NIGH ENERGY NEUTRINO FLUXES AND DETECTION

TODOR STANEV
Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
E-mail: *stanev bartol.udel.edu*

ABSTRACT

We discuss the new developments in our understanding of the production of astrophysical fluxes of high energy neutrinos in galactic and extragalactic systems. These developments are inspired by the increasing amount of data on GeV, TeV and higher energy gamma rays as well as other striking recent astronomical observations, such as the afterglows of gamma ray bursts. The most recent calculations of the deep inelastic scattering cross section, photoproduction cross section and some interesting theoretical suggestions are also discussed.

1. Introduction

The existence of high energy astrophysical neutrino fluxes has become the topic of an almost philosophical debate. In spite of the vastly increased amount of observational data on GeV and TeV gamma ray fluxes from different powerful astrophysical objects, most classical astrophysicists do not see need to include hadronic processes in the gamma ray production models. Observed TeV gamma ray fluxes can be attributed to electromagnetic processes of electrons accelerated up to 10^{14} eV, through Inverse Compton scattering (IC) for the high energy portion of the observed spectra. The typical problem with such models, the decreasing IC cross section in the Nishina–Klein regime, is avoided by increasing the Lorentz factor for the bulk motion of the jet material. Hadronic processes are being neglected because of two main reasons: much faster cooling of electrons (higher cross section) and lower energy threshold for IC, compared to hadronic photoproduction, which is the relevant hadronic process for astrophysical jets.

Hadronic production models are based on general considerations: it is difficult to construct jet models models, where the electron number density is much higher then nucleon density – so electrons and protons must be accelerated in parallel; astrophysical shocks are supported by protons and electron injection is more difficult; faster electron cooling, especially synchrotron energy loss may easily limit the maximum electron energy at acceleration. On top of all this we do know that cosmic rays with energies exceeding 10^{20} eV have been observed and we suspect that they are accelerated at powerful astrophysical objects. Hadronic gamma ray production models have their own problems, as noted above, but they can also describe the observed photon spectra in wide energy range [1)].

I do not believe that the argument could be solved even if the current theoretical models are much improved. The answer can only come from the observations of astrophysical neutrino fluxes by future neutrino telescopes. The extremely fast experimental developments in recent years make us optimistic that we will not have to wait very long for the answer.

At GeV energies the neutrino sky is dominated by atmospheric neutrinos that are produced by cosmic rays. These neutrino fluxes peak at about 50 MeV, but when the increasing interaction cross section is taken into account the peak in detected neutrinos moves an order of magnitude higher. At lower energy we thus have the window for observation of solar and supernova neutrinos. At much higher energy, say 1 TeV, starts the window for high energy astrophysical neutrinos.

Astrophysical neutrinos should have much flatter energy spectrum than atmospheric neutrinos. The interaction/decay competition in the atmosphere and time dilation make the spectrum of neutrinos resulting from meson decay steeper than the primary cosmic ray spectrum by one power of the energy. Neutrinos from muon decay that result from a two decay chain are depressed by two powers of the energy. In astrophysical environments one can safely assume that all mesons and muons decay without energy loss (decay length for 1 TeV muon is 6000 km, large for the atmosphere but negligible in astrophysics) and neutrinos have the same differential spectra as the primary nucleons, i.e. $E^{-2.7}$ for diffuse galactic fluxes and $E^{-(2+\varepsilon)}$ for cosmic ray sources. The flux normalization is yet unknown, but if astrophysical neutrinos exist at all, they will take over the atmospheric fluxes at some high energy.

The production of astrophysical neutrinos is the same as of atmospheric ones: the decay chains of charged mesons. The interaction processes could though be different. Accelerated nuclei could interact on nuclear targets, mostly protons on protons. In some astrophysical systems the photon field density is much higher than matter density and photoproduction interactions could be the main meson (and neutrino) production process. Proton photoproduction cross section is lower than the proton–proton inelastic cross section by roughly a factor of 300, 100 μb vs. 30 mb. The same ratio of the photon to matter density will be the first requirement for dominance of photoproduction. The second one comes from the high energy threshold for proton photoproduction – having an additional pion mass in the CM system of a $p\gamma$ collision on optical (1 eV) photons, means proton energy of 7×10^7 GeV even for head–on collisions. This high energy threshold increases the requirements to the acceleration sites which have to have very high maximum acceleration energy.

