Multiwavelength correlation studies in the era of CTAO

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Abstract

Correlations between various multiwavelength bands are an intermittent feature in blazar light curves; that is, they are observed in some instances but not in others. In order to understand the cause of this intermittency, high-cadence observations are required in as many bands as possible. In turn, correlations have been studied predominantly during flaring states. However, with the CTAO we will obtain detailed VHE gamma-ray light curves for many sources also during their low states enabling correlation studies of the VHE gamma-ray band with all other energy bands during both high and low states. The observed light curves can then be used to feed time-dependent models to reproduce the observed patterns as closely as possible and to check for the required parameter evolution. Here, we present the first steps in an ongoing effort within the CTAO. For two blazars, the HBL *Mrk 421* and the FSRQ *PKS 1510-089*, the long-term X-ray and optical light curves are used to induce variations in input parameters of the lepto-hadronic one-zone code `OneHaLe`. The important outputs are light curves in the CTA energy range employing 3 different energy thresholds. The main initial results are: 1) the presence of relativistic protons has a significant effect on the correlation of the 3 light curves due to the emerging pair cascade which prolongs flaring states at the highest energies; and 2) comparison of the theoretical light curves with existing VHE gamma-ray data shows that both leptonic and hadronic models can only partially reproduce the data with the current simple setup.

