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Neutrino emission from HBLs and LBLs

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Abstract. The Synchrotron Proton Blazar model is a promising model to explain high energy emission from γ-ray loud BL Lac objects like Mkn 421. In contrast to leptonic models, the hadronic explanation of γ-ray emission predicts ultrahigh energy neutrinos.

The predicted neutrino spectra from a typical High-energy cutoff BL Lac Object (HBL) and a Low-energy cutoff BL Lac Object (LBL) are presented. We find that cooling due to muon synchrotron radiation causes a cutoff of the neutrino spectrum at $\sim 10^{18}$ eV, with the exception of ν_μ from kaon decay which may extend to higher energies if meson production takes place in the secondary resonance region of the cross section.

The impact of the neutrino output from both source populations to the diffuse neutrino background is discussed.

1 Introduction

Most models of gamma ray emission from blazar jets consider Inverse Compton scattering of energetic electrons off low energy photons as the main gamma ray production mechanism. In the Synchrotron-Proton Blazar (SPB) model, recently proposed by, e.g., Mücke & Protheroe (2001) accelerated protons interact with the synchrotron radiation field produced by the co-accelerated electrons via meson photoproduction and Bethe-Heitler pair production, and more importantly, with the strong ambient magnetic field, emitting synchrotron radiation (pions and muons also emit synchrotron radiation). Since this model neglects external photon field components, it is most applicable to BL Lac objects which have weak accretion disks. Mücke & Protheroe (2001) have shown that this model can reproduce the commonly observed double-humped blazar spectral energy distribution (SED).

Gamma ray loud BL Lac objects are commonly classified as HBLs or LBLs on the basis of their ratio of radio to X-ray flux i.e. HBLs have a broad-band spectral index $\alpha_{\rm RX} \leq 0.75$ and LBLs have $\alpha_{\rm RX} > 0.75$ (Padovani & Giommi, 1995). Consequently, for LBLs, the synchrotron peak is generally observed at optical/IR-frequencies while the X-ray band covers the local minimum of νL_ν between the two spectral humps. LBLs are thought to represent an intermediate object class between quasars, which have generally a much higher bolometric luminosity than BL Lac objects, such that νL_ν peaks in the IR and at MeV-GeV-energies, and HBLs, which are the least luminous blazars, and have νL_ν spectral peaks at soft to medium-energy X-rays and GeV-TeV gamma rays.

In this paper we present for the first time the predicted neutrino emission from a typical HBL and LBL in the SPB model, assuming that Mkn 421 and PKS 0716+714 are typical for each source population, respectively.

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2 The model

We inject an spectrum of $E_p'^{-2}$ protons into the jet (primed quantities are in the jet frame), and they are assumed to remain quasi-isotropic in the jet frame due to pitch-angle scattering. The co-accelerated relativistic electrons radiate synchrotron photons which serve as the target radiation field for proton-photon interactions, and for the subsequent pair-synchrotron cascade which develops as a result of photon-photon pair production in the highly magnetized environment. In the SPB model, the target photon density $u'_{\rm phot}$ is much smaller than the magnetic field energy density, and thus Inverse Compton losses can be neglected. The pair-synchrotron cascade redistributes the photon power to lower energies where the photons escape from the emission region, or "blob", of size R' which moves relativistically in a direction closely aligned with our line-of-sight.

The proton energy loss processes considered in the model are photomeson production, Bethe Heitler pair production, proton synchrotron radiation and adiabatic losses due to jet expansion. Synchrotron radiation from $\mu^\pm$ and $\pi^\pm$ (from photomeson production) prior to their decay becomes important in highly magnetized environments with $B' >$ several tens of Gauss (Rachen & Mészáros, 1998), and is taken into account in our calculations. The acceleration rate for any acceleration mechanism is $dE'/dt' = \eta(E')ec^2B'$ where $\eta(E') \leq 1$ describes the efficiency, and B' is the magnetic field in the blob. The maximum proton energy is limited by the balance between energy gain and loss rates.

