

ASTROPHYSICAL SOURCES OF HIGH ENERGY NEUTRINOS

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ABSTRACT

I give a brief critical review of the predicted intensity of diffuse high energy neutrinos of astrophysical origin over the energy range from $\sim 10^{12}$ eV to $\sim 10^{24}$ eV. Neutrinos from interactions of galactic cosmic rays with interstellar matter are guaranteed, and the intensity can be reliably predicted to within a factor of 2 up to 10^{17} eV. Somewhat less certain are intensities in the same energy range from cosmic rays escaping from normal galaxies or active galactic nuclei (AGN) and interacting with intracluster gas. At higher energies, neutrinos will be produced by interactions of extragalactic cosmic rays with the microwave background. Other sources, such as AGN, in particular blazars, and topological defects, are more speculative. However, searches for neutrinos from all of these potential sources should be made because their observation would have important implications for high energy astrophysics and cosmology.

1 Introduction

The technique for constructing a large area (in excess of 10^4 m²) neutrino telescope has been known for more than a decade [1]. The pioneering work of the DUMAND Collaboration developed techniques to instrument a large volume of water in a deep ocean trench with strings of photomultipliers to detect Cherenkov light from neutrino-induced muons. Locations deep in the ocean shield the detectors from cosmic ray muons. The DUMAND detector [2] was designed to be most sensitive to neutrinos above about 1 TeV, and prototypes of other similar experiments are already in operation such as that in Lake Baikal, Siberia [3], and NESTOR off the coast of Greece [4]. An exciting recent development has been the construction of a DUMAND type detector deep in the polar ice cap at the South Pole. This experiment called AMANDA uses the same principle as DUMAND but takes advantage of excellent transparency of the polar ice under extreme pressures and a stable environment in which to embed the detectors [5]. These experiments have the potential to be expanded in the future to a detector on the 1 km³ scale, and a workshop was held in Aspen in 1996 to consider this possibility, and decide on the most suitable energy ranges for observation. It is therefore appropriate and timely to review the predicted intensity of astrophysical sources of neutrinos over the entire energy range from $\sim 10^{12}$ eV to $\sim 10^{24}$ eV.

2 Neutrinos from Cosmic Ray Interactions

There will definitely exist an important galactic diffuse neutrino background due to interactions of the galactic cosmic rays with interstellar matter. The spectrum of galactic cosmic rays is reasonably well known, as is the matter distribution in our galaxy. Estimates of the intensity have been made by Domokos et al [6], Berezhinsky et al. [7], and Ingelman and Thunman [8] and their predictions are shown in Fig. 1. The differences of about a factor of 2 between the predictions are accountable in terms of the slightly different models of the interstellar matter density, and cosmic ray spectrum and composition used. Also shown is the atmospheric neutrino background as estimated by Lipari [9]. In addition, there will be a very uncertain background (not plotted) due to charm production (see Gaisser et al. [10] for a survey of predictions).

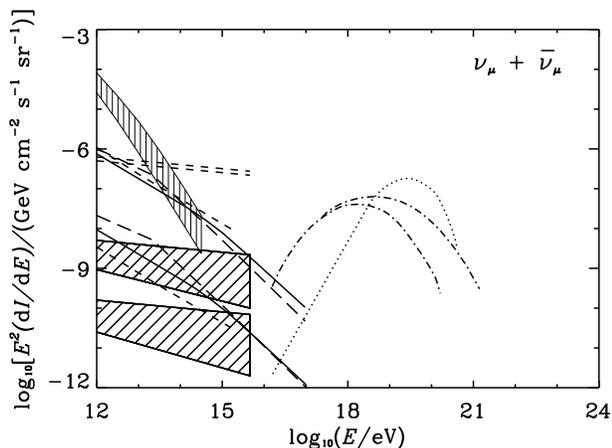


Figure 1: Neutrinos from cosmic ray interactions with the interstellar medium (upper curves for $\ell = 0^\circ$, $b = 0^\circ$, lower curves for $b = 90^\circ$): --- Domokos et al. [6]; ---- Berezhinsky et al. [7]; — Ingelman and Thunman [8]. The band with vertical hatching shows the range of atmospheric neutrino background as the zenith angle changes [9]. Neutrinos from cosmic ray interactions with the microwave background: - · - · - Protheroe and Johnson [17]; · · · · Hill and Schramm [18]. Neutrinos from cosmic ray interactions in clusters of galaxies (Berezhinsky et al. [19]): lower hatched area – normal galaxies; upper hatched area – AGN; = = = = upper limit if diffuse γ -ray flux originates in clusters.

