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A source property based estimate of the neutrino flux from blazars and steep spectrum sources

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Large volume neutrino telescopes like Antares and IceCube are being built as successors of AMANDA-II, Baikal and others to detect a neutrino signal at ultrahigh energies (i.e. $E >$PeV) from extraterrestrial sources. One of the most interesting extragalactic source candidates are Active Galactic Nuclei (AGN). Previous neutrino flux models have been normalized to the charged Cosmic Ray component or to the photon spectrum at Earth at different wavelengths. In this prediction, two source types with very different appearance in the photon light, i.e. blazars and steep spectrum AGN, will be examined. The spectrum is normalized by assuming that the disk luminosity is connected to the power of the AGN jets as it has been pointed out by Falcke et al. [4, 5, 3]. There, it was also shown that the maximum proton energy is dependent on the disk luminosity which has been implemented into the calculations presented in this paper as well. The result is highly dependent on the spectral index of the photon energy spectrum. The normalization of the spectrum will be examined in detail and a comparison of a mean diffuse prediction to a coincident spectrum of a source subsample will be made.

1. Introduction

Since the atmospheric neutrino spectrum represents a very intense background, a detection of an extragalactic neutrino signal was not possible yet. Thus, the investigation of a possible signal from various extragalactic sources is necessary to analyze the potential of different source types, see [6] for a summary. The total diffuse neutrino spectrum from a certain source class at Earth is given by the single source spectrum dN/dE_ν convoluted with the redshift and luminosity dependent source number. A factor $1/(4\pi\, d_L^2)$ is applied to account for the decrease of the source flux with the luminosity distance d_L. The source number is given by the product of the Radio Luminosity Function (RLF), dn/dL, of AGN and the comoving volume dV/dz. Thus, the total diffuse neutrino Φ flux can be written as

$$\Phi(E_\nu^0) = \int_z \int_L dz\, dL\, \frac{dN}{dE_\nu}(E_\nu^0, L, z) \cdot \frac{dn}{dL}(L, z) \cdot \frac{dV}{dz} \cdot \frac{1}{4\pi\, d_L(z)^2}\,.$$

A shift of the neutrino energy at the source E_ν to lower energies at the detection site due to the expanding Universe, $E_\nu^0 = E_\nu/(1+z)$, is taken into account. A simple cosmology of $\Omega_m = 1$ and $\Omega_\Lambda = 0$ will be used, since the spatial distributions of the source samples are given according to this cosmology. The changes in the normalization of the result when using the experimentally confirmed model of $\Omega_m \sim 0.3$ and $\Omega_\Lambda \sim 0.7$ [9] should be negligible as it has been pointed out in [2].

2. Samples and Source Spectra for a diffuse prediction

For the derivation of a source spectrum, it is assumed that the neutrino spectrum follows the proton spectrum in first order approximation. Effects from multipion production are neglected, since the changes to the spectrum due to this effect would be negligible with respect to other remaining uncertainties in the calculation such as the lack of knowledge of the sources' optical depth. The spectrum is normalized using the *jet-disk symbiosis* approach which has been developed in [4, 5, 3], where it is stated that jet and disk luminosity are directly connected. In the following it is further assumed that particles from an AGN produce the same order of magnitude of luminosity as the jet power, and neutrinos contribute with a fraction $q_\nu < 1$. A detailed derivation of the normalization is given in [1]. Two different source samples of AGN subclasses will be taken into account. The first one consists of 356 steep spectrum sources selected by Willott et al. [11]. For this source type, two models will be presented in the following: the spectral index of the proton spectrum and thus of the neutrino flux, p ($dN/dE \propto E^{-p}$), can be expressed through the synchrotron spectral index α as $p = 2 \cdot \alpha + 1$ ($F_\nu \propto \nu^{-\alpha}$). This approach will be referred to as *model 1* in the following. In *model 2*, $p = 2$ will be assumed following the derivation of particle spectra from diffuse shock acceleration. The second sample contains 171 flat spectrum sources as is presented by Dunlop and Peacock [2]. In this case, the observed photon spectrum is an overlap of all emitted synchrotron radiation in the AGN jets, since these sources point their jets directly towards Earth. In this case, model 1 cannot be applied and calculations will be presented for $p = 2$ according to the model of shock acceleration. The spatial distribution functions of the two source types are given in [11] and [2] respectively.

