A spatially resolved SSC shock-in-jet model

Stephan Richter[1] and Felix Spanier[1]

[1] ITPA Universität Würzburg

So called Synchrotron Self Compton (SSC) models have been quiet successful in explaining the emissions of blazars. However, observational results of the last years have led to the conclusion that the usual approach of modelling blobs in blazar jets as homogeneous regions employing SSC codes is not sufficient. Especially the observation of intra day variability introduces unreasonable constraints for either the size of the emission regions or the Doppler factor that are both not consistent with observations. Furthermore the observed time delays between the light curves of different frequencies can't be explained by such models.
An attempt to resolve these issues is presented here in form of a spatially resolved, self-consistent SSC model. The observable spectral energy distribution evolves entirely from a low energetic delta distribution of electrons by means of the implemented microphysic of the jet. Hence a large variety of scenarios can be computed, e.g. the acceleration of particles via multiple shocks. The model can explain SEDs where cooling processes are crucial. It can verify high variability results from acausal simulations and produce variability without artificial injection of particles, but due to the presence of multiple shocks.

Electron Model

In the here presented model the well known homogeneous models are extended by the spatial coordinate z along the jet axis. Hence the Vlasov-Equation yields:

$$\frac{\partial F}{\partial t} + v\mu \cdot \frac{\partial F}{\partial z} = \frac{1}{p^2}\frac{\partial}{\partial \mu} p^2 D_{\mu\mu} \frac{\partial F}{\partial \mu} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \cdot \left(\langle \dot{p}_{FII}\rangle \frac{\partial F}{\partial p} + \dot{p}_{cool} \cdot F\right)\right] + S(z,p,t)$$

($D_{\mu\mu}$ - pitch angle diffusion coefficient; $\dot{p}_{FII}$ - Fermi II acceleration; $\dot{p}_{cool}$ - includes synchrotron and inverse compton losses; S - source function)

The electron distribution is assumed to be isotropic in μ, hence the pitch angle is integrated out for each half space. The spatial resolution is achieved by extending the idea of Two-Zone-Models. The simulation region is divided into linearly aligned slices ($\# \sim 100$). The control flow is as follows:

- Calculate the change in electron density for each slice due to convection from/to neighbouring regions and the source function
- Integrate the Vlasov-Equation in momentum space in each slice via the Crank-Nicolson scheme
- Perform scattering of electrons from one half-space into the other due to pitch angle scattering

The last point leads to an effective acceleration, if the scattering happens around a shock front. This is usually referred to as Fermi I acceleration. The parameter entering the calculation is the bulk Lorentz factor γ_{bulk} of the plasma. To compute this quantity for each slice the plasma bulk velocities have to be calculated from the shock properties. The downstream velocity behind each shock V_P, expressed in the upstream frame is

$$V_P = \frac{V_S(R-1)}{R - V_S^2} \quad .$$

Here V_S is the velocity of the shock and R the compression ratio.

Photon Model

In each slice the photon density is calculated, using full IC cross section, via:

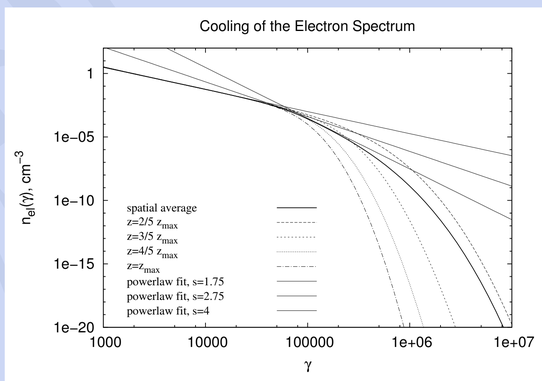
$$\frac{\partial N}{\partial t} = -c \cdot \kappa_{\nu,SSA} \cdot N + \frac{4\pi}{h\nu} \cdot (\epsilon_{\nu,IC} + \epsilon_{\nu,sync})$$

($\kappa_{\nu,SSA}$ - Synchrotron Self Absorption coefficient; $\epsilon_{\nu,IC}$ - changes due to invers compton scattering; $\epsilon_{\nu,sync}$ - yields due to synchrotron radiation)

Cooling- and shock-properties

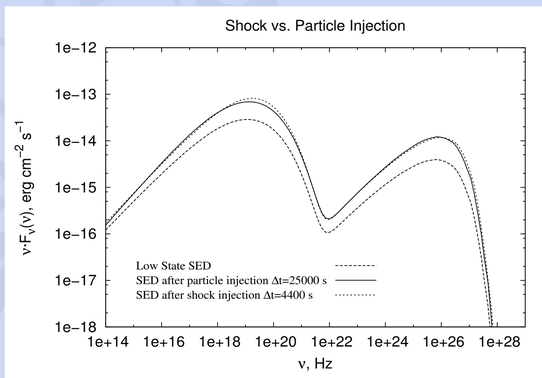
The spatial resolution of the presented modell opens a couple of prospects. First and foremost this is the cooling of particles after they have been accelerated and escaped from the shock.

