Neutrino production in AGN jets and GRBs

A. Mücke[1]**, R. Engel**[2]**, R.J. Protheroe**[1]**, J.P. Rachen**[3] **and T. Stanev**[2]
[1]*University of Adelaide, Dept. of Physics & Math.Physics, Adelaide, SA 5005, Australia*
[2]*Bartol Research Institute, University of Delaware, Newark, DE 19716, USA*
[3]*Universiteit Utrecht, Sterrenkundig Instituut, 3508 TA Utrecht, The Netherlands*

Abstract

We present neutrino spectra and diffuse fluxes from jets of Active Galactic Nuclei (AGN) using the synchrotron proton blazar model, and from Gamma Ray Bursts (GRB) assuming that they accelerate protons. The photohadronic interactions are simulated using the Monte Carlo technique. Synchrotron emission from mesons and leptons is taken into account. We derive diffuse ν-fluxes from both source types by reconsidering the relation between ν- and γ-ray production in photohadronic interactions and using the contribution to the extragalactic diffuse γ-ray background by unresolved point sources.

1 Introduction

Neutrinos (νs) from jets of Active Galactic Nuclei (AGN) has been predicted within the so-called "Proton-Blazar-Models". These models are promising concepts to explain the observed GeV–TeV γ-ray emission from blazars. γ-rays are produced by the decay of π^0s (and subsequent cascading), arising from interactions of relativistic protons in either external radiation fields (Protheroe 1997), or the synchrotron radiation field ("Synchrotron-Proton-Blazar-Model") from electrons co-accelerated with the protons (e.g. Mannheim 1993). The decay of charged pions ($\pi^{\pm} \rightarrow e^{\pm}\nu_\mu\bar{\nu}_\mu(\nu_e/\bar{\nu_e})$), then leads to the production of νs. Also in fireball models for Gamma Ray Bursts (GRB), shock acceleration of ultrahigh energy (UHE) protons has been predicted (e.g. Waxman 1995). Because of their dense radiation fields, they also provide a very suitable environment for ν-production.

In this paper we study ν-emission from hadronic AGN jet and GRB models using the recently developed Monte-Carlo event generator SOPHIA for photomeson production (Mücke et al. 1999a).

2 Gamma Ray Bursts

The observed radiation from GRBs is explained as synchrotron radiation from electrons accelerated at shock waves in an ultrarelativistic outflow from a compact object. It may serve as the target radiation field for photopion production of relativistic protons (p) accelerated at the same shock. In the comoving shock frame it may be approximated by a broken power law with photon index $-2/3$ below the break energy of 1keV, and -2 above this break up to 100keV for a typical Doppler factor of $D = 200$ for external shocks. Characteristic bolometric luminosities of $L \approx 10^{53}$erg/s in the observer frame are required for bright cosmological GRBs. The magnetic field B can be estimated from the photon energy density $u_{\rm ph}$ using equipartition arguments (for details see Rachen & Mészáros, 1998, hereafter RM98). For a variability time scale of $T = 10$s, typical for long, bright bursts, we derive $u_{\rm ph} \approx 10^{17}$eV/cm^{-3} and $B \approx 10^3$G.

The maximum p energy to which CRs may be accelerated is limited by adiabatic losses in the decreasing magnetic field, or by radiative cooling, i.e. synchrotron radiation or $p\gamma$ interactions. In Fig. 1 we show the mean loss distances for π-photoproduction (using the SOPHIA code), Bethe-Heitler pair production (using the formula given in Chodorowski 1992) and p synchrotron radiation. Obviously, energy losses due to Bethe-Heitler pair production can be neglected here. The loss distances are compared with the acceleration distance of the protons. We see that synchrotron losses limit the proton energy for the parameters chosen here.

Using the SOPHIA Monte-Carlo package for photomeson production (Mücke et al. 1999a), ν-spectra are calculated for a p input spectrum $\propto E_p^{-2}$, which is typical for shock accelerated particles, ranging from $E_p = 10^5$GeV to $E_{p,\rm max} \approx 3 \cdot 10^9$GeV in the shock frame. The efficient interaction rate for pion production is calculated by considering all competing energy losses.

