Neutrino production in active galaxies

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ABSTRACT. We discuss the production of neutrinos in radio-quiet and radio-loud AGN. The diffuse background of neutrinos from these extragalactic sources should be detectable with dedicated neutrino telescopes currently under construction.

RESUMEN. Discutimos la producción de neutrinos en los núcleos activos de galaxias, AGN, y "blazars". El fondo difuso de neutrinos que proviene de estas fuentes extragalácticas debería poder ser detectado con los telescopios dedicados a neutrinos que ahora se construyen.

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1. INTRODUCTION

The active nuclei of galaxies (AGN), ranging in luminosity from Seyfert galaxies to quasars, are the most powerful individual sources of radiation in the Universe. Even though so far only electromagnetic radiation has been observed, it is generally assumed that other particles are accelerated and emitted as well in order to explain the tight relationship between the non-thermal and thermal components in the UV and hard X-ray spectra [1–5]. Here we are interested in neutrinos, since they can travel cosmological distances without losing the information on the direction they originated from. Large underwater detectors [6, 7] or detectors in the antarctic ice cap [8] are used as neutrino telescopes. In fact, data from proton decay experiments [9] and airshower arrays [10] already provides some constraints on the neutrino background.

2. THE AGN MODEL

In the following we are interested in the production of neutrinos in radio-loud and radio-quiet AGN. First, we would like to review briefly the "standard" model for AGN (for a review, see [11] and references therein). One assumes the existence of a supermassive black hole in the centre of the AGN, surrounded by an accretion disk of infalling matter. Perpendicular to the disk, two plasma jets are emitted. Such jets can be seen in different objects with disk accretion and in many AGN [12, 13]. One expects shocks in the plasma of the jets [14] which could accelerate protons through first order Fermi acceleration. The maximal energy ranges from \(10^6\) GeV to \(10^9\) GeV, depending on the distance to the black hole, with a powerlaw spectrum of \(E^{-2}\) [15]. The observation of \(\gamma\)-rays with the same kind
of spectrum [16] indicates that indeed there is shock-acceleration outside the core of the AGN, so that the photons can escape.

The reason that AGN appear widely different depends on the details of a given source:
- The power emitted by the AGN depends largely on the rate of accretion onto the black hole. This can vary from several solar masses per year to less than $0.01 M_\odot$ per year.
- In a dense surrounding gas, the jets cannot propagate far before they get dissipated. On the other extreme, in the case of radio galaxies, jets can be seen which propagate up to $\approx$ Mpc out into the intergalactic medium.
- If we are aligned with the axis of a jet, the radiation emitted will be focused due to relativistic boosting. Such sources, commonly referred to as blazars, appear particularly powerful.

3. NEUTRINO PRODUCTION

Neutrino production takes place either in the inner region of the accretion disk, where $pp$-interactions dominate, or inside the jet, where $p\gamma$-reactions are more important.

3.1. Hadronic cascades

The first class of AGN we want to discuss here are the radio-quiet sources, which make up about 90% of all AGN. In these sources, no visible jets develop.

From the observed short timescale variations of the hard X-ray and UV components of the AGN spectrum one concludes that this radiation must originate in a small, central
region of the disk around the black hole [17, 18] with a typical mass of $10^8 M_\odot$ for luminous AGN. We expect neutrino production to take place in the same region, so we need to know the incoming flux of accelerated particles from the jets to this region.

To get a sufficient proton flux in the inner region of the accretion disk the acceleration region in the jet has to be sufficiently close to the centre of the AGN. In [19], Niemeyer and Biermann used the same population of protons to heat up dust further out in the accretion disk in order to fit the far infra-red (FIR) emission from AGN. Their best fits suggest a distance of $z_0 \approx 3 \cdot 10^{15}$ cm $\approx 100 R_S$ from the centre of the disk for the acceleration region.

In the inner region of the accretion disk, the column density of the disk is somewhat larger than the interaction length for $pp$-interactions. The magnetic field confines the protons to the disk, which leads to an even further increase of the effective column density seen by the protons. Even though neutrons, which are produced in the cascade, are not confined by the magnetic field, the amount of gas present is sufficient to prevent them from escaping; they interact before they can decay.

