Towards modeling gamma-ray blazar light curves

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Abstract. Blazars are known as inherently variable extragalactic objects emitting non-thermal radiation from its jet across the whole electromagnetic band. Variability time scales range from weeks (in the radio band) up to a few minutes at the highest gamma-ray energies. Such information has so far been used for modeling the observed jet radiation only to a limited extent, owing to the capabilities of current jet emission codes.

We have developed a self-consistent time-dependent code to model the temporal evolution of the spectral energy distribution of astrophysical jet sources taking into account all relevant radiation processes including both hadronic and leptonic interactions. Here we report on first preliminary results of a parameter study with particular focus on the temporal behaviour of the emission at gamma-ray and optical energies upon instantaneous injection of a relativistic particle population of various composition.

Our results demonstrate that complex relationships between the light curves at low and high energies are possible.

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INTRODUCTION

Among the most numerous sources of the high-energy (HE) sky are active galactic nuclei of the blazar type. Their continuum emission covers the complete electromagnetic band, from radio up to gamma-ray energies, and is thought to originate from well-defined emission regions, or 'blobs', that are outflowing relativistically along the axis of a prominent jet. The broadband continuum spectral energy distribution (SED) of blazars is mostly dominated by inherently strongly variable nonthermal emission and consists of two broad components: A low-energy component from radio through UV or X-rays, commonly explained as synchrotron radiation from a ultrarelativistic primary electron population, and a HE component from X-rays to gamma-rays, produced from energetic processes involving charged ultrarelativistic particles whose nature is still a matter of debate, and depends strongly on the matter content and global structure of the emitting region. Modelling snapshot or time-averaged broadband SEDs using time-independent emission models was to-date unable to discriminate between purely "leptonic jet models" and those which additionally consider a significant radiation component from relativistic protons ("hadronic jet models"). Observationally, well-sampled light curves are available from selected bright blazars at low energies, and recently also at gamma-ray energies. This variability information adds crucial information to blazar emission modelling which can only be exploited by using fully time-dependent emission models that treat all relevant processes (leptonic and hadronic) on an equal footing. Here we present first preliminary results from such code.

PARTICLE AND RADIATION TRANSPORT INITIATED BY RELATIVISTIC PARTICLES – CODE DESCRIPTION

We have devised a time-dependent jet emission code that has the capability to follow the time evolution of injected relativistic particles of arbitrary lepton - hadron composition and calculates the emitted radiation.

Our model considers a homogeneous initially spherical emission region of (jet-frame) size R'_0 upon injection in a constant speed conical jet. The emission region is interfused by tangled magnetic fields of strength B'_0 upon injection. Relativistic particles inside this emission region may interact and lose energy via photomeson production [1], Bethe-Heitler pair production, photon-photon pair production, inverse Compton scattering (incl. Klein-Nishina treatment), synchrotron radiation (incl. quantum regime treatment [4]) from protons, electrons/positrons, charged pions and muons. Furthermore, the decay of unstable particles, adiabatic losses, charged particle and photon escape are taken into account as well. Photon and particle transport is accomplished using the matrix multiplication method [2, 3]. In this study we do not take into account external radiation fields. Although our code allows several injection scenarios (instantaneous, continuous) for the relativistic particle population, we here focus on impulsive injection, and follow the subsequent evolution of the particles and photons.

PARAMETER SETTINGS AND RESULTS

For the present study we use this code to investigate the decay of light curves as a result of instantaneous and simultaneous injection at time $t = 0$ of a proton (p) and electron (e) component with power law spectra $\propto E_{\rm e,p}^{-\alpha_{\rm e,p}}\delta(t)$, where $E_{\rm e,p,min} \leq E_{\rm e,p} \leq E_{\rm e,p,max}$ is the range of particle energies injected into the emission region. We consider the equipartition case between particles and fields upon injection (i.e., $(u_{\rm e,0} + u_{\rm p,0})/u_{\rm B,0} = 1$). In the examples shown below we further assumed for the“leptonic case” one cold proton per electron, while for hadronic compositions one relativistic proton per electron. The injected proton and electron spectra are described by a power law with index $\alpha_p = \alpha_e = 2$ in the range 0.05GeV$\leq E_{\rm e} \leq$ 40GeV and 2GeV$\leq E_{\rm p} \leq 10^{10}$GeV. Adiabatic losses on a time scale $t_{\rm ad} = 10R'/c = 10t_{\rm esc,ph}$ with $t_{\rm esc,ph}$ the photon escape time scale are taken into account. Photon spectra are then calculated with a Doppler factor $D = 20$.

To characterize the simulated light curves we measure the flux decay by the e-folding decay time $\tau_{\rm dec,d}$, i.e., the time in units of days passed since peak flux where the flux has decayed to $1/e$ of its peak value, and indicate the flux maxima at various energies (optical, GeV, TeV).