A standard check for models of astrophysical neutrino production is the comparison to observed gamma ray spectra. Because of their vastly higher interaction cross sections, gamma ray fluxes could be easily absorbed at source and on propagation. One could say that if gamma rays and neutrinos are generated in hadronic interactions, the observed gamma ray flux sets the lower limit for the corresponding neutrino flux. The neutrino fluxes and event rates shown below are therefore 'pessimistic' estimates in the assumption that gamma rays are of hadronic origin.

2. Galactic neutrino sources

The production of neutrinos by astrophysical systems in our Galaxy depends on two factors: the ability of such systems to accelerate charged nuclei and the existence of target material in the vicinity of the accelerators. The luminosity of the Galaxy in cosmic rays suggests particle acceleration at *some yet unknown* objects. Observational and theoretical arguments support the existence of matter targets. It is believed that galactic astrophysical neutrinos are produced in inelastic nuclear interactions.

The first suspect sources of high energy neutrino emission were compact binary systems [2,3]. Although there is no proof for particle acceleration at such systems, they do possess the necessary ingredients: very high total luminosity and extremely strong magnetic fields. The luminosity could come either from the spindown of the highly magnetized compact object (neutron star or black hole) or from accretion of matter, from the companion star or the interstellar matter. Both energy sources could be very powerful. A millisecond pulsar with 10^{12} Gauss magnetic field could emit 4×10^{43} ergs/s $\times$ $\mathrm{P}_{\mathrm{ms}}^{-4}$ B_{12}^{-2}. Accretion power is limited by the amount of matter that can accrete on an object against the pressure of the X–ray luminosity created by the accretion – the Eddington luminosity is $\sim10^{38}$ erg/s per solar mass of the accreting object. While it is not obvious that pulsar powered systems can have the necessary target density, accretion systems almost certainly do – this could be the binary companion start, the accretion disk and various other concentrations of matter generated by gravitation of the compact object and/or by the high luminosity of the system. Indeed a binary system exhibiting the vicious circle of particle acceleration, heavy mass loss of the companion star induced by the radiation of the accelerated particles and creation of multiple shocks (PSR 1957+20) was observed [4], where the evolution of the system led to companion star mass loss of 95% or more. There is no indication that hadronic interactions are essential for the dynamics of this system.

Supernova remnants are natural suspects for galactic neutrino sources. These are candidate sites for cosmic ray acceleration to at least 100 TeV. Shock structures surrounding supernova remnants of various ages has been observed in different energy bands. A most interesting recent observation is this of SN1006 [5] for which the age is very well known from ancient chinese skywatchers – it did explode in year 1006. A precise study of the X–ray energy spectrum in different regions of the remnant showed that while the emission from the internal part of the remnant has thermal spectrum overlayed with nuclear lines, two regions along the edge of the remnant show distinct non–thermal power law spectra. These regions are understood as strong shocks where the rim of the expanding remnant hits the ordered galactic magnetic field. If the observed power law X–ray spectrum is due to synchrotron radiation by accelerated electrons on 3μG magnetic field, the maximum electron energy is 100 TeV [6]. TeV

