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Time-dependent multi-zone radiation transfer modeling of fast blazar variability

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Abstract. We present the first applications of a new time-dependent multi-zone jet radiation transfer code to the study the multiwavelength emission of the TeV Blazar Mrk 421. The code couples Fokker-Planck and Monte Carlo methods. For the first time all light travel time effects are fully considered as well as proper self-consistent treatment of Compton cooling, which depends on them. The first tests focus on the March 2001 observations of Mrk 421, still one of the best datasets available for phenomenology and X-ray/TeV data coverage. We summarize the results of scenarios of variability induced by injection of relativistic electrons in a blob encountering a shock, and with different combinations with a second component, either co-spatial or independent from the active region.

Keywords. radiation mechanisms: nonthermal, radiative transfer, galaxies: active, BL Lacertae objects: individual (Mrk 421), galaxies: jets

1. Blazars multiwavelength spectra and variability

Blazars emit strongly from radio through γ-ray energies. Their spectral energy distribution (SED) comprises two major continuum, non-thermal, components attributed to synchrotron and inverse Compton (IC) radiation by ultrarelativistic electrons (Maraschi *et al.* 1992, Marscher & Travis 1996, Dermer *et al.* 1992, Sikora *et al.* 1994). Rapid and large-amplitude multiwavelength variability is a defining observational characteristic of blazars (Ulrich *et al.* 1997).

In a subclass of blazars, commonly referred to as high-peaked BL Lacs (HBL) the synchrotron component peaks (in νF_ν) in the X-ray band, the higher energy component (IC) reaches up to TeV γ-rays, a combination accessible observationally thanks to ground based Cherenkov telescopes and the availability of several X-ray observatories. Hence, the brightest HBLs have been studied extensively. Simultaneous X-ray/γ-ray observations showed that variations around the two peaks are well correlated (Fossati *et al.* 2000a,b, 2008, Sambruna *et al.* 2000, Krawczynski *et al.* 2004, Błażejowski *et al.* 2005, Aharonian *et al.* 2009). The variability observed at/above $\nu_{\rm peak}$ is likely the result of the rapid change of the electron distribution, in the regime where acceleration and cooling are approximately balanced: by studying the variability around $\nu_{\rm peak}$, we are investigating the behavior of the electrons that are the most direct probe of the physical conditions of the emitting plasma (Inoue & Takahara 1996, Kirk *et al.* 1998, Kusunose *et al.* 2000).

2. Time-dependent modeling

The theoretical interpretation of the multiwavelength observations has remained relatively basic (Sikora *et al.* 2001, Krawczynski *et al.* 2002, Böttcher & Chiang 2002). One of the biggest challenges is the treatment of light crossing time effect (LCTE), rarely fully modeled, which affect the observer's "perception" of the variability (e.g. because of delayed times) and the physical evolution within the source, mainly because it affects the correct computation of the IC cooling of the emitting particles. Previous work dealt with the effect of time delays from the observer point of view (Chiaberge & Ghisellini 1999, Kataoka *et al.* 2000, Katarzyński *et al.* 2008), and in some cases included the internal effect to calculate the IC emission but without properly accounting for it when calculating IC energy losses (Sokolov & Marscher 2005, Graff *et al.* 2008).

2.1. *Our code*

We have developed a code in which for the first time all the LCTE are fully considered, internal and external, as well as proper self-consistent treatment of Compton cooling, which depends on them. This code affords us the freedom to "play" with (inhomogeneous and varying) physical conditions, internal and external to the active region, and simulate a broad range of scenarios for blazar variability. The code and its first application are discussed in detail by Chen *et al.* (2010). It couples Fokker-Planck and Monte Carlo (MC) in a 2 dimensional (cylindrical) geometry. It is built on the MC radiative transfer code developed by Böttcher and collaborators (2003). MC is ideal for multizone 2D/3D radiative transfer problems because it tracks the trajectory of every photon, thus automatically accounting for LCTE, regardless of the geometry.

3. Observational open questions

We focused on observational findings that seem to be common to various sources:

• (quasi-)symmetry of flares, in the sense that the rise and decay timescales are often very similar. This would suggest that the flare evolution is governed by a factor that is energy independent, such as the geometry of the active region via its crossing time.

• Amplitude and phase correlations of variations in different bands, typically X-ray and TeV γ-rays for the best observed blazars so far. Particularly challenging is that the TeV emission has been seen to vary super-quadratically with respect to variations in X-ray, in the case of Mrk 421 and PKS 2155−304, the two best studied HBLs (Fossati *et al.* 2008, Aharonian *et al.* 2009).

• Intra-X-ray band lags, which can be soft or hard, without (so far) a clear observational understanding of what determines the sign. Physically, at least qualitatively, there are good reasons to expect lags of both signs depending on the combination of the relevant timescales (e.g. cooling, acceleration).

• Limited variability in the optical band. The case for two components, a flaring and a steady one, to interpret some of the observations has become compelling with better of multiwavelength observations.

4. Summary of results

The first tests focus on the March 19 2001 flare of Mrk 421 an ideal test-bench because of its isolation, large amplitude and good data coverage.

