

Best-Bet Astrophysical Neutrino Sources

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Abstract. Likely astrophysical sources of detectable high-energy (\gg TeV) neutrinos are considered. Based on gamma-ray emission properties, the most probable sources of neutrinos are argued to be GRBs, blazars, microquasars, and supernova remnants. Diffuse neutrino sources are also briefly considered.

1. Introduction

This discussion of sources of high-energy astrophysical neutrinos focuses on candidate discrete sources of neutrinos (see also [1]). Arguments for detectable neutrino sources are based on the γ/ν connection: photohadronic and secondary nuclear processes, which are the most important astrophysical neutrino production mechanisms, will also produce γ rays. By identifying the brightest and most fluent γ -ray sources, we therefore identify the most likely neutrino point sources. This argument is, however, far from airtight. A source can be γ -ray bright without being neutrino bright if the γ -rays originate from leptonic processes, for example, when relativistic electrons Compton scatter ambient target photons to γ -ray energies. Conversely, a bright neutrino source can be γ -ray dim if the γ rays are attenuated. This can occur either in a buried source, where the surrounding material or the local radiation field provides large opacity to γ rays or, for cosmologically distant objects, when high-energy γ -rays are attenuated by the extragalactic background light (EBL).

At EGRET and GLAST energies ($E \approx 100$ MeV – 10 GeV), attenuation by the EBL is unimportant, even for the highest redshift objects. Thus the EGRET catalog can be enlisted to identify the brightest γ -ray sources and, by the γ - ν argument, the most probable neutrino point sources. The new discoveries with HESS, MAGIC, and VERITAS at TeV energies provide additional important information, especially for galactic sources.

Diffuse γ -ray emissions include those that are genuinely diffuse, namely cosmogenic GZK neutrinos and neutrinos produced by cosmic-ray interactions in our Galaxy, as well as apparently diffuse neutrino fluxes from the superposition of unresolved sources, such as star-forming galaxies and clusters of galaxies.

2. The γ - ν connection, γ -ray sources, and candidate neutrino sources

Photohadronic and secondary nuclear production processes are the two principal mechanisms responsible for high-energy neutrino production. The dominant near-threshold channel for neutrino production through either of these processes involves the excitation of a Δ^+ isobar.

For proton/photon and proton/nucleon interactions, these reactions take the form

$$p + \gamma', p + N \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \rightarrow p + 2\gamma \\ n + \pi^+ \rightarrow n + e + 3\nu \rightarrow p + 2e + 4\nu \end{cases}, \quad (1)$$

where γ' represents a target photon and N represents a target nucleon. The charge-changing reaction takes place one-third of the time. For a large number of such reactions, therefore, the outcome is a high-energy lepton and three high-energy neutrinos for every four high-energy γ rays. In addition, neutron β -decay forms an electron and a neutrino with $\approx 10^2$ times less energy than the other secondaries. Approximately four times as much energy is radiated in electromagnetic secondaries as in neutrinos. Any high-energy neutrino source will therefore be a strong γ -ray source if the γ rays reach the observer without intervening attenuation.

For such γ -ray sources, the “best-bet” neutrino sources are those where a neutrino telescope such as IceCube can detect a neutrino above the cosmic-ray induced background. IceCube’s background is at the level $\gtrsim 0.4\nu(> 1 \text{ TeV})$ per yr per square degree and $0.08\nu(> 10 \text{ TeV})$ per yr per square degree [2]. To be detected with a km-scale neutrino telescope such as IceCube, the neutrino fluence, and therefore the photon fluence, must be at the level of $\Phi_\gamma \gtrsim 10^{-4}$ ergs cm^{-2} , as we now show [3].