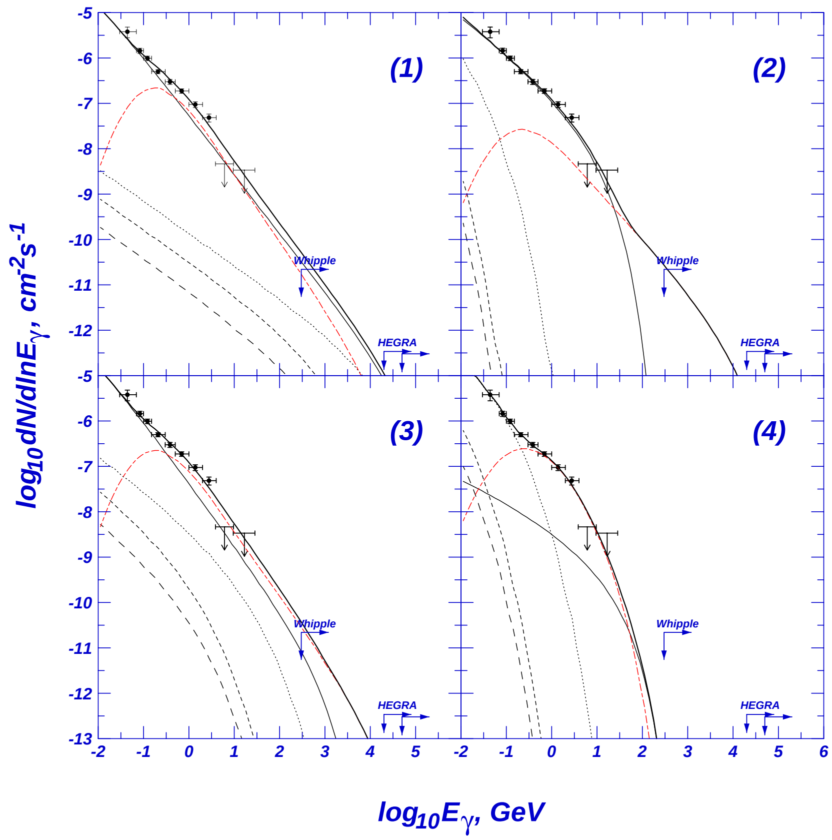

Fig. 1. Four fits of the gamma ray emission from the supernova remnant γCygni from Ref. 9.

γ–ray emission from SN1006 was detected by the Cangaroo telescope [7]. Once again there is no evidence for hadronic interactions. The TeV gamma ray spectrum is consistent with IC emission [8] corresponding to the luminosity in X–rays.

The EGRET detector on the Compton Gamma Ray Observatory has detected gamma ray emission from four identified supernova remnants [10] that extends to the higher end of the detector energy range, 50 GeV or so. Numerous other unidentified EGRET sources are concentrated along the galactic plane and many of them have to be supernova remnants. If the γ–ray emission by these supernova remnants extended to TeV and PeV energies with the theoretically favoured flat (γ = 1 – 1.1) energy spectra [11]), they would have been detected with the existing Cherenkov telescopes and air shower arrays. The observed GeV γ–ray spectrum is somewhat steeper [9] (γ = 1.3 – 1.4) and fits that extend it to 100 TeV are at the edge of the sensitivity of most current observations.

Fig. 1 shows four different fits of gamma ray flux from the supernova remnant γCygni [9]. The long–short dash lines show the contribution from π^0 decays to the gamma ray flux and can be used for normalization of the expected neutrino flux. The neutrino flux from $\pi^{\pm}$ decays should be

$$\phi_\nu \;=\; \phi_\gamma \times (1 - (m_\mu/m_\pi))^{\alpha-1} \;, \tag{1}$$

where α is the differential spectral index of the gamma ray energy spectrum. The observation of neutrinos from such an object depends only on the maximum cosmic ray acceleration energy. Hopefully some supernova remnants will be observed soon by the newest generation of gamma ray telescopes, but the current lack of detections is worrisome – we may have to revise our conviction that all supernova remnants are cosmic ray acceleration sites.

One guaranteed galactic source is the neutrino production by cosmic rays propagating in the Galaxy. The matter density as a function of the galactic radius is fairly well known, as is the flux of cosmic rays. Diffuse galactic gamma rays have been detected by all satellite gamma ray experiments, most recently by EGRET [12]. The emission is concentrated within 10° of the galactic disk. The total gamma ray flux above 100 MeV, which is considered predominantly of π^0 decay origin, is well described by a model that describes the galactic matter density and assumes that cosmic rays a coupled to it. The high energy (above ~10 GeV) behaviour of the measured spectra, except in the region of the galactic anticenter, is not consistent with the assumption that the local cosmic ray power law spectrum ($\gamma = 1.7$) is typical for the whole Galaxy. Observed gamma ray spectra suggest a flatter cosmic ray spectrum, consistent with the spectra observed from individual supernova remnants. Unless it is due to a systematic error in the subtraction of the known gamma ray sources, this indicates that the diffuse radiation from the galactic plane is due mostly to unresolved gamma ray sources. The corresponding neutrino spectra can be easily derived directly from the gamma ray spectra through the kinematics of charged and neutral pions decays. The observation of such diffuse galactic neutrino flux would not be a fundamental discovery, rather an important proof of the capabilities of a neutrino telescope and its sensitivity.

3. Extragalactic neutrino sources

Similar diffuse neutrino fluxes should be generated by almost all galaxies. Because of the large intergalactic distances, they would not, however, add up to a detectable neutrino background. Possible detectable sources are the extreme high luminosity active galactic nuclei (AGN) and catastrophic events, such as the gamma ray bursts (GRB).

