Sources of UHE Neutrinos

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In this paper we give a brief systematic study of different models of astrophysical point sources of ultra high energy ($\geq 1$ TeV) neutrinos.

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I. INTRODUCTION

We look at possible ultra high energy (UHE) neutrino point sources, galactic and extragalactic, focusing in particular on neutrinos of energies $\geq 1$ TeV. We present neutrino fluxes from all sources in common units. Owing to their small interaction cross section, neutrinos arrive undeflected from the source, carrying information about extremely high energy processes at cosmological distances. Recent detection of UHE photons from different astrophysical sources indicate that UHE neutrinos could also be produced provided the photons are of hadronic origin, via the $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ decay chain.

A brief outline of the paper is as follows: Section II illustrates Active Galactic Nuclei models for high energy neutrino emission. Section III describes feasible scenarios where such high energy neutrinos could emanate from supernova remnants and pulsars, also emphasizing possible nuclear interactions. In Section IV we look at TeV neutrino emission from two recent $\gamma$ ray burst models followed by the discussion of topological defect models predicting UHE neutrino emission in Section V. In Section VI we give the conclusions and an overview.

II. ULTRA HIGH ENERGY NEUTRINOS EMANATING FROM AGN

Active Galactic Nuclei (AGN) are the most luminous objects in the Universe, their luminosities ranging from $10^{42}$ to $10^{48}$ ergs/sec. They are believed to be powered by central supermassive black holes whose masses are of the order of $10^{4}$ to $10^{10} M_\odot$. The detection of ultrahigh energy neutrinos from AGNs would confirm the hadronic model associated with high energy $\gamma$ ray production since there is no source for high energy neutrinos in electromagnetic models. The production of such neutrinos can be described in terms of the spherical accretion AGN model [1] or the blazar model [2,3]. However, since the observed UHE gamma rays ($\geq 1$ TeV) by the Whipple, HEGRA and CANGAROO observatories originate from known blazars (Mkn 421 and Mkn 501), the favored model for UHE neutrino production would be the blazar model of AGN $^1$. Most recent data indicates $\gamma$ ray energy spectra up to 5-8 TeV from Mkn 421 and $\sim 10$ TeV from Mkn 501 without any well defined cutoff [5]. However, spherical accretion instrumental in the production of UHE particles should not be ruled out completely. Recent models predict our galaxy to harbor a $\sim 10^6 M_\odot$ black hole at the center which could emit such neutrinos; a theoretical explanation of this scenario would be similar to the spherical accretion model of AGN as we have discussed below.

$^1$ Also the second EGRET catalog of high-energy gamma ray sources [4] contains 40 high confidence identifications of AGN, and all appear to be blazars.
A. Blazar Models for Ultrahigh Energy Neutrino Production

Models predicting $\gamma$ ray emission from AGN jets are primarily leptonic in nature. Most of these models assume that the $\gamma$ rays are produced by inverse Compton scattering off electrons contained in a blob of plasma which itself is in relativistic motion in the general direction of the observer [6]. The most relevant process is assumed to be the SSC (Synchrotron Self Compton) process in which high energy gamma rays are produced by relativistic electrons via Compton scattering off synchrotron photons. If this is the mechanism, the radiation energy density must dominate the magnetic energy density. Such leptonic models do not predict the production of UHE neutrinos. However, there are hadronic models for particle emission from blazars which are consistent with all the data. Such models have been proposed by Mannheim [2] and Protheroe [3] independently. Photoproduction by shock accelerated protons in a relativistic jet at some distance from the central black hole is assumed by both models, though these two models assume different target spectra. Mannheim assumes a synchrotron spectrum whereas Protheroe assumes a disk spectrum. A brief description and some salient features of each are given below.

1. Proton Initiated Cascade (PIC) model

In the PIC (Proton Initiated Cascade) model [2] relativistic shocks are hypothesised to be propagating down an expanding jet. Particle acceleration at relativistic and oblique shocks by diffusive and drift mechanisms has been studied in detail in the past [7]. Protons obey such mechanisms and upon entering the jet are accelerated to energies where they initiate cascades due to photoproduction ($p + \gamma \rightarrow \pi^0, \pi^\pm...$). The crucial idea is that shock acceleration theory gives us a relativistic proton population and also provides soft synchrotron photons from accelerated electrons which act as ‘targets’ for production of pions and pairs. Ultrahigh energy neutrinos ($\geq$ TeV) and photons are produced from pion decays. Another crucial requirement for these models is that the acceleration is faster than expansion and the Larmor radius of gyrating particles does not exceed the radius of curvature of the shocks [8]. Considering first order Fermi acceleration across the shock the maximum achievable proton energy is calculated to be $\sim 10^6$ TeV for a typical AGN jet magnetic field value of 1 G [2]. The corresponding maximum Larmor radius would be $\sim 10^{15}$ cm. If observed hot spots in active galaxies are believed to be termination shocks of jets carrying energy from active nuclei to the lobes, a typical value of the maximum radius of the jet would be $\sim 10^{21}$ cm, which is the maximum radius of curvature of the shock [8]. The neutrino production site would then be well within the jet as described in both the blazar models investigated here.
2. Proton Acceleration, Disk Radiation Interaction

There is another plausible model [3] describing energetic $\gamma$ ray and neutrino emission in blazars which is consistent with gamma ray observations. In this model protons are accelerated and directly interact with accretion disk radiation. This involves only proton acceleration unlike the previous model which requires the acceleration of both protons and electrons.