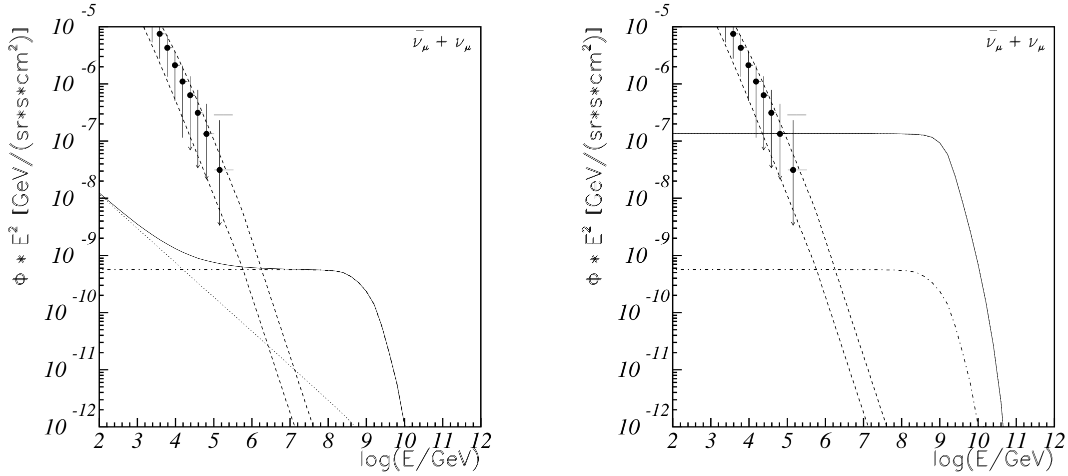

Figure 1. AGN $\nu_\mu + \overline{\nu}_\mu$ neutrino spectrum. *Left panel:* $p = 2.6$ for steep spectrum sources and $p = 2.0$ for flat spectrum sources (model 1). The steep spectrum sources (dotted line) make up most of the spectrum at lower energies ($E_\nu > 10^6$ GeV). The flat spectrum sources (dot-dashed line) dominate the total spectrum (solid line) at energies of $E_\nu > 10^6$ GeV. A signal that exceeds the atmospheric contribution is expected starting at $E_\nu > 10^7$ GeV. *Right panel:* $p = 2$ (model 2). The flat spectrum sources (dot-dashed line) do not contribute significantly compared to the steep spectrum population - the solid line represents the sum of flat and steep spectrum sources which does not differ from the result for steep spectrum sources. The data points result from unfolding the AMANDA-II neutrino spectrum. They follow the conventional atmospheric neutrino spectrum (dashed lines) and an upper limit is derived as is indicated in the figure, see [7] for details.

3. Diffuse prediction and a coincidence expectation

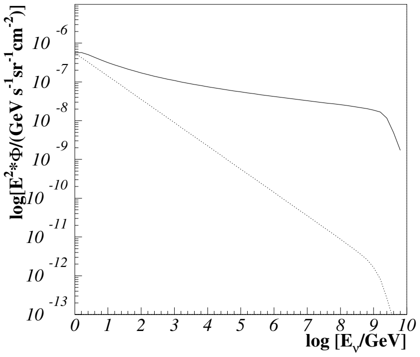

Figure 2. Total flux of steep spectrum sources, the coincidence spectrum of 114 sources (solid line), normalized to the total diffuse prediction (dashed line) at $E = 1$ GeV. It can clearly be seen that the behavior of the spectral index differs significantly from the diffuse prediction.

A diffuse prediction can be made by using the radio luminosity functions as they have been developed for the two source samples (see [2] for flat spectrum sources and [11] for steep spectrum sources). In this case, the spectral index is assumed to be the same for each source in a sample. Model 1 uses $p = 2.6$ for steep spectrum sources which is based on a mean synchrotron spectral index of $\alpha = 0.8$. Model 2 uses $p = 2$ for both samples as it is predicted by diffuse shock acceleration. The resulting diffuse flux is shown in Fig. 1 (left panel: model 1, right panel: model 2). It can be seen that the flux is very low using model 1, but that the prediction is near to the sensitivity level of current neutrino telescopes as AMANDA-II for an E^{-2} spectrum.

A more precise way of determining the total flux of a specific source sample is to use specific source parameters to determine the single source spectra and calculate the coincident flux for these sources. A subsample of 109 sources from the steep spectrum sample [11] has been used to analyze the differences between an average prediction and a source property based estimate. Fig. 2 shows the resulting spectrum when using flux density S, spectral index α and redshift z as given in the S1-S5 catalogs [8]. The calculations have been done using model 1. Since only a small fraction of all steep spectrum sources has been considered, an overall diffuse normalization cannot be derived easily. Thus, only differences in the spectral behavior between coincidence and diffuse prediction are relevant. The coincidence flux (solid line) is normalized to the diffuse prediction at $E_\nu = 1$ GeV. It can clearly be seen that the coincidence spectrum is much flatter ($dN/dE_\nu \propto E_\nu^{-2.2}$) that the diffuse prediction, although the subsample that is used for the coincidence prediction shows a mean spectral index of $\alpha = 0.8$ as it has been used for the diffuse prediction.

4. Conclusions

Fig. 3 summarizes various neutrino flux predictions of different extragalactic sources. With this work, it can be shown that there is a good potential to detect a neutrino flux from flat and steep spectrum AGN with an E^{-2} spectrum (model 2). The prediction in model 1 is very low, however, the calculation of a coincidence neutrino flux suggests that the spectral behavior of $E^{-2.6}$ as it has been used for the diffuse prediction (model 1) is not necessarily valid, since a few sources with a flatter spectrum will dominate the total flux with a resulting $\sim E_\nu^{-2.2}$ spectrum.

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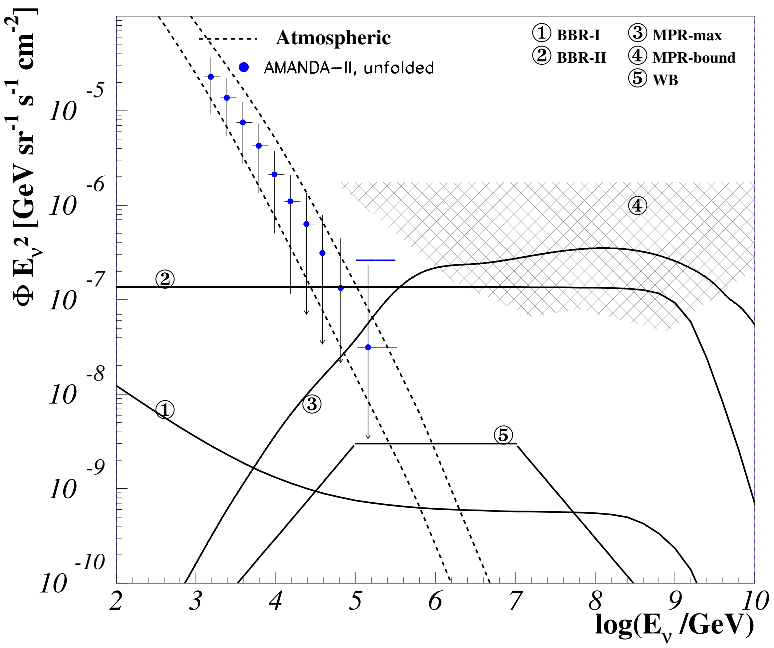

Figure 3. Combined figure of various UHE neutrino flux predictions. Data are taken from AMANDA-II, see [7]. The detection of neutrinos at these energies is currently still restricted to atmospheric neutrinos (dashed line). Models 1 and 2 are the predictions presented here, 1 applying the connection of the synchrotron radiation index for steep spectrum sources resulting in $p = 2.6$ for the steep spectrum source contribution (BBR-I), 2 using a spectral index of $p = 2$ following diffuse shock acceleration for both source types (BBR-II). Model 3 is the maximum prediction of the diffuse neutrino flux from blazars given (MPR-max). The shaded area (labeled 4) is the corresponding upper bound, given sources with high optical depth for $\gamma\, n$ interactions ($\tau_{n\gamma} >> 1$ upper straight line) and low optical depth ($\tau_{n\gamma} << 1$ lower part of shaded area). Model 5 gives the standard prediction of [10] for a diffuse neutrino flux from GRBs (WB). The atmospheric prediction and models 3-5 are reviewed in [6].

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