The signatures of Bethe-Heitler emission on the blazar SED

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Abstract

We present the spectral signatures of the Bethe-Heitler pair production (pe) process on the spectral energy distribution (SED) of blazars, in scenarios where the hard γ-ray emission is of photohadronic origin. We consider relativistic protons interacting with the synchrotron blazar photons and produce γ-rays through photopion processes. Using both analytical and numerical means we show that besides the copious $\sim 2-20$ PeV neutrino emission, the typical blazar SED should have an emission feature due to the synchrotron emission of pe secondaries that bridges the gap betweeen the low-and high-energy humps of the SED, namely in the energy range 40 keV – 40 MeV. We propose the expected "pe bumps" as a good diagnostic for leptohadronic models of blazar emission.

The model

The blazar emitting region is described as a spherical blob with radius R, moving with a Doppler factor δ with respect to an observer. It is also assumed that it contains a tangled magnetic field of strength B and that both relativistic protons and primary electrons are being injected uniformely with a constant rate; their distribution is described by a power-law with index s_i and high-energy cutoff $\gamma_{i,\max}$, where the subscript i is used to discriminate between protons (p) and electrons (e). Electrons lose energy through the synchrotron and inverse Compton processes, while synchrotron radiation and photohadronic interactions count to the main energy loss processes for relativistic protons. In the present context, we assume that the target photons for the photohadronic interactions, which include both pe and photopion production processes, are internally (or locally) produced, i.e. they are the result of primary electron (and proton) synchrotron radiation. Figure 1 shows a cartoon representation of the blazar SED obtained within this framework.

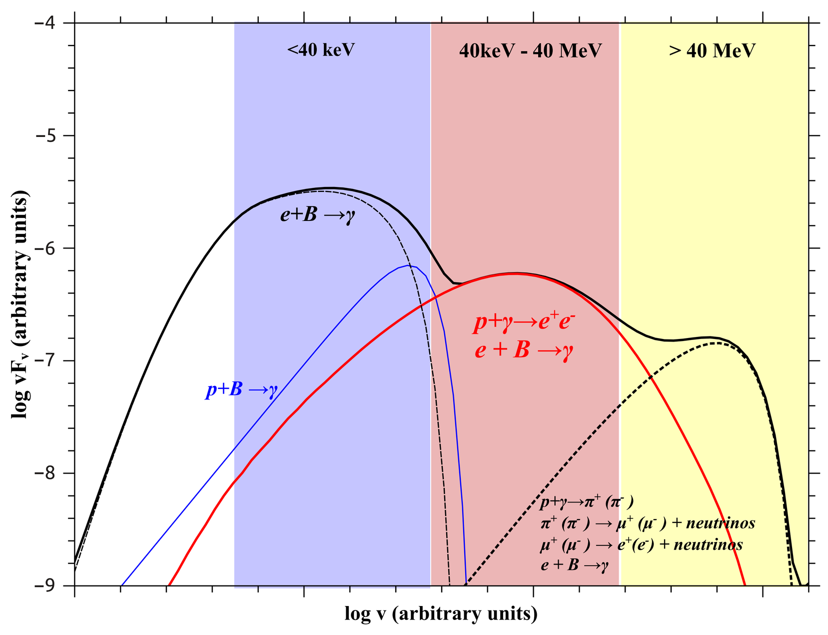

Fig. 1: A cartoon blazar SED. The contribution of the different physical processes at various energy bands is indicated by different types of lines.

Photopion vs. Bethe-Heitler energy loss rates

The expressions for the optical depth of photopion ($p\pi$) and Bethe-Heitler (pe) processes due to interactions between protons and photons of the low-energy hump of the SED can be expressed in terms of:

Observables
- redshift, z
- luminosity of the low-enery SED component, $L_{\rm syn}$
- peak energy (frequency) of the low-energy SED component, $\epsilon_s(\nu_s)$
- spectral index, β