Active galactic nuclei are the most luminous objects in the Universe. Many of them show very high velocities in their central part which suggest the existence of a very massive black hole. Quite many AGN show one or two jets, extending far away (typical distance is 100 kpc) from the central region of the AGN. A conversion of the observed AGN total luminosity to black hole mass suggests 10^6– 10^8 $M_\odot$. Apart from the luminosity, the fast (and increasing with the frequency) variability observed in such objects is difficult to apprehend knowing the vast dimensions of these systems.

A simple zero order model (unification model) postulates that all AGN are basically the same type of object and the observational differences are related to the angle at which we view these objects. They consist of a central black hole, an accretion disk and jets expanding with very high velocity at some angle to the accretion disk. The jets may be formed by magnetic fields emanating from the fast rotating inner edge of the accretion disk. A side view would show the general glow of the accretion disk, where the energy emitted by the central engine is almost perfectly thermalized, and the two jets. If we look directly into the jet, the observation would be dominated by the jet emission, with an apparent luminosity exaggerated by Γ^4 along the jet direction, where Γ is the Lorentz factor. Intermediate viewing angle may allow us to see the central region or/and one of the jets.

Calculations of the proton acceleration and neutrino production in the central regions of AGN are based on work performed by Kazanas, Protheroe and Ellison[13,14] which assumes that close to the black hole the accretion flow becomes spherical and a shock is formed where the ram pressure of the black hole radiation is balanced by the accretion flow. The shock is formed at a distance $R_1 = x_1 \times R_S$, where R_S is the gravitational (Schwarzschild) radius of the black hole. All the continuous emission of the black hole, from IR to X–ray, is assumed to come from the radius enclosed by the shock. Since that region is optically thick, the radiation density at the shock can be estimated from the surface brightness of the AGN as

$$U_{rad} \simeq L \times (\pi R^2 c)^{-1} \mathrm{eV/cm}^3 \tag{2}$$

The radiation energy density defines also the magnetic field value B at the shock in the assumption of equipartition of the radiation and magnetic energy.

The proton density at the shock n_p can be estimated from the accretion rate needed to support the black hole luminosity, and from the shock radius and velocity.

$$n_p \simeq 1.3 \times 10^8 x_1^{1/2} R^{-1.5} L^{1/2} Q^{-1} \mathrm{cm}^3, \tag{3}$$

where Q is the source efficiency, a factor of order 1. Such proton densities are not only a good injection source for proton acceleration, but also a possible target for pp interactions.

Protons also interact on the photon background via photoproduction or Bethe-Heitler electron positron pair production. The energy loss distance λ_E for a proton could be expressed as $(n_t \sigma \langle K \rangle)^{-1}$ where n_t is target density, σ is the total cross section for a given process and $\langle K \rangle$ is the average inelasticity, i.e. the fraction of of the proton energy lost per interaction.

Although $\sigma \times \langle K \rangle$ is higher for pp collisions, $p\gamma \to n\pi^+ (p\pi^0)$ dominates the proton energy loss simply because the target photon density n_{ph} is much higher than n_p. In the assumption of fixed photon energy the ratio of the target densities is

$$\frac{n_p}{n_{ph}} \simeq 10^{-9} x_1^{3/2} (\langle\epsilon\rangle/\mathrm{eV}) Q^{-1}. \tag{4}$$

Photoproduction limits the maximum proton acceleration energy E_p^{max}, contrary to the case of cosmic ray acceleration at supernova blast shocks, where the maximum energy is limited by diffusion away from the shock. E_p^{max} is roughly proportional to the AGN luminosity, reaching a value of 10^{17} eV for $L = 10^{46}$ erg/s.

Neutrino production based on these considerations was first introduced by Stecker et al. [15)] and subsequently developed by Szabo&Protheroe [16)]. The main difference between these two calculations is that the latter one accounts for the proton containment at the source and thus predicts 'low energy' neutrinos that have a characteristic E_ν^{-2} spectra, which is very important when detectable neutrino signals are considered. The important feature of the central production region is that neutrinos are the only secondaries for which the AGN is optically thin. The protons themselves, as well as π^0 decay gamma rays are all absorbed, their energy is downgraded and added to the total AGN luminosity.

