Modeling variable multi-wavelength emission during blazar flares

A. Dmytriiev, H. Sol, A. Zech

LUTH, Paris Observatory

Paris, November 28, 2019

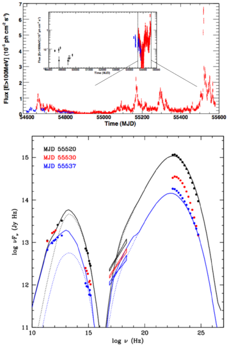
Outline

Outline

1. Introduction
2. Development of the SSC code
3. Application of the code: Mrk 421 flare
4. Conclusions

Blazars are AGN with jet aligned with line of sight

- non-thermal continuum from radio to γ-rays
- two bump SED
- highly variable
  - VHE flares: flux increase by factor $\sim$10 at time scale minutes – days



blazar 3C 454.3

Why study? Ideal laboratories to study AGN jets physics
- broad band emission origin
- particle acceleration mechanisms
- origin of flares

Method: MWL studies of temporal and spectral characteristics of radiation from radio to VHE γ-rays

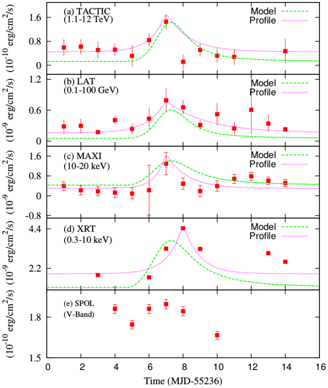
+

Modeling of observed SEDs and light curves

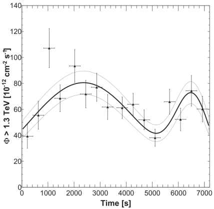
Outline

- Origin of blazar flares is still not understood very well.
- *Full* MWL coverage is quite rare. Very precious for getting a better insight of the physical processes involved.

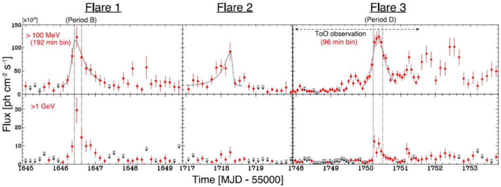
Goal: develop a code for modeling broad-band spectra and light curves (LC) of blazars during flaring activity.



Mrk 421, 2010



Mrk 501, 2014



3C 279, 2015

Approach

I have developed a code **EMBLEM** (Evolutionary Modeling of BLob EMission)

Ingredients of my code:

- conventional one-zone leptonic scenario (blob-in-jet, δ_{blob})
- electrons are injected (instant./cont.) into blob and experience:
  - stochastic (Fermi II) or/and shock (Fermi I) **acceleration**
  - escape
  - synchrotron and SSC cooling
- radiation: synchrotron + synchrotron self Compton (SSC)

$$\boxed{\frac{\partial N_e}{\partial t} = \frac{\partial}{\partial \gamma}\left([\beta_{cool}\gamma^2 - 2D_0\gamma - a\gamma]N_e\right) + \frac{\partial}{\partial \gamma}\left(D_0\gamma^2\frac{\partial N_e}{\partial \gamma}\right) - \frac{N_e}{t_{esc}} + Q_{inj}} \quad (1)$$

- Kinetic equation is solved with *Chang & Cooper* numerical scheme ⇒ electron spectrum evolution
- SED is computed from electron spectrum (SSC scenario) for a set of time steps
- LC ⇒ integration of SEDs

Assumptions

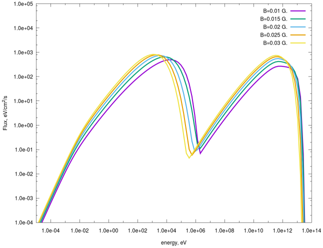
- The magnetic field in the blob is tangled, homogeneous in strength and constant
- Hard-sphere approximation is assumed (turbulent spectrum with slope $q = 2$) $\Rightarrow$ time scale of Fermi II acceleration is energy-independent
- The particle escape is energy independent