We studied simple scenarios generally intended to simulate variability caused by the encounter of a blob with a shock, i.e. produced by injection of relativistic electrons as a "shock front" crosses the emission region. We consider emission from two components, with the second component either being pre-existing and co-spatial and participating in the evolution of the active region (background), or being spatially independent, only diluting our observation (foreground) (Chen *et al.* 2010).

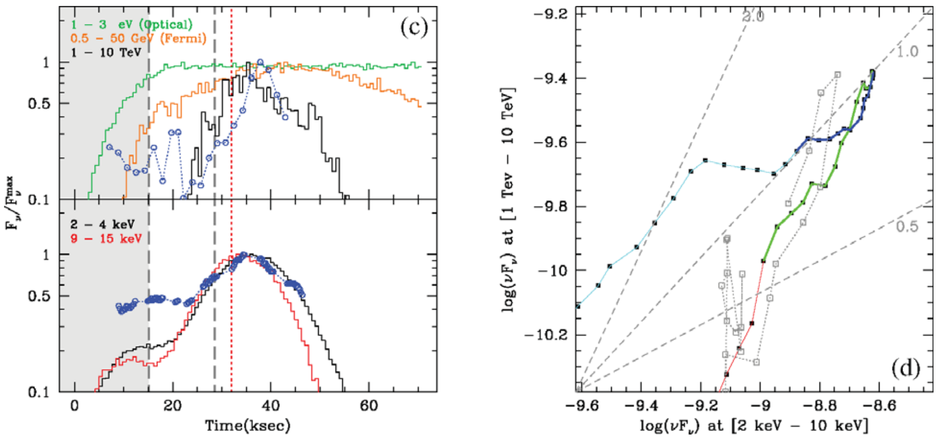

Figure 1. Summary of results of the case with pre-existing background electron population. Left: Light curves, normalized to their peak values. In blue the *RossiXTE*/PCA 2–4 keV and TeV data. The grey shaded area marks the initial phase not meaningful because it corresponds to the source "setup". The long dashed vertical grey lines mark the injection period. The dotted red line marks the time when the largest slice of the active region becomes visible, i.e. when one could expect the flare peak accounting for LCTE. Right: The flux vs. flux plot for X-ray and γ-rays. Colors highlight different time intervals (red end at t=25 ks, and each color spans 10 ks). The grey points and dotted line show the March 19 2001 data (shifted for plotting purposes).

A scorecard of the results of the three main cases is reported in Table 1. Figures 1 show an example of the simulations results for case #1, light curves and flux–flux correlation.

While each scenario seems to reproduce adequately some of the observed features, none of them was able to reproduce all the characteristics of the 2001 March 19 flare. Features particularly challenging to match are: 1) The symmetry of the light curves, in particular for the TeV band; 2) The intra-band X-ray time lag, showing a systematic soft lag; 3) Reproducing the (super)quadratic relationship between TeV/X-ray fluxes.

The first two points are among those more affected by the spatial extent and geometry of the source, whose influence varies with observed energy band because of the relative importance of geometrical and physical time-scales. The impact of the spatial extent of the source on the observed phenomenology is indeed quite significant. It affects not only the shape of the light curve (e.g. its symmetry), but also other less obvious observables such as time lags. Differences in physical time-scales for particles of different energy effectively adds a further geometric effect by inducing inhomogeneities (e.g. stratification) in the source. The impact of the geometry effects, due to the source intrinsic structure and to the stratification of properties due to the physical processes, emphasizes the necessity of a code like the one we introduce here for modeling the variable high energy emission from blazar jets.

The difficulty of producing a quadratic relationship between X-ray and γ-ray fluxes during the declining phase of the flare indicates that radiative cooling cannot fully explain electron cooling, and that there is need for an energy-independent mechanism. One possibility is adiabatic cooling, which could be associated with expansion of the blob.

One of the most interesting aspects of our analysis was the comparison between two possible hypotheses for the presence of an additional SED component. Disentangling variable and steady components is necessary to see more clearly the properties of the transient one and in turn understand its nature.

Table 1. Summary of Simulations Results

Feature	Obs.	Case #1		Case #2		Case #3	
Flare symmetry							
soft X-ray	Y	Y	+	N	−	N	−
hard X-ray	Y	Y	+	Y	+	Y	+
TeV γ-ray	Y	N	−	N	−	N	−
Flux-Flux Correlation							
trend up	2	2	+	2	+	2	+
trend down	2	2, 1	$\simeq$	1	−	1	−
paths overlap?	Y	Y/N	$\simeq$	N	−	N	−
Time Lags							
X-ray−X-ray	hard (2 ks)	soft	−	soft	−	soft	−
X-ray−γ-ray	γ-ray (2 ks)	N	−	Y (2 ks)	+	Y (8 ks)	−

Case #1: injection of new electrons in a region filled with a pre-existing population, then evolving together.
Case #2: injection in an empty volume, whose radiation is diluted by that of a separate emission component.
Case #3: like #1, with parameters adjusted to match better the TeV spectrum.

Our simulations would seem to favor the scenario with a simply diluting component. One important difference between the two alternatives concerns the IC emission. If the observed SED consists of the sum of two independent contributions, then the only seed photons for variable IC component will be those produced by the injected electrons themselves. Starting from an empty blob, the energy density of synchrotron seed photons needs some time to build up, which naturally results in a delay in the variation of the IC scattered γ-rays. This delay is present in the simulations for case #2, as in the observations.

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