Timing Signatures of the Internal-Shock Model for Blazars

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Abstract: We have developed a semi-analytical model for the time-dependent radiative output from the internal-shock model for blazars. Accounting for spatial inhomogeneities due to the forward- and reverse-shock propagation and light travel time effects, the synchrotron and external-Compton emissions are evaluated completely analytically, while the synchrotron self-Compton emission is reduced to a two-dimensional integral. We explore the influence of various parameters on the time-averaged spectral energy distributions and timing features for parameters suitable for flat-spectrum radio quasars and low-frequency peaked BL Lac objects. Light curves at various representative photon energies are subjected to the Discrete Correlation Function to evaluate inter-band time lags, as is routinely done for observational data.

Model Setup

Figure 1 illustrates the geometry of our model: Two shells of initially cold (i.e., internal energy << bulk kinetic energy) plasma with Lorentz factors Γ_a and Γ_b ($\Gamma_b > \Gamma_a >> 1$) collide, leading to a forward shock propagating into shell *a* and a reverse shock propagating into shell *b*.

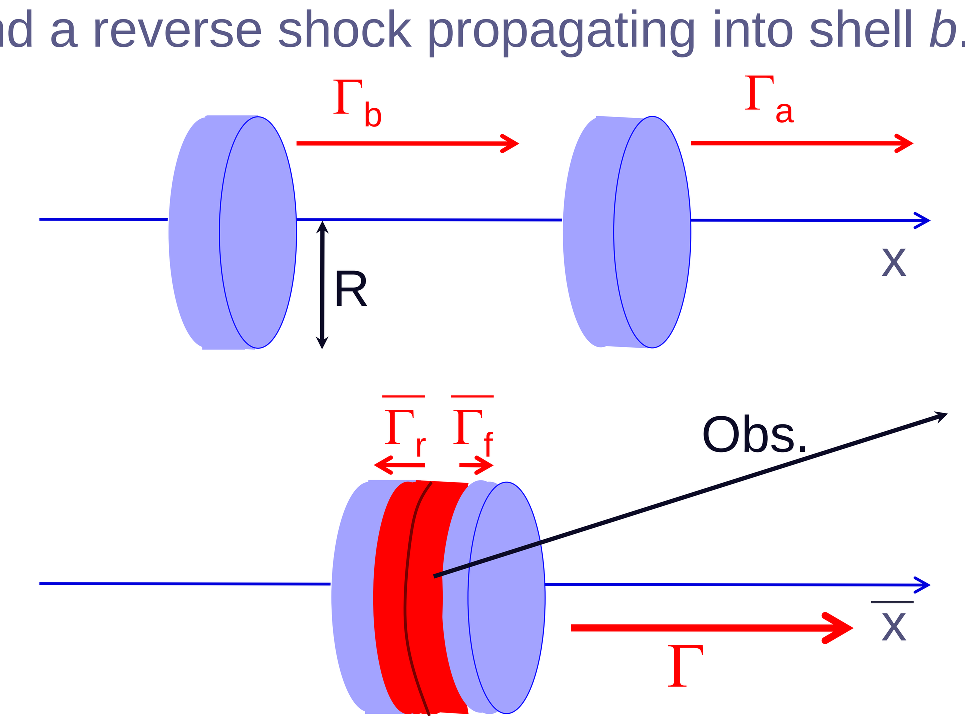

Fig. 1: *Geometry of the shell collision leading to internal shocks in a blazar jet.*

The shocked fluid will move with Lorentz factor Γ with respect to the stationary frame. In the frame comoving with the shocked fluids, the shocks propagate with Lorentz factors $\overline{\Gamma}_f$ and $\overline{\Gamma}_r$, respectively.

Particle Dynamics: At the shocks, particles are assumed to be accelerated into a power-law distribution with index *q*, with normalization and low- and high-energy cutoffs determined by energy conservation and balancing of acceleration and radiative cooling time scales. Subsequent radiative cooling is taken into account assuming synchrotron + Compton cooling in the Thomson regime, leading to a fully analytical space- and time-dependent electron energy distribution throughout the shocked region.