Currently the code application is limited only to BL Lac objects

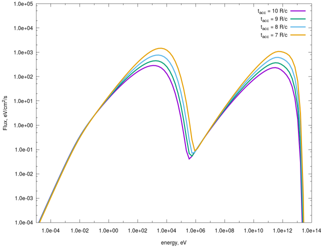
(The external IC is not treated)

We explore effect of several parameters on the *peak* SED during a flare caused by Fermi II acceleration acting in emitting blob

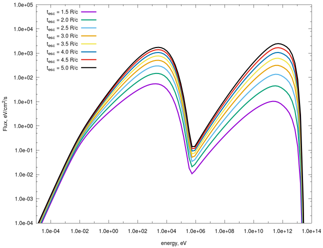
B



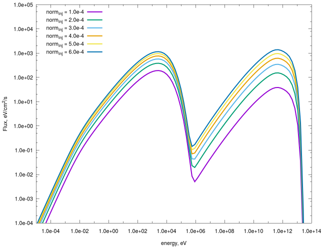
t_{acc}



t_{esc}



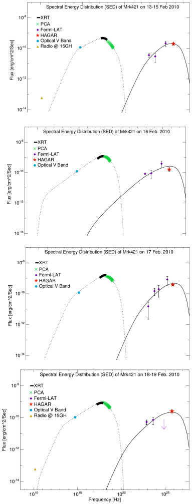
n_{inj}

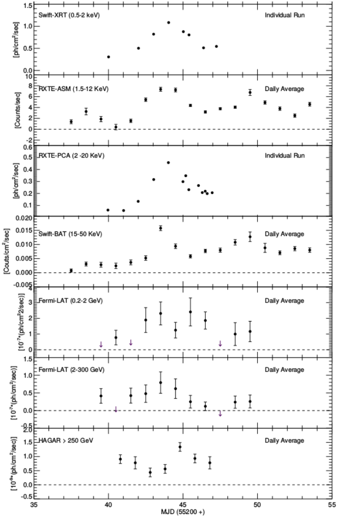


Outline

BL Lac Mrk 421: strong flare during February 10-23, 2010.

>> RARE dataset: almost full time coverage across EM spectrum!





Shukla et al., 2012

Modeling the quiescent state: approach

$\boxed{\textit{Flare} = \textit{perturbation above quiescent state}}$

>> We aim at *connecting* the steady-state emission to the high state

Approach:

1. Physical scenario:
   - continuous *injection* of electrons from the base of the jet (power law with exp cutoff - Fermi I process)
   - *escape* with time scale $t_{esc} = 1$ R/c
   - synchrotron + SSC *cooling*

$\Rightarrow$ processes compete and asymptotically steady state is established

2. Fit SED data points for low state (*Abdo et al., 2011*) with above-mentioned model and deduce the physical parameters.

Parameters of the source:

$B = 0.022\ G.$

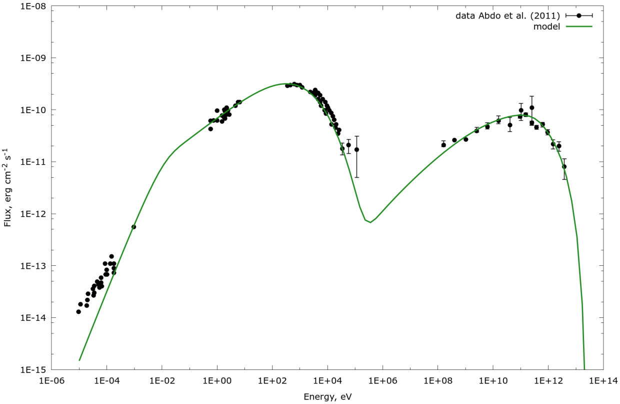
$\gamma_{min,inj} = 1000$

$R_b = 4.9 \cdot 10^{16}\ cm.$

$\delta_b = 28$

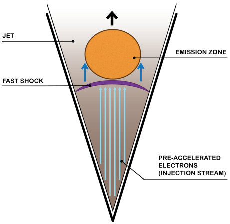
$Q_{inj} = A \cdot \gamma^{-2.18} \cdot exp(-\gamma/5 \cdot 10^5)$

