-rays, due to cascading even in a 10^{-12} G field, would probably exceed the GeV flux. The intensities are compared in Fig. 5. A novel feature of the work of Yoshida et al. [62] is the inclusion of interactions of high energy neutrinos with the 1.9 K cosmic neutrino background, and this can be important at the very highest energies.

I emphasize that the predictions summarized in Fig. 5 are *not* absolute predictions, but the intensity of γ-rays and nucleons in the resulting cascade is normalized in some way to the highest energy cosmic ray data. It is my opinion that GUT scale TD models are neither necessary nor able to explain the highest energy cosmic rays without violating the GeV γ-ray flux observed. The predicted neutrino intensities are therefore *extremely* uncertain. Nevertheless, it is important to search for such emission because, if it is found, it would overturn our current thinking on the origin of the highest energy cosmic rays and, perhaps more importantly, our understanding of the Universe itself.

7. DISCUSSION

Very recently, Waxman and Bahcall [32] have used some arguments based on the observed cosmic ray spectrum to obtain an upper bound to high energy neutrinos from astrophysical sources. Their argument hinges on sources of astrophysical neutrinos being sources of the highest energy cosmic rays which happen also to produce neutrinos by $p\gamma$ interactions. Hence, except for sources with a very high optical depth for protons, the maximum neutrino intensity will be about 10% of

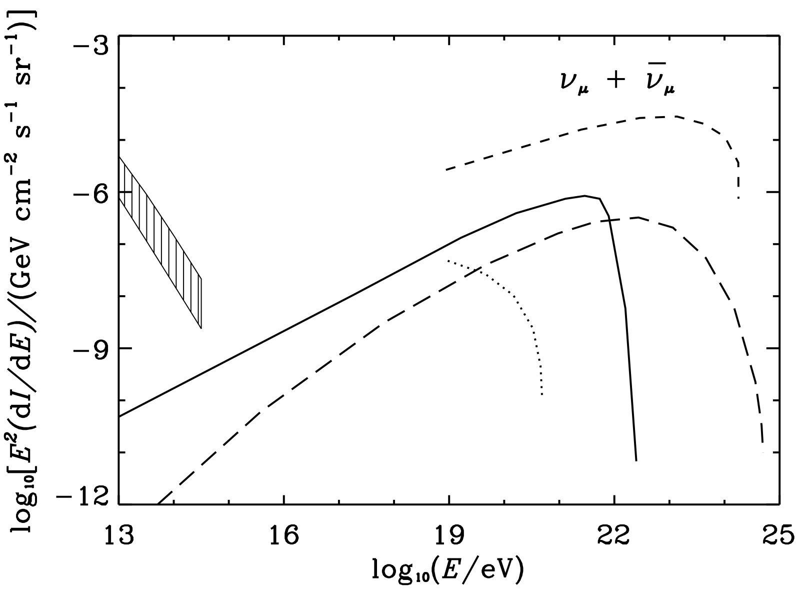

Figure 5. Neutrinos from topological defects: ——— TD model just ruled out according to Protheroe & Stanev [58] ($10^{14.1}$ GeV, 10^{-9} gauss); — — — — TD model just allowed according to Sigl et al. [60] (2×10^{16} GeV, 10^{-12} gauss); ······ Birkel & Sarkar [61] (10^{12} GeV, 0 gauss); - - - - - Yoshida et al.[62] (10^{16} GeV, 0 gauss).

the extragalactic ($\sim E^{-2}$) component of the highest energy cosmic rays. Examining AGN models, they find that predictions for proton blazar models exceed their bound.

In the case of AGN, they also suggest that the optical depth to $p\gamma$ at $\sim 10^{19}$ eV must be much less than 1 (to enable TeV γ-rays to escape without significant $\gamma\gamma$ pair production losses), with the consequence that the ultra high energy cosmic ray production far exceeds the ultra high energy neutrino production, pushing the neutrino upper bound even lower.