If the accelerated protons interacted with matter to produce gamma rays at a time scale consistent with the observed variability of AGN ($\sim 1$ day), then the proton number density must be $> 10^9 \text{cm}^{-3}$. Such a high density is not normally expected in AGN jets. Interaction with the radiation field is therefore necessary if protons are accelerated, but a sufficiently high density of target photons for proton interactions would present problems for gamma ray escape if the radiation were isotropic. To solve this problem the $\gamma$ ray emission region is assumed to be positioned so that the impinging radiation is highly anisotropic. The photon spectrum used is a modified version of the standard thin accretion disk spectrum [9].

Both blazar models described above find that the $\gamma$ ray spectra from hadronic synchrotron cascades can explain the observed properties of $\gamma$ ray emitting AGN. They also predict very similar neutrino fluxes from the source. The disk spectrum is expected to be more important if particle acceleration occurs at distance less than a parsec from the central black hole and the synchrotron spectrum dominates at larger distances. If there is continuous proton acceleration along the jet, both target fields are important. Figure 1 illustrates the expected diffuse neutrino flux from the two different blazar AGN models described here in comparison to the atmospheric neutrinos due to cosmic ray interactions.

FIG. 1. Plot of the expected diffuse $\nu_\mu + \bar{\nu}_\mu$ flux from AGN using the blazar model due to Protheroe (top), the blazar model due to Mannheim (bottom). The dashed line represents angle averaged flux from cosmic ray interactions in the atmosphere (see section VI). Here $F$ is in $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ and neutrino energy $E$ is in GeV.
The hadronic models compete with the leptonic models in explaining the TeV \(\gamma\) ray emission from nearby blazars. Hadronic emission models naturally predict emission above \(\sim 10\) TeV unlike leptonic models as indicated below. This can be understood in two ways. Considering first order Fermi acceleration at shocks in the hadronic blazar model [2], the maximum achievable proton and electron energies can be attained for a given value of the magnetic field by balancing the proton and electron energy losses from different processes with energy gains from Fermi acceleration. The maximum Lorentz factor for electrons is found to be,

\[
\gamma_{\text{emax}} = 4 \times 10^7 K^{\frac{1}{2}} B^{-\frac{1}{2}} f_e^{-\frac{1}{2}}
\]

where \(B\) is the associated magnetic field, \(K < 0.4\) depends on diffusion coefficients and \(f_e\) typically \(\sim 2\), depends on different energy loss mechanisms (takes into account the relative contributions of synchrotron, inverse Compton, Bethe-Heitler pair production and pion production) \(^2\). Now if as an example, the 5-8 TeV emission from Mkn 421 is to be explained by a purely leptonic model, the electron Lorentz factor must reach at least \(10^7\). If these same electrons are assumed to produce the observed X ray spectrum by synchrotron process, for reasonable parameters a magnetic field of only \(10^{-4}\) G is expected \(^3\). Such a magnetic field is observationally found in the hot spots of jets at kiloparsec scale which is \(\sim 10^6\) larger than the size of \(\gamma\) ray emitting zone inferred by observed AGN variability. This therefore cannot account for the \(\sim 10\) TeV emission by purely leptonic processes.

In a separate model [10] the maximum achievable energy of a leptonic photon is also shown to be 10 TeV. The variable flux of TeV \(\gamma\) rays detected from Mkn 421 and Mkn 501 requires the presence of high energy electrons which could in principle produce a large number of electron positron pairs, leading to an electromagnetic cascade. In [10] it is described how this scenario can be avoided if electrons are accelerated rectilinearly in an electric field rather than being isotropically injected into a blob as in most models of the GeV \(\gamma\) ray emission. If electrons are considered to be subject to rectilinear acceleration balanced by inverse Compton losses from scattering on accretion disk photons, the maximum achievable photon energy is found to be \(\sim 10\) TeV, by the effective exclusion of the possibility of electromagnetic cascades during acceleration.

A surprisingly strong \(\gamma\) ray flux observed from Mkn 501 extending to 10 TeV [5] without a well defined cut off therefore strongly suggests hadronic models and points to the production of TeV neutrinos.

\(^2\) \(f_e = 1 + u_\gamma / u_B\) which is typically 2 considering the radiation energy density \(u_\gamma\) to equal the magnetic energy density \(u_B\).

\(^3\) A magnetic field of \(0.1 - 100\) G is expected in the \(\gamma\) ray and neutrino emitting zone of the jet [2]
B. Spherical Accretion Model for Ultrahigh Energy Neutrino Production

High energy neutrino production in an AGN environment can also be described using the spherical accretion model [1]. According to this model, close to the black hole the accretion flow becomes spherical and a shock is formed where the inward pressure of the accretion flow is balanced by the radiation pressure. The pions leading to neutrino production are produced in this model through the collision of fast protons (accelerated through first-order diffusive Fermi mechanism at the shock [1]) with the photons of the dense ambient radiation field. These neutrinos, produced in the central regions of the AGN, are expected to dominate the neutrino sky at energies of 1 TeV and beyond.

