Modeling the X-ray and γ–ray light curves of blazar Mrk 421 observed during flare in February 2010

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Abstract

Strong X-ray and γ–ray flares have been detected in February 2010 from the high synchrotron peaked blazar Mrk 421 (z=0.031). With the motivation of understanding the physics involved in this flaring activity, we study the variability of the source in X-ray and γ–ray energy bands during February 10-23, 2010. We use nearly simultaneous X-ray data collected by MAXI, RXTE-ASM and γ–ray data collected by *Fermi*-LAT and *TACTIC* for the present study. We show that the flaring activity of the source observed at X-ray and γ–ray energies can be explained using two zone homogeneous synchrotron and synchrotron self Compton model, where acceleration and main emission are not co-spatial, with time dependent particle injection. The kinetic equation describing the evolution of particle distribution in the emission region is solved analytically and resultant synchrotron and synchrotron self Compton emission is used to reproduce the X-ray and γ–ray light curves. The model parameters are further constrained by reproducing the broad band spectral energy distribution during the flaring episode. Our study suggests that the present flaring activity of Mrk 421 blazar can be an outcome of an efficient acceleration process associated with the increase in underlying non-thermal particle distribution.

Introduction

- The extragalactic universe is largely populated with the X-ray and γ–ray sources and most of them are identified as *blazars*.
- Blazars are the radio-loud active galactic nuclei (AGN) with a relativistic jet closely aligned to the line of sight from the Earth [8] and are most probable source of broad band emission that spans over entire electromagnetic spectrum from radio to very high energy (VHE, E $>$ 100 GeV) γ–rays.
- The broad band radiation from blazars is best understood in a paradigm where the emission results from the magnetized plasma ejected with relativistic speeds in a collimated outflow powered by a super massive black hole (SMBH).
- The spectral energy distribution (SED) of blazars is characterized by two distinct and broad humps located in UV/Optical/X-ray and in high energy (HE, E $>$ 100 MeV) γ–ray regimes respectively.
- Origin of low energy component is well understood and is attributed to synchrotron radiation from a population of relativistic electrons losing energy in the jet magnetic field.
- The physical mechanism for second hump in MeV-GeV regime is poorly understood and is still under debate. *Leptonic*, *Hadronic* and *Hybrid* models have been proposed.
- The *leptonic models* [4] attribute the γ–ray emission to the inverse Compton (IC) scattering of ambient photons by the same electrons that emit synchrotron radiation.
- The *hadronic models* [3] invoke the presence of highly relativistic protons, that directly emit HE γ–ray photons and neutral pion decay.
- The *hybrid models* [1] incorporate both leptonic and hadronic processes to a comparable level of sophistication in understanding the γ–ray emission from blazars.
- Blazars are classified in two main subclasses : BL Lacertae objects (BL Lacs, featureless optical spectra with weak/no emission/absorption lines) and Flat Spectrum Radio Quasars (FSRQs, otical spectra with strong and broad emission lines).
- Multi-wavelength emission from blazars is characterized by rapid variability at different time scales from few minutes to years. Rapid γ–ray variability poses strong challenge to *hadronic models*.

Mrk 421

- One of the closest (z=0.031) high-synchrotron peaked type BL Lac object.
- First detetced at energies above 100 MeV by *EGRET* on Compton observatory [2].
- First extragalactic source discovered with TeV γ–ray emission by ground based γ–ray telescope in 1991 [5] and also one of the brightest TeV sources in sky at present.
- During 1991-2010, various intense flaring activities from Mrk 421 have been observed by ground and space based telescopes, but their physical mechanism is poorly understood.
- Due to its proximity and frequent episodes of high activity, Mrk 421 is among the best sources to study the multi-wavelength emission emission.

February 2010 Flare of Mrk 421

- In February 2010, the source was observed in high activity state reaching its maximum around February 16, 2010.
- Multi-wavelength campaign involving X-ray satellites, γ–ray satellites, ground based VHE, optical and radio telescopes during outburst was performed.
- Near simultaneous multi-wavelength data have been used to perform an extensive study of the source during this flaring activity [7, 6].
- VHE observations of the source during this flare have also been reported by *VERITAS*, *HESS* and *TACTIC* ground based imaging atmospheric Cherenkov telescopes.

X-ray and γ–ray Observations

- Observation period: February 10-23, 2010 (MJD 55237- 55250)
- X-ray observations : 2-10 keV from *All Sky Monitor (ASM)* and 2-20 keV from *Monitor of All sky X-ray Image (MAXI)*.
- γ–ray observations : 100 MeV-100 GeV from *Fermi-Large Area Telescope (LAT)* and 1-15 TeV from *TeV Atmospheric Cherenkov Telescope with Imaging Camera (TACTIC)*