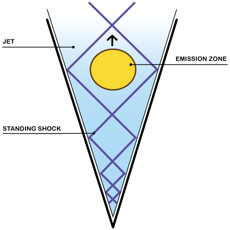
$t_{esc} = 1\ R_b/c$



Modeling of the flare: single-zone scenario

Simplest scenario: perturbation localized to the emitting blob (shock and/or turbulence) initiates the flare





Results

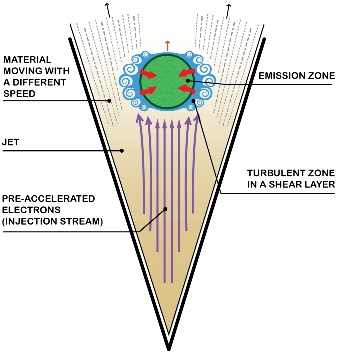
- ! Model predicts *too high optical flux* while describing adequately the X-ray data.
- ▷ Obtained analytical solution for the case of shock passing through the blob and developed a general criterion to test such 1-zone model

X SINGLE-ZONE SCENARIO DOESN'T WORK

Modeling of the flare: two-zone scenario A

- Acceleration and emitting zone (spatially separated)
- Suddenly appearing turbulence around the blob (e.g. KH instability??)
- Electrons from the base of the jet (pre-accelerated) reach turbulent zone and experience stochastic acceleration
- Accelerated electrons from turbulent zone are injected into the blob
  - have harder spectrum
  - radiate SSC emission

  $\Rightarrow$ additional emission on top of quiescent $\Rightarrow$ FLARE



>> In this scenario flare is caused by **additional external injection** on top of quiescent

Approach for the modeling

1. We model electron acceleration in the turbulent region

- Same injection spectrum as for steady state
- Emission from acc. zone subdominant $\Rightarrow$ $R_{acc.zone} < R_{blob}$, $B_{acc.zone} < B_{blob}$
- *Try simple case*: turbulence abruptly starts, lasts for $t_{life,acc.zone}$ and then ends

2. We model emission from the blob

- $N_{e,low.state}$ as initial condition, same physical parameters as for quiescent state
- Adjust parameters of acc. zone that the simulated light curves match the data

Parameters of the turbulent zone:

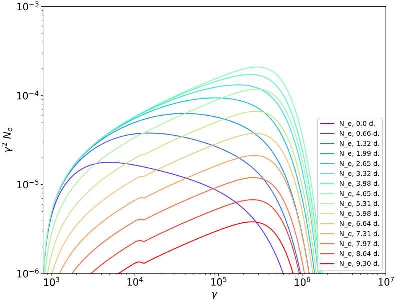
$B_{az} = 0.027\,G.$ $\qquad$ $R_{az} = 5.51 \cdot 10^{15}\,cm.$

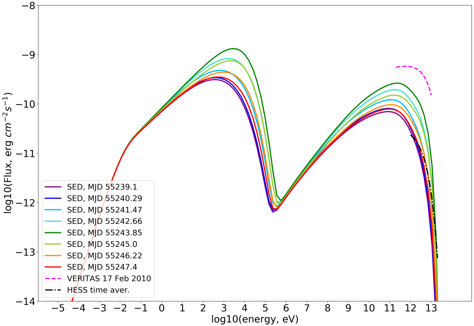
$t_{FII,az} = 43\,R_{az}/c$ $\qquad$ $t_{esc,az} = 18\,R_{az}/c$