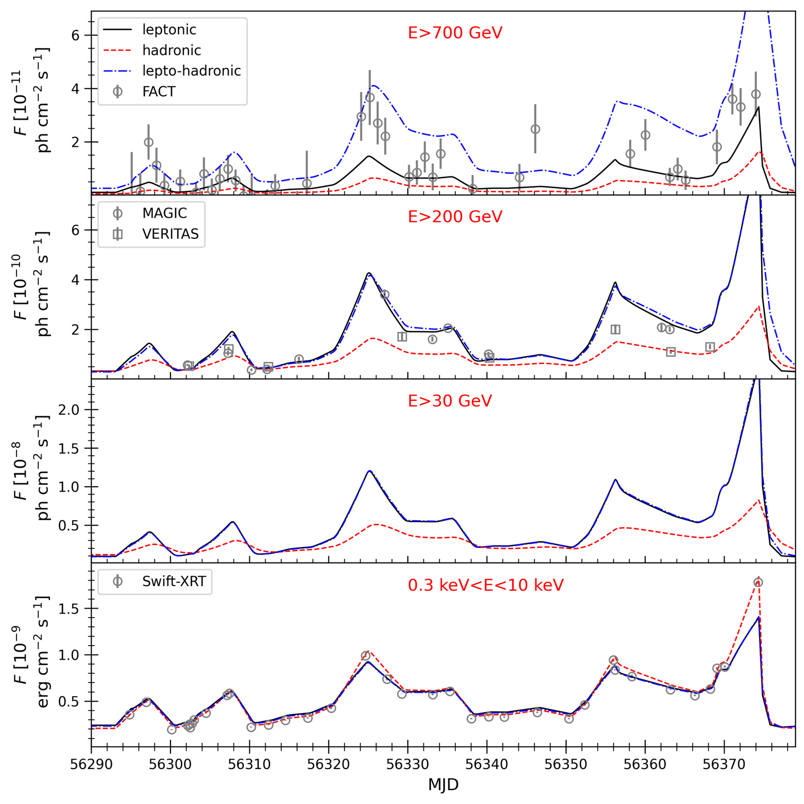
Goal

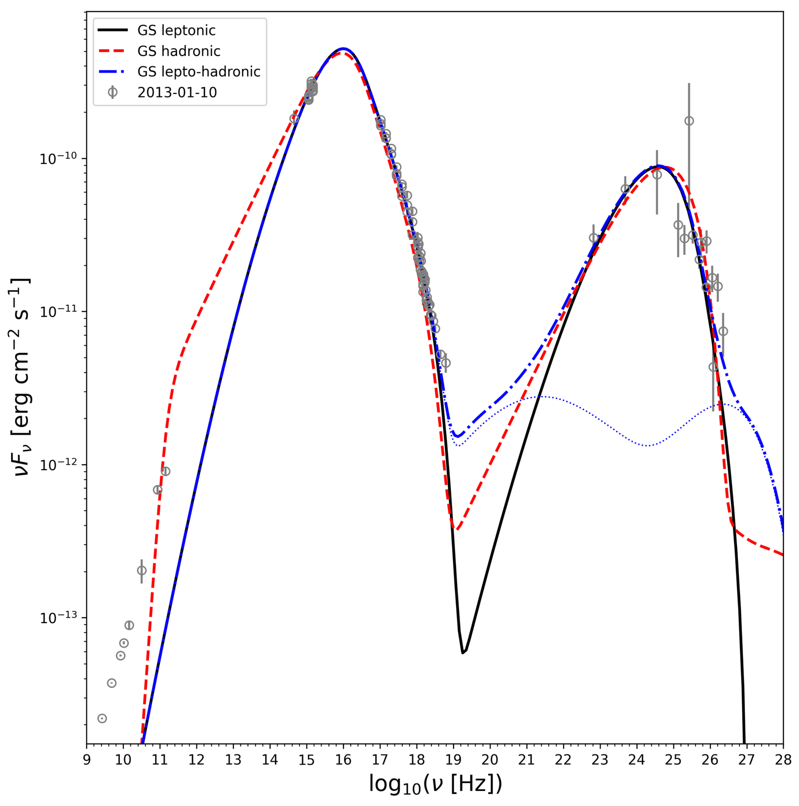
Recreate a low-energy light curve and produce different predictive light curves for the CTAO energy domain

Strategy

- A synchrotron light curve (X-ray or optical) serves as a template to create a variability pattern:
$$P(t) = \frac{F(t) - F_{\rm low}}{F_{\rm low}}$$
where $F_{\rm low}$ is the minimum value in the light curve ensuring $P(t) \geq 0$
- The time steps t are equidistant; a linear interpolation is done between subsequent light curve points to obtain $P(t)$
- $P(t)$ is used to create a time-dependent variation in an input parameter of the radiation code, e.g. for the particle density:
$$n(t) = n_0[1 + P(t)]$$
with the initial density n_0 recreating the minimum flux of the light curve
- We use the time-dependent, lepto-hadronic one-zone code **OneHaLe** (**MZ21**, **MZ+22**) available upon reasonable request to M. Zacharias
- Three different setups are chosen for the γ-ray mechanism: leptonic (SSC/EC), hadronic (p-syn), lepto-hadronic (SSC/EC + pair-syn)
- Note: EBL absorption is not considered in the simulations shown below