The hadronic cascade in the disk is much simpler than cascades in the earth's atmosphere [20–23], since the density of the accretion disk is so low that all unstable particles decay rather than interact. Therefore the cascade consists of a nucleonic part which feeds into the mesonic and electro-magnetic channels; no pion-nucleon reactions occur. The structure of the cascade is therefore:

$$
p \rightarrow N + \pi \nonumber$$

$$n \rightarrow N + \pi \nonumber$$

$$\pi^0 \rightarrow \gamma + \gamma \nonumber$$

$$\pi^\pm \rightarrow \nu_\mu + \mu \nonumber$$

$$\mu \rightarrow \nu_\mu + \nu_e + e \nonumber$$

where $N = p, n$. Furthermore, the pion channel will always be the dominant channel for the production of neutrinos. This is different from the production of cosmic ray neutrinos in the atmosphere, since there reactions of pions with nuclei remove the pions from the parent population for neutrino production. Under the assumptions of scaling hadronic cross-sections, the power law of the incident protons is kept and inherited by all the secondaries, i.e., the flux of particle $x$ is

$$\dot{n}_x(E) = C_x \dot{n}_p(E), \quad \dot{n}_p(E) = \tilde{C} E^{-\gamma-1}, \quad (1)$$

where $\tilde{C}$ is the normalization of the proton spectrum. The specific power in protons is then

$$\dot{E}_p^{(\text{tot})} = \int_{E_p^{(\text{min})}}^{E_p^{(\text{max})}} E' \dot{n}_p(E') dE', \nonumber$$

$$= \begin{cases} \tilde{C} (1 - \gamma)^{-1} \left( (E_p^{(\text{max})})^{-\gamma+1} - (E_p^{(\text{min})})^{-\gamma+1} \right) \quad \text{for } \gamma \neq 1, \\ \tilde{C} \ln \left( \frac{E_p^{(\text{max})}}{E_p^{(\text{min})}} \right) \quad \text{for } \gamma = 1. \end{cases} \quad (2)$$
NEUTRINO PRODUCTION IN ACTIVE GALAXIES

<table>
<thead>
<tr>
<th>Species</th>
<th>$\epsilon_x$</th>
<th>$C_x = \frac{E_x^{\text{tot}}}{E_p^{\text{tot}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>0.070</td>
<td>0.29</td>
</tr>
<tr>
<td>$e$</td>
<td>0.056</td>
<td>0.16</td>
</tr>
<tr>
<td>$\nu_\mu$ from $\pi$</td>
<td>0.040</td>
<td>0.13</td>
</tr>
<tr>
<td>$\nu_\mu$ from $\mu$</td>
<td>0.056</td>
<td>0.16</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>0.048</td>
<td>0.14</td>
</tr>
</tbody>
</table>

For the secondaries, the energy range is shifted down by a factor $\epsilon_x$; the resulting power is

$$\dot{E}_x^{\text{tot}} = \int_{E_p^{\text{min}}}^{E_p^{\text{max}}} E' \hat{n}_x(E') \, dE',$$

$$= C_x \epsilon_x^{-\gamma+1} \dot{E}_p^{\text{tot}}. \quad (3)$$

The solution of the cascade equations is summarized in table 1 [24]. We see that $\approx 49\%$ of the power is emitted as neutrinos where $\approx 33\%$ of the power goes into muon type neutrinos. The rest is electromagnetic where twice as much luminosity is emitted in photons as in electrons. Muon neutrinos and anti-neutrinos, which are the species which experiments are most sensitive to, carry about $2/3$ of the power emitted in the electromagnetic channel.

3.1.1. Electromagnetic radiation

The electromagnetic output of the hadronic cascade is reprocessed in the inner disk. Pair cascades, inverse Compton scattering, and reflection on cold material change the shape of the initial $E^{-2}$-spectrum and provide a steep turnover around $E_\gamma \approx m_e \approx 511$ keV [25–30]. This produces the observed hard X-ray and gamma emission of the AGN.