- observe the electron spectrum at different distances from the shock (see figure to the right)
- averaging over whole simulation box yields spectral break
- possibility of predicting morphology of emission region $\Rightarrow$ in principle testable with VLBI observations

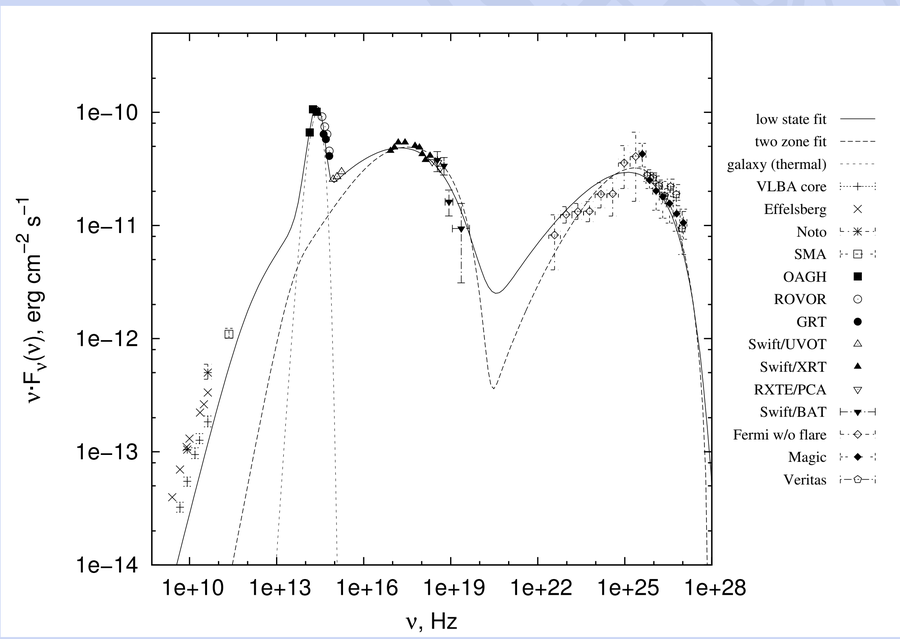


A second advantage is the explicit modelling of the shock. Hence multiple-shock-scenarios can be computed.

- hitting a powerlaw electron distribution with a second shock immediately effects all energies
- in contrast, injected particles have to be accelerated first of all
- $\Rightarrow$ additional shocks yield faster variation scales in the gamma range (see figure to the right)



Fit of the multi-frequency campaign on Mrk501



The Blazar *Mrk501*, a HBL situated in the *Hercules* constellation with a redshift of $z = 0.034$, was observed in a multi-frequency campaign between March and August 2009 (*Abdo et al., 2011*). The plot to the left shows the fit of the averaged low state of this source.

- In the radio range the *VLBA core* data is most important: it is claimed, that the radiation originates from a region of size $\sim 10^{17}$ cm $\Rightarrow$ VLBA core data can be seen as close upper bounds. In contrast to the best fit of a Two-Zone-Model (*Weidinger, 2009*), the data is now represented much better.
- In the optical the SED is dominated by the thermal spectrum of the surrounding galaxy.
- The different data sets for the γ-range are averages of different observing intervals. Hence they are not fully consistent. Moreover, Fermi observed a change in the spectral index during the observation period.

The presented fit was realised in a simulation region of 10^{15} cm with a magnetic background field of 1 G. Particles were injected with a rate of $\sim 200\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1}$ and a Lorentz factor of $\gamma_{inj} = 345$. The shock responsible for the acceleration had a velocity $v_S = 0.2$ c and a compression ratio $R = 3$. The Doppler factor was set to $\delta = 20$.

With the here presented model it is possible to confirm results regarding the particle acceleration from one- and two-zone-models and therefore trace them back to the jets microphysics. Variation of the flux can be achieved by causal (i.e. at the edge of the simulated region) injection of particles as well as by appending additional shocks. The resulting timescales for the latter are short enough to possibly explain lightcurves with variation timescales in the order of minutes.
In the fit of the Mrk501 data the difference to homogeneous models is most prominent in the radio range. Usually the generated fluxes are much smaller then the observed ones. However, due to the spatial resolution there is a contribution from electrons far away from the shock that are already cooled. These contributions will have their maximum at low frequencies and will only give small fluxes in the γ-range.
Starting from the above fit for the low state we're now trying to get a consistent high state fit as well as to resemble actual lightcurves. In particular time lags between different bands could be resolved taking into account light travel times through the simulation region and probably be produced by the implemented mechanisms.