Moving to higher energies, cosmic rays above $\sim 10^{20}$ eV will interact with photons of the cosmic microwave background radiation [11, 12]. Again, we know that both ingredients exist (the two highest energy cosmic rays detected

have energies of 3×10^{20} eV [13] and 2×10^{20} eV [14]), and so the pion photoproduction at these energies will occur resulting in a diffuse neutrino background. However, the intensity in this case is model-dependent because it is not certain precisely what is origin of the highest energy cosmic rays, and indeed if they are extragalactic, although this seems very probable (see my first lecture [15] for a discussion of the highest energy cosmic rays). One of the most likely explanations of the highest energy cosmic rays is acceleration in Fanaroff-Riley Class II radio galaxies as suggested by Rachen and Biermann [16]. Protheroe and Johnson [17] have repeated Rachen and Biermann's calculation in order to calculate the flux of diffuse neutrinos and γ -rays which would accompany the UHE cosmic rays, and their result has been added to Fig. 1. Any model in which the cosmic rays above 10^{20} eV are of extragalactic origin will predict a high energy diffuse neutrino intensity probably within an order of magnitude of this at 10^{18} eV. For example, I also show an earlier estimate by Hill and Schramm [18].

Somewhat less certain is the flux of neutrinos from clusters of galaxies. This is produced by pp interactions of high energy cosmic rays with intracluster gas. Berezhinsky et al. [19] have recently made predictions of this, and I have added to Fig. 1 their estimates of the diffuse neutrino intensity due to interactions of cosmic rays produced by normal galaxies and AGN. Also shown is their upper limit estimated assuming that all the diffuse γ -ray background is due to such interactions in clusters. However, this is unlikely to be the case (see next section).

3 Neutrinos from Active Galactic Nuclei

The second EGRET catalog of high-energy γ -ray sources [20] contains 40 high confidence identifications of AGN, and all appear to be blazars. Clearly, the γ -ray emission is associated with AGN jets. Blazars appear also to be able to explain the bulk of the diffuse γ ray emission [21], and models where γ -ray emission does not originate in the jet are unlikely to contribute significantly to the diffuse γ -ray (and neutrino) intensity (see Protheroe and Szabo [22] and references therein for predictions for non-blazar AGN). Several of the EGRET AGN show γ -ray variability with time scales of ~ 1 day [23] at GeV energies, and variability on time scales of ~ 1 hour or less [24] has been observed at TeV. This variability places an important constraint on the models, and not all models developed so far are consistent with this. I shall survey the neutrino emission predicted in blazar models irrespective of this, optimistically assuming these models may be made to accommodate the latest variability measurements.

Most theoretical work on γ -ray emission in AGN jets involved electron acceleration and inverse Compton scattering, and these models will predict no neutrinos. The alternative approach is to accelerate protons instead of, or as well as, electrons. In this case interactions of protons with matter or radiation would lead to neutrino production. In some of the proton models energetic protons interact with radiation via pion photoproduction (see my first lecture [15] for a discussion of $p\gamma$ interactions). This radiation may be reprocessed or direct accretion disk radiation [25], or may be produced locally, for example, by synchrotron radiation by electrons accelerated along with the protons [26, 27]. Pair synchrotron cascades initiated by photons and electrons resulting from pion decay give rise to the emerging spectra, and this also leads to quite acceptable fits to the observed spectra. This approach has the obvious advantage of leading to potentially much higher photon energies, because protons have a much lower synchrotron energy loss rate than electrons for a given magnetic environment. In both classes of model, shock acceleration has been suggested as the likely acceleration mechanism (see my first lecture [15] for a discussion of and references to shock acceleration).

By appropriately integrating over redshift and luminosity in an expanding universe, using a luminosity function (number density of objects per unit of luminosity) appropriate to blazars, and using the proton blazar models to model the γ ray and neutrino spectra one can estimate the diffuse neutrino background expected from blazars. Fig. 2 shows intensities of $(\nu_\mu + \bar{\nu}_\mu)$ in proton blazar models estimated by Mannheim [27] and Protheroe [25] together with estimates for blazars obtained under very different assumptions by Stecker [28] and Nellen *et al.* [29]. For some of these models Hill [30] has calculated expected muon rates.