1. UHE Neutrino Emission from the Center of the Milky Way

Our galaxy harbors a compact non thermal source named Sagittarius A* (or Sgr A*) whose characteristics suggest that it may be a massive ($\sim 10^6 M_\odot$) black hole accreting matter from an ambient wind in that region [11] which is assumed to originate from IRS 16, a nearby group of hot massive stars. X-ray and $\gamma$ ray emissions have been detected from the galactic center. Recently the EGRET instrument on the Compton Gamma Ray Observatory has identified a central continuum source with luminosity $\sim 10^{36}$ ergs/sec [12]. Considering that a single supermassive black hole could be present the activity of the galactic center could be similar to the activity at the center of an AGN [13]. The shock acceleration mechanism would follow spherical accretion since there is no observed evidence for a blazar. Due to the absence of the dense radiation fields, typical of AGN conditions, the collisions between relativistic and ambient matter to produce $\gamma$ rays and neutrinos would be the dominant process. All suggested models till now [11] attempt to accommodate the observed EGRET data, which is of relatively low energy ($\sim 30$ MeV - 10 GeV). However the galactic center could be a potential source of UHE $\gamma$ ray and neutrino emission; future observations by ground based telescopes e.g. CANGAROO is necessary to ascertain this.

III. NEUTRINOS FROM SUPERNOVA REMNANTS AND PULSARS.

Supernova remnants (SNRs) could be the principal sources of galactic cosmic rays up to energies of $\sim 10^{15}$ eV [14]. A fraction of the accelerated particles interact within the supernova remnants and produce $\gamma$ rays. If the nuclear component of cosmic rays is strongly enhanced inside supernova remnants, then $\gamma$ rays and $\nu$s are invariably produced through nuclear collisions which lead to pion production and subsequent decay. Observations of both UHE $\gamma$ ray and $\nu$ from SNR sources would suggest accelerated hadrons in SNR.

Recent observations above 100 MeV by the EGRET instrument have found $\gamma$ ray signals from several SNRs (e.g. IC 443, $\gamma$ cygni, etc.) [15]. However, the production mechanisms of these high energy gamma-rays has not been unambiguously identified. The emission may be due to the interaction of the SNR blast wave accelerated protons
with adjacent molecular clouds [16]. Evidence that this is the dominant process would be the identification of a pion bump near 70 MeV which has not been seen in the EGRET SNR data—possibly due to poor statistics. It is also possible that the high energy \( \gamma \) rays arise from pulsars residing within the SNRs.

Evidence for electron acceleration in SNRs comes from the ASCA satellite observation of non-thermal X-ray emission from SN 1006 [17] and IC 443 [18]. Ground based telescopes have detected TeV emission from SN 1006 [19] and the Crab Nebula [20]. For recent reviews see [14]. Our objective in this paper is to look closely at SNRs as sources of UHE neutrinos and we investigate different possibilities in the sections below.

**A. Neutrinos from Supernova Remnants Assuming p-p Interactions**

There are two schools of thought describing the acceleration mechanisms in SNRs. In one, TeV \( \gamma \) rays are suggested to be leptonic in origin [21] and it is shown that SNRs could produce a TeV photon flux through inverse Compton scattering off the microwave radiation and other ambient photon fields. In the second, accelerated protons produce \( \gamma \) rays by the decay of neutral pions produced in proton nucleon collisions. We are interested in the possibility of TeV neutrino emission from SNRs which is possible only in hadronic models. Protons are accelerated by the SNR blast wave, or, if a pulsar is present within the remnant, acceleration could be due to pulsar wind terminated shock (termination at the surrounding nebula). Non linear particle acceleration concepts have been used in [16] considering a general SNR model. Following [16] the production rate of \( \gamma \) rays per unit volume can be written as,

\[
Q_\gamma = E_\gamma n = q_\gamma n E_C
\]

where \( n \) is the number density of the gas, \( E_C \) is the cosmic ray energy density, \( E_\gamma \) is the \( \gamma \) ray emissivity per unit volume and the production rate \( q_\gamma = \frac{E}{E_C} \). Considering a differential energy spectrum of accelerated protons inside the remnant of \( E^{2-\alpha} \), \( q_\gamma \) would be given by,

\[
q_\gamma (> E) = q_\gamma (\geq 1 \text{TeV}) \left( \frac{E}{1 \text{TeV}} \right)^{3-\alpha}
\]

Numerical values of \( q_\gamma \) for different spectral indices of the parent cosmic ray distributions are given in Table 1. The contribution of nuclei other than H in both the target matter and cosmic rays is assumed to be the same as in the ISM [22]. The units of \( q_\gamma \) are \( s^{-1} \text{ erg}^{-1} \text{ cm}^3 (\text{H – atom})^{-1} \). The corresponding total \( \gamma \) ray luminosity can be estimated by \( \int q_\gamma E_C d^3 r \) which, for simplified models, can be written as

\[
L_\gamma = \theta q_\gamma E_{sn} n
\]

where \( \theta \) is the fraction of the total supernova explosion energy \( (E_{sn}) \) converted to cosmic ray energy. The flux of \( \gamma \) rays with energy \( > 1 \) TeV from a SNR at a distance \( d \) from the Earth calculated using \( F_\gamma = \frac{L_\gamma}{4\pi d^2} \), can be written as [16],
\[ F_{\gamma}(\text{TeV}) \sim 8.4 \times 10^6 \theta_{\gamma}(\alpha) \left( \frac{E_1}{1\text{TeV}} \right)^{3-\alpha} \left( \frac{E_{\text{sn}}}{10^{54}\text{erg}} \right) \left( \frac{n}{1\text{cm}^{-3}} \right) \left( \frac{d}{1\text{kpc}} \right)^{-2} \text{cm}^{-2}\text{s}^{-1}. \] (5)

