Multiwavelength variability study of the BL Lac objects PKS 0735+178 and OJ 287

Arti Goyal

Astronomical Observatory of the Jagiellonian University, Krakow, PL.

in collaboration with : L. Stawarz, M. Ostrowski, V. Larionov, I. Agudo, S. Jorstad, A. Marscher, T. Hovatta, M. Aller, H. Aller, S. Zola, et al.

Issues with the current Blazar SED modeling

1. Too simplified model set : “single spherically symmetric blob moving along the jet”– characteristic/relaxation timescales
2. Data used for model fitting is RARELY simultaneous – which flux measurements should really be used in SED modelling?
3. Correlated multi-frequency variability is an issue (data not available, correlation not always persistent (orphan flares!), correlations are not statistically significance (e.g., Max-Moerbeck et al., 2014).

Characteristics of blazar light curves

•Blazars display strong continuum emission variability from radio to TeV$\gamma-$rays on timescales ranging from decades to minutes.

•The typical shape of power spectral density (PSD; i.e., variability power at given time period) is a power-law (COLORED NOISE) indicating that variability is due to underlying stochastic process(es).

Power spectral density, defined as $P(\nu_k) = A\nu_k^{-\beta}$, where ν_k is the temporal frequency, A is the normalization and β is the spectral slope:
$\beta = 0$: White noise
$\beta = 1$: Flicker/Pink noise (long memory process)
$\beta = 2$: Red/Brownian noise (damped process)

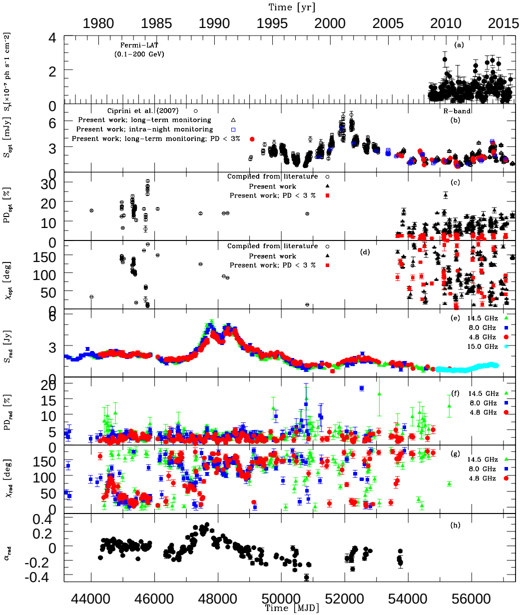
PKS 0735+178 and OJ 287 : Data and methodology

- Target for **UMRAO** and **OVRO** (GHz band) monitoring programmes, **Tuorla** (optical) and several others
- Optical data dating back to circa 1880 for OJ 287 (Hudec et al. 2013).
- Optical good-quality, high cadence, multi-frequency lightcurves (including $\gamma-$rays and X-rays) from **Fermi-LAT**, **Swift/XRT**, **Kepler**, ground-based optical, and various radio facilities – ideal for characterizing statistical properties of multi-frequency variability over extremely broad temporal frequency range.

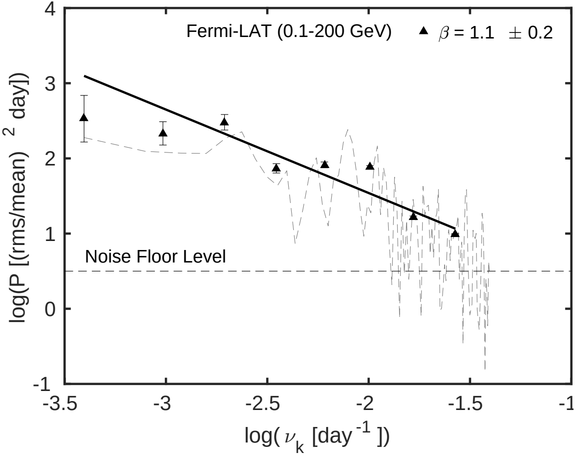
PSD Generation :