The detection probability for muon neutrinos is $P_{\nu_\mu}(\epsilon_{14}) \approx 10^{-4}\epsilon_{14}$, for $0.1 \lesssim \epsilon_{14} \lesssim 10$, where $\epsilon_{14} = \epsilon_\nu/100 \text{ TeV} = \epsilon_\nu/160 \text{ ergs}$ [4]. Consider a neutrino source with number flux $\phi_\nu(\epsilon_{14}) = dN/dAdtd\epsilon_{14} = K\epsilon_{14}^{-s}$ in the energy range $0.1 \lesssim \epsilon_{14} \lesssim 10$. The neutrino energy fluence received during the time interval Δt is $\Phi_\nu(\text{ergs cm}^{-2}) \cong (160 \text{ ergs})\Delta t \int_{0.1}^{10} d\epsilon_{14} \epsilon_{14} \phi_\nu(\epsilon_{14})$. The detection of N_{ν_μ} muon neutrinos occurs when $N_\nu \cong A\Delta t \int_{0.1}^{10} d\epsilon_{14} P_{\nu_\mu}(\epsilon_{14})\phi_\nu(\epsilon_{14}) = 10^{-4}A \Phi_\nu(\text{ergs cm}^{-2})/160 \text{ ergs} > 1$, where A is the detector area. Thus the detection of one ν_μ with a km-scale neutrino detector ($A \cong 10^{10} \text{ cm}^2$) requires that the neutrino fluence $\Phi_\nu \gtrsim 10^{-4}$ ergs cm^{-2} . By the γ - ν connection, this means that the γ -ray fluence from a source must be $\Phi_\gamma \gg 10^{-4}$ ergs cm^{-2} .

EGRET reported results of their observations in units of $10^{-8}\phi_{-8} \text{ ph}(>100 \text{ MeV}) \text{ cm}^{-2} \text{ s}^{-1}$ [5]. For a flat νF_ν spectrum, the mean photon energy in the EGRET range, $\approx 100 \text{ MeV} - 5 \text{ GeV}$, is $\approx 400 \text{ MeV}$, which corresponds to a bolometric νF_ν flux in this energy range of $\approx 6 \times 10^{-12}\phi_{-8} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The integral photon flux sensitivity for a two-week on-axis pointing with EGRET is at the level of $\phi_{-8} \approx 15$, so that the limiting sensitivity of EGRET for a 5σ detection was $\approx 10^{-10}$ ergs $\text{cm}^{-2} \text{ s}^{-1}$. To reach a fluence of $10^{-4}\Phi_{-4}$ ergs cm^{-2} therefore requires that $\Delta t\phi_{-8} \cong 1.5 \times 10^7\Phi_{-4} \text{ s}$. The standard EGRET observation lasted for two weeks. When taking into account Earth occultation, the typical observing time was $\approx 6 \times 10^5 \text{ s}$. Thus sources with $\phi_{-8} \gg 30$ fulfill the requirement that if neutrinos are produced with comparable fluence as γ rays, then they would be detectable neutrino sources. Even though the EGRET energy range is at a much lower value than that of the neutrino telescopes, the γ rays produced in association with the neutrinos could cascade down into this energy range. Extrapolating the γ -ray spectrum into the PeV range means that bright γ -ray sources with nearly flat νF_ν spectral indices (or photon number indices $\alpha_{ph} \approx 2$, defining photon number fluxes $\phi_\gamma(\epsilon) \propto \epsilon^{-\alpha_{ph}}$) are good candidate neutrino sources.

By examining the Third EGRET catalog [5], one finds many γ -ray sources that fit this criterion. The following objects have at least one and sometimes many two-week observing periods during which $\phi_{-8} \gtrsim 100$: the blazars PKS 0208-512, PKS 0528+134, NRAO 530, 3C 279, PKS 1622-297; pulsar 1706-44 and the Crab, Vela and Geminga pulsars; the EGRET sources associated with the supernova remnants W44, IC 443, and γ Cygni; the sources 3EG J1824-1514 and 3EG J0241+6103 associated with the microquasars LS 5039 and LSI +61 303, respectively; and several unidentified EGRET sources, including some in the Galactic plane and some at high latitude. In addition to these persistent or flaring sources, a bright Solar flare

was detected with EGRET, and several GRBs were strongly detected with the EGRET spark chamber. We discuss these various classes of sources in increasing likelihood of being detectable neutrino sources.

2.1. Solar Flares

The June 11, 1991 Solar flare radiated a > 100 MeV energy fluence exceeding 10^{-4} ergs cm^{-2} [6]. The flare spectrum was fit by a slowly decaying (~ 255 minutes) pion emission component and a fast-decaying (~ 25 minutes) electron bremsstrahlung component. The very soft γ -ray spectrum, with number index $\gtrsim 3 - 4$, and lack of evidence for \gg GeV proton and ion acceleration in Solar flares (for example, from ground-based neutron monitors) make it unlikely that very high-energy neutrinos are produced by Solar flares, though they could be sources of GeV – TeV neutrinos.