Radiation: Synchrotron and external-Compton emission is evaluated analytically using a δ-function approximation. The space- and time-dependent synchrotron photon density is also evaluated analytically and used for a numerical computation of the space- and time-dependent SSC emissivity. All time delays from shock- and light-travel time effects are properly taken into account.

Baseline Model: For a baseline model, we use parameters reproducing a Spectral Energy Distribution (SED) typical of Flat Spectrum Radio Quasars (FSRQ) or Low-frequency peaked BL Lac Objects (LBL), as listed in the table.

These parameters lead to a bulk Lorentz factor of the shocked fluid of $\Gamma = 18.2$, and we choose the observing angle so that the Doppler factor $D = \Gamma = 18.2$.

Parameter	Symbol	Value
Lorentz Factor of shell a	Γ_a	15
Lorentz Factor of shell b	Γ_b	25
Kinetic power of shell a	L_a	10^{47} erg/s
Kinetic power of shell b	L_b	10^{47} erg/s
Time scale for ejection of shells	Δt	10^3 s
Electron equipartition fraction	ε_e	0.2
Magnetic-field equipartition fraction	ε_B	10^{-3}
Electron injection spectral index	q	2.3
External radiation energy density	u_{ext}	10^{-4} erg/cm^3
External radiation peak frequency	ν_{ext}	$3*10^{14}$ Hz
Cross-sectional radius of shells	R	$3*10^{15}$ cm
Redshift	z	0.2

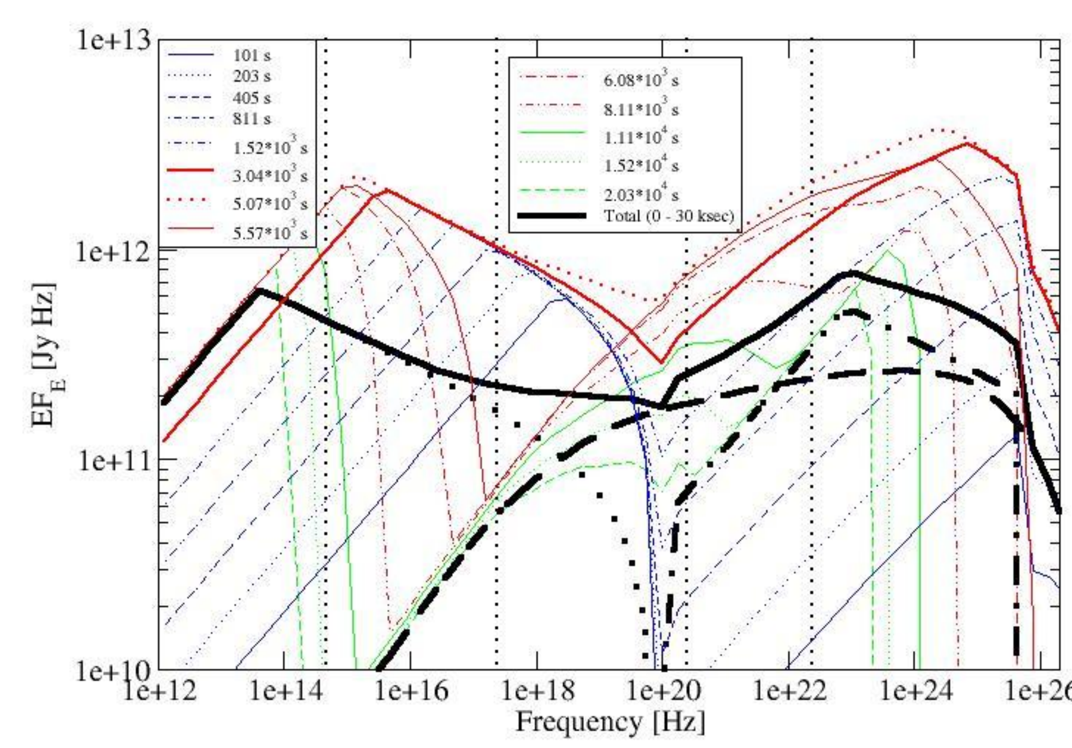

Fig. 2: *Snap-shot SEDs from our baseline model, along with the SED time-averaged over 30 ksec (heavy black curves). Dotted vertical lines indicate the frequencies at which light curves have been extracted.*

In addition to snap-shot SEDs, we calculate the time-averaged spectrum over an integration time of 30 ksec to investigate averaged SED characteristics.