Markarian 421

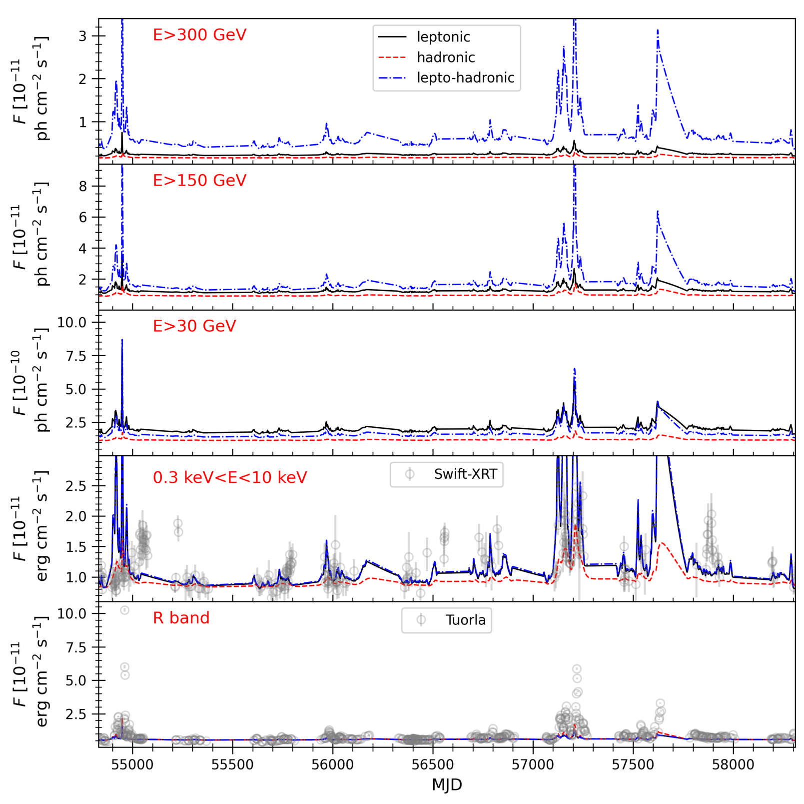


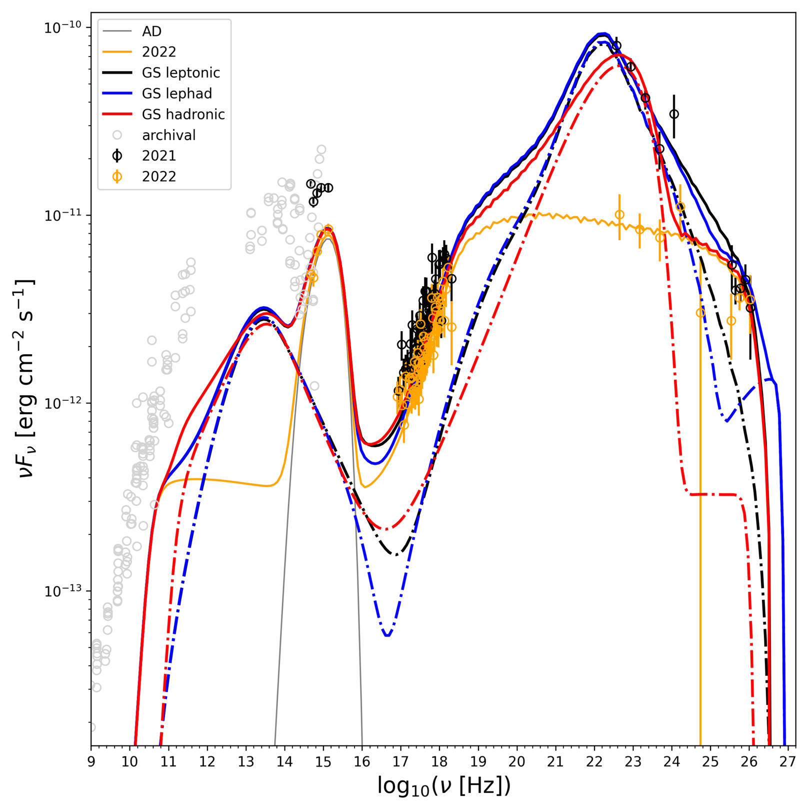


Left: *Simulated light curves for the models and energy ranges as labeled. Data from* ***MB+16*** *and* ***AA+21***. **Right:** *Low-state spectra for the 3 models. The blue dotted line shows the e-syn flux including pairs. Data from* ***MB+16***

- Mrk 421 is an HBL at $z = 0.0308$ and generally well described with a one-zone SSC model
- We test this on a "low-state" data set gathered in early 2013 by varying the electron and proton density
  - (i) The X-ray light curve is well reproduced as intended; the highest fluxes are underproduced in the leptonic and lepto-hadronic setup as the SSC process becomes dominant
  - (ii) There are clear differences in the γ-ray domain between the leptonic and lepto-hadronic setup on the one hand and the hadronic scenario on the other hand due to the different dependency of SSC and synchrotron on the particle density
  - (iii) For $E > 700$ GeV, there are clear differences between the leptonic and lepto-hadronic scenario due to the additional pair-synchrotron component
- The FACT data suggests that SSC alone is not sufficient to explain the data; nor is proton-synchrotron

PKS 1510-089





Left: *Simulated light curves for the models and energy ranges as labeled. Data from* ***KN+18*** *and Swift.* **Right:** *Low-state 2-zone models as labeled (total model: solid; variable zone: dot-dashed). Data from* ***FA+23***.