Model Parameters
- radius of emitting region, R
- doppler factor, δ

The relevant expressions are:

$$f_{p\pi}(\xi_{p\pi}) \simeq 4.4\times10^{-3}\frac{L_{\rm syn,45}\lambda(\beta,\epsilon_s)}{R_{15}\delta_1^3\nu_{s,16}(1+z)}\begin{cases}\xi_{p\pi}^{\beta}, & \xi_{p\pi}<\frac{\epsilon_s}{\epsilon_{\min}}\\ \left(\frac{\epsilon_s}{\epsilon_{\min}}\right)^{\beta}, & \xi_{p\pi}>\frac{\epsilon_s}{\epsilon_{\min}}\end{cases} \quad (1)$$

$$f_{pe}(\xi_{pe}) \simeq 6\times10^{-5}\frac{L_{\rm syn,45}\beta(\beta+2)\lambda(\beta,\epsilon_s)}{R_{15}\delta_1^3\nu_{s,16}(1+z)}\xi_{pe}^{\beta}I(\gamma_p,\beta), \quad (2)$$

where $\xi_{p\pi}=2\gamma_p\epsilon_s(1+z)/\delta m_\pi c^2$, $\xi_{pe}=2\gamma_p\epsilon_s(1+z)/\delta m_e c^2$, λ is a function of β and ϵ_s (see Eq. (27) in [1]), and $I(\gamma_p,\beta)$ is a function that may be expressed in terms of error functions (see Appendix in [1]).

Remarks

- Eq. (1) is in good agreement with previous results (e.g. [2], [3]).
- Eq. (2) is a new approximate analytical expression for the pe loss rate, in the case of power-law photon distribution, which has an excellent accuracy with the numerically calculated exact one, especially at energies much above the threshold for pair production.
- There are parameters leading to similar, at least within the same order of magnitude, energy loss rates.
- Higher ϵ_s push the threshold Lorentz factors to lower values. Thus, for a fixed proton energy much above the threshold for pe pair production, higher ϵ_s translates to lower f_{pe}.

Generic blazar SEDs

We present the numerically obtained SEDs for two indicative parameter sets (Table). The adopted parameter values lead to SEDs that resemble these of high-frequency peaked (HBL) and low-frequency peaked (LBL) blazars [4].

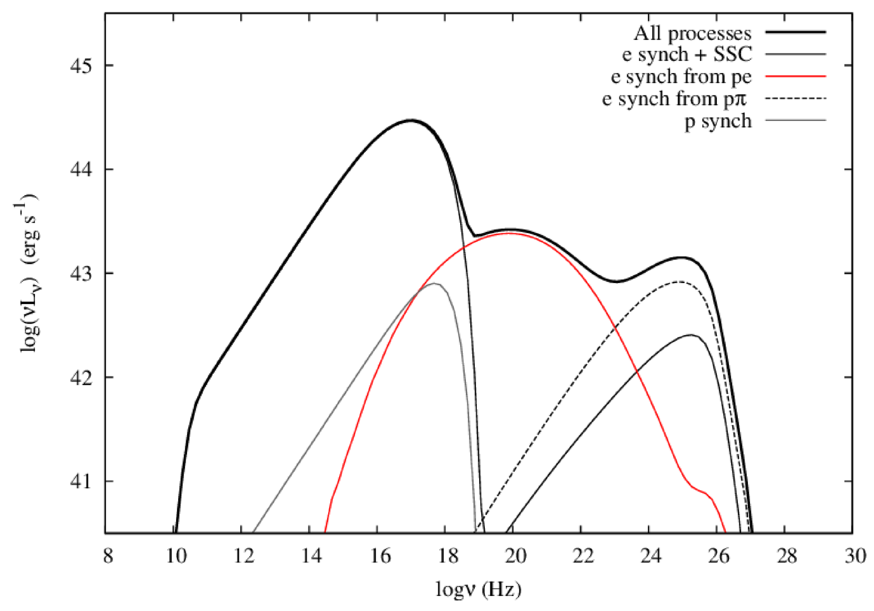

Fig. 2: A generic model SED resembling a HBL (Model A).

Parameter	Model A	Model B
B (G)	0.1	10
r_b (cm)	3×10^{16}	3×10^{15}
δ	30	15
$\gamma_{e,\min}$	1	3×10^2
$\gamma_{e,\max}$	3×10^5	3×10^6
s_e	2.0	2.5
$\ell_e^{\rm inj}$	1.2×10^{-6}	2×10^{-3}
$\gamma_{p,\min}$	1	1
$\gamma_{p,\max}$	1.2×10^7	6.3×10^6
s_p	2.0	2.0
$\ell_p^{\rm inj}$	10^{-3}	1.2×10^{-2}