TeV γ-rays, however, have so far only been seen from 3 blazars, and it is by no means certain that TeV γ-rays are emitted by all blazars and so high $p\gamma$ optical depths are not necessarily ruled out (note, however, that the infrared background limits how far away one can observe objects at TeV energies [63]). Also, in at least one of the proton blazar models [46] the optical depth of protons to $p\gamma$ at 10^{19} eV is high because the proton directions are isotropic in the jet frame whereas the radiation field is highly anisotropic, coming from near the base of the jet, and the photons cascade down to TeV energies where the $\gamma\gamma$ optical depth along the jet direction is low because of the radiation being anisotropic. Admitedly, neutrons are produced in a fraction of $p\gamma$ interactions, and the neutrons escape as cosmic rays, and so the effective optical depth for nucleons can not exceed ~ 1 by much, and so it is probable that this proton blazar model is ruled out.

The main argument relating the neutrino upper bound to the observed ultra high energy cosmic ray flux relies on the cosmic rays of energy 10^{19} eV being able to reach Earth from AGN during the Hubble time. There is evidence to suggest that magnetic fields between galaxies in cores of clusters (the most likely place to find an an AGN) could be as high as 10^{-6} G [59]. With such high magnetic fields it is not obvious that 10^{19} eV protons will reach us from most AGN contributing high energy neutrinos.

Thus, I believe that the "upper bound" is model dependent, and that its calculation is complicated by cosmic ray propagation effects. While

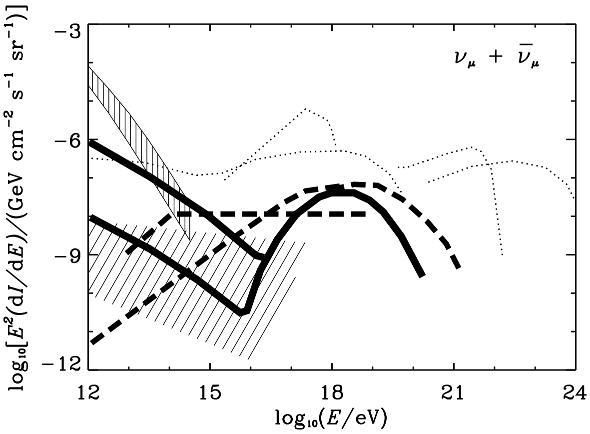

Figure 6. Grand Unified Neutrino Spectrum – a personal opinion about the predicted neutrino intensities: thick solid lines – certain; long dashed lines – almost certain; short dashed lines – speculative; dotted lines – highly speculative.

I would certainly classify the higher AGN fluxes as speculative, or highly speculative, I believe the lower ones are not ruled out by the argument of Waxman and Bahcall. Nevertheless, the work of Waxman and Bahcall is very important in reminding us that for any model used to predict high energy neutrino fluxes we must check that it does not overproduce cosmic rays.

Plotting a representative sample of the diffuse flux predictions from Figs. 1, 2, 3 and 5 in the same figure one has a "grand unified neutrino spectrum" (with apologies to Ressell and Turner [64]). This is shown in Fig. 6 where I have labelled the various curves as "speculative", "highly speculative", "certain" or "almost certain". These labels reflect my own personal opinion or prejudice and should not be taken too seriously – other opinions are equally valid.

8. PROSPECTS FOR OBSERVATION

With the construction in the relatively short term of 0.1 km^2 neutrino telescopes, and in the longer term of 1 km^2 detectors, it is useful to estimate the signals expected due to various possible neutrino intensities. At high energies, electron neutrinos may also be detected through the resulting cascade, and this is particularly important when looking for horizontal air showers, for example with the proposed AUGER detectors [62]. Several estimates of event rates have been made for various energy thresholds, or for horizontal air showers due to neutrino interactions (including ν_e and $\bar{\nu}_e$, see e.g. Gandhi et al. [52]).

