HIGH ENERGY NEUTRINO FLUXES FROM COSMIC ACCELERATORS

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We constrain high-energy neutrino fluxes with the observed cosmic ray and gamma ray fluxes, include flavor oscillations and propagation through Earth, and show that blazars could possibly be detected by cubic-kilometer neutrino telescopes.

1 Introduction

As several cubic-kilometer neutrino telescopes are being planned, it is instructive to ask about the maximum event rate one should expect for these telescopes. Evidently any answer to this question depends on some crucial assumptions, especially concerning the nature of possible neutrino sources.

Following the discussion in Mannheim et al., we derive an upper flux limit under the assumptions that (i) protons do not escape from the acceleration region (whereas neutral particles do), (ii) the power index of the target flux density spectrum (i.e. the synchrotron photons which accelerated electrons and protons can interact with photohadronically) is given by $\alpha = -1$, and (iii) the cosmic ray proton flux has the value

$$N_{p,\text{obs}}(E_p) = 0.8 \times (E_p/1 \text{ GeV})^{-2.75} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}. \quad (1)$$

Eq. (1) is an upper limit consistent with all observations for proton energies $E_p$ between $3 \times 10^6$ and $10^{12}$ GeV. Assumption (ii) implies that the bolometric gamma-ray luminosity $L_\gamma$ of the sources considered equals twice the neutrino luminosity $L_\nu$:

$$L_\gamma = 2L_\nu.$$  

Using particle physics, one may obtain the muon neutrino production rate from the corresponding neutron production rate:

$$Q_{\nu_\mu}(E) \approx 83.3Q_n(25E). \quad (2)$$
Here and in the following particles and antiparticles are not distinguished. The cosmic ray proton flux (which is due to the decay of neutrons leaving the source) is given by

\[ Q_{\text{cr}}(E_p) \approx Q_n(E_p) \times P_{\text{esc},n}(E_p), \tag{3} \]

where \( P_{\text{esc},n} \) denotes the neutron escape probability.

### 2 Constructing neutrino flux bounds

The recipe for constructing a generic upper bound on the neutrino flux can now be stated as follows: Given some neutron production rate one may compute the corresponding production rates of muon neutrinos and cosmic ray protons by means of Eqs. 2 and 3. In order to compute the neutrino and proton fluxes \( I \) at Earth resulting from these production rates, one has to integrate over all sources in the universe, bearing in mind that interactions during the flight (e.g. Bethe-Heitler processes and pion production) change the particle spectra:

\[
I(E) \propto \frac{1}{4\pi} \int_{z_{\text{min}}}^{z_{\text{max}}} M(E,z) \frac{(1+z)^2}{4\pi d_L^2} \frac{dV_c}{dz} \frac{dP_{\text{source}}}{dV_c} Q((1+z)E,z) dz. \tag{4}
\]

Here \( z \) denotes the redshift factor, \( V_c \) the comoving volume, \( d_L \) the luminosity distance, and \( dP_{\text{source}}/dV_c \) the redshift distribution. \( M(E,z) \) takes into account the modification of the spectrum due to interactions during the flight. For neutrinos \( M(E,z) = 1 \) holds valid.

Finally, the expressions for \( I_{\nu\mu} \) and \( I_{\text{cr}} \) thus obtained are normalized so that \( I_{\text{cr}} \) is tangent to the observational cosmic ray proton flux limit (Eq. 1). If gamma-rays are overproduced for this normalization (i.e. if \( L_\gamma = 2 L_\nu \) is greater than the bolometric diffuse gamma-ray luminosity), the proton and neutrino fluxes are reduced appropriately.

Fig. 1 shows several bounds obtained by means of the formalism just described:

1. Generic bound for optically thin sources with \( Q_n(E_n) \propto E_n^{-1} \exp(-E_n/E_{\text{max}}) \), the redshift distribution of which equals that of AGN and galaxies. The generic bound (denoted by \( \tau_{n\gamma} < 1 \)) is the envelope of the flux limits computed for each \( E_{\text{max}} \).
2. Generic bound for optically thick sources. Here the bound (denoted by \( \tau_{n\gamma} \gg 1 \)) is derived by demanding consistency with the diffuse gamma ray background only.
3. Generic bound for blazars. The construction parallels that of the generic bound for optically thin sources, but we assume a spectral break between \( 10^7 \) GeV and \( 10^{11} \) GeV in the escaping cosmic ray flux due to opacity effects (still allowing for \( > GeV \) photon emission).
4. Bounds for EGRET blazars and BL Lac objects. In computing the flux limit from Eq. 4 \( Q_{\text{cr}} \) and \( Q_\nu \) are averaged over the luminosity function and redshift distribution of EGRET-detected blazars and BL Lacs, respectively.

