Neutrino production through hadronic cascades in AGN accretion disks

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Abstract

We consider the production of neutrinos in active galactic nuclei (AGN) through hadronic cascades. The initial, high energy nucleons are accelerated in a source above the accretion disk around the central black hole. From the source, the particles diffuse back to the disk and initiate hadronic cascades. The observable output from the cascade are electromagnetic radiation and neutrinos. We use the observed diffuse background X-ray luminosity, which presumably results from this process, to predict the diffuse neutrino flux close to existing limits from the Frejus experiment. The resulting neutrino spectrum is $E^{-2}$ down to the GeV region. We discuss modifications of this scenario which reduce the predicted neutrino flux.

1
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. To explain the power emitted by such objects, one generally assumes the existence of a central engine in which the gravitational energy of matter falling into a supermassive black hole gets converted into radiation. Even though so far only electromagnetic radiation has been observed, it is generally assumed that other particles are accelerated and emitted as well to explain the tight relationship between the non-thermal and thermal components in the UV and X-ray spectra [1, 2, 3, 4, 5]. Of special interest are 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. Recent calculations have shown that the flux of neutrinos originating in an AGN could be detected by such experiments [9, 10, 11, 12, 13]. Data from proton decay experiments [14] and airshower arrays [15] is already sensitive enough to constrain such models significantly.

2 The AGN model

In the following we are interested in the production of neutrinos in radio-quiet AGN. In the “standard” model for AGN one assumes that the central black hole is surrounded by an accretion disk of infalling matter. Besides that, one expects to find bipolar outflow of gas and plasma perpendicular to the disk (jet). Jets can be seen in different objects with disk accretion and in many AGN [16, 17]. One expects shocks in the plasma of the jets [12] which could accelerate protons through first order Fermi acceleration to energies up to $O(10^9 \text{GeV})$ with a powerlaw spectrum of $E^{-2}$ [18]. The observation of $\gamma$-rays with the same kind of spectrum [19] indicates that indeed there is shock-acceleration outside the core of the AGN, so that the photons can escape.

In [20], Niemeyer showed that the far infra-red (FIR) emission of AGN can be explained by assuming that the accelerated protons diffuse back from the jet to the accretion disk and heat dust clouds beyond the outer region of the accretion disk. In the inner part of the disk, protons hitting the disk
will initiate hadronic cascades through interactions with the gas in the disk. This could feed into an electromagnetic cascade and thereby generate the observed X-ray and gamma emission [13].

To describe the accretion disk, we use the model by Shakura and Sunyaev [21]. For our purposes, we will concentrate on the inner region, which is the radiation dominated part of the disk (neglecting the thin, innermost ring around the black hole).

### 3 Hadronic cascades

Due to the observed short timescales of the variability of the X-ray and UV components of the AGN spectrum, this part of the electromagnetic radiation must predominantly originate in a small, central region around the central black hole [10, 9] 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 particle flux in this region. From [20] we know that the FIR spectra are best fitted by assuming that the protons originate from a point source in the jet at $z_0 \leq O(10^{18} \text{ cm}) \approx 3 \cdot 10^4 R_S$ above the disk. We consider two possibilities how protons from this or a similar source can travel back to the central region of the disk and initiate hadronic cascades in the accreting gas.

I) The region interesting for the production of neutrinos is much closer to the centre of the disk; it extends to about $200 R_S \approx 10^{16} \text{ cm}$. In the disk model [21], this corresponds to the innermost region of the disk. An isotropic proton source in the jet, similar to the kind of source mentioned above, located close to the origin, i.e., at $z_0 \ll 200 R_S$, could then deposit at least half its luminosity into the disk. This happens simply for geometrical reasons, since the inner disk occupies about half of the horizon of the proton source. In this approximation, there is no dependence on the exact distribution of the proton source along the jet or on details of the proton transport.