To illustrate how the $(\nu_\mu + \bar{\nu}_\mu)$ signals expected from different astrophysical neutrino spectra would be detected by telescopes with different energy thresholds, I have made approximate estimates of the event rates *as a function of minimum muon energy* using the $P_{\nu\to\mu}(E_\nu, E_\mu^{\min})$ function given in Fig. 2 of ref. [13] for $E_\mu^{\min} = 1$ GeV, modified for other $E_\mu^{\min}$ values in a way consistent with that given for $E_\mu^{\min} = 1$ TeV. The effects of shadowing for vertically upward-going neutrinos have been included using the shadow factor $S(E_\nu)$ given in Fig. 20 of ref. [51]. I have estimated the expected neutrino induced muon signal for four representative neutrino intensities. The vertically upward-going and horizontal muon signals are shown separately for each case in Fig. 7 together with the atmospheric neutrino induced muon signals for the two directions. As can be seen, the highest signals would be due to the proton blazar models, with several events per year expected in a 0.1 km^2 detector. However, one should be cautious as these intensities are somewhat speculative (as discussed earlier). Detection of muon signals in one year from the other intensities estimated would be marginal for a 0.1 km^2 detector, but achievable with a 1 km^2 detector. Detection of transient neutrino signals, correlated with observations of the same source in photons (e.g. GRB, AGN) should therefore be the goal of high energy neutrino astronomy in the short term.

One should consider the consequences for astrophysical neutrinos of the discovery of the oscillation of atmospheric ν_μ, probably into ν_τ, by Super-Kamiokande [65] with an oscillation length of $\lambda_{\rm osc} \sim 10^3(E/\mathrm{GeV})$ km. On an astrophysical scale, the oscillation length $\lambda_{\rm osc} \sim 3\times10^{-11}(E/\mathrm{TeV})$ kpc is very small, and integrating contributions to the neutrino intensity over

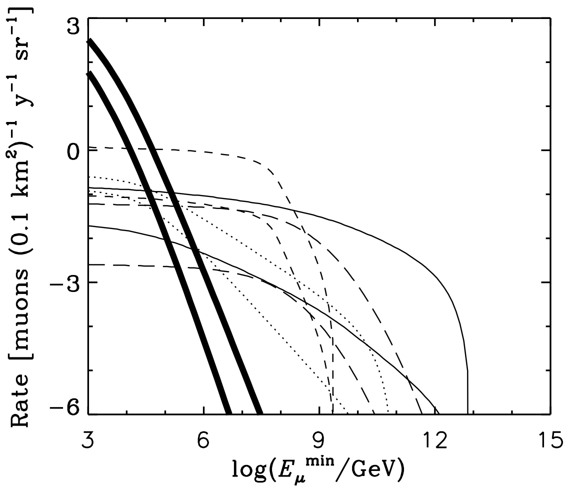

Figure 7. Atmospheric neutrino induced muon signal (thick solid lines) and putative astrophysical neutrino induced muon signals expected for the following $(\nu_\mu + \bar{\nu}_\mu)$ intensities: GRB intensity [31] extended to 10^{20} eV (dotted curves); $p\gamma$ proton blazar [48] (short dashed curves); TD model just ruled out according to ref. [58] (solid curves); interactions of the highest energy cosmic rays with the CMBR [23] for $E_{\max} = 3 \times 10^{21}$ eV (long dashed curves). Upper curves show horizontal signals, lower curves show vertical (upward) signals.

astrophysical dimensions one would naively expect the $(\nu_\mu + \bar{\nu}_\mu)$ flux to be 50% lower (assuming $\sin^2 2\theta = 1$), and to be accompanied by a similar $(\nu_\tau + \bar{\nu}_\tau)$ flux. The unique signature for detection of tau neutrinos has been discussed in ref. [66].

Neutrino astronomy is developing during an era in which exciting discoveries are being made in other areas of high energy astrophysics. These include detection of rapidly varying TeV γ-ray signals from AGN, discovery that GRB are extragalactic and probably the most energetic phenomena ocurring in the Universe today, and detection at Earth of cosmic rays with energies well above 10^{20} eV opening the question of whether their origin is through particle acceleration at radio galaxies or GRB, or from topological defects left over from the big bang. Hadronic processes may have a role in all these phenomena, and searching for high energy neutrinos may lead to greater understanding of the highest energy phenomena in the Universe. Clearly, for this to happen in parallel with the other observations rapid development of neutrino telescopes with sensitive areas of ~ 1 km^2 or larger, operating over a wide range neutrino energies, is essential.

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