These results correspond to the SNR in the Sedov Phase where the luminosity is roughly constant. The total luminosity is low during the free expansion phase and the Sedov phase starts when the amount of swept out matter equals the ejecta mass. Typically this occurs at a radius \( \sim 10 \) pc and the SNR spends most of its useful life in this phase. TeV neutrinos can be predicted to be produced as a byproduct of the decay of charged pions. To find the corresponding UHE neutrino flux \( (F_{\nu_{\mu} + \bar{\nu}_{\mu}}) \) for different spectral indices we resort to the calculated ratios \( \frac{F_{\nu_{\mu} + \bar{\nu}_{\mu}}}{F_{\gamma}} \) [16,23] as illustrated in the table below. \( q_{\gamma}(\alpha) \) values for different \( \alpha \) values are also included. A comprehensive discussion of the spectrum weighted moments for secondary hadrons based on the accelerator beams with fixed targets at beam energies \( \leq 1 \) TeV has been presented by Gaisser [23]. This has also been shown to characterize correctly the energy region beyond 1 TeV [16]. A direct ratio estimate can be made as in [16] to give results very close to that in [23]. For harder spectra the ratio is found to approach unity. These values are for particles at the production site. The highly penetrating neutrino flux at the Earth can be estimated to be similar to the one at the site of production whereas the corresponding photons are readily absorbed.

| \( \alpha \) | 4.2 | 4.4 | 4.6 | 4.8 |
| \hline
| \frac{F_{\nu_{\mu} + \bar{\nu}_{\mu}}}{F_{\gamma}} \ [\text{Gaisser (1990) [23]}] | 0.80 | 0.67 | 0.56 | 0.46 |
| \frac{F_{\nu_{\mu} + \bar{\nu}_{\mu}}}{F_{\gamma}} \ [\text{Drury et.al. (1993) [16]}] | 0.86 | 0.77 | 0.66 | 0.58 |
| \( q_{\gamma}(\alpha) \) [16] | \(4.9 \times 10^{-18}\) | \(8.1 \times 10^{-19}\) | \(1.0 \times 10^{-19}\) | \(3.7 \times 10^{-20}\) |

\textbf{TABLE I.} Values of expected UHE neutrino and gamma ray ratio at production site.
We have taken the average of the two ratios as given in Table 1 to calculate the corresponding neutrino flux from equation (5) for each spectral index. As an example, the expression for the neutrino flux for $\alpha \sim 4.2$ would be given by

$$F_{\nu\mu}(>\text{TeV}) \sim 3.4 \times 10^{-11} \theta \left( \frac{E}{1\text{TeV}} \right)^{-1.2} \left( \frac{E_{\text{cm}}}{10^{31}\text{erg}} \right) \left( \frac{n}{1\text{cm}^{-3}} \right) \left( \frac{d}{1\text{kpc}} \right)^{-2} \text{cm}^{-2}\text{s}^{-1} \quad (6)$$

![Graph showing expected neutrino flux from the Crab](image)

**FIG. 2.** Plot of the expected neutrino flux from the Crab considering hard source spectra, $\alpha \sim 4.0$ (a), 4.2(b), 4.4(c). Here F is in cm$^{-2}$s$^{-1}$ and neutrino energy E is in GeV.

Very recent data from the CANGAROO detector [20] indicate that the energy spectrum of $\gamma$ rays from the Crab pulsar/nebula (filled center SNR) extends up to at least 50 TeV. The IC (Inverse Compton) $\gamma$ ray spectrum for the Crab has been calculated by several authors on the basis of the SSC (Synchrotron Self Compton) model and recently it has been suggested that [24] cosmic microwave background and infrared photons emitted from the dust in the nebula are the main seed photons for the TeV $\gamma$ ray production by the IC process. However, as the energy increases, IC processes produce a steeper spectrum because of synchrotron energy loss in magnetic fields. All models based on electron processes have difficulty in explaining the observed hard spectrum that extends to beyond 50 TeV. This observation may indicate that very high energy relativistic protons are accelerated by the pulsar wind, thereby supporting hadronic models of $\gamma$ ray emission.