2.2. Pulsars and Pulsar Wind Nebulae

Pulsars are the brightest point sources in the EGRET catalogs, with > 100 MeV νF_ν fluxes of some pulsars exceeding 10^{-9} ergs cm^{-2} s^{-1} . Moreover, they are persistently bright. Consequently it only took EGRET ≈ 1 day to measure pulsed fluences $\gtrsim 10^{-4}$ ergs cm^{-2} . It is unlikely, however, that they would be detectable neutrino sources. The pulsed spectrum always cuts off below several hundred GeV. If this is due to an electromagnetic cascade, as expected in both polar cap or outer gap models for pulsed γ -ray emission, then the emission originates from electron acceleration and cascades, which would not produce neutrinos.

The nebulae formed by the cold but highly relativistic MHD winds expelled by rotating, highly magnetized neutron stars could accelerate protons and ions that would subsequently undergo interactions to produce neutrinos. The Crab nebular emission is at the level of 10^{-10} ergs cm^{-2} s^{-1} in the EGRET energy band, but is convincingly explained as the self-Compton component from the electrons that radiate the synchrotron nebular emission.

The pulsar wind nebulae discovered at TeV energies with HESS could be the result of accelerated protons that interact with ambient material to form the power-law spectra measured from these sources. In its preliminary galactic plane scan [7], HESS reached 5σ sensitivities at the level of 3×10^{-11} ph(> 100 GeV) cm^{-2} s^{-1} implying, for a mean photon energy of 400 GeV, a limiting bolometric sensitivity of 2×10^{-11} ergs cm^{-2} s^{-1} . For example, the pulsar wind nebula in the supernova remnant MSH 15-52 radiated $\approx 3.3 \times 10^{-11}$ ergs cm^{-2} s^{-1} in the energy range 0.3 – 40 TeV with $\alpha_{ph} = 2.27 \pm 0.2$ [8]. Extrapolating into the PeV range gives a flux of $\approx 5 \times 10^{-12}$ ergs cm^{-2} s^{-1} , or a fluences $\gtrsim 10^{-4}$ ergs cm^{-2} in ≈ 1 years time. Because of similar morphology to the keV synchrotron emission, the TeV γ rays are likely to be the result of Compton-scattering rather than hadronic emission. If this emission is the result of hadronic processes, however, such sources could be marginally detectable neutrino sources (see [9, 10] for a more on Galactic neutrino sources).

2.3. Supernova Remnants

Some of the brightest EGRET sources are associated with supernova remnants [11], and they display relatively hard spectra (≈ -2). They are also believed to accelerate cosmic rays to the knee of the spectrum (≈ 3 PeV). If due to π^0 decay emission from secondary nuclear production, the spectra will soften at energies well above the π^0 peak, which is at several hundred MeV in a νF_ν representation. In the TeV energy range, a bolometric νF_ν flux reaching 10^{-10} ergs cm^{-2} s^{-1} is observed with HESS [12] from RX J1713.7-3946. One would optimistically expect [13] this SNR to be detected as a neutrino sources after only some months of observing except, unfortunately, the γ -ray spectrum exhibits a remarkable cutoff above ≈ 10 TeV, though IceCube should still detect one or two $\nu_\mu(> 1$ TeV)/yr [10]. The cutoff might indicate that acceleration to higher energies has not yet occurred, though the remnant should be well into the Sedov phase. The higher energy cosmic ray protons and ions, being more diffusive, could leave the acceleration

region quickly. The emission could also be leptonic, arising from Compton-scattered ambient radiation.

2.4. Microquasars and X-ray Binaries

The discovery that LS 5039 is a TeV source [14] confirmed the association of the EGRET source 3EG J1824-1514 with LS 5039 [15]. Its bolometric νF_ν flux in the 0.2 – 10 TeV range is at the level of $\approx 10^{-11}$ ergs cm $^{-2}$ s $^{-1}$. The flux is modulated at the 3.9 day orbital period [16]. Orbital modulation was also recently reported by the MAGIC collaboration from the northern hemisphere microquasar LSI +61 303 [17], with a mean bolometric νF_ν flux of $\approx 4 \times 10^{-11}$ ergs cm $^{-2}$ s $^{-1}$ in the 0.2 – 4 TeV range and mean photon spectral index $\alpha_{ph} \cong 2.5$.