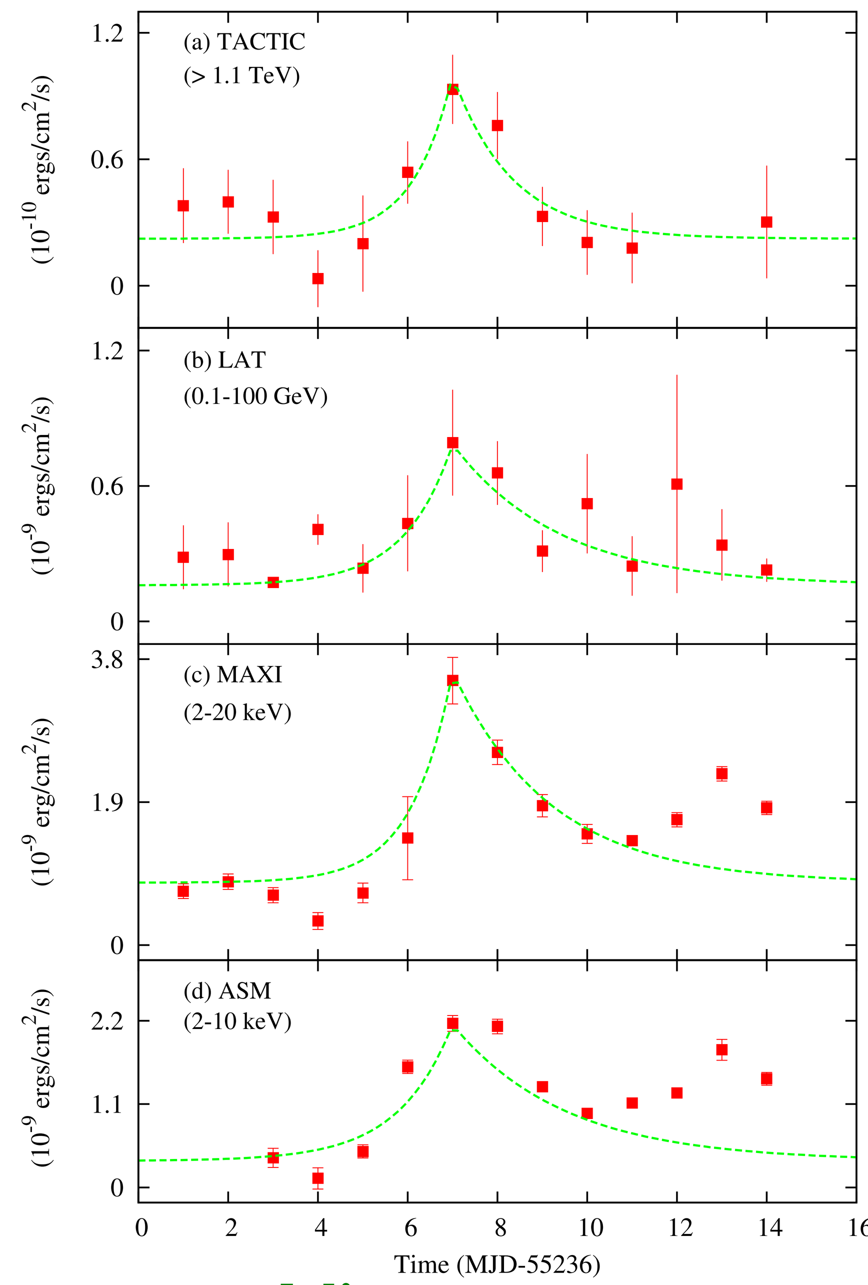
Temporal Analysis

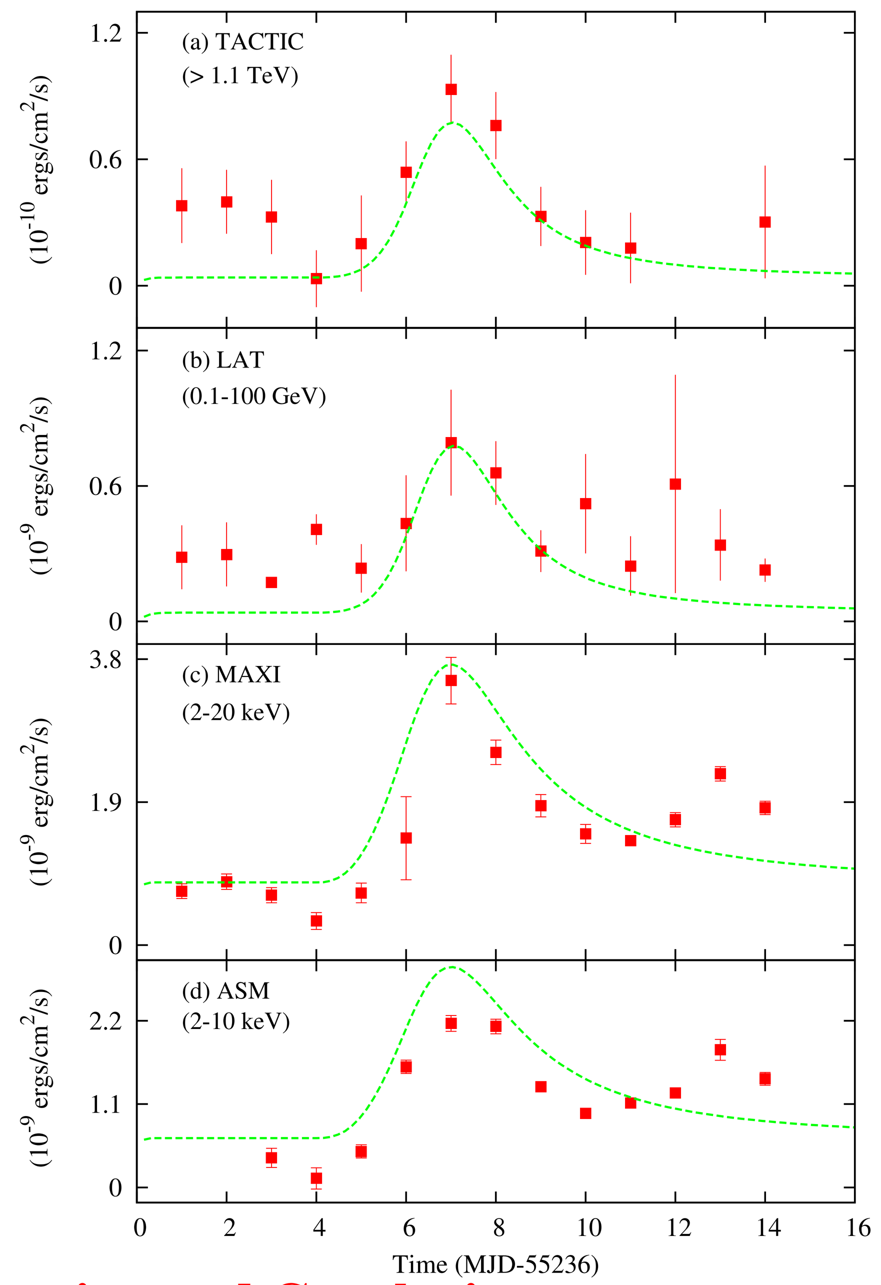
- Light curve fitted with an exponential profile:

$$F(t) = A_0 + A\left[e^{(t-t_p)/\tau_r}H(t_p - t) + e^{-(t-t_p)/\tau_d}H(t - t_p)\right] \quad (1)$$

where, τ_r and τ_d are the rise and decay timescales respectively, t_p is the time of maximum flux, A_0 and A are the constants for determining the quiescent and peak fluxes respectively, and H is the *Heaviside function*. t_p is fixed at 55243 MJD.

- Rise time of flare in all energy bands is similar ($\sim$ 0.86 days), suggesting that physical process involved in the flare is energy independent.
- Similar decay times ($\sim$ 1.2 days) in all energy bands disfavour the flare decay due to radiative loss mechanism.
- Asymmetric flare with fast rise and slow decay.
- Accelertaion and emission regions are spatially separated.





Light curve modeling

- Synchrotron Self Compton (SSC) Model *(Leptonic)* with power law distribution of electrons $N(\gamma)d\gamma = K\gamma^{-p}d\gamma$ is employed.

$$F_{syn}(\nu_{syn}) \approx \delta^{(p+5)/2}R^3KB^{(p+1)/2}\nu_{syn}^{-(p-1)/2} \quad (2)$$

and

$$F_{SSC}(\nu_{SSC}) \approx \delta^{(p+5)/2}R^4K^2B^{(p+1)/2}\nu_{SSC}^{-(p-1)/2} \quad (3)$$

- Size of emission region constrained by variability time scale