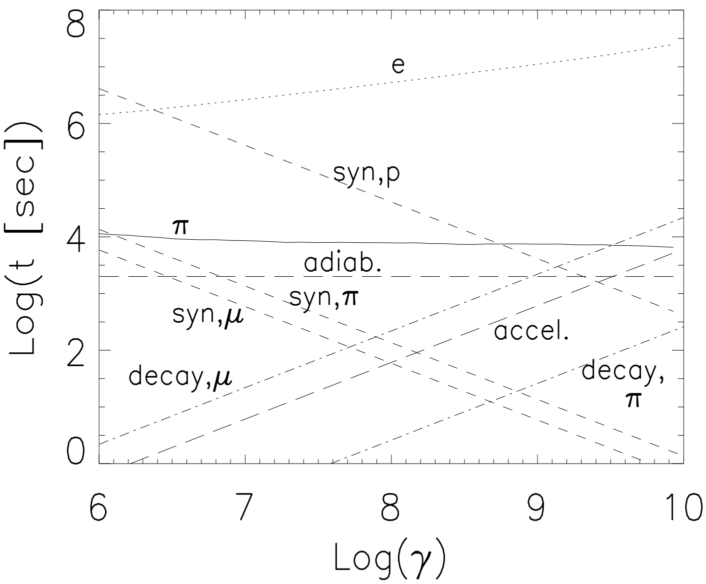

Figure 1: *Mean energy loss distance of protons for pion photoproduction (π), Bethe-Heitler pair production (e) and synchrotron radiation (p syn), and for pion and muon synchrotron radiation (syn π, syn μ) with their decay length (decay π, decay μ) for long GRBs. All quantities are given in the comoving frame of the shock.*

It has been noted recently (RM98) that synchrotron losses of the produced πs and μs may limit the maximum ν-energy rather than the high energy cutoff of the incident proton spectrum, because of the relatively long mean life time of charged πs and μs and the high magnetic field. The synchrotron loss distances of πs and μs with their corresponding decay length are also shown in Fig. 1. For both particles we find cooling breaks below the proton cutoff. Figure 2 shows the ν-spectra at source location expected for long, bright GRBs, with parameters as discussed above. Neutrinos with energies $>10^8$GeV are produced predominantly in the high energy region of the cross section. Here, the multiplicity of π^- and π^+ is equal, whereas in the resonance region π^-, and thus $\bar{\nu}_e$-production is suppressed. The effects of μ-synchrotron radiation show up as a break at about 10^8GeV, and is in particular relevant for the $\nu_e + \nu_{\bar{e}}$ component which is solely produced through μ-decay. The π-synchrotron cooling break is apparent in the $\nu_\mu + \bar{\nu}_\mu$ component slightly below 10^{10}GeV. We note that for the parameters typical in bright, long bursts, ν fluxes $>10^{10}$GeV as proposed by Vietri (1998), are strongly suppressed due to the pion and muon cooling breaks.

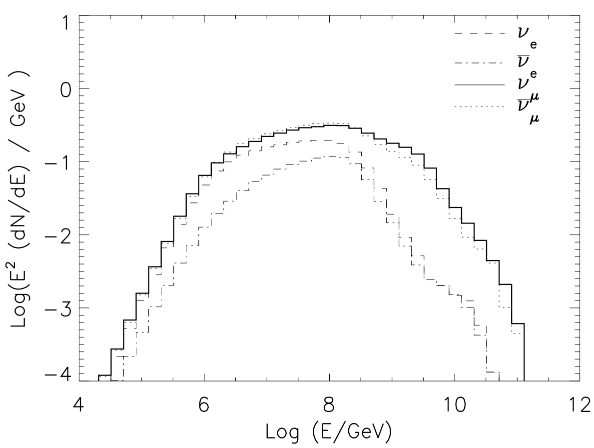

Figure 2: *Predicted power spectra of ν_e, $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$ for long GRBs at source location. Spectra are normalized to $E^2dN/dE = 1$ at 10^8GeV for photo-produced γ-rays.*