Stecker et al. [15)] took the important step to integrate over the AGN luminosity and evolution functions and define an isotropic neutrino background. This is currently the final product of all such calculations which yields higher fluxes than any of the individual sources considered. The integration over all cosmological AGN also gives the isotropic 100 MeV gamma ray fluxes, generated by surviving high energy gamma rays, that could be compared to the measured and thus limit the range of model parameters,

3.1. Neutrino production in AGN jets

In AGN jets the idealized spherically symmetric picture presented above is replaced with a highly asymmetric one, where all acceleration and interaction processes take place in the AGN jet frame that moves towards the observer with a Lorentz factor $\Gamma \simeq 10$. The matter density of the jet is very small and photoproduction is again the basic energy loss process for protons. The geometry is very complicated and may include anisotropic angular distributions for the accelerated particles, as well as for the target field. All particle energies in the jet frame are smaller by a factor of Γ than the observed ones.

More than fifty AGN has been observed by EGRET as sources of GeV gamma rays, most of which are blazars [17)]. The Egret source that is closest to us, Mrk 421 (z = 0.031), was detected by the Whipple observatory [18)]. The second TeV source [19)] Mrk 501 is also at small redshift z = 0.33. Mrk 501 is not an EGRET source since its GeV emission was below the adopted statistical significance. It is possible that only these two close–by sources were detected in the TeV region because of gamma ray absorbtion on the extragalactic O/IR background radiation.

In 97/98 both TeV sources underwent huge flares with the intensity of the emission increasing factors of ten or more [20]. This allowed the TeV Cherenkov telescopes to study the short time variability of the sources. Flux doubling times as short as a fraction of an hour were detected. The high gamma ray fluxes also allowed for good measurements of the gamma ray energy spectra. The interpretation of the spectra is however difficult because of the possible absorption at source and on propagation.

The purely electromagnetic models of AGN jet emission model the photon emissivity of the sources by synchrotron and IC emission of accelerated electrons. The radiation field for IC could be either internal [21] (synchrotron–self Compton (SSC) model) or external [22]. Synchrotron and IC contribute to different frequencies to form a double peaked spectrum in the energy output, where the synchrotron radiation covers the radio and optical ranges and IC takes over for X–rays and gamma rays. These models have to use significant (≥ 10) Lorentz factors to beat the decrease of the IC cross section in the Klein–Nishina regime and be successful in the description of multi–TeV radiation. Mannheim created the 'proton blazar' model which is the hadronic equivalent of SSC [23]. The low energy spectra are created by electron synchrotron emission of primary and secondary (generated in pp interactions) electrons. The high energy end is generated by π^0 decay gamma rays. The model can be fine–tuned to fit observations at all frequencies. The main problem is not the high gamma ray energy, rather the fast variability, which is more difficult to explain with hadronic interactions, because of the lower cross section and high energy threshold for photoproduction. A detailed analysis of the hadronic interactions in jets was performed by Rachen and Meszaros [24]

3.2. Sources of the highest energy cosmic rays

All models of the origin of the highest energy cosmic rays also generate certain levels of ultra high energy neutrinos. In classical acceleration models neutrinos are secondary, i.e. produced in proton interactions during the acceleration process or after it. TD (top–down or topological defects) models [25,26] are a world apart. They postulate the existence of ultra heavy (10^{14} to 10^{16} GeV) X particles that decay to form flat spectra ($\gamma = 1/3$ to $1/2$) extending up to the heavy particle mass. Such spectra are dominated by gamma rays and neutrinos, roughly 95% of the final state particles. Observed ultra high energy cosmic rays are most likely gamma rays. Because of all energy losses of gamma rays in propagation the major limiting factors are the isotropic 100 MeV gamma ray fluxes generated in such models, that can be compared to observations, as well as the spectra of the highest energy cosmic rays themselves [27]. TD models favor moderate X particle masses and low intergalactic magnetic fields. Since the neutrinos are primary particles their spectra extend to the same energy and the flux magnitude is approximately the same as of the observed cosmic (gamma) rays.