Direct proton and muon synchrotron radiation seems to be mainly responsible for the high energy hump whereas the low energy hump is dominanted by synchrotron radiation from the directly accelerated e^-, with a contribution of synchrotron radiation from secondary electrons produced by the proton- and $\mu^\pm$-synchrotron initiated cascade. The contribution from Bethe-Heitler pair production turned out to be negligible. For our calculations we use a Monte-Carlo method and utilize the recently developed SOPHIA code for the photohadronic event generation (Mücke et al., 2000).

3 HBLs and LBLs in the SPB Model: the case Mkn 421 and PKS 0716+714

Mkn 421 is a well-known TeV-blazar, and is classified as an HBL. We have used the average SED published by Ghisellini et al. (1998) to derive its model parameters in the framework of our model.

The *observed* low energy hump, identified as synchrotron radiation, serves as the target photon field in our model for pion photoproduction and cascading. We have parametrized the observations by a broken power law with photon spectral index –1.5 below the lab frame break energy $\epsilon_b \approx 100$ eV, and index –2.25 up to the cutoff energy of $\epsilon_c \approx 40$ keV.

Our model represents the data well (Mücke et al., in prep.) for Doppler factor $D \approx 10$, $\epsilon'_b \approx 10$ eV, and $\epsilon'_c \approx 4$ keV, u'$_{\rm phot} \approx 10^9$ eV/cm^3, an emitting volume of $\approx 10^9$AU^3, $B' \approx 50$G, ambient proton energy density $u'_P \approx 10^2$ erg cm^{-3} and $\eta \approx 0.8$. Fig. 1 shows the relevant time scales. The clear dominance of the proton synchrotron radiation at high energies is apparent, while pion production is rather of minor importance. The proton spectrum is cut off at $\gamma'_p \approx 10^{10.5}$ due to proton synchrotron radiation. Significant $\pi^\pm$ synchrotron losses do not occur below the proton cutoff, while $\mu^\pm$ synchrotron radiation cannot be neglected.

The LBL PKS 0716+714 has been chosen for its well-defined low-energy synchrotron component (Ghisellini et al., 1998). Again, the same power-law spectral indices has been used as before to represent this component, a lab-frame break energy $\epsilon_b \approx 0.7$ eV and cutoff energy $\epsilon_c \approx 3.5$ keV. Our model parameters used are: $u'_{\rm phot} \approx 10^{11}$ eV/cm^3, $D \approx 7$, $R' \approx 10^{17}$cm, $B' \approx 30$G, $u'_p \approx 40$ erg cm^{-3} and $\eta \approx 10^{-2}$.

In this environment, losses due to photo-meson production limit the injection proton spectrum to about $\gamma_{\rm p,max} \approx 10^9$ (see Fig. 2). With proton synchrotron radiation being rather unimportant here, photo-pion production dominates the electromagnetic energy output, and is responsible for a stronger neutrino flux than in the HBL case (see Sect. 4). Due to the low cutoff of the proton spectrum, pion synchrotron radiation can again be neglected.

Our modeling seems to favour the hypothesis that the low luminosities observed from HBLs might be due to an *intrinsically* low jet-frame target photon density while the more luminous LBLs may possess rather *intrinsically* high jet-frame target photon fields. The consequences of this hypothesis for the Synchrotron-Proton Blazar model will be presented elsewhere (Mücke et al., in prep.).