1. Fourier transfroming the light curve (Uttley et al. 2002)
2. Time domain modeling of the light curve as a CARMA process (Kelly et al. 2014)

PKS 0735+178 - Multi-wavelength light curve

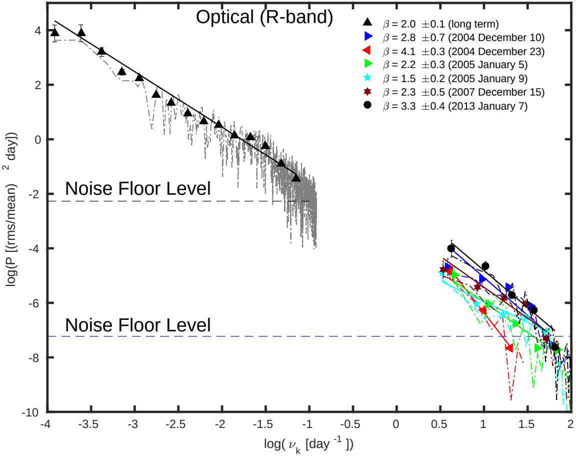


PSD : Fermi-LAT



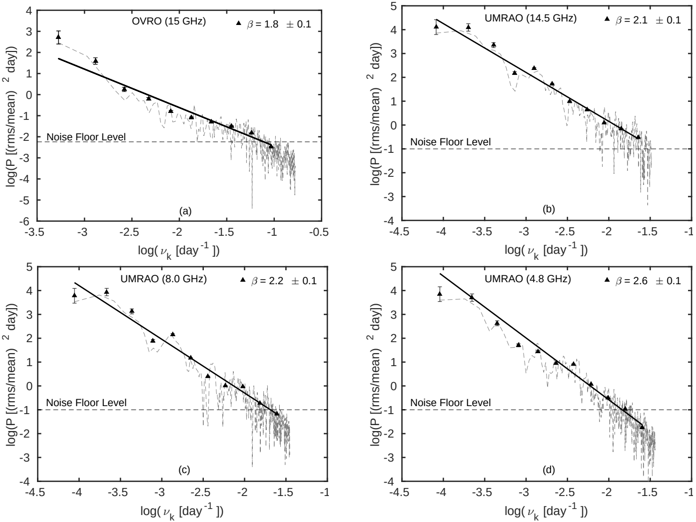
- $\beta \sim 1$: Flicker/pink noise type on time scales from years to months !

PSDs: Optical (long-term + intra-night)



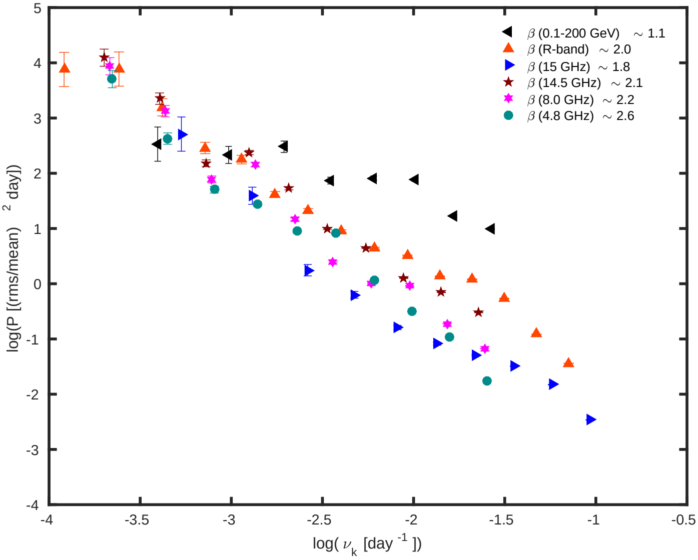
• $\beta \sim 