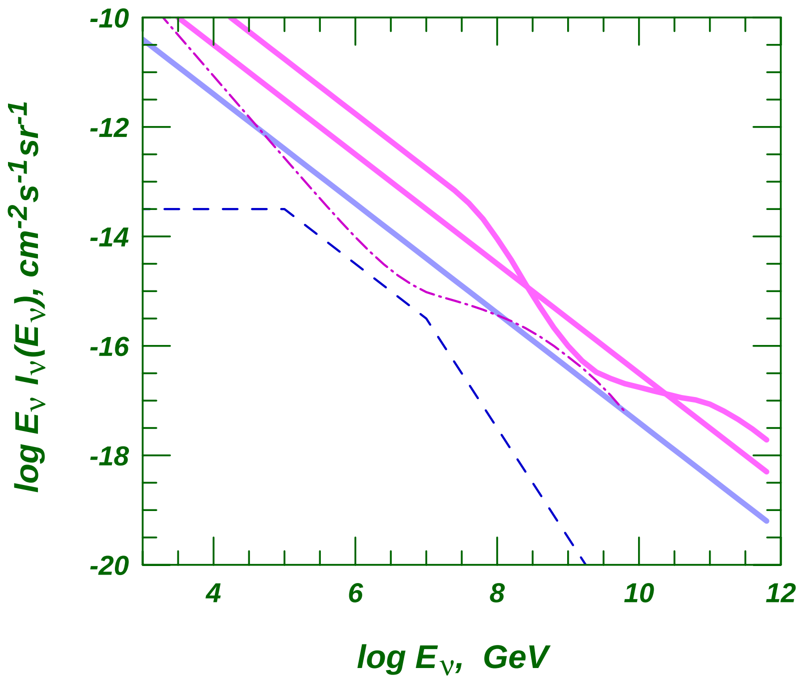

Fig. 2. Neutrino limits from the flux of ultrahigh energy cosmic rays are shown with thick lines: the lowest limit is of Ref. 30. The dashed line is for GRB (Ref. 29) and the dash–dotted line is from Ref. 28

A recent fashionable topic is the acceleration of the highest energy cosmic rays in GRB, which followed from the observation that the required source luminosities for the two phenomena are very similar. After the observations of afterglows that confirmed the cosmological distances of the GRB sources it was realized that observed GRB have to be also produced in jets (*see T. Piran and A. Dar's talks at this workshop*) with Lorentz factor of ~ 300. Waxman and Bahcall discussed first the neutrino spectra [29] that would correspond to the ultra high energy protons. These would have a very flat spectrum ($\gamma = 0$) extending to 10^{14} eV, that steepens by one power of E_ν at higher energy.

The extension of this work is the limit on the fluxes of ultra high energy neutrinos [30], derived from the flux of the highest energy cosmic rays in the assumption that cosmic rays and neutrinos are both generated in jets. The argument is logical and simple, although it contains quite many assumptions. If the acceleration spectrum of the highest energy cosmic rays is fit by E^{-2} differential power law spectrum, the luminosity of the Universe in such particles is 5×10^{44} ergs $\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$. All these particles may have experienced a fractional energy loss ϵ through photoproduction at source, that resulted in the generation of neutrino fluxes. Knowing the proton energy spectrum and assuming the ϵ is independent of the energy, one could limit the neutrino flux setting $\epsilon = 1$ and integrating over the lifetime of the Universe. This limit comes out to be

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \;=\; 2 \times 10^{-8} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \tag{5}$$

for the sum of muon neutrinos and antineutrinos. This limit does not apply to optically thick sources like AGN cores.

Mannheim, Protheroe and Rachen [31] argue that a limit cannot be set with such simple arguments. They point out that the evolution of cosmic ray and neutrino fluxes are very different (because of different energy loss horizons) and one should account for this in the integration over time. They also discuss the adiabatic energy loss of the accelerated protons and consider jet geometries that are optically thick even for neutrons. Since the two approaches are so different, it is surprizing that the two groups obtain the same neutrino limit at neutrino energy of 10^{19} eV. which is the normalization point in Waxman&Bahcall estimate. The derived limits are shown in Fig. 2.

4. Detection

Standard neutrino detection technique for high energy neutrinos is the detection of upward going neutrino induced muons. This technique has the advantage of increasing the effective volume of the detector by the range of the muons that are generated in charge current neutrino interactions in the rock that surrounds the detector. Muon tracks in the detector give very good directional information for muon energy above 1 TeV. Lower energies are fully dominated by atmospheric neutrinos. Signal is represented by the probability $P_{\nu\to\mu}$ that a neutrino of energy E_ν will produce a muon of energy above E_μ.