Light curves have been extracted at four frequencies: Optical (**R-band**), X-rays (**1 keV**), soft γ-rays (**1 MeV**), and high-energy γ-rays in the Fermi range (**100 MeV**). Cross-correlations and time lags between the light curves have been investigated using the **Discrete Correlation Function** (DCF; Edelson & Krolik 1988).

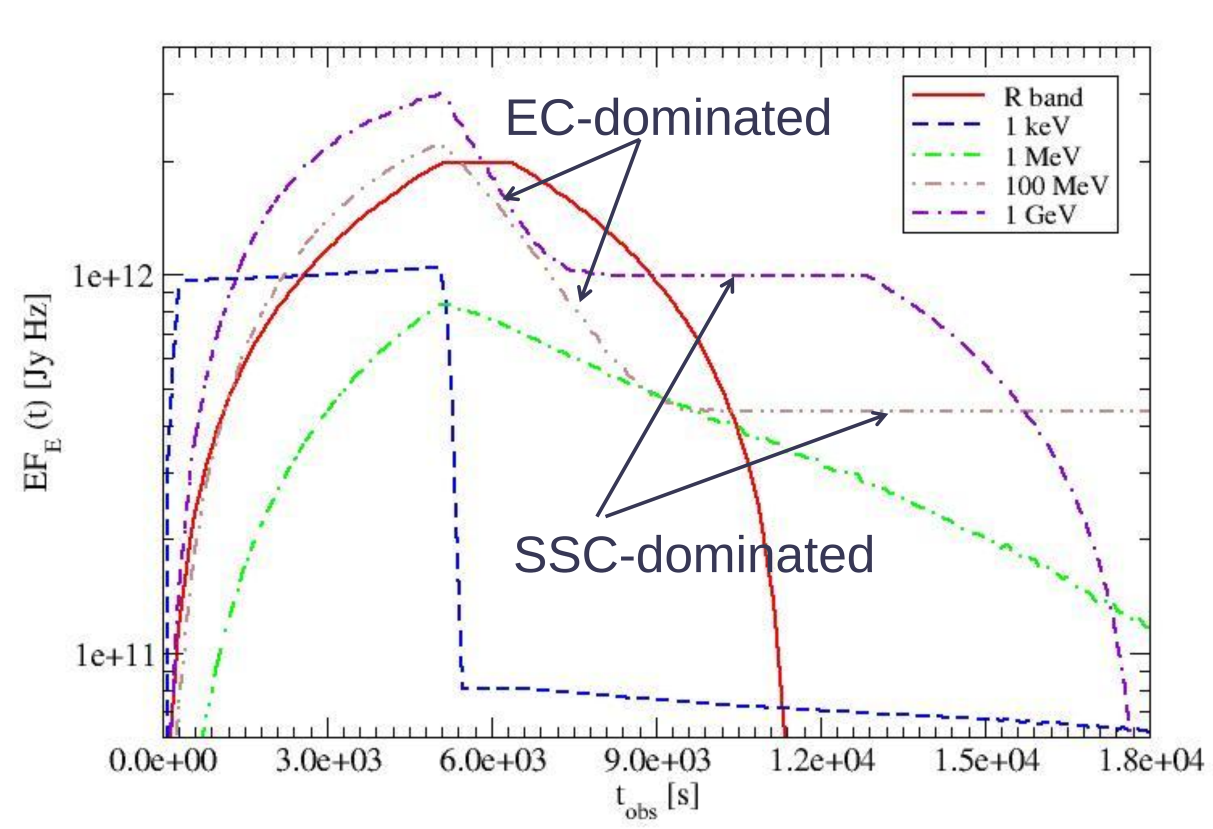

Fig. 3: *Light curves resulting from our baseline model*

Figure 4 illustrates the DCF results for our baseline model: It predicts lags of the R-band and soft γ-rays behind soft X-rays by ~ 1 – 2 hrs with sub-hr time lags between other bands.