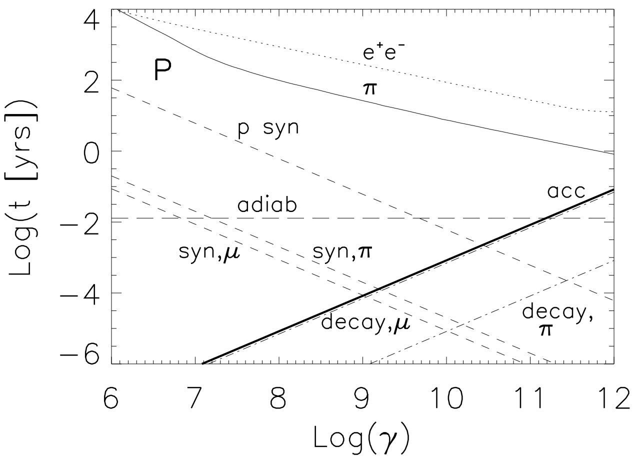

Fig. 1. Mean (jet frame) energy loss and acceleration time scales for the HBL Mkn 421 as modeled in Mücke et al. (in prep.): π-photoproduction (π), Bethe-Heitler pair production (e^+e^-) and proton synchrotron radiation (syn); $\pi^\pm$- and $\mu^\pm$ for synchrotron radiation (syn π, syn μ) are also shown and compared with their mean decay time scales (decay π, decay μ). The acceleration time scale (acc) is indicated as a thick straight line. Model parameters are: $B' = 50$ G, $D = 10$, $R' \approx 10^{16}$ cm, $u'_{\rm phot} = 2 \times 10^9$ eV cm^{-3}, $u'_p \approx 100$ erg cm^{-3}, $\gamma'_{p,\max} = 3 \times 10^{10}$, $\eta = 0.8$.

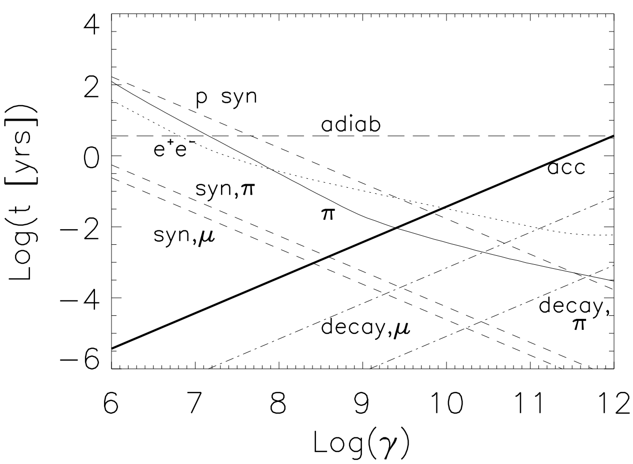

Fig. 2. Mean (jet frame) energy loss and acceleration time scales for the LBL PKS 0716+714 as modeled in Mücke et al. (in prep.). Annotations are the same as in Fig. 1. Model parameters are: $B' = 30$ G, $D \approx 7$, $R' \approx 10^{17}$ cm, $u'_{\rm phot} = 4 \times 10^{11}$ eV/cm^3, $u'_p = 40$ erg/cm^{-3}, $\gamma'_{\rm p,max} = 3 \times 10^9$, $\eta \approx 10^{-2}$.

4 Neutrino Spectra

Hadronic blazar models produce neutrino emission mainly through the production and decay of charged mesons, e.g. $\pi^{\pm} \to \mu^{\pm} + \nu_\mu/\bar{\nu_\mu}$ followed by $\mu^{\pm} \to e^{\pm} + \nu_e/\bar{\nu}_e + \nu_\mu/\bar{\nu}_\mu$. The neutrinos escape without further interaction.

Fig. 3 shows the predicted neutrino output from Mkn 421, which is considered as a typical HBL, and the typical LBL PKS 0716+714. We give the predicted neutrino emission from the objects themselves, and do not consider here any additional contribution from escaping cosmic rays interacting while propagating through the cosmic microwave background radiation.

The clear dominance of neutrino emission from LBLs in comparison to HBLs is obvious. The reason for this is the higher meson production rate in the LBL source population (see also Fig. 1 and 2) due to their higher target photon fields in comparison to the HBL population.