$$P_{\nu\to\mu} \;=\; \int_E \mu^E \nu \sigma(E_\nu, E'_\mu) R(E'_\mu, E_\mu) dE'_\mu \;, \tag{6}$$

where $\sigma(E_\nu, E'_\mu)$ is the cross section for production of a muon of energy E'_μ and $R(E'_\mu, E_\mu)$ is the distance at which a muon of energy E'_μ arrives with energy E_μ. The expected signal rate [32] can be then represented as an integration over the predicted neutrino flux folded with $P_{\nu\to\mu}$

$$\text{Signal} \;=\; \int_{E_\mu}^{E_\nu^{\max}} F_\nu(E_\nu) P_{\nu\to\mu} dE_\nu \;. \tag{7}$$

Recent HERA measurements of the structure functions in a wide x and Q^2 region gave us a chance to improve the calculations of the neutrino cross sections at extremely

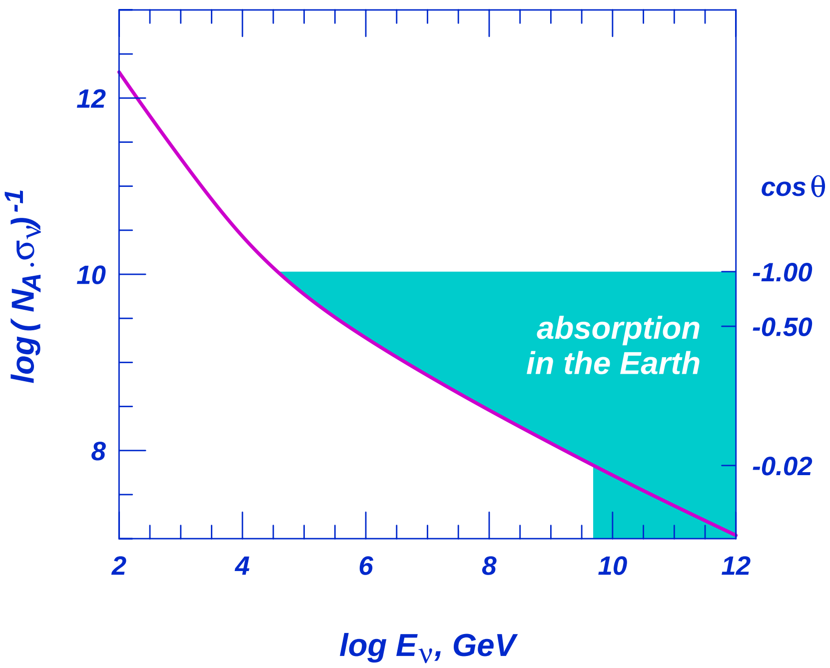

Fig. 3. Mean free path for charge current atmospheric neutrinos interactions, g/cm^2.

high energy. There are several articles discussing the high energy neutrino cross sections [33]. The conclusion is that the general increase of the high energy cross section does not lead to proportional increase in the expected event rate because of the increase in the absorption of neutrinos in passage through the Earth.

Fig. 2 shows the neutrino charge current cross section and the shadowing of the Earth as a function of the neutrino angle expressed by $\cos\theta$ measured from the vertical direction where $\cos\theta$ = -1. For neutrinos that travel through the center of the Earth the absorption is almost full at 10^5 GeV, while for almost horizontal neutrinos the Earth is opaque at $\sim 5\times10^9$ GeV. In 'practical terms' this means that the limits quoted in the previous section do not dominate the event rate even for muon energies as high as 1 TeV. It is the 'low energy' neutrino flux, below 10^5 GeV that dominates the event rate. Unfortunately the estimates of these fluxes from extragalactic sources are less certain and involve secondary terms, such as proton to neutron conversions, neutron decays and *pp* interactions.

There have been several interesting new ideas. Halzen and Saltzberg [34] considered neutrino astronomy in the presence of neutrino oscillations. On astrophysical distances 1/2 of all muon neutrinos would oscillate into τ neutrinos. Because of the short τ–lepton lifetime ($c\tau = 87\ \mu$m) ν_τ fluxes will not be absorbed in the Earth. A ultra high energy ν_τ will emerge as a sub 10^5 GeV neutrino, below the absorption threshold. Even for flat primary neutrino fluxes this does not add a lot to the event

Table 1: SUMMARY OF EVENT RATES IN KM^3 DETECTOR

- DIFFUSE FLUX (per steradian)

muon energy	atm. ν's	AGN	AGN jets
> 10 GeV	43000	600 – 800	188
> 1 TeV	1040	400 – 800	45
also ν_e (6.3 PeV) $+ e \to W^-$		300 per km^3	
		1	