$t_{life,az} = 4.65\,d.$ $\qquad$ $injected\ \ fraction \approx 3\%$

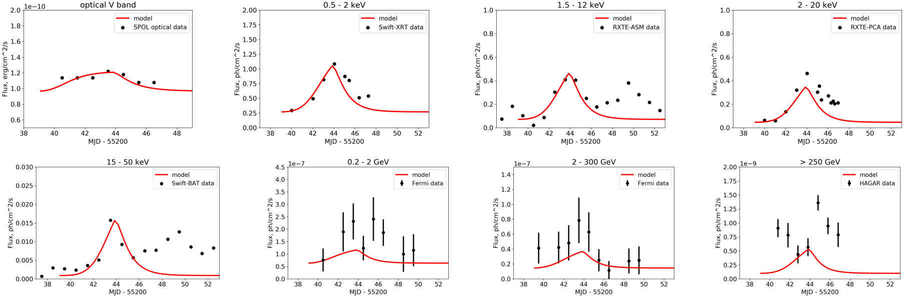
Time evolution of the electron spectrum in the turbulent zone and total SED

(*time advances from violet to red)





Two-zone scenario A: data vs. model



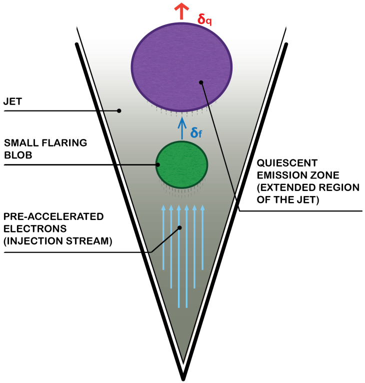
✓ **GOOD, BUT NOT PERFECT**: Optical to X-ray data is described satisfactory

! Model underpredicts γ-ray flux by a factor of $\sim$3

? Completely decouple quiescent and flaring emission?

Modeling of the flare: two-zone scenario B

- Two emitting zones (spatially separated)
- Quiescent emission region and a smaller flaring blob
- Flaring emission is coming from the small blob
- The small blob is moving faster than the quiescent blob and is crossing it
- During passage, turbulence is induced in the small blob (*simplification*: entire volume of small blob is turbulent, quiescent region not affected)
- Particles are accelerated via Fermi II process $\Rightarrow$ FLARE



>> In this scenario flaring emission is originating from a different emitting zone

Approach for the modeling

1. Constraints on the parameters of the flaring blob

– Same injection spectrum for both blobs (the one for quies. state of Mrk 421)

– Low-state emission of flaring blob is negligible $\rightarrow$ $R_{flar.blob} < R_{quies.blob}$

– Doppler factor of flaring blob is defined by the time of the flux rise:

$$t_{cross} = \frac{\delta_f^2 + \delta_q^2}{\delta_f^2 - \delta_q^2} \cdot \frac{2R_{quies.blob}}{c} = t_{rise} \cdot \delta_f \quad \Rightarrow \quad \delta_f = 37.7$$

– Escape time scale during the turbulence is linked
to the Fermi II acceleration time scale:

$$t_{esc,f}^{(turb)} = \frac{R^2_{flar.blob}}{c^2 \beta_A^2 \, t_{FII}} > t_{esc,f} \quad , \quad \beta_A = \frac{1}{\sqrt{1 + (4\mu_0 {<}\epsilon{>})/(3B^2)}}$$

$$< \epsilon > = \frac{1}{t_{max} - t_{min}} \cdot \int_{t_{min}}^{t_{max}} \int_{\gamma_{min}}^{\gamma_{max}} N_{e,fb}(\gamma, t) \cdot \gamma m_e c^2 d\gamma dt$$

2. Modeling the emission from the flaring blob

– *Try simple case*: turbulence suddenly starts, lasts for $t_{cross} = t_{rise} \cdot \delta_f$ and then ends
– Adjust parameters of the small blob in a way that the sum of flaring
and quiescent emission describes the data

Parameters of the flaring blob:

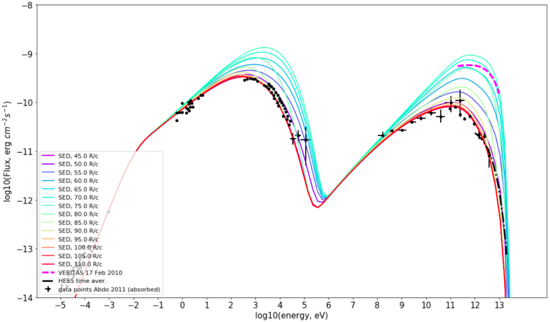
$B_f = 0.016\,G.$ $\qquad$ $R_{flar.blob} = 1 \cdot 10^{16}\,cm.$