The proton injection spectrum is modified by photohadronic losses. For Mkn 421 the photopion production rate approximately follows a broken power law, $t_\pi^{-1} \propto \gamma_p^{1.25}$ for proton energies below $\sim 10^7$ GeV, and $\propto \gamma_p^{0.5}$ above $E_p' \sim 10^7$ GeV (see Fig. 1) due to the break in the target photon spectrum. This leads to a break in the neutrino spectrum at $\sim 10^7$ GeV (observer frame), from power spectral index $\alpha_\nu \approx 1.25$ to $\alpha_\nu \approx 0.5$ ($(E^2 dN/dE) \propto E^{\alpha_\nu}$). The cutoff at $\sim 10^9$ GeV in the observer's frame is caused by $\mu^{\pm}$-synchrotron losses, whereas $\pi^{\pm}$-synchrotron emission turns out to be unimportant. Another important source of high energy neutrinos is the production and decay of charged kaons if the proton-photon interaction takes place predominantly in the secondary resonance region of the cross section (Mücke et al., 2000). This might be the case for HBLs because their target photon field can extend up to X-ray energies. The positively charged kaons decay in $\sim 64\%$ of all cases into muons and direct high energy muon-neutrinos. In contrast to the neutrinos originating from $\pi^{\pm}$ and $\mu^{\pm}$-decay, these muon-neutrinos will not have suffered energy losses through $\pi^{\pm}$- and $\mu^{\pm}$-synchrotron radiation, and therefore appear as an excess in comparison to the remaining neutrino flavors at the high energy end ($E_\nu \approx 10^9$–10^{10} GeV) of the emerging neutrino spectrum, and in addition cause the total neutrino spectrum to extend to $\sim 10^{10}$ GeV.

In contrast, the neutrino emission from PKS 0716+714 is cutoff at $\sim 10^9$ GeV (observer frame) for all neutrino flavors (see Fig. 3) due to a roughly one order of magnitude lower proton cutoff. Also $\mu^{\pm}$ synchrotron losses may play a role here. The neutrino spectrum follows a power law with index $\alpha_\nu \approx 1.25$ below the cutoff, and is caused by photohadronic interactions with the target photon field above ϵ_b'. Because of the π-production threshold and the relatively low proton cutoff in LBLs, meson production in the photon field below ϵ_b' cannot occur, leading to a simple power law for the neutrino spectrum.

The photon-hadron interactions for both, LBLs and HBLs, take place predominantly in the resonance region. Here, π^-, and thus $\bar{\nu}_e$ production is suppressed (see Fig. 3).

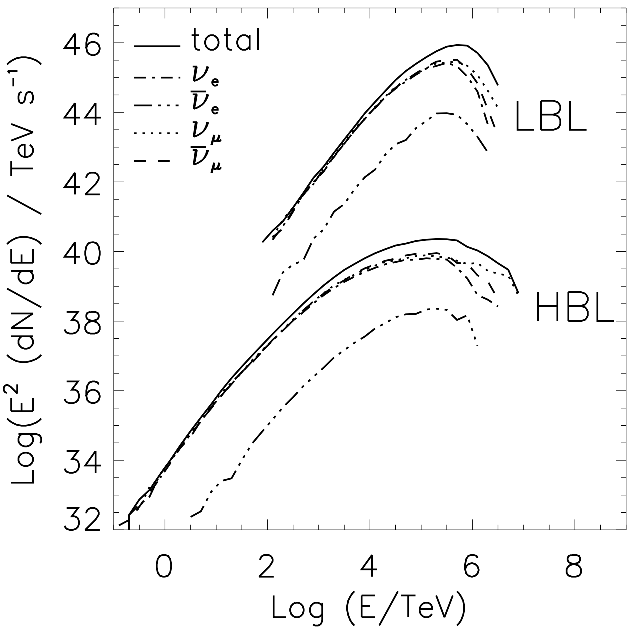

Fig. 3. Predicted neutrino spectra for the HBL Mkn 421 (lower curves) and the LBL PKS 0716+714 (upper curves) as modeled in Mücke et al. (in prep.).

Previous hadronic jet models expected equal photon and neutrino energy fluxes (e.g. Mannheim (1993)). Our model predicts for HBLs a peak neutrino energy flux approximately two to three orders of magnitude lower than high energy gamma rays ($q_{\gamma\nu} \approx 10^{2\ldots3}$), while for LBLs the neutrino and gamma ray output is approximately comparable ($q_{\gamma\nu} \approx 1$).

5 Diffuse neutrino background

From inspecting Fig. 3 it is immediately clear that LBLs would dominate the BL Lac contribution to the diffuse neutrino background unless HBLs turn out to be significantly more numerous than LBLs.