- INNER GALAXY (0.73 ster)

muon energy	atm. ν's	inner galaxy	gal plane
> 10 GeV	31400	880 – 2000	120 – 200
> 1 TeV	760	160 – 470	15 – 30

- ATMOSPHERIC ν's IN 1° BIN

muon energy	$\cos\theta = 0.05$	$\cos\theta = 0.95$
> 10 GeV	79	29
> 1 TeV	2.1	0.5

- POINT SOURCES

	muon energy $>$1 TeV
(Sources of galactic CR)/100	26
Supernova remnants (γCygni)	3
Extragalactic source (3C273)	1 – 100
GRB source of UHECR(B&W)	3 per burst
Topological defects (UHECR)	5

- LIMITS FROM UHECR (per sr)

	muon energy $>$1 TeV
(Waxman & Bahcall)	36
Mannheim, Protheroe&Rachen 1	1590
Mannheim, Protheroe&Rachen 2	289
Mannheim, AGN jets	51

rate, but still modifies the picture presented in Fig. 2. Kwiecinski et al. extended this idea in a discussion of the neutral current cross section – all neutrino flavors will somewhat regenerate as their energy is downgraded in neutral current interactions. The effect is generally small because the σ_{NC}/σ_{CC} ratio is $\sim$3 and the highest energy neutrinos suffer numerous collisions.

Muon to tau neutrino oscillations add an interesting twist to projects for detection of high energy astrophysical neutrinos. As noted by Learned and Pakvasa [35)], the decay length of a PeV τ–lepton is $\sim$50 m and charge current ν_τ interactions and subsequent τ decays have an unique signature.

We summarize the event rates for upward going muons expected from different astrophysical sources as well as from the atmospheric neutrino background in Table 1. All numbers are given for exposure of 1 km^{2}yr. Neutrino absorption is taken into account, but regeneration due to neutral currents is not. According to Ref. 36 the regeneration may increase the rates of upward going muons no more than 10–20%. For the case of diffuse galactic fluxes the prediction for the inner galaxy comes from two extreme fits of the EGRET data [12)] for the central Galaxy for solid angle 0.73 ster. The conventional galactic plane flux [37)] is per steradian. The comparison of the two sets of numbers emphasizes the importance of the flat energy spectra observed by EGRET.

Some notes for the fluxes expected from point sources: line 1 shows 1/100 of the neutrino flux expected from luminosity of the Galaxy in cosmic rays. Line 2 gives the neutrino flux corresponding to the observed GeV gamma ray flux from the supernova remnant γCygni [10)]. The rate for GRB corresponds to a burst at 100 Mpc. The rate for TD scenarios of the origin of the ultra high energy cosmic rays is so low in part because these neutrinos are very energetic and the Earth is opaque for them.

As a summary I want to address in somewhat qualitative terms the chances for detection of high energy astrophysical neutrinos. On one hand it appears that the very high early expectations have come down considerably after the application of some observational limits and the development of more detailed astrophysical models. Indeed even the most optimistic rates in Table 1 are not exactly striking. One the other hand in representing the fluxes in terms of rates of >1 TeV muons (with relatively high atmospheric background) does not do justice to the extremely high energy astrophysical neutrinos. Neutrino cross sections grow with energy and the window for upward going muons is narrowing because of absorption. This does not preclude the observation of very high energy neutrinos. There is very little background, for example, for 10^8 GeV showers around the km^3 underwater(ice) detectors. Different observational techniques are being tested, including radio detection and atmospheric showers.

The theoretical homework on calculations of the astrophysical neutrino fluxes is still not finished. A recent state of the art model of photoproduction interactions [38)] demonstrated that for many astrophysical scenarios the generally accepted ratio of gamma ray to neutrino energy $\varepsilon_\gamma/varepsilon_\nu = 3$ is wrong. This value, that comes from the Δ^+ production, fails at high center of mass energy, as well as at the photoproduction threshold. Astrophysical applications of this event generator will change significantly the predictions for neutrino production at GRB (high $\sqrt{s}$) and maybe even the neutrino production at ultra high energy cosmic ray propagation, where most interactions are at the photoproduction threshold.

Acknowledgements This work is based on collaboration with V.S. Berezinsky,

T.K. Gaisser, F. Halzen, R.J. Protheroe and many others.

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