Lepto-hadronic modelling of blazar emission

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I. Context : blazar emission models

The spectral energy distribution (SED) of blazars is characterised by two non-thermal emission bumps, the first one peaking between visible light and X-rays, the second one peaking in γ-rays. The origin of this emission is thought to be a region of high density, filled with a magnetic field and moving in a relativistic jet aligned to the line-of-sight.

While there is a general consensus that the low energy bump is due to synchrotron emission from electons and positrons in the emitting region, the origin of the high energy emission is interpreted differentely in leptonic or hadronic models. In the first scenario, the emission is entirely dominated by leptons, which produce the high energy bump through inverse Compton scattering off the synchrotron photons themselves (Synchrotron-Self-Compton, SSC) or off an external photon field. In the hadronic scenario the high energy bump is usually attributed entirely to proton synchrotron emission or photo-hadronic interactions.

We have developped a lepto-hadronic code that reproduces both “extreme” scenarios and allows to study interesting mixed scenarios as well.

II. Description of the code

Leptonic processes

The framework of our model is the stationary one-zone SSC code developped by Katarzyński et al. (2001). A spherical region (characterised by its radius R) moves in the relativistic jet with Doppler factor δ : it is filled with a homogenous magnetic field B and a primary electron population $n_e(\gamma{=}E/(mc^2))$, which is parametrised by a broken power law (defined by the two slopes $\alpha_{1,2}$, the Lorentz factors $\gamma_{e,min}$, $\gamma_{e,break}$, $\gamma_{e,max}$ and the normalization factor K_e).

The leptonic part of the original code has been improved in the following :

- The synchrotron emission is evaluated computing the exact integration. The approximation used by Katarzyński et al. (2001) is valid only if the emitting particles are $e^{\pm}$.
- The internal absorption due to γ-γ pair production is evaluated using the cross-section formula given by Aharonian et al. (2008), instead of a δ-function.
- The pair injection rate is computed following Aharonian et al. (1983). A stationary distribution of secondary pairs (1^{st} generation), taking into account synchrotron cooling, is evaluated following Inoue & Takahara (1996). Synchrotron emission from the stationary pair distribution is evaluated as well.
- The absorption induced by the extra-galactic background light (EBL) on TeV photons is evaluated using the EBL model by Franceschini et al. (2008).

Hadronic processes

The spherical emitting region is filled with a primary proton population $n_p(\gamma)$, parametrized by a power law with slope α_p, normalization factor K_p and minimal and maximal Lorentz factor $\gamma_{p,min}$ and $\gamma_{p,max}$. The proton synchrotron emission is corrected for internal $\gamma-\gamma$ absorption and the associated first generation pair spectrum is evaluated as described above.

In hadronic scenarios, an important role is played by photo-hadronic interactions. They have been computed using the public Monte Carlo code *SOPHIA* (Mücke & Protheroe 2001).

- Synchrotron radiation from primary electrons and protons serves as the target photon field.
- The energy of the interacting protons is corrected for synchrotron losses following Mücke & Protheroe (2001).
- *SOPHIA* is called for 10 sampled proton energies. The distributions of the generated particles ($\gamma, e^{\pm}, p, n, \nu^{e,\mu}, \bar{\nu}^{e,\mu}$) are summed and normalized to the number of protons in the blob suffering p-γ interactions.
- The spectra of the generated $e^{\pm}$ are corrected for radiative cooling to arrive at a steady-state solution.
  Synchrotron emission from secondary leptons and from the first generation pair spectrum is then evaluated.
- $\mu^{\pm}$ can emit synchrotron radiation before decaying into $e^{\pm}$. They are retrieved from *SOPHIA*, and their synchrotron emission is evaluated.

III. Application to PKS2155-304 observations

Figs. 1 to 3 show an application to the data from the 2008 multi-wavelength campaign on the blazar PKS 2155-304 (Aharonian et al. 2009). This data set represents at this time one of the most complete simultaneous SEDs of a TeV blazar: the shape of the high energy bump is fully characterised by the Fermi and H.E.S.S. data. PKS 2155-304 has been found to be in a low activity state during the campaign. In the interpretations presented here, the emission from the blob explains only the X-ray to γ-ray emission, assuming that from radio to visible light the emission from the extended jet dominates.

We report the modelling of the SED in three different scenarios : a purely SSC leptonic model, a purely proton synchrotron hadronic model and a third, mixed, scenario in which both the synchrotron emission from protons and the inverse Compton component contribute to the high energy bump.