Details of the calculation of these bounds may be found in Mannheim et al.

### 3 Event rates in neutrino telescopes

So far, we have considered muon neutrinos only. However, as neutrinos are produced predominantly via pion decays, one should expect the ratio \( Q_{\nu_e} : Q_{\nu_\mu} : Q_{\nu_\tau} \approx 1 : 2 : 0 \) for the various neutrino production rates. In addition, flavor oscillations during the flight to Earth lead to a flux ratio of \( I_{\nu_e} : I_{\nu_\mu} : I_{\nu_\tau} = 1 : 1 : 1 \). Hence in the following, we will assume equal numbers of neutrinos for the three flavors and change the upper bounds accordingly.
Furthermore, the neutrino fluxes are altered due to neutrino-nucleon interactions during the crossing of the inner Earth:

\[
\frac{dI_{\nu_i}(E)}{dt} = -\sigma_{i,\text{tot}}(E)I_{\nu_i}(E) + \sum_k \int_{E}^{\infty} dE' \frac{d\sigma_{k\rightarrow i}}{dE}(E', E)I_{\nu_k}(E') + \text{decay of } \tau.
\]

In this equation, \(i\) and \(k\) denote neutrino flavors, \(t\) the column number density. \(d\sigma_{k\rightarrow i}/dE\) constitutes the differential cross section for turning a neutrino of flavor \(k\) and energy \(E'\) into one of flavor \(i\) and energy \(E\). \(\sigma_{i,\text{tot}}\) is the total (charged and neutral current) cross section of \(\nu_i\).

Limiting ourselves to muon neutrinos, we may write the differential muon event rate \(d\dot{N}/dE\) in a neutrino telescope with an effective area \(A_{\text{eff}}\) as a sum of two terms covering the muons due to neutrino-nucleon interactions inside and outside the detector:

\[
\frac{d\dot{N}}{dE} = \frac{\rho}{m_p} A_{\text{eff}} \left( L \int_{E}^{\infty} dE' \frac{d\sigma_{\text{CC}}}{dE}(E', E)I_{\nu_\mu}(E') + \int_{0}^{\infty} dx \int_{E}^{\infty} dE' \frac{d\sigma_{\text{CC}}}{dE}(E', E_0(E, x))I_{\nu_\mu}(E') \right).
\]

Here \(d\sigma_{\text{CC}}/dE\) constitutes the differential cross section for charged current interactions, \(\rho\) the density of the detector medium (i.e., \(\rho = 1\) g/cm\(^3\) for water), \(L\) the detector length, and \(m_p\) the proton mass. \(E_0(E, x)\) denotes the energy a muon must have so that after crossing a distance \(x\) of the detector medium (and thus suffering radiative losses) it retains the energy \(E\).

The event rates corresponding to various neutrino flux bounds are shown in Fig. 2 for horizontal and vertical incidence, assuming a cubic kilometer telescope.

4 Discussion

Fig. 2 clearly shows that whereas EGRET-blazar-like neutrino spectra might imply an event rate of about ten events per year and steradian, generic blazar models could allow neutrino event rates of several hundred events per year and steradian (most sources would then not be
gamma ray emitters above GeV). This exceeds the limit obtained by Waxman and Bahcall for optically thin sources (which is comparable to our BL Lac case) by one to two orders of magnitude, reflecting the different assumptions.

Any derivation of an upper neutrino flux limit faces two important unknowns: Firstly, intergalactic magnetic fields (which affect protons but have no influence on neutrinos) might considerably change the number of neutrinos compatible with cosmic ray observations. Secondly, the same applies to exotic processes such as the decay of superheavy particles.

The planned cubic-kilometer neutrino telescopes will reach the sensitivity necessary to probe the assumptions that enter the flux-limit calculations. If photohadronic processes play an important role in blazars, we have shown that they will very likely be detected by such telescopes.

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