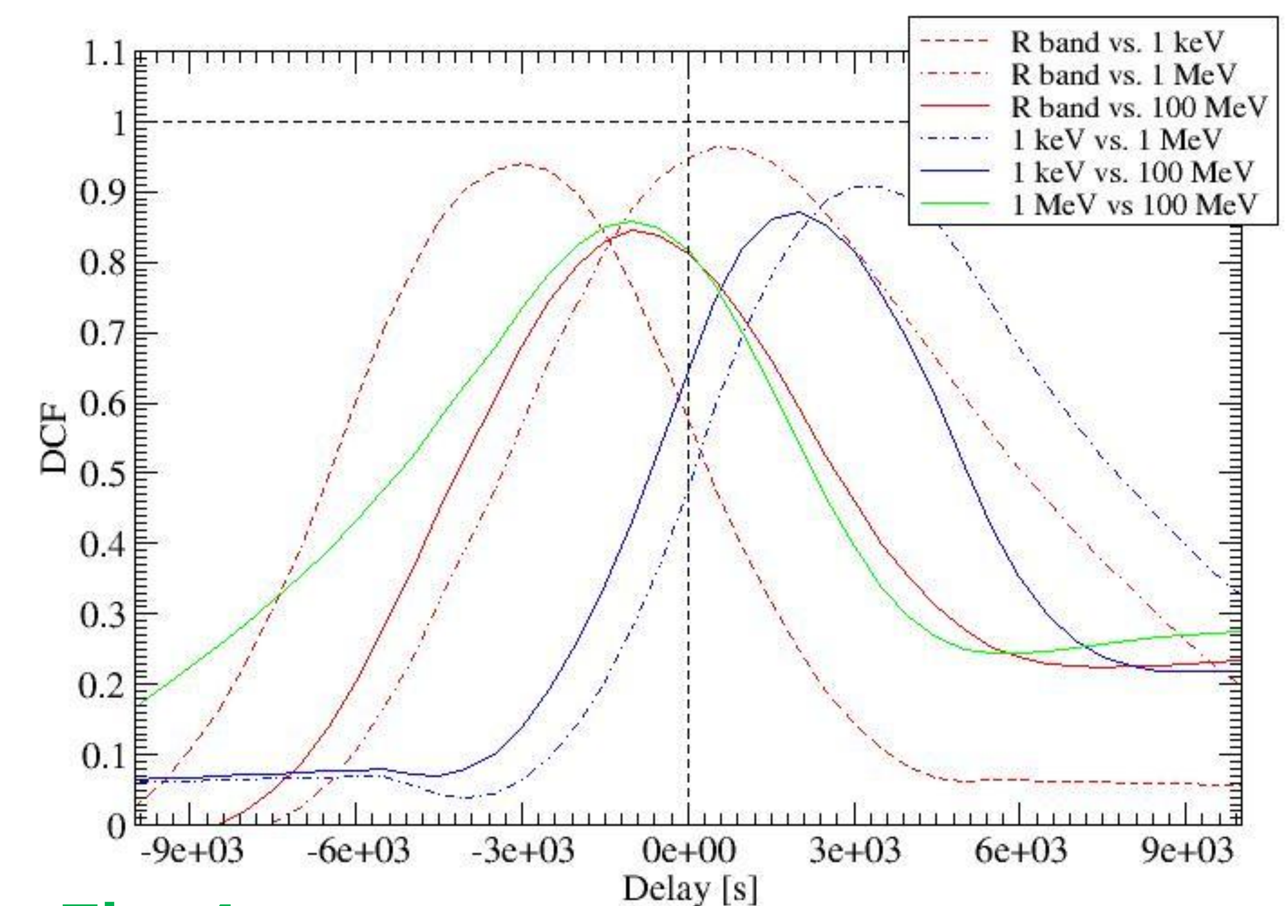

Fig. 4: *Discrete Correlation Functions (DCFs) between light curves from our baseline model.*

The dependence of these features on various parameters has been investigated. As an example, Fig. 5 illustrates the dependence of DCF characteristics on the external radiation field. Most notably, this and other parameter variations may lead to a **change in sign of time lags**, e.g., a transition from an R-band lag behind HE γ-rays to an R-band lead with increasing external radiation energy density.