A commonly used method to estimate the diffuse neutrino background due to unresolved blazars is to determine the ratio gamma ray to neutrino emission, $q_{\gamma\nu}$, in the objects in question, and then normalize to the observed extragalactic gamma ray background (e.g. Mannheim (1995)). The different photon to neutrino ratio we found in HBLs and LBLs leads to various implications for the diffuse neutrino emission.

The extragalactic diffuse gamma ray background (EGRB) as detected by EGRET is $(1.45 \pm 0.05) \times 10^{-5}$ photons cm^{-2} s^{-1} sr^{-1} above 100 MeV (Sreekumar et al., 1998). Thus, the extragalactic neutrino background (ENB) due to unresolved EGRET blazars can be estimated by: $(E^2 dN/dE)_{\rm ENB} \approx 7.4(1+f) q_s q_{\gamma\nu}^{-1} \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} where $f < 1$ is the fraction of photon power lost in the cosmic background matter and radiation field, and $q_s \approx 0.25$ is the presumed blazar contribution to the EGRET EGRB (Chiang & Mukherjee, 1998). Propagation of gamma rays at ≤ 100

GeV is relatively unattenuated, and is therefore comparable to neutrino propagation, so we set $f = 0$. Since LBLs are EGRET-sources, and with $q_{\gamma\nu} \approx 1$, a diffuse neutrino flux of $(E^2 dN/dE)_{\rm ENB} \approx 2 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} follows *if LBLs dominate the blazar contribution to the EGRET diffuse gamma ray background*. This is slightly above the neutrino upper bound derived using cosmic ray constraints by Waxman & Bahcall (1999) and Mannheim, Protheroe & Rachen (2001) for optically thin sources, but well below the upper bound for optically thick sources. Thus, we conclude that either LBLs do not dominate the blazar contribution to the EGRET EGRB, or LBLs are rather thick sources (like quasars).

Our estimate of the ENB due to HBLs follows a similar procedure. Since HBLs emit, however, most of their photon power at TeV-energies, we extrapolate the $E^{-2.1}$ EGRB spectrum as observed by EGRET up to 25 TeV, the highest energy observed from any HBL, to estimate the unattenuated EGRB flux in the ≥ 100 GeV energy range. The resulting ENB from HBLs is then $(E^2 dN/dE)_{\rm ENB} \approx 3q_s \times (10^{-9} \ldots 10^{-10})$ GeV cm^{-2} s^{-1} sr^{-1}, where q_s is here the HBL contribution to our estimated diffuse TeV-background. Even for $q_s = 1$ the predicted ENB intensity lies several orders of magnitude below the neutrino upper bounds (Waxman & Bahcall 1999; Mannheim et al. 2001, MPR), and is also lower than the estimate from MPR of the BL Lac contribution to the ENB using the observed XBL luminosity function. Note, however, that MPR assumed pion photoproduction was the main proton loss process, whereas in the SPB model for HBLs proton synchrotron losses dominate at the expense of pion (and neutrino) production. The same is true for Mücke et al. (1999), where one to two order of magnitude higher contribution from TeV-blazars to the diffuse neutrino background was estimated in comparison to this work.

6 Summary

Neutrino production spectra of BL Lac objects are calculated in the framework of the Synchrotron-Proton Blazar model (Mücke & Protheroe, 2001) using the SOPHIA event generator for photomeson production (Mücke et al., 2000). The ν spectra presented here for Mkn 421 and PKS 0716+714, typical of HBLs and LBLs, respectively, are modeled using a parameter set which reproduces well the average SED of those blazars. We find higher pion production rates for LBLs in comparison to the HBLs, and this leads a higher neutrino output for a typical LBL by $\sim 10^6$ compared to HBLs. Muon synchrotron losses are responsible for a spectral cutoff in the neutrino SED at $\sim 10^{18}$ eV, with a possible extension of ν_μs up to $\sim 10^{19}$ eV, due to kaon decay.

The total power deposited in gamma rays and neutrinos is approximately equal for LBLs, while a two to three order of magnitude smaller neutrino peak flux is predicted in HBLs in comparison to their peak photon power. This leads to a significantly higher LBL contribution to the extragalactic diffuse neutrino background than from HBLs, when the method of normalizing to the observed EGRB is used for estimating the diffuse neutrino flux.

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