To estimate an upper limit to the diffuse ν-flux (ENB) from unresolved cosmological GRBs, the relation between ν- and γ-ray production for photohadronic processes is used. In a typical GRB radiation field the total energy deposited into γs ($\mathcal{E}_\gamma$) and νs ($\mathcal{E}_\nu$) is approximately $q_{\gamma\nu}{\equiv}\mathcal{E}_\gamma/\mathcal{E}_\nu{\approx}\frac{6}{5}$ at $E_p{>}10^6$GeV (Mücke et al. 1999b). Propagation of γ-rays $\leq$100 GeV is comparable to ν-propagation, and we can directly link the diffuse ν-flux to the diffuse extragalactic γ-ray flux (EGRB) presumably originating from unresolved point sources. We obtain $(E^2dN/dE)_{\rm ENB} < 6.2(1+f)q_s \cdot 10^{-7}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$, where $f<1$ is the fraction of the photon power lost in the cosmic background matter and radiation field, and $q_s < 0.75$ the GRB contribution to the observed EGRB (Sreekumar et al. 1998; Chiang & Mukherjee 1998). The GRB neutrino flux estimated by Waxman & Bahcall (1997, 1999) is much lower, $\sim 3\cdot 10^{-9}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$. This flux is comparable to the total observed (MeV) γ-ray flux from *resolved* GRB, and implies $q_s \ll 1$.

3 TeV-blazars

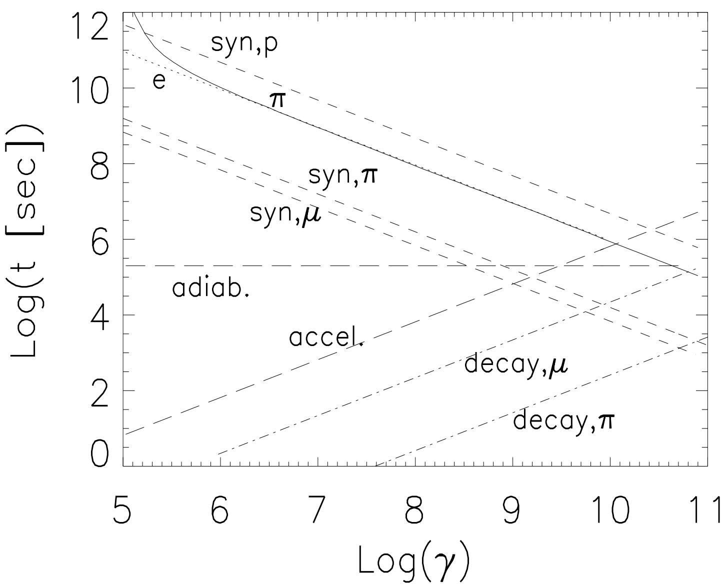

Figure 3: *Mean energy loss distance of protons for pion photoproduction (π), Bethe-Heitler pair production (e) and synchrotron radiation (p-syn), and for pion and muon synchrotron radiation (syn π, syn μ) with their mean decay lengths (decay π, decay μ) in the Synchrotron-Proton-Blazar model. All quantities are in the comoving frame of the jet.*

We restrict our calculations to the Synchrotron-Proton-Blazar model, which considers the synchrotron radiation as dominating over any external radiation fields within the source. We identify TeV-blazars as a suitable object class for this model. For the *local* synchrotron radiation spectrum in the jet frame we adopt a broken power law photon spectrum with index -1.5 up to the break energy of 10^{-4}eV, and -2 up to 1 keV, assuming a Doppler factor of D=10. For $T = 10^4$s and a typical bolometric synchrotron luminosity of L=10^{45}erg/s we estimate the photon energy density $u_{\rm ph} \approx 7 \cdot 10^{10}$eV/cm^3. Hadronic blazar models typically invoke magnetic fields $B \approx$ 10 G. For the adopted blazar environment, the maximum proton energy is limited by adiabatic losses to $E_{p,\max} \approx 3 \cdot 10^9$GeV. Figure 3 shows the mean energy loss distances of protons for the most important processes. Both proton-photon processes have comparable loss rates.