The hadronic mechanism for production of $\pi^0$ and hence $\gamma$ rays as described above has been used in [24] to explain the UHE photon emission from the Crab. Nuclear p-p interactions are considered to occur among the protons accelerated in the nebula. The spectrum of $\gamma$ rays from $\pi^0$ in this model gives a hard differential spectrum which matches the CANGAROO observations thereby lending credence to the hadronic model. An approximate expression for the UHE gamma ray spectrum from equation (5) could be written for spectral index $\alpha$ varying between 4.0-4.5 as [24],

$$F_{\gamma}(>\text{TeV}) \sim 2.0 \times 10^{-3-3\alpha} \left( \frac{W_p}{10^{48}\text{erg}} \right) \left( \frac{n}{100\text{cm}^{-3}} \right) \left( \frac{d}{2\text{kpc}} \right)^{-2} \left( \frac{E_{1\text{TeV}}}{1\text{TeV}} \right)^{3-\alpha} \text{cm}^{-2}\text{s}^{-1} \quad (7)$$
where $d$ is the distance to the source (distance to Crab is 2 kpc), $W_p$ is the kinetic energy of relativistic accelerated protons (reasonable value for the Crab would be $\sim 10^{48}$ erg) and $n$ is the effective number density ($\sim 100$ cm$^{-3}$). The corresponding UHE neutrino flux can be calculated directly using values from Table 1. For reasonable parameters for $\alpha \sim 4.2$ as an example the neutrino flux from the Crab would be,

$$F_\nu(> \text{TeV}) \sim 8.3 \times 10^{-13} \left( \frac{E}{1 \text{TeV}} \right)^{-1.2} \text{cm}^{-2} \text{s}^{-1}$$

(8)

Figure 2 illustrates the expected neutrino flux from the Crab Nebula for different spectral indices as calculated above. The spectra are normalized such that $A = \left( \frac{W_p}{10^{48} \text{erg}} \right) \left( \frac{n}{100 \text{cm}^{-3}} \right) \left( \frac{d}{2 \text{kpc}} \right)^{-2} = 1$. SNR can therefore be considered to be effective sources for UHE neutrino production. More details can be found in [25].

**B. UHE neutrinos from SNR and pulsars due to Nuclear Interactions**

It is widely believed that the nuclear component of cosmic rays is produced in supernova remnants, at least for particle energies less than about $10^{14}$ eV per nucleon. However, there is no direct observational evidence for accelerated nuclei in SNR. In an effort to study the importance of nuclear interactions to the possible production of UHE neutrinos from astrophysical point sources, we turn to a model proposed by Protheroe et al. [26]. In this model very young SNR are considered in which nuclei, mainly Fe, extracted from the neutron star surface and accelerated to high Lorentz factors are photodisintegrated during propagation through the neutron star’s radiation field. Photodisintegration can also occur in the presence of extremely strong magnetic fields typical of neutron star environments ($\sim 10^{12}$ G).

For acceleration to sufficiently high energies we need a short initial pulsar period ($\sim 5$ ms). The energetic neutrons produced as a result of photodisintegration interact with target nuclei in the shell as they travel out of the SNR, producing gamma ray and neutrino signals; those neutrons passing through the shell decay into relativistic protons, contributing to the pool of galactic cosmic rays. For a beaming solid angle to the Earth of $\Omega_b$, the neutrino flux in this model can be calculated from,

$$F_\nu(E_\nu) \sim \frac{\dot{N}_{\text{Fe}}}{\Omega_b d^2} \left[ 1 - \exp(-\tau_{pp}) \right] \int N_n(E_n) P_{\nu n}^M(E_\nu, E_n) dE_n$$

(9)

where $\dot{N}_{\text{Fe}}$ is the total rate of Fe nuclei injected, $d$ is the distance to the SNR, $P_{\nu n}^M(E_\nu, E_n) dE_n$ is the number of neutrinos produced with energies in the range $E_\nu$ to $(E_\nu + dE_\nu)$ (via pion production and subsequent decay), and $N_n(E_n)$ is the spectrum of neutrons extracted from a single Fe nucleus. $\tau_{pp}$ is the optical depth of the shell to nuclear collisions (assuming shell type SNR) which is a function of the mass ejected into the shell during the supernova explosion and of the time after explosion. Figure 3 (solid line) gives the $\nu_\mu + \bar{\nu}_\mu$ spectra obtained from this model at a distance of 10 kpc with the time after explosion being 0.1 year. Signals from nuclei not completely fragmented are ignored because these particles are charged and would be trapped in the central region of the SNR which has a relatively low matter density and therefore would not make any significant contribution to neutrino fluxes.
Energetic radiation from the Crab Nebula could also be a consequence of acceleration of heavy nuclei in the pulsar magnetosphere [27]. Accelerated nuclei can photodisintegrate in collisions with soft photons produced in the pulsar’s outer gap, injecting energetic neutrons which decay either inside or outside the Crab Nebula. The protons from neutron decay inside the nebula are trapped by the Crab magnetic field ($\sim 10^{12}$ G) and accumulate inside the nebula producing gamma rays and neutrinos in collisions with matter in the nebula. The nuclei which survive are confined to the inner parts of the Crab Nebula which has no evidence for dense matter and hence neutrino production is negligible. Figure (3) (dashed line) shows the predicted spectrum from Crab Nebula assuming this model for some reasonable pulsar parameters.