II) It is also possible that the proton source at $z_0 = O(10^{18} \text{ cm})$, needed for the explanation of the FIR radiation, emits a strong downward proton flux. Such an anisotropy in the proton emission arises naturally, since the interaction of the protons in the source with upward UV to X-ray photons from the accretion disk preferably produces downward neutrons through the reaction $p\gamma \rightarrow \Delta \rightarrow n\pi^+$, if the photon scattering in the ambient medium...
is negligible. The upcoming photon density is sufficiently low that $\tau_{\nu,\gamma} < 1$, i.e., the neutrons will reach the disk without further reactions with photons. Furthermore, above 50 TeV, the neutrons will reach the disk without decaying back into protons. The incident nucleons will then induce a hadronic cascade in the inner accretion disk. In this scenario, we get beaming for high energy neutrinos. At lower energies, where protons are part of the cascade, the magnetic field in the disk randomises the orientation of the cascade. Also, the spectrum of the nucleons emitted from the source is flatter than $E^{-2}$ at high energies which leads to a flatter high energy neutrino spectrum as well.

In the following, we will concentrate on scenario I with a pure $E^{-2}$ spectrum for the proton source. In the inner region of the accretion disk, the column density of the disk is

$$u_0 \approx 4.6 \alpha^{-1} \left( \frac{\dot{M}}{\dot{M}_{\text{edd}}} \right)^{-1} \left( \frac{R}{3R_S} \right)^{3/2} \frac{g}{\text{cm}^2}. \quad (1)$$

If we take $\dot{M}/\dot{M}_{\text{edd}} \approx 0.1$ and $\alpha \approx 0.1$, we see that the column density is high enough compared to the mean free path for $pp$-collisions of $O(50 \text{ g/cm}^2)$ for a hadronic cascade to develop. 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.

The hadronic cascade in the disk is much simpler than cascades in the earth’s atmosphere [22, 23, 24], 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 electromagnetic channels; no pion-nucleon reactions occur. 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. This leads to a steeper neutrino spectrum and to the increasing importance of kaons and charmed mesons for the neutrino production in the atmosphere while heavy mesons are of little importance for AGN neutrino production. Under the assumptions of scaling hadronic cross-sections, the power law of the incident protons is kept and
\begin{align*}
p & \rightarrow N + \pi \\
n & \rightarrow N + \pi \\
\pi^0 & \rightarrow \gamma + \gamma \\
\pi^\pm & \rightarrow \nu_\mu + \mu \\
\mu & \rightarrow \nu_\mu + \nu_e + e
\end{align*}

Figure 1: The structure of the hadronic cascade: \(pp\) and \(pn\) interactions drive the cascade and feed the production of pions, leptons and hard photons. We do not distinguish particles and anti-particles in this figure. So the leptonic final channels need to be doubled.

Inherited by all the secondaries, \(i.e.,\) the flux of particle \(x\) is

\[
\dot{n}_x(E) = C_x \dot{n}_p(E), \quad \dot{n}_p(E) = \tilde{C} E^{-\gamma - 1}, \quad (2)
\]

where \(\tilde{C}\) is the normalisation of the proton spectrum. The specific power in protons is then

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

\[
= \begin{cases} 
\tilde{C} (\gamma - 1)^{-1} \left( \frac{E_p^{(\text{min})}}{E_p^{(\text{max})}} \right)^{\gamma + 1}, & \text{for } \gamma \neq 1, \\
\tilde{C} \ln \left( \frac{E_p^{(\text{max})}}{E_p^{(\text{min})}} \right), & \text{for } \gamma = 1.
\end{cases} \quad (3)
\]

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

\[
\tilde{E}_x^{(\text{tot})} = \int_{\epsilon_x E_p^{(\text{min})}}^{\epsilon_x E_p^{(\text{max})}} E' \dot{n}_p(E') \, dE',
\]

\[
= C_x \epsilon_x^{-\gamma + 1} \tilde{E}_p^{(\text{tot})}. \quad (4)
\]

The cascade equations can be solved approximately to determine \(C_x\) and \(\epsilon_x\). For scaling hadronic cross-sections, the experimental data is summarised by the spectrum weighted moments

\[
Z_{ab} = \int_0^1 x_L^{-1} F_{ab}(x_L) \, dx_L, \quad (5)
\]
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 \cite{25, 26, 27, 28, 29, 30}. This produces the observed X-ray and gamma emission of the AGN which we will calculate in detail elsewhere.