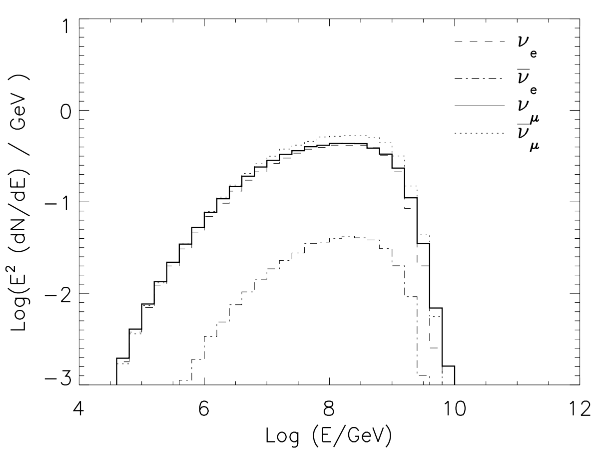

Figure 4: *Predicted power spectra of ν_e, $\nu_{\bar{e}}$, ν_μ and $\nu_{\bar{\mu}}$ for Synchrotron-Proton-Blazar models at source location. Spectra are normalized to $E^2dN/dE = 1$ at 10^8GeV for photoproduced γ-rays.*

Figure 4 shows the ν-spectrum at source location resulting from SOPHIA simulations, taking into account synchrotron losses of μs, which, however, hardly modify the spectrum. The proton input spectrum is again $\propto E_p^{-2}$, but in contrast to GRBs the photohadronic interaction rate increases here $\propto E_p$, making the neutrino spectrum one power flatter (e.g., Mannheim, 1993). The maximum ν-energy is limited by the maximum p energy to $\sim 10^{10}$GeV. In this environment π-production takes place mainly near threshold. Here, π^--production, and thus $\bar{\nu}_e$-production, is suppressed, as visible in Fig. 4.

To estimate the diffuse ν-flux from TeV-blazars we proceed similarly to the GRB case. For the ν-to-γ energy we receive $q_{\gamma\nu} \approx 2.2$ including Bethe-Heitler pair production. We normalize the diffuse ν-flux to 25% EGRB due to unresolved blazars (Chiang & Mukherjee 1998), extended by a $E^{-2.1}$ photon spectrum as observed by EGRET (Sreekumar et al. 1998) to 25 TeV, the so far highest energy observed from a TeV-blazar (Aharonian et al. 1999), to derive the unattenuated EGRB flux in the $\geq$100GeV range, where TeV-blazars presumably dominate the background. We find for the diffuse ν-flux $(E^2dN/dE)_{\rm ENB} \approx 0.4 \cdot 10^{-7}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$.

4 Conclusions

ν-spectra at source location from hadronic external shock GRB models and Synchrotron-Proton-blazar models are calculated using the SOPHIA Monte-Carlo code for meson photoproduction. We found that for both TeV-blazars and long GRBs the ν spectrum extends up to $\sim 10^{10}$GeV. Synchrotron losses of μs and πs in GRBs lead to a spectral break below the cutoff, while TeV-blazar spectra are hardly affected by μ losses.

The point source contribution from both source types to the diffuse ν background is estimated by normalizing to the point source contribution of the EGRB. Comparing our derived ν-fluxes with the ν upper bounds recently derived using CR constraints (Waxman & Bahcall, 1999; Mannheim et al., 1998), we find that the contribution from GRBs to the EGRB below 100GeV must be very small. In contrast, for hadronic TeV-blazars we find a value comparable to the cosmic ray bound. This implies that the hypothesis of TeV-blazars being the source of both, UHECRs and diffuse TeV-photons, is in agreement with current observational constraints. Observations of correlated neutrinos would be an important test for this scenario.

Acknowledgements

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