IV. NEUTRINOS ASSOCIATED WITH GAMMA RAY BURSTS: COSMOLOGICAL SCENARIOS

Gamma ray bursts (GRB) are presently the most enigmatic astrophysical phenomenon. Recent observations indicate that they originate from cosmological sources. Here we look at the only two GRB models which predict neutrinos of energy $\geq 1$ TeV, namely the ultra-relativistic fireball model [28] and the cosmic string model [29]. Neutrinos from GRBs could be used to test the simultaneity of neutrino and photon arrival to an accuracy of $\sim 1$ ms, checking the assumption of special relativity that photons and neutrinos have the same limiting speed. These observations would also test the weak equivalence principle according to which photons and neutrinos should suffer the same time delay as they pass through a gravitational potential.
A. Ultra-relativistic Fireball Model

General phenomenological considerations indicate that GRBs could be produced by the dissipation of the kinetic energy of a relativistic expanding fireball [30]. Until recently neutrinos expected as byproducts of GRBs from the fireball model have been predicted to have energies of \( \sim 100 \text{ MeV} \) [31]. According to Waxman and Bahcall [28] however, a natural consequence of the dissipative cosmological fireball model of gamma ray bursters is the conversion of a significant fraction of fireball energy into an accompanying burst of \( \sim 10^{14} \text{ eV} \) neutrinos, created by photomeson production of pions in interactions between the fireball gamma rays and accelerated protons.

The basic picture is that of a compact source producing a relativistic wind. The variability of the source output results in fluctuations of the wind bulk Lorentz factor which leads to internal shocks in the ejecta. Both protons and electrons are accelerated at the shock and gamma rays are radiated by synchrotron and inverse Compton radiation of shock accelerated electrons. The observed GRB photon spectrum is well fitted by a broken power law, \( dN_\gamma/dE_\gamma \sim E_\gamma^{-\beta} \) with the break energy \( E_{\gamma b} \) (where \( \beta \) changes from 1 to 2) typically being \( \sim 1 \text{ MeV} \) in the range 30 KeV - 3 MeV (BATSE range). The interaction of protons accelerated to a power law distribution \( dN_p/dE_p \sim E_p^{-2} \) with GRB photons results in a broken power law neutrino spectrum similar to the gamma ray spectrum [28]. The accelerated protons undergo photomeson interactions and produce a burst of neutrinos to accompany the GRB. The neutrino break energy \( E_{\nu b} \) is fixed by the threshold energy of protons for photo-production in interaction with dominant \( \sim 1 \text{ MeV} \) photons in GRB [5]. If GRBs are sources of ultra high energy cosmic rays, assuming the sources are cosmologically distributed the expected neutrino flux from this model [28] would be

\[
F_\nu \sim 1.5 \times 10^{-9} \left( \frac{f_\pi}{0.2} \right) \left( \frac{1 \text{GeV}}{E_\nu} \right) \min \left( 1, \frac{E_\nu}{E_{\nu b}} \right) \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
\]

where \( E_\nu \) is the neutrino energy and the neutrino break energy \( E_{\nu b} \) is given by,

\[
E_{\nu b} \sim 5 \times 10^{14} \Gamma^2_{300} (E_\gamma/1 \text{MeV})^{-1} \text{eV},
\]

where \( \Gamma_{300} = \frac{\Gamma}{300} \), \( \Gamma \) being the wind bulk Lorentz factor typically 300. The normalization of the flux depends on the efficiency of pion production. In equation (10), \( f_\pi \) is the fraction of energy lost to pion production by protons producing the neutrino flux above the break, which is essentially independent of energy and is given by,

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4 The overall idea of a fireball model is that a large amount of energy is released in a compact region of radius \( R \sim c\Delta t \) which is opaque to photons. The system turns into a fireball with dense radiation and \( e^+ e^- \) pair fluid. The fluid then expands and cools adiabatically in the process and photons escape only when the optical depth of the fireball is sufficiently reduced.

5 The fractional energy loss rate of a proton due to pion production is calculated taking into account \( \Delta \) resonance effects. The corresponding fraction of energy lost in the expanding fireball is found to be maximum when the proton energy is \( \sim 10^{16} \text{ eV} \) dominantly interacting with a 1 MeV photon.
\[ f_\pi = 0.20 \frac{L_{51}}{(E^b_\gamma/1\text{MeV}) \Gamma_3 \Delta t} \]  

where \( L_\gamma \), the average source luminosity = \( \frac{L_\gamma}{10^{51}} \), and \( \Delta t \) the time scale of the variability of the source is typically \( 10^{-3} \text{ s} \). For typical GRB producing parameters therefore \( f_\pi = 0.2 \). From (10), the neutrino flux at the neutrino break energy and below is found to be, \( \sim 1.5 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \). At still higher energies (> \( 10^{16} \text{ eV} \)), the synchrotron losses are the dominant effect suppressing the neutrino flux [28]. For interaction with a 1 MeV photon the pion production threshold proton energy is \( \sim 10^{11} \text{ eV} \) [32] and so the expected neutrino flux drops off at lower energies. In this model therefore, most of the neutrino energy is carried by neutrinos with energy close to the break energy, \( \sim 10^{14} \text{ eV} \).

Figure 4 illustrates the expected neutrino flux from the GRB model described above. These neutrino bursts should be easily detected above the background due to atmospheric neutrinos, since they would be correlated both in time and angle to the GRB \( \gamma \) rays.