### 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.

| Species   | $\epsilon_x$ | $C_x = E_x^{(\text{tot})}/E_p^{(\text{tot})}$ |
|-----------|--------------|---------------------------------|
| $\gamma$  | 0.070        | 0.29                            |
| $e$       | 0.056        | 0.16                            |
| $\nu_\mu$ from $\pi$ | 0.040 | 0.13                            |
| $\nu_\mu$ from $\mu$ | 0.056 | 0.16                            |
| $\nu_e$   | 0.048        | 0.14                            |

where $x_L = E_b/E_a$ is the fraction of the energy of the primary particle transferred to the secondary and $F_{ab}(x_L) = E_b \, d\nu_b(x_L)/dE_b$ is the dimensionless, inclusive cross-section for the production of particles of type $b$. For $\gamma > 1$, the weighting factor $x_L^{\gamma-1}$ reduces the importance of the small-$x_F$ region, where the accuracy of experimental data is low. Unfortunately, in the case relevant here, there is no such suppression of the small-$x_F$ region. The percentage of energy not accounted for in the last column of table 1 is a rough measure for the uncertainty resulting from this. We see that $\approx 49\%$ of the power is emitted as neutrinos where $\approx 33\%$ are 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 electromagnetic power.
4 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 \[13\].

The Neutrino luminosity: To get an estimate of the neutrino luminosity of a source, we use its total emission in X-rays and \( \gamma \)-rays as a reference. We assume that the power emitted at 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 \[3.1\]). The relation we get is then

$$\dot{E}_{\nu}^{(\text{tot})} = 0.95 \dot{E}_{X+\gamma}^{(\text{tot})}. \quad (6)$$

Using an observation for $E_{X+\gamma}^{(\text{tot})}$, equation \(6\) 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 $10^{-2}$ GeV ... $10^{6}$ GeV.

4.1 X-ray background

To be able to use the relation between electromagnetic output and neutrino production to predict the diffuse neutrino background, we have to estimate how much of the observed, diffuse X-ray and \( \gamma \)-ray background results from hadronic cascades in AGN. There is growing evidence from the ROSAT all sky survey that an appreciable fraction of the background is due to active galactic nuclei, possibly a dominant proportion \[31\].

The active nucleus in a quasar is often surrounded by a zone of very active star formation. ROSAT X-ray observations of the Seyfert galaxy NGC1068 \[32\] demonstrate that even the 2–10 keV X-ray emission might be dominated by starburst activity near to the nucleus. On the other hand, X-ray observation of the starburst galaxy M82 \[33\] show that the X-ray spectrum is rather hard and is likely to contain an inverse Compton component, \textit{i.e.}, a powerlaw component. Hence the starburst surrounding the active nucleus is likely to contribute a hard powerlaw X-ray emission component. What fraction of the total emission from a radioquiet quasar might then
arise from this hard X-ray emission component? In starburst galaxies the radio (5 GHz), mid-infrared (60 µm), and X-ray (2 keV) emission is correlated (see [3] for a comparison of starburst galaxies with quasars), and thus the weakness of the radioemission attributable to the starburst speaks against a dominant contribution from the starburst region, as does the often observed variability of the X-rays emitted by radioweak quasars. On the other hand, this argument is not sufficiently general to eliminate a strong contribution by a starburst in all quasars.