$t_{_{FII}} = 25\,R_{flar.blob}/c$ $\qquad$ $t_{esc,f} = 11\,R_{flar.blob}/c$

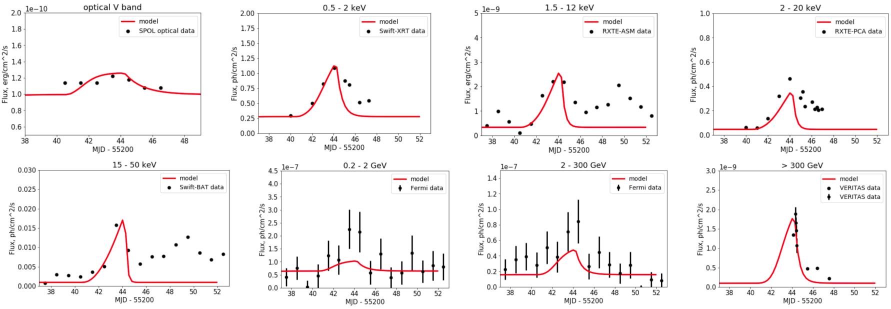
$t_{esc,f}^{(turb)} = 14\,R_{flar.blob}/c$ $\qquad$ $\beta_A = 0.05$

Time evolution of the total SED

(*time advances from violet to red)



Two-zone scenario B: data vs. model



- ✓ **WORKS BETTER**: Model describes MWL dataset fairly well in all the bands.
- ! Too short decay of the simulated LC compared to the data!
- ? More realistic *gradually* growing and decaying turbulence???
- ? Possible interaction (IC) between electrons in small blob and photons in large one?
- ? Is integrity of blobs preserved after crossing?

Outline

Conclusions

- We developed a time dependent SSC code for modeling of varying MWL emission during blazar flares
- We applied our code to archival flare of Mrk 421 which occurred in February 2010
- A single-zone scenario in which the emitting zone is perturbed by a shock and/or turbulence can't explain the data
- A two-zone scenario with emitting and acceleration zone works better, but underpredicts γ-ray emission
- A scenario with two emitting zones in which flaring emission is originating from a smaller blob works quite well
- The decay of the simulated light curves is shorter than in the data. Possible explanation – gradually developing and fading turbulence
- The inverse Compton scattering of quiescent emission photons by the electrons of flaring blob might be important – need to consider that

Back-up slides

Input parameters of the code

- Physical parameters of the emitting blob
  - B (magnetic field)
  - $\gamma_{min,inj}$ (minimal Lorentz factor of injected electrons)
  - R_b (radius of the blob)
  - δ_b (Doppler factor of the blob)
  - z (redshift of the source)

- Evolution parameters
  - t_{inj} (duration of particle injection)
  - t_{esc} (time scale of particle escape)
  - $Q_{inj}(\gamma, t)$ (injection function/spectrum)
    - Power law in γ with exponential cutoff (parametrized with normalization A_{inj}, slope α_{inj} and cutoff Lorentz factor γ_{cut})

      $$Q_{inj}(\gamma) = A_{inj} \cdot \gamma^{-\alpha_{inj}} \cdot exp(-\gamma/\gamma_{cut})$$
    - Arbitrary function (could be also time-dependent)

Input parameters of the code

- $t_{FII} = 1/D_0$ (time scale of stochastic acceleration)
- $t_{FI} = 1/a$ (time scale of shock acceleration)
  - It is possible to activate acceleration processes for only certain period of time $t_{life,FI,II}$
  - Arbitrary parametrization of time-dependent acceleration process

- SED parameters
  - EBL model name (Dominguez/Finke/Inuoe/Gilmore/Kneiske)