**B. Cosmic String Model of neutrino production**

Cosmic strings are topological relics from the early universe which could be superconducting and carry electric current under certain circumstances. A free string (a nonconducting string uncoupled from electromagnetic and gravitational fields) generically attains the velocity of light at isolated points in time and space, which are known as cusps [33]. Superconducting cosmic strings (SCS) emit energy in the form of classical electromagnetic radiation and ultra-heavy fermions or bosons which decay or cascade at or near the cusp. Using recent progress on the nature of electromagnetic symmetry restoration in strong magnetic fields, the study of the decay products of ultra-heavy fermions near SCS cusps consistent with an SCS explanation of \( \gamma \) ray bursts shows that the energy emitted from the cusps is found to be mostly in the form of high energy neutrinos [29,33]. The neutrino flux is roughly nine orders of
magnitude higher than that of the $\gamma$ rays. The flux for a typical neutrino burst using this model is given approximately by [31],

$$N_{\nu} = 10^4 \left( \frac{10^{-10}}{\eta_\gamma} \right) \left( \frac{\text{TeV}}{E_{\nu}} \right) \left( \frac{F_\gamma}{10^{-9} \text{J} \text{m}^{-2}} \right) \text{cm}^{-2} \text{s}^{-1}$$

(13)

where $\eta_\gamma$ is the fraction of energy lost to $\gamma$ rays which is very small with values $\sim 10^{-9} - 10^{-10}$. $E_{\nu}$ is the corresponding neutrino energy in TeV, and $F_\gamma$ is the observed $\gamma$ ray flux for a typical burst which can be taken to be $\sim 10^{-9} \text{J} \text{m}^{-2}$. A simple calculation yields, $N_{\nu} \sim 10^4 \times E_{\nu}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. If the observed neutrinos are of energy $\sim 10^{14} \text{ eV}$ as predicted by the previous model, it can be seen that the flux for a typical neutrino burst considering the cosmic string model is much larger being $\sim 10^2 \text{ cm}^{-2} \text{ s}^{-1}$. Neutrinos predicted by this class of models have a large energy range, from $\sim \text{MeV}$ to TeV, in contrast to the fireball model which predicts abundant neutrino production only up to the break energy.

This is therefore another model that predicts high energy neutrinos to be observed in coincidence with $\gamma$ ray bursts. If this model is true, TeV neutrinos from such sources are most likely to be seen and cannot escape the scrutiny of detectors.

V. NEUTRINOS FROM TOPOLOGICAL DEFECT MODELS

Topological defect models can directly predict UHE neutrino production. The main problem with these models is the wide range of model parameters in which these scenarios could be applied. In all other models described above the parameters are restricted by observation. Due to the uncertainty there appears no direct reason to invoke these models, though the theoretical predictions cannot be ignored.

In the conventional topological defect model, the network of long strings (curvature radius greater than the Hubble radius) lose their energy predominantly by gravitational radiation resulting in very small high energy particle flux. As an extension to this [34] describes a model where particle production is the dominant energy loss mechanism in which case therefore, the predicted flux of high energy particles would be much larger.

Physics beyond the standard model might imply the cosmological production of particles with grand unification scale energies. In [35] a class of models has been explored of exotic heavy particle decay that ultimately leads to UHE neutrinos. In particular, UHE neutrinos are produced by the direct decay of a supermassive elementary “X” particle associated with some grand unified theory (GUT). These particles may arise from the collapse of networks of ordinary cosmic strings or from annihilation of magnetic monopoles. The predicted flux is very model independent and found to be smaller in comparison with the model mentioned above.
Figure 5 gives a plot of the expected neutrino flux from the modified conventional topological defect model [34] and also the expected neutrino flux from [35] due to the decay of the exotic X particle.

VI. OVERVIEW AND CONCLUSIONS

A neutrino can be described as a standard Dirac or Majorana particle. It is well established that neutrino interactions in nature take place precisely according to the standard electroweak model. However, whether or not neutrinos have mass is one of the key questions of particle physics today. Neutrinos can be used to probe the core of some of the most interesting cosmological objects. Due to their small interaction cross sections these particles can stream out unaffected from even the most violent environments such as those present in Active Galactic Nuclei (AGN). The presence of several neutrino flavors and spin states could modify this picture: in their trek from their source to the detector the neutrinos can undergo flavor and/or spin oscillations which could obscure some of the features of the source. Because of this, and due to the recent interest in neutrino astronomy [36], it becomes important to understand the manner in which these flavor-spin transitions can occur, in the hope of disentangling these effects from the ones produced by the properties of the source. Without such an understanding it will be impossible to determine the properties of the UHE neutrino source using solely the neutrino flux received on Earth. Incorporation of all oscillation effects for different UHE neutrino sources and corresponding expected neutrino fluxes can be found in [37].