- PKS 1510-089 is an FSRQ at z=0.361; the external photon field is described by $L_{\rm ext} = 6 \times 10^{45}$ erg/s, $R_{\rm ext} = 4 \times 10^{19}$ cm, $T_{\rm ext} = 100$ K (**FA+23**)
- **FA+23** recently established that a 2-zone model with a steady outer zone is required; we follow this description here by adding the steady flux to the variable flux of the inner zone
- The R-band light curve is used as variability input
  - (i) The bright, steady disk flux inhibits a correct reproduction of the R band flux suggesting that the simple scaling of electron density is not sufficient to reproduce it
  - (ii) The 3 γ-ray bands typically show similar variability patterns, but the flux ratios between the bands depend on the setup
  - (iii) The X-ray band is not reproduced well by any model owing to models fluctuating too strongly, non-simultaneity of data, etc.
- Clearly, the chosen simple approach is not sufficient to reproduce PKS 1510-089 on long time scales

Summary

- Both sources suggest that a simple scaling by particle density does not reproduce well the high-energy component
- Mrk 421 is known to adhere to simple SSC models during flares, but our model suggests that this is not the case for longer periods of time (however, spectral changes in the X-ray domain have not been accounted for)
- PKS 1510-089 is a much more complicated source, which was recently found to probably have at least 2 emission zones
- Along with the complicated optical spectrum, it was not possible to properly reproduce the optical light curve with our simply scaling model
- Nevertheless, flux ratios between various γ-ray light curves may help distinguishing between scenarios

CTAO's superior capabilities to current-generation instruments especially at energies far above the peak energy will much more strongly constrain the models allowing for more complicated setups (beyond mere density variations) to be tested. This study is part of the CTAO AGN variability task ($\rightarrow$ G. Grolleron, ID 152).

Low-state parameters

Source		Mrk 421			PKS 1510-089	
Model	leptonic	hadronic	lepto-hadronic	leptonic	hadronic	lepto-hadronic
Mag. field	0.17 G	10 G	0.17 G	0.12 G	30 G	0.12 G
Radius	1.5×10^{16} cm	1.5×10^{16} cm	1.5×10^{16} cm	1.0×10^{16} cm	6.0×10^{16} cm	1.0×10^{16} cm
Doppler factor	25	25	25	20	20	20
e inj. luminosity	1.5×10^{40} erg/s	1×10^{40} erg/s	1.5×10^{40} erg/s	1.3×10^{42} erg/s	3.5×10^{40} erg/s	1.3×10^{42} erg/s
e $\gamma_{\rm min}$ / $\gamma_{\rm max}$	2.2×10^4 / 4×10^5	3×10^3 / 4×10^4	2.2×10^4 / 4×10^5	1.5×10^3 / 3×10^5	1.1×10^2 / 4×10^4	1.5×10^3 / 5×10^4
p inj. luminosity	—	7×10^{40} erg/s	3×10^{42} erg/s	—	1×10^{43} erg/s	3×10^{43} erg/s
p $\gamma_{\rm min}$ / $\gamma_{\rm max}$	— / —	2 / 1×10^{10}	2 / 1×10^8	— / —	2 / 5×10^8	2 / 1×10^8
e / p spectral index	3.5 / —	3.5 / 2.0	3.5 / 1.5	3.0 / —	3.0 / 1.9	3.0 / 1.5
Escape time	35 R/c	35 R/c	35 R/c	10 R/c	10 R/c	10 R/c

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