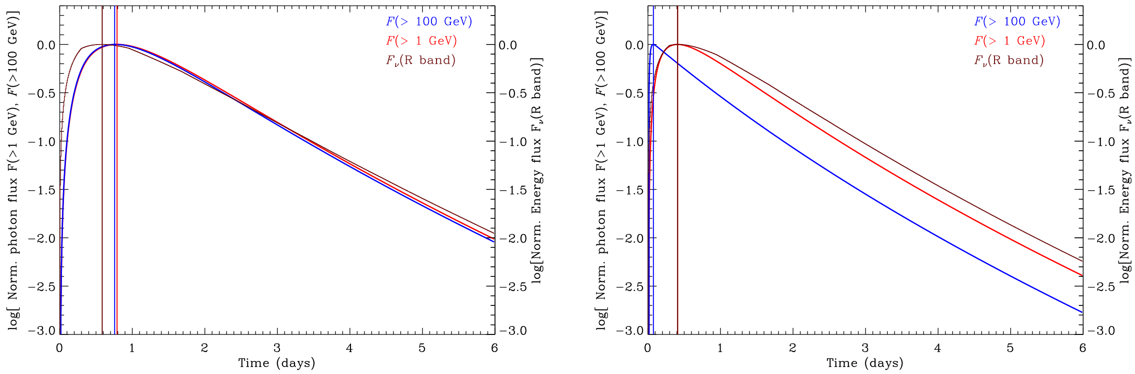

FIGURE 1. Log-linear representation of light curves, normalized to its peak value, from instantaneous injection at time t=0 at optical & γ-rays for $R_0' = 10^{16.5}$cm for the leptonic case. Vertical lines indicate the time of flux maximum in the respective energy band. Left: $B_0' = 0.01$G, $\tau_{\rm dec,d} \sim 1.4(\gamma) - 1.5$ (R-band). Right: $B_0' = 1$G, $\tau_{\rm dec,d} \sim 0.8$(TeV) .. 1.1(GeV).. 1.3(opt).

Leptonic Model

Relativistic electrons only (and cold protons of equal number) are injected resulting in a Synchrotron-Self Compton (SSC) SED. Depending on the free parameter values we find a variety of temporal relations between the flux maxima at the considered energies (e.g., quasi-simultaneous GeV-to-TeV, R-band-GeV, R-band-TeV flux peaks) possible (see Fig. 1). Time scales become longer with increasing R' and decrease with B_0'.

Hadronic Model

Relativistic electrons & protons are injected in equipartition with the initial magnetic field energy density; equal numbers of injected electrons and protons are assumed.

Here, it appears that light curves at GeV energies decay slower than at TeV- & R-band, light curves in the optical band decay faster (see Fig. 2). Simultaneous optical/γ-ray flux peaks seem possible.

CONCLUSION

Preliminary results from simulations of models with and without relativistic proton injection indicate:

- Flux decay time scales in models where the proton energy density dominates over the electron energy density appear slightly longer but comparable within an order of magnitude of corresponding leptonic models.
- Impulsive particle injection leads to flares within ~ 1 day for typical blazar parameters (emission region size of order 10^{15-16}cm, $D \sim 20$).

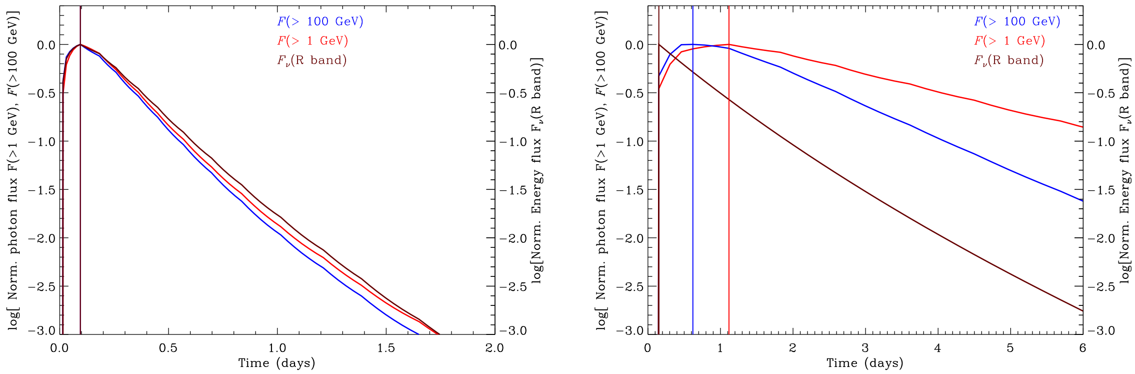

FIGURE 2. Same as Fig. 1 but for the hadronic case and different R'_0. Left: $R'_0 = 10^{15.5}$cm, $B'_0 = 1$G, $\tau_{\rm dec,d} \approx 0.2-0.3$. Right: $R'_0 = 10^{16.5}$cm, $B'_0 = 20$G, $\tau_{\rm dec,d} \sim 0.8$(opt).. 2.0 (TeV).. 2.7(GeV).

- Our study indicates that a variety of relationships between the light curves at low and high energies in leptonic and hadronic blazar emission models are possible. This complicates their interpretation in view of the relativistic matter composition of the jet.

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