The study of UHE neutrinos would be incomplete without the mention of atmospheric neutrino background. Neutrinos produced by cosmic ray interactions in the atmosphere dominate other sources for neutrino energy below a few TeV. This is why we focus on neutrinos with higher energy. The “conventional” atmospheric neutrino flux [38] is derived from the decay of charged pions and kaons produced by cosmic ray interactions in the atmosphere. The atmospheric neutrino flux is large at 1 TeV but falls with energy as $E^{-4}$. The angle averaged atmospheric flux can be parametrized [39] by the equation

\[
\log F = \log E - 16.5
\]
\[ F_\nu = 7.8 \times 10^{-8} \left( \frac{E_\nu}{1 \text{TeV}} \right)^{-2.6} \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]  

(14)

An order of magnitude calculation indicates that at 1 TeV the flux is \( \sim 10^{-8} \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \), at 10 TeV it is \( \sim 10^{-10} \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) and this goes down to \( \sim 10^{-13} \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) at 100 TeV. For a few TeV energies therefore neutrinos from other sources as discussed in this paper will dominate. If we raise the energy threshold to 100 TeV the atmospheric neutrino background is essentially eliminated. An additional “prompt” contribution of neutrinos [40] to the atmospheric flux arises from charm production and decay. The vertical prompt neutrino flux has been recently reexamined using the Lund model for particle production and has been shown to be small compared to the conventional flux for energies \( \leq 10^5 \) GeV. Since atmospheric neutrinos are important only for energies \( \leq \) a few TeV neutrinos from charm decay can be neglected in our event rate calculations. Also the vertical muon flux could be an unavoidable background. By deploying a detector at great depths or observing upward going muons or both one can reduce the cosmic ray muons to a manageable background.

UHE neutrinos can be detected by observing muons, electrons and tau leptons produced in charged-current neutrino nucleon interactions [39,41,42]. The primary means of detection of muon neutrinos and antineutrinos is by charged current conversion into muons and antimuons. To minimize the effects of atmospheric muon and neutrino background, one observes upward going muons. To observe \( \nu_\mu \) one looks at the contained event rates for resonant formation of \( W^- \) in the \( \bar{\nu}_e \) interactions at \( E_\nu = 6.3 \) PeV for downward moving \( \nu_e \). Also the rapid development of electromagnetic showers may make it possible to detect upward going air showers initiated by an electron neutrino that interacts near the earth surface. In all the models discussed above there is negligible Tau neutrino flux, hence the observation of Tau neutrinos by the neutrino detectors would indicate oscillations of the neutrinos, thereby confirming physics beyond the standard model. The key signature for the detection of \( \nu_\tau \) is the charged current \( \nu_\tau \) interaction, which produces a double cascade on either end of a minimum ionizing track [41]. The threshold energy for detecting these neutrinos however is near 1 PeV at which these cascades are separated by roughly 100m which is easily resolvable in the planned neutrino telescopes.

We have summarized the different models of astrophysical point sources for TeV neutrinos in this paper. A complete and elaborate calculation of expected event rates from UHE muon and electron neutrinos looking at selected AGN models has been carried out using new neutrino cross section values (taking into account most recent parton distributions) in [39] for a detector area of 0.1 km\(^2\). However a more detailed study of the expected neutrino detection rates by the proposed ice/water detectors should incorporate all the astrophysical sources described above and also include the possibility of detection of Tau neutrinos (adding the effects of neutrino oscillations). This work is in preparation [37].

To show that neutrinos from the above sources are detectable we can make an estimate looking solely at muon
neutrino detection. In that case the expected event rate for a detector with effective area $A$ is given by [39],

$$\text{Rate} = A \int dE_\nu P_\mu(E_\nu; E_\mu^{\text{min}})S(E_\nu) \frac{dN}{dE_\nu} \quad (15)$$

where $P_\mu(E_\nu; E_\mu^{\text{min}})$ is the probability that a neutrino of energy $E_\nu$ produces an observable muon with threshold energy $E_\mu^{\text{min}}$, $dN/dE_\nu$ is the diffuse neutrino flux and $S(E_\nu)$ is the shadow factor of the earth. Order of magnitude calculations of the astrophysical sources discussed above show the fluxes to be detectable by kilometer scale detectors. Let us restrict ourselves as an example to km$^2$ detector area, neutrino energy 100 TeV and muon threshold energy 10 TeV. Considering AGN neutrinos the expected event rates would be approximately 6 events/sr/yr and 38 events/sr/yr for the two blazar models respectively whereas the optimistic spherical accretion model would expect $10^4$ events/sr/yr (Section II). The SNR models would predict $\sim 3$ events per year from the Crab considering hard source spectrum which necessitates a detector with high angular resolution (Section III). The GRB model due to Bahcall would predict about 2 events/sr/yr; though the flux is low this prediction is advantageous because observed neutrinos can be correlated in time and position with GRBs (Section IV). The Cosmic String Model of GRB which is the most optimistic of all these models would expect $\sim 10^4$ events/sec (Section IV) and the topological defect models predict about 1 event per year (Section V). The last two models are dependent on the choice of parameters not restricted by observations and are therefore uncertain.

The field of high energy neutrino astronomy is looking forward to the construction and development of the next generation km$^3$ scale neutrino detector in water or in ice. Several initiatives are underway namely AMANDA, Baikal, NESTOR, ANTARES and the water km$^3$ scale initiative at Berkeley. For neutrino astronomy to be a viable science several of these, or other projects will have to succeed. Astronomy, whether on the optical or in any wave band thrives on the diversity of complementary instruments, not on a single best instrument. The important fact remains in the effort to uncover the vast amount of Physics behind the successful operation of any or all of the efforts to detect neutrinos in such high energy ranges.

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