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SED evolution modeling of Mrk421 during January 2010: insights from a stochastic acceleration model

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Blazars are highly variable sources which show variability down to minute time scales. The current generation of Imaging Atmospheric Cherenkov Telescopes like Major Atmospheric Gamma Imaging Cherenkov (MAGIC) are able to probe the spectra of the brightest blazars on short time scales, especially in their flaring states. In this work, we characterize the variability and daily Spectral Energy Distribution (SED) evolution of the archetypal TeV blazar Markarian 421 (Mrk 421) using simultaneous MAGIC Very High Energy (VHE) band (>100 GeV) and Multi-Wavelength (MWL) observations from radio all the way up to gamma ray bands during the November 2009 to June 2010 campaign.

Mrk 421 displayed its strongest flare ever observed in February 2010 when VERITAS measured VHE flux of 15 Crab units above 200 GeV. The source was already in a elevated flux state in January 2010 prior to this extreme flare. We model the SED evolution during January 2010 with a physically motivated single zone leptonic population and study the phenomenology and spectral evolution in the context of a stochastic acceleration scheme. VLBA data unveils contemporaneous ejections of radio features for the first time for Mrk 421. The variability and MWL cross-correlations were analyzed along with the temporal evolution of the daily SEDs to gain insights into the emission processes of this flare that exhibits unprecedented characteristics for the source.

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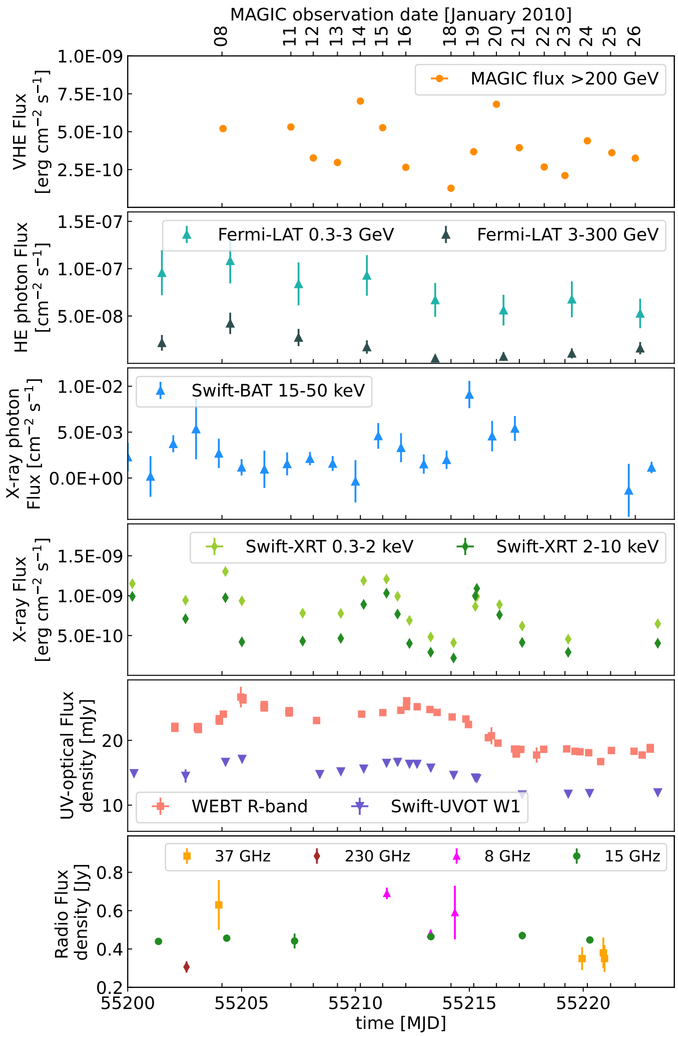

Figure 1: The MWL LC of Mrk 421 during January 2010.

1. Introduction

Mrk 421 displayed its brightest recorded TeV flare to date in February 2010 and it was already in a high state in the days preceding this giant flare [1–3]. The Light Curve (LC) of the source during this flaring activity of January 2010 can be seen in Fig 1. We build up on the work done in [1], where the VHE flux was found to be correlated with the X-ray and MeV-GeV γ-ray bands, suggesting the standard energy stratified single zone Synchrotron Self Compton (SSC) scenario typical of BL Lac type blazars to be at work.

We analyse the flaring activity in January 2010 in detail with a 'snap-shot' evolution SED model where the observed SEDs are modelled as a sequence and compare the fit results for physically motivated Electron Energy Distributions (EEDs): Log-Parabolic with a low energy Power Law branch (LPPL) and pile-up.