Both of these sources are high-mass microquasars: the companion stars in LS 5039 and LSI +61 303 have masses $\approx 23M_\odot$ and $\approx 10M_\odot$, respectively. The orbital modulation shows that the TeV emission has to be produced in the vicinity of the binary system. Both leptonic [18, 19] and hadronic models [20] for microquasar jet emission have been proposed. Even though their spectra are soft or cut off at multi-TeV energies, this could be a result of $\gamma\gamma$ attenuation, so that the actual γ -ray and neutrino production spectrum from hadronic interactions could extend to very high energies [20, 21].

In addition to these two microquasars, the binary system B1259-63, consisting of a pulsar and a high-mass Be star, is a TeV source [22]. This raises the interesting possibility [23] that all three sources are binary systems consisting of a pulsar and a high-mass star, with the TeV emission due to nonthermal particles accelerated by the shock formed by interactions between the MHD wind of the pulsar and the stellar wind of the high-mass star. The formation of the emission in the inner region of the system would naturally follow from this scenario. Accreting X-ray binaries have also been proposed [24] as detectable neutrino sources when protons and ions, accelerated in the magnetosphere of the system, collide with material of the accretion disk, though the absence of TeV emission suggests they would not be bright neutrino sources.

2.5. Blazars

The intense, highly variable γ -ray fluxes from blazars suggest that they are also bright neutrino sources. It is important to distinguish between the flat spectrum radio quasars (FSRQs), which have strong atomic emission lines in their spectra, from the BL Lac objects with their nearly featureless continua. All known TeV blazars are X-ray selected BL Lac objects.

Though one might think that TeV blazars are the most probable neutrino sources, given that particle acceleration to \gg TeV energies must take place in these sources, it is more likely that FSRQ blazars are bright neutrino sources [25]. First, the brightest FSRQs have νF_ν fluxes \approx one order of magnitude brighter than the TeV νF_ν fluxes of the brightest BL Lac objects. The absence of TeV radiation in FSRQs is probably a consequence of $\gamma\gamma$ attenuation on the EBL, and does not indicate that TeV γ rays are not produced. Moreover, the intense scattered accretion-disk radiation in the vicinity of the supermassive black hole in FSRQs, as indicated by the strong atomic lines, provides an important source of target photons for photohadronic production [26]. Making the conservative assumption that the energy injected in protons is equal to the energy inferred from observations of the electron synchrotron radio/X-ray emission, we [25, 26] have shown that IceCube could detect one or several neutrinos during bright FSRQ blazar flares, such as that observed from 3C 279 in 1996.

2.6. Gamma Ray Bursts

This topic was recently reviewed [3], and details can be found there. Neutrino production in GRBs depends most sensitively on two parameters: the baryon-loading factor and Doppler factor of the GRB blast wave. The baryon-loading factor refers to the energy in nonthermal protons compared to the electromagnetic energy inferred from direct measurements of the keV/MeV

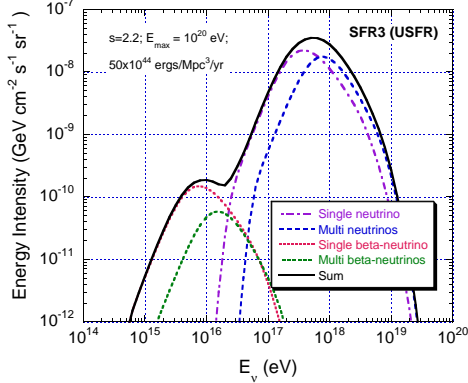


Figure 1. GZK neutrino flux using a star formation rate history used to model the UHECR spectrum from GRBs [35].