$$R \leq \frac{c\delta t_{var}}{(1+z)} \quad (4)$$

- Evolution of particle distribution $n(\gamma, t)$ in the emission region can be described by the kinetic equation:

$$\frac{\partial}{\partial t}n(\gamma, t) = \frac{\partial}{\partial \gamma}[P(\gamma)n(\gamma, t)] - \frac{n(\gamma, t)}{t_{esc}} + Q(\gamma, t) \quad (5)$$

- The injection spectrum from the acceleration region is assumed to be a time dependent power law of the form

$$Q(\gamma, t) = K(t)\gamma^{-p} \quad ; \quad \gamma_{min} < \gamma < \gamma_{max} \quad (6)$$

with a time dependent normalization $K(t)$ given by

$$K(t) = K_0 + 2(K_p - K_0)\left[\left(\frac{t-t_0}{t_p-t_0}\right)^{-\alpha_1} + \left(\frac{t-t_0}{t_p-t_0}\right)^{\alpha_2}\right]^{-1} \quad (7)$$

Discussion and Conclusions

- Energy independent physical processes are observed to be operational in the source during flare.
- Flaring activity can be attributed to the sudden enhancement in the relativistic particle distribution and the emission in VHE regime to be dominated by SSC process.
- Acceleration and emission processes cannot co-exist, therefore, acceleration zone needs to be spatially separated from the emission region. Injection from acceleration region is considered to be time dependent power law, which causes flare in the source

References

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