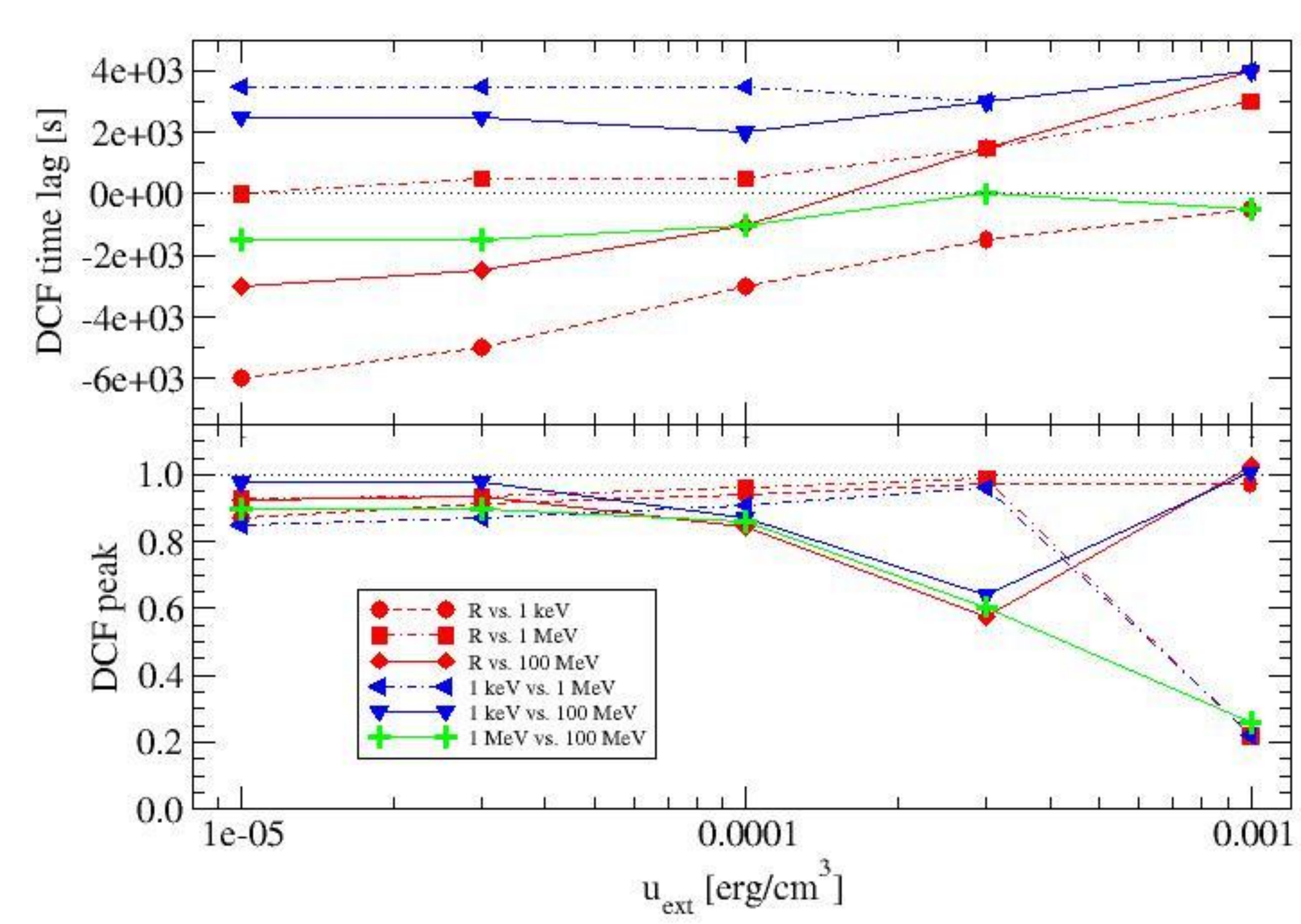

Fig. 5: *Dependence on DCF parameters on the external radiation energy density.*

With current observational capabilities, our results may be compared to cross correlations of observations of FSRQs and LBLs by ground-based optical observatories and pointing X-ray telescopes, while the required time resolution at gamma-ray energies is currently beyond the capabilities of INTEGRAL (soft γ-rays) and Fermi and AGILE (HE γ-rays).