Thus we cannot decide conclusively to what extent a starburst surrounding the active nucleus in many radioweak quasars contributes hard X-ray emission similar to that of the nuclear emission. As a matter of fact, extensive work on compton reflection models for AGN X-ray emission cannot explain all features of the observed X-ray background spectrum [34]. To be conservative, we allow for a factor of three maximum between the total hard X-ray emission from an AGN galaxy (starburst and active nucleus together) and the contribution strictly from the hadronic cascade.

The observations of the hard X-ray background at those photon energies minimally influenced by reprocessing [3], i.e., at energies where the original $E^{-2}$ powerlaw is still visible, give a possible range for the unprocessed energy total of $1.0 \cdot 10^5$ to $1.4 \cdot 10^5$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Using the abovementioned conservative estimate, we arrive at a lower limit of $3 \cdot 10^4$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for the contribution of hadronic cascades to the X-ray and $\gamma$-ray background.

4.2 Neutrino background

Since the cosmological redshift is the same for neutrinos and photons, we can scale the background neutrino luminosity using the fraction of the X-ray and $\gamma$-ray background derived above. Using equations (4) and (6), we get

$$N(E_\nu) = 1.6 \cdot 10^{-12} \left( \frac{E_\nu}{\text{TeV}} \right)^{-2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$$

(7)

as a conservative limit for the sum of all neutrino species. About 2/3 are muon neutrinos, the remaining 1/3 are electron neutrinos. This prediction is a factor of 2.5 lower than the experimental limit set by the Frejus experiment [14, 35]. For each family, the number splits evenly into neutrinos and anti-neutrinos. Again, we have a weak dependence of the scale factor on the range of the neutrino energies. This expression is valid up to energies
of $\approx 0.05 E_p^{(\text{max})} = 10^{7 \pm 1}$ GeV; the spectrum turns over at this energy due to the lack of parent particles to produce neutrinos. Actually, we expect the background spectrum to have a less sharp cutoff at high energies than a single source, since the maximum neutrino energy varies between different AGN. Therefore, the cutoff in the superposition of all spectra will be smoothed out.

Such a spectrum is similar to the results of the Monte-Carlo calculation in [11]; but the flux of muon neutrinos predicted here is about one order of magnitude lower. Compared to the prediction for the neutrino background made in [9], we expect the $E^{-2}$ powerlaw for the neutrino spectrum down to the GeV range without the flattening seen in [9] below $10^6$ GeV — a difference which should be visible in the experiment.

5 Discussion

The main point in our model is the production of neutrinos as the result of a hadronic cascade. Compared to the $p\gamma$-channel, which has a threshold of $E_p \approx 8 \cdot 10^6$ GeV for photoproduction on UV photons, all protons above a few hundred MeV contribute in $pp$-interactions. As a consequence, we expect neutrino emission even from sources with a low cutoff in the primary proton spectrum. This way, we include contributions from a larger class of sources both to the neutrino background and to the diffuse X-ray background. Similar to the result of other authors [9, 11], our model displays the tendency to produce neutrinos strikingly close to existing limits [14, 35, 15].

Modifications of this $pp$-model can lead to a reduced neutrino flux while reprocessing of the electromagnetic component ensures an unchanged X-ray emission. The most drastic modification — reducing the maximum proton energy and correspondingly the maximum neutrino energy — can ultimately decrease the observable extragalactic neutrino flux by moving the cutoff below the cross-over with the steeper spectrum of atmospheric neutrinos. More realistically, steepening of the AGN proton distribution at a sufficiently low break energy is an alternative to reduce the predicted event rate in a neutrino detector. In both cases, neutrino production via $p\gamma$-reactions becomes ineffective.

On the other hand, a proton spectrum flatter than $E^{-2}$ leads to the dominance of $p\gamma$-reactions at high energies. This, again keeping the X-ray background unchanged, enhances the neutrino flux far above the TeV range.
while reducing the flux below. Details depend on the modelling of the target photon field (i.e., contributions from the disk, corona, jet, etc.).

Another important point in our model is that the acceleration of the protons takes place above the disk. This way, the acceleration takes place in an environment more suitable than an accretion disk.

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