3.1.2. Resulting neutrino spectrum

The neutrino spectrum from a single source mirrors the $E^{-2}$-spectrum of the protons, only that it is shifted down by a factor of $\epsilon_\nu \approx 0.05$. The upper cutoff of the neutrino spectrum depends on the details of the shock acceleration process in the jet, since that determines the maximum energy reached by the protons [31].

The Neutrino luminosity: To get an estimate of the neutrino luminosity of a source, we use its total emission in hard X-rays and $\gamma$-rays as a reference. We assume that the power emitted at hard X-ray and $\gamma$-ray energies is the electromagnetic power output of the hadronic cascade, reprocessed in the inner disk to yield the observed spectrum (see section 3.1.1). The relation we get is then

$$\dot{E}_\nu^{\text{tot}} = 0.95 \dot{E}_X^{\text{tot}} + \dot{E}_\gamma^{\text{tot}}. \quad (4)$$

TABLE 1. Relative normalization of the spectrum of secondaries, shift of particle energies, and fraction of the incident proton luminosity energy carried by the stable secondaries for $\gamma = 1$. The total energy in one species is split evenly between particles and anti-particles.

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$$\dot{E}_\nu^{\text{tot}} = 0.95 \dot{E}_X^{\text{tot}} + \dot{E}_\gamma^{\text{tot}}. \quad (4)$$
Using an observation for $\nu_{\chi+\gamma}^{(\text{tot})}$, equation (3) allows us to determine $C_{\nu}$. There is actually a logarithmic dependence on the energy range of the neutrinos; for definiteness we take the range $10^{-2}\text{ GeV} \ldots 5 \cdot 10^3\text{ GeV}$.

### 3.2. Neutrinos from $p\gamma$-reactions

In radio-loud AGN, the jets are the main source of the radiation. Compared to radio-quiet AGN, the jets in radio-loud AGN reach further out from the host galaxy. Furthermore, the plasma flow in the jets can be relativistic with Lorentz-factors $\gamma_j = 10 \ldots 20$ [32], which gives additional enhancements to the radiation from the jet.

From observation, it is known that blazars can emit photons in the TeV region with an $E^{-2}$ spectrum [16]. In models which use a proton initiated cascade to produce the gamma spectrum from blazar sources [32, 33], neutrinos necessarily arise. We use this model for radio-loud sources in general.

In the environment of the jet, the proton density is too low for $p\pi$-reactions to be significant. However, the photon density is sufficiently high for a significant rate of $p\gamma$-reactions. The dominant channel is pion production via $p\gamma \rightarrow \Delta \rightarrow N\pi$. The decay of the pions ultimately leads to the production of photons, electrons and neutrinos exactly as in the case of $p\pi$-initiated reactions discussed above. In particular, this means that the neutrino luminosity is the same as the gamma luminosity.

In the case of the jets of radio-loud AGN, the photon target is the local photon field with an $E^{-2}$ powerlaw spectrum. The reaction rate for the production of $\Delta$'s is

$$q_{\Delta}(E) \propto n_{\gamma}(E) \sigma_{p\gamma \rightarrow \Delta},$$

where $n_{\gamma}(E)$ is the number of available target photons for protons of energy $(E)$. Since the cross-section for the process $p\gamma \rightarrow \Delta$ has a very pronounced peak at the threshold, only photons with an energy

$$E_{\gamma} \geq \frac{s^2_{\text{threshold}}}{E_p}$$

are available as target photons. The integrated photon spectrum in the jet is $N_{\gamma}(\geq E) \propto E^{-1}$. Which, together with equations (5) and (6), leads to a reaction rate of

$$q_{\Delta}(E) \propto E^{-1}.$$  

This means that the produced neutrinos will have a differential spectrum of

$$\frac{dN_{\nu}}{dE_{\nu}} = C_{\nu} E^{-1}$$

instead of the $E^{-2}$ we got in the $pp$ case, since they inherit the proton power law. The electrons and photons are reprocessed in the jet, ultimately producing the $E^{-2}$ photon target [32].