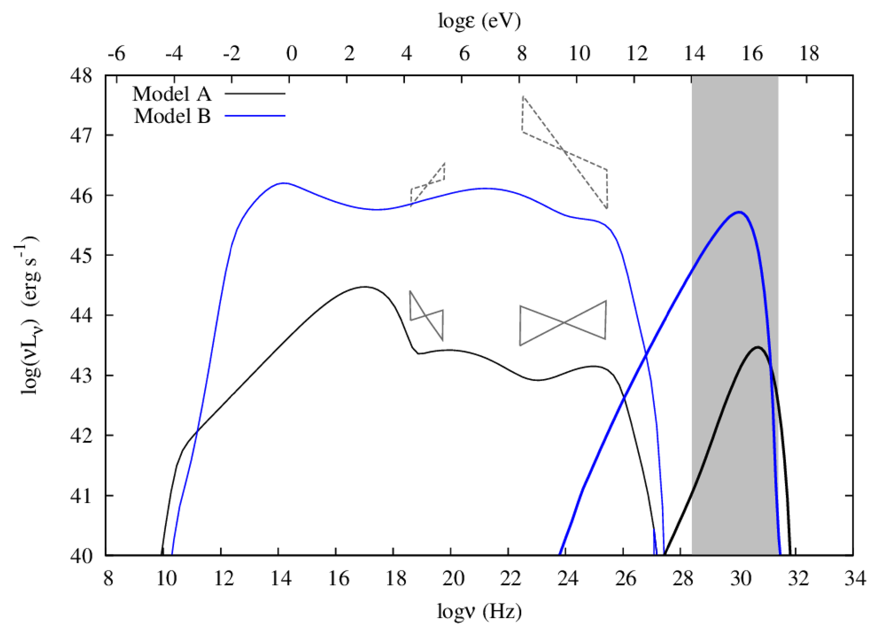

Fig. 3: Combined photon (thin lines) and $\nu_e+\nu_\mu$ (thick lines) spectra obtained for Models A (black lines) and B (blue lines). Our scenario establishes a connection not only between the observed γ-ray flux and the expected neutrino flux from a BL Lac object, but also links the hard X-ray/soft γ-ray flux with both of them

The case of Ap Librae

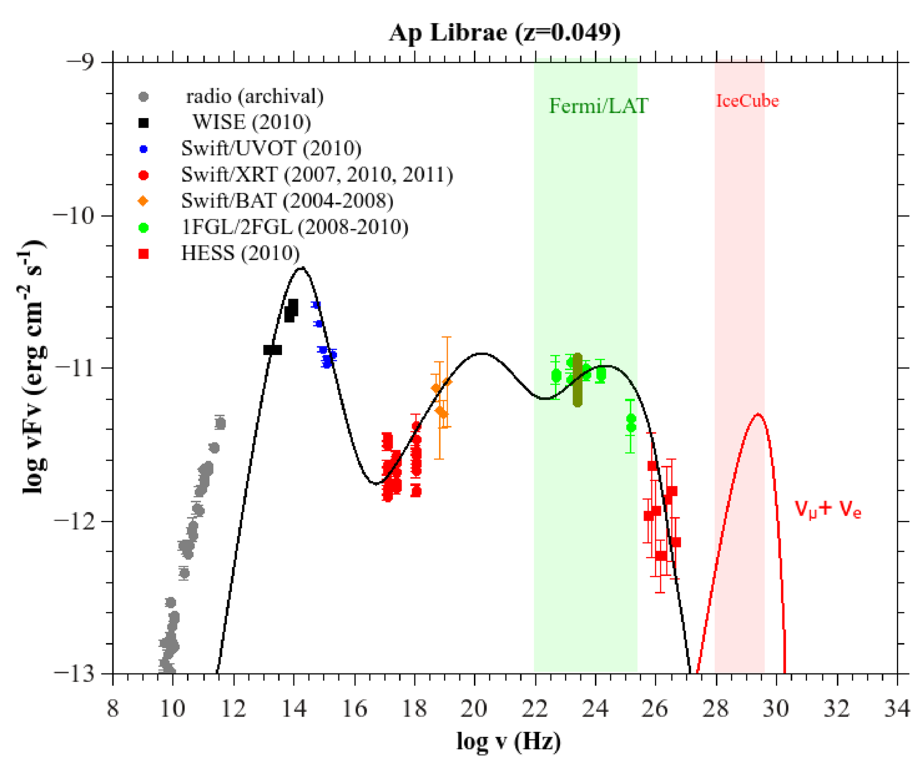

Fig. 4: Application of our leptohadronic model to Ap Librae, a TeV emitting LBL [5]. The wide (in energy) high-energy component, which cannot be explained by synchrotron self-Compton leptonic models, here has a photohadronic origin. The role of the pe process is important, since it (i) produces the hard X-ray emission and (ii) provides the photon targets for the ν production.

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