Stochastic acceleration of particles in a turbulent magnetic field can lead to curvature in the high energy tail of the EED [4–6] manifesting as the log-parabolic component of the LPPL EED, with the particle distribution $n(\gamma)$ taking the following form:

$$n_{\rm LPPL}(\gamma) \propto \begin{cases} (\gamma/\gamma_0)^{(2s+1)/2} & \text{for } \gamma \leq \gamma_{\rm inj}, \\ (\gamma/\gamma_0)^{-s} & \text{for } \gamma_{\rm inj} < \gamma < \gamma_0, \\ (\gamma/\gamma_0)^{-s-r\cdot log(\gamma/\gamma_0)} & \text{for } \gamma \geq \gamma_0 \end{cases} \tag{1}$$

where γ is the lorentz factor, $\gamma_{\rm inj}$ is the particle injection energy, s is the spectral slope and γ_0 is the onset of the spectral curvature r. Additionally, if the particle escape timescales are long, a fraction of the population can 'thermalise' close to the acceleration-cooling equilibrium ($\gamma_{\rm eq}$) and form a relativistic Maxwellian component termed as pile-up. The general form of the pile-up components is as follows [4]:

$$F_{\text{cut-off}}(\gamma) = \exp\left[-\frac{1}{a}\left(\frac{\gamma}{\gamma_{\rm eq}}\right)^a\right] \tag{2}$$

$$n_{\text{pile-up}}(\gamma) \propto \gamma^2 \cdot F_{\text{cut-off}}(\gamma) \tag{3}$$

where a is the cut-off index which depends on the dominant cooling process and the magnetic turbulence index [4].

We combine the LPPL and pile-up components (Eq 1, 3) into a single EED, by applying $F_{\text{cut-off}}(\gamma)$ to the LPPL component and using appropriate normalisations for the LPPL and pile-up components, with the following final form of the EED:

$$n(\gamma) \propto n_{\rm LPPL}(\gamma) \cdot F_{\text{cut-off}}(\gamma) + f \cdot n_{\text{pile-up}}(\gamma) \tag{4}$$

The emitted MWL SED from this particle distribution is then computed in `JetSeT` [7] and we fit the MWL SEDs obtained by grouping the dataset in [1] into ~daily time bins. We build a sequential fitting scheme where the best fit of the preceeding night serves as the starting point for the model minimiser on a given night, leading to a temporal evolution model for the observational snap-shots of the Jet of Mrk 421 in different states.

2. Results

We compared the results of the sequential fitting scheme for a purely LPPL EED and a pile-up EED and found that the pile-up EED improved the reduced χ^2 of the fit on 3 nights: 15, 19 and 20 January 2010. The pile-up model captures the increased curvature in the synchrotron peak of the SED as can be seen in Fig 2. These nights correspond to the local maxima of the *Swift*-XRT LC (Panel 4 of Fig 1) where we expect the flare to transition from an acceleration dominated to a cooling dominated phase. The fit quality is reported in Table 1. The implication of the parameter evolution and associated phenomenology will be presented in our upcoming paper [MAGIC collaboration, in preparation].

3. Acknowledgements

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SED	LPPL χ^2/N_{DoF}	pile-up χ^2/N_{DoF}
15 Jan	14.1/27	9.0/26
19 Jan	22.6/25	15.9/24
20 Jan	16.8/29	12.7/28

Table 1: Comparison of the reduced χ^2 of the pile-up vs the pure LPPL EED model where N_{DoF} is the number of degrees-of-freedom of the model. An example of the improvement in the fit can be seen in Fig. 2

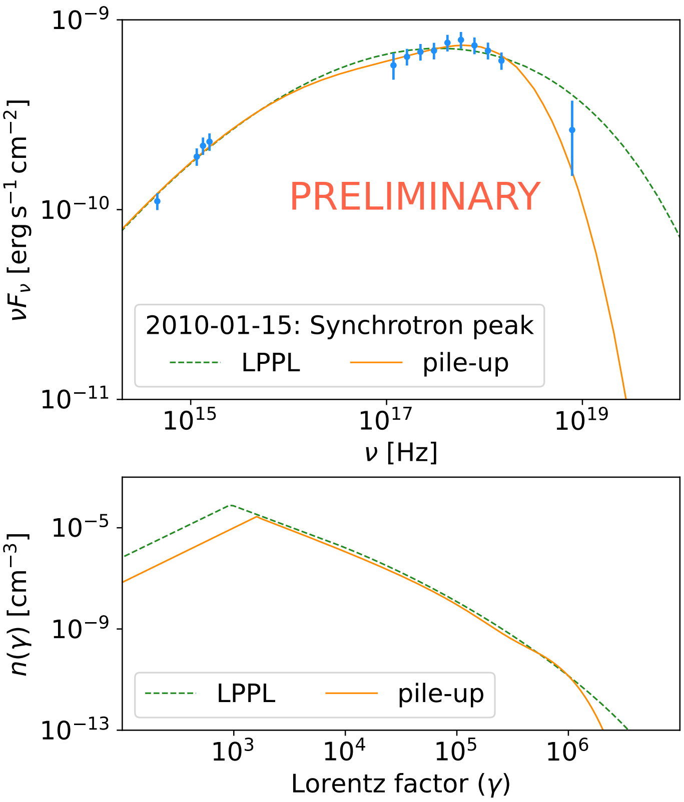

Figure 2: A comparison of the pile-up and LPPL models with a zoomed inset of the SED. The pile-up EED replicates a more nuanced structure in the synchrotron peak owing to larger curvature around $\gamma \sim 10^6$.

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