4 Neutrinos from Exotic Sources

Finally, I discuss perhaps the most uncertain of the components of the diffuse high energy neutrino background, that due to exotic sources such as topological defects. The possibility that topological defects could be responsible for the highest energy cosmic rays was discussed briefly in my first lecture [15]. Although these models appear to be ruled out by the high GeV γ -ray intensity produced in cascades initiated by X-particle decay [31, 32], I plot in Fig. 3 the neutrino emission for a set of TD model parameters just ruled out according to Protheroe and Stanev [32] and just allowed according to Sigl *et al.* [33]. I emphasize that these predictions are *not* absolute predictions but the intensity of γ -rays and nucleons in the resulting cascade is normalized in some way to the highest energy cosmic ray data. It is my opinion [15, 31, 32] that these

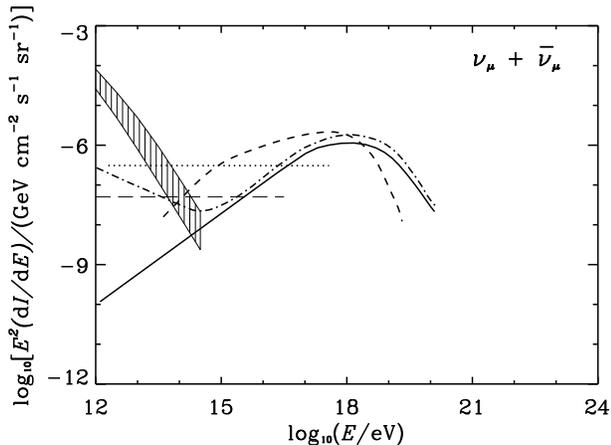


Figure 2: Diffuse neutrinos from blazars: ——— $p\gamma$ Mannheim [27]; - · - · - · - pp and $p\gamma$ Mannheim [27]; - - - - $p\gamma$ Protheroe [25]; — — — — Stecker [28]; ····· Nellen [29].

models are neither necessary nor able to explain the highest energy cosmic rays without violating the GeV γ -ray flux observed. Also shown is an estimate of the diffuse neutrino intensity estimated in a model in which the highest energy cosmic rays have their origin in sources of gamma ray bursts [34]

The intensities shown in Fig. 3 are *extremely* uncertain. Nevertheless, it is important to search for such emission because, if it is found, it would overturn our current thinking on the origin of the highest energy cosmic rays and, perhaps more importantly, our understanding of the universe itself.

5 Conclusion

It is beyond doubt that astrophysical sources of high energy neutrinos exist. Given that we know cosmic rays exist in our galaxy which contains interstellar matter, cosmic ray interactions will result in the galaxy glowing in high energy neutrinos. The neutrino intensities are likely to be just observable with the 1 km³ neutrino detectors currently under consideration. The real challenge and interest is in attempting to detect emission from other possible astrophysical sources such as AGN, and the emission due to cascades initiated in the microwave background by high energy cosmic rays accelerated in radio galaxies, or by topological defects. However, we cannot predict everything – unexpected discoveries have always occurred whenever a new window on the universe is

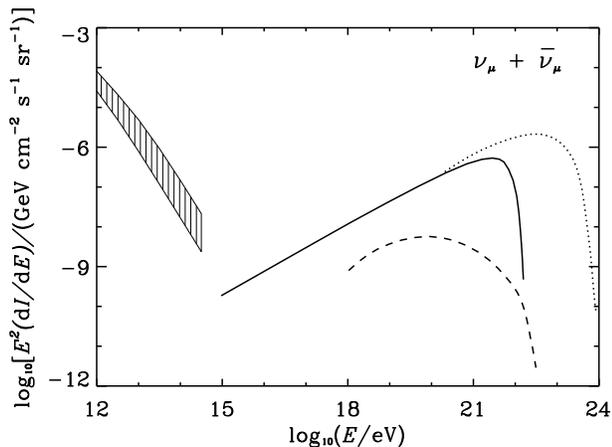


Figure 3: Neutrinos from exotic sources: ——— TD model just ruled out according to Protheroe and Stanev [32]; ····· TD model just allowed according to Sigl et al. [33]; - - - - - GRB model according to Lee [34].

opened and it would be surprising if this time there were no surprises! It is therefore very important that neutrino astronomy with 1 km³ detectors proceed rapidly.

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