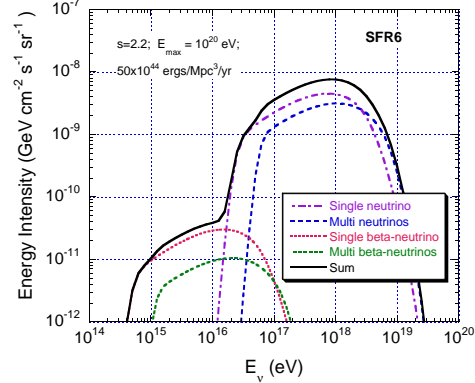


Figure 2. GZK neutrino flux using the star formation history used to fit the statistics of GRBs with measured redshifts [36].

emission from GRBs. Provided that the baryon-loading factor is $\gg 10$, which is required if GRBs are the sources of UHECRs, and the Doppler factor is $\lesssim 200$, neutrinos from GRBs are detectable with IceCube or a northern hemisphere neutrino detector. These calculations [29] are made in the framework of the collapsar model, with values of the Doppler factor in the range commonly expected for GRB outflows. Anomalous γ -ray emission components [27, 28] in GRBs give further evidence for hadronic acceleration by GRB blast waves.

3. Diffuse Neutrinos

Cosmic ray interactions in the disk of the Milky Way will make a diffuse neutrino glow [30]. A flux of $\approx 160 \nu (> 250 \text{ TeV}) \text{ km}^{-2} \text{ yr}^{-1}$ from a 5 square degree region surrounding the galactic center is calculated in Ref. [1], though the exact result is sensitive to the hardness of the cosmic-ray spectrum. Superpositions of emissions from the classes of point sources listed above, in particular, GRBs and blazars, will make a diffuse high-energy neutrino background radiation. Dim extragalactic γ -ray sources can also make important neutrino backgrounds due to their abundance.

Star-forming galaxies, which include normal spiral galaxies, starburst galaxies, and infrared luminous galaxies, might be considered as likely neutrino point sources because cosmic rays would certainly be accelerated by the core-collapse supernovae resulting from the late stages of evolution of the massive stars in these systems. These systems are, however, relatively dim γ -ray sources and, furthermore, have soft spectra. The only extragalactic galaxy that was detected with EGRET was the Large Magellanic Cloud [31], with an integral γ -ray flux equal to $14.4(\pm 4.7) \times 10^{-8} \text{ ph}(> 100 \text{ MeV}) \text{ cm}^{-2} \text{ s}^{-1}$ and a spectral index of $s = 2.2$, implying a νF_ν flux of $\approx 2.3 \times 10^{-11} (E/100 \text{ MeV})^{-0.2} \text{ ergs cm}^{-2} \text{ s}^{-1}$. Thus it would take $\gg 2$ years to detect neutrinos from the LMC unless there was an anomalous hardening of the spectrum.

Nevertheless, the superpositions of the neutrino emissions from star-forming galaxies will form a guaranteed background. An estimate [32] of the neutrino background based on the synchrotron radio luminosity associated with cosmic-ray acceleration in star-forming galaxies is at a level detectable by IceCube, though the assumptions and derived intensity have been challenged [33].

Photohadronic interactions of UHECRs with photons of the EBL forms the diffuse cosmogenic GZK neutrino flux. The spectrum of this background depends on the UHECR activity in the early universe [34]. Figs. 1 and 2 show calculations (work in preparation with J. Holmes) of the effect on the GZK neutrino background due to different histories of GRB production.

4. Summary

The best-bet neutrino sources are GRBs, blazars, microquasars, and SNRs because of their bright and hard γ -ray spectra that could originate from hadronic processes. These results should be placed within the context of theories of cosmic ray origin. Supernova remnants are thought to be the sources of cosmic rays to at least the knee of the cosmic ray spectrum, because they have adequate power and will produce strong shocks. But the TeV spectrum of RX J1713.7-3946 shows a cutoff at ≈ 10 TeV. Supernova remnants probably differ greatly in their cosmic ray acceleration efficiencies, with Type 1b/c supernovae and those associated with GRBs being the strongest such accelerators. Microquasars and Be/X-ray binaries, though less powerful than SNRs, will also form strong shocks and will have stellar wind material that can provide a target for secondary nuclear production.

UHECRs must be extragalactic given the $\sim \mu\text{G}$ strength of the Milky Way's magnetic field, so that GRBs and blazars, the brightest extragalactic γ -ray sources, are the most probable sources of UHECRs and high-energy neutrinos. The highly relativistic outflows and shocks required to model these systems can accelerate particles to $\approx 10^{20}$ eV.

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