The model parameters used in the three different scenarios are shown in Table 1.

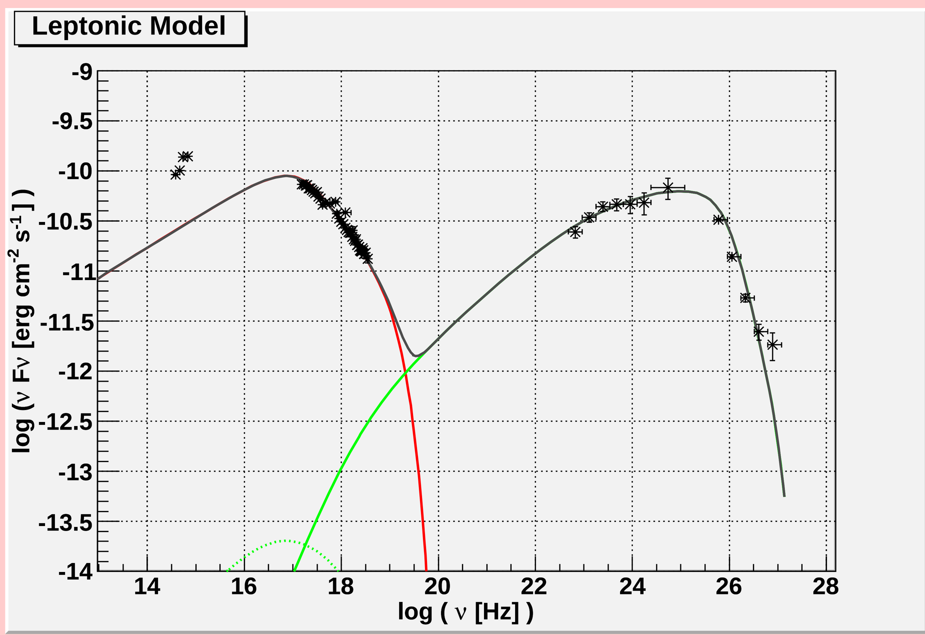

Figure 1: Modelling of PKS 2155-304 in a SSC scenario.

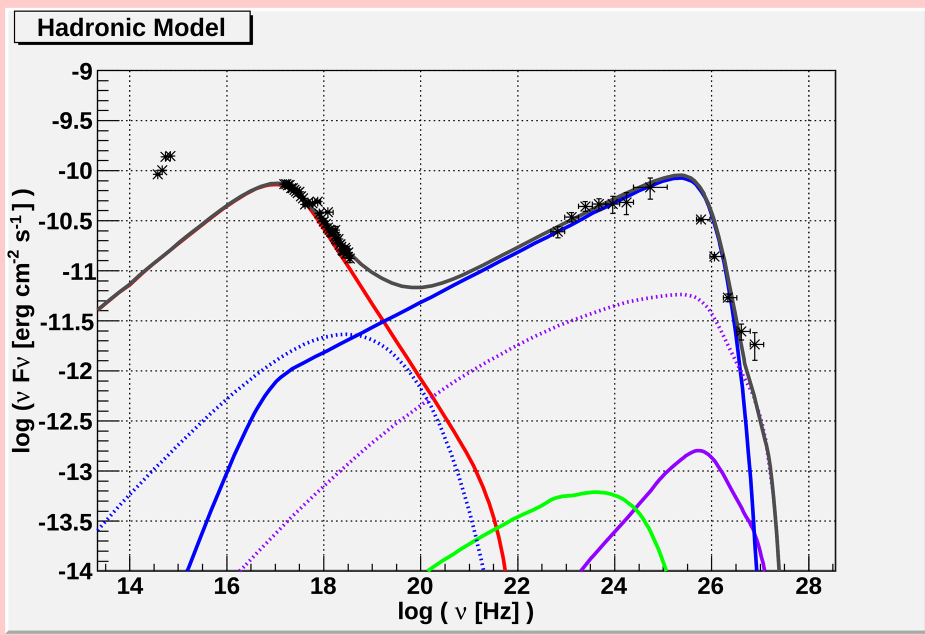

Figure 2: Modelling of PKS 2155-304 in a proton synchrotron scenario.