To determine the constant $E_{\nu}$, we use again that $\dot{E}_{\nu}^{(\text{tot})} \approx \dot{E}_{\gamma}^{(\text{tot})}$ to relate $C_{\nu}$ and $C_{\gamma}$. Therefore, using information on the $\gamma$-luminosity of the source, we can determine its
neutrino luminosity. However, since the neutrino spectrum has a spectral index of $\gamma = 0$, we see from equation (2) that the normalization constant $C_\nu$ has a significant dependence on the maximum neutrino energy $E_\nu^{\text{max}}$, which we have to keep as a free parameter.

4. THE DIFFUSE NEUTRINO BACKGROUND

To compute the diffuse neutrino background, we start from the observation of the hard X-ray and $\gamma$ emission from radio-loud and radio-quiet AGN. The data on the source population is summarized in the form of luminosity functions $\rho(L, z)$, which are the density of sources with a given luminosity $L$ at a given redshift $z$ [34, 35]. The diffuse background can be computed by integrating over all sources at all redshifts:

$$\frac{dI}{dE} = \frac{c}{4\pi H_0} \int_0^{L_{\text{max}}} dz \int_{L_{\text{min}}}^{L_{\text{max}}} \frac{dN_s}{dE} \left(\frac{1+z}{E_s}E_s, z, L_s\right)(1+z)^{-\alpha} \rho(L_s, z),$$

where $dN_s/dE_s(E_s, z, L_s)$ is the neutrino spectrum for a source of luminosity $L_s$ at redshift $z$. The parameter $H_0$ is the Hubble constant and $\alpha$ characterizes the geometry of the universe:

$$\alpha = \begin{cases} 2 & \text{for } \Omega = 0, \\ 5/2 & \text{for } \Omega = 1. \end{cases}$$

For the radio-quiet AGN's, we use the X-ray luminosity functions from [34]. They fit different models for the evolution of the AGN population as a function of the redshift. It turns out, though, that all their models lead to the same prediction for the neutrino spectrum.

To compute the contribution of radio-loud AGN to the diffuse neutrino background, we use the radio luminosity functions from [35] and the correlation between radio luminosity and $\gamma$-ray luminosity from [36]. Since we have to keep the maximum neutrino energy $E_\nu^{\text{max}}$ as a free parameter, we get a family of possible neutrino spectra.

The results of this calculation are summarized in Figure 2. The radio-quiet AGN contribution can be described by the power law

$$\frac{dN_{\nu}^{\text{r}}}{dE} = 1.7 \cdot 10^{-12} \left(\frac{E}{\text{TeV}}\right)^{2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$$

for energies below $\approx 2 \cdot 10^{5}$ GeV. In the case of the radio-loud AGN, their contribution to the diffuse background can be summarized by

$$\frac{dN_{\nu}^{\text{l}}}{dE} = 6.9 \cdot 10^{-11} \left(\frac{E}{\text{TeV}}\right)^{1} \left(\frac{E_{\nu}^{\text{(max)}}}{\text{TeV}}\right)^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$$

for energies below $\approx 0.5E_{\nu}^{\text{(max)}}$. 

We notice that for values of $E^{(\text{max})}_\nu$ below 100 TeV, the contribution of radio-loud AGN to the diffuse neutrino background is not detectable. For more typical values of $E^{(\text{max})}_\nu \approx 10^4 \ldots 10^6$ TeV, neutrinos from radio-loud AGN will be the dominant component beyond $\approx 10^3$ TeV. Furthermore, we expect the spectral index to change at the same energy from $\gamma = 1$ to $\gamma = 0$.

5. DISCUSSION

We see that the interesting energy region for extragalactic neutrino astronomy starts at a few $10^4$ GeV. Below this energy, atmospheric neutrinos — produced locally as secondaries in reactions of incident cosmic rays — dominate the diffuse neutrino background. Above that, extragalactic neutrinos should be detectable in the next generation of neutrino telescopes like AMANDA, DUMAND or NESTOR — in fact, our prediction is already close to the limits set by the Frejus proton decay experiment [9, 10, 37].
ACKNOWLEDGMENTS

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34. K. Morisawa and F. Takahara, Publ. Astron. Soc. Japan 41 (1989) 873, Note: due to a typing mistake, an exponent of $-1.6$ was omitted at the end of equation (1c).