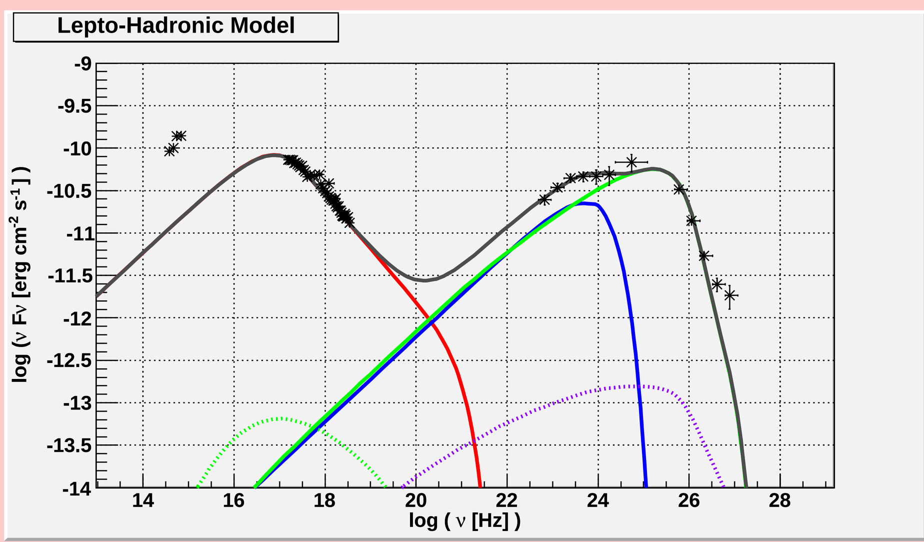

Figure 3: Modelling of PKS 2155-304 in a mixed lepto-hadronic scenario.

In all the plots, colour code is as follow : red bold line : primary e synchrotron emission; green bold line : inverse Compton emission; blue bold line : p synchrotron emission; violet bold line : μ synchrotron emission; dotted lines show the synchrotron emission from first generation of pairs generated by the associated process.

IV. Model parameters

	SSC	Proton synch	Mixed
θ	1°	1°	1°
δ	30	30	30
$\gamma_{e,min}$	5×10^2	1×10^3	1×10^3
$\gamma_{e,break}$	1.2×10^5	4×10^3	6×10^4
$\gamma_{e,max}$	1×10^6	5×10^5	5×10^6
$\alpha_{e,1}$	2.4	2.2	2.0
$\alpha_{e,2}$	4.32	4.5	4.25
K_e	7×10^4	3.1×10^3	6.7×10^3
u_e	1.1×10^{-2}	4.8×10^{-4}	1.0×10^{-2}
$\gamma_{p,min}$	-	1×10^5	1×10^5
$\gamma_{p,max}$	-	5×10^9	1×10^{10}
α_p	-	2.5	2.0
$\eta = K_p/K_e$	-	4.8×10^4	8
u_p	-	1.4×10^3	9.2×10^2
R_{src}	1.7×10^{16}	5.0×10^{14}	4.8×10^{15}
B	0.075	80	0.22
u_B	2.2×10^{-4}	2.5×10^2	2×10^{-3}
L_{jet}	8×10^{43}	1×10^{46}	5×10^{47}

Table 1 The table shows the different parameters used in the modelling of the PKS 2155-304 SED for the three different scenarios (purely SSC, synchrotron proton and mixed scenario) plotted in Figs. 1 to 3. Common values of redshift $z = 0.116$, Doppler factor $\delta = 30$ and viewing angle $\theta = 1°$ have been used.

The normalization parameter $K_{e,p}$ is in units of cm^{-3}, and represents the number density of the primary particle distribution at $\gamma = 1$; the size of the emitting ragion R_{src} is given in cm; the magnetic field is given in gauss.
The density energies $u_{e,p,B}$ are given in units of ergs cm^{-3}; the jet luminosity is given in units of ergs s^{-1}. In the evaluation of the jet luminosity the cold proton content of the jet, evaluated following Sikora et al. (2009), has been included.

V. Conclusions and Perspectives

The code presented here permits to reproduce the observed blazar SED in different scenarios, spanning a wide parameter space: a leptonic or a hadronic solution can be found assuming different physical conditions (magnetic field, density and distribution of primary particles) in the blob. In addition, mixed lepto-hadronic scenarios naturally arise in this framework.

The increasing data quality at high energies, provided by *Fermi* in the GeV range, and by current and planned Cherenkov telescopes in the TeV range, will hopefully help to evaluate contributions from both leptons and hadrons. The next step towards a more realistic emission model would be a time-dependent lepto-hadronic code, which could take into account constraints from the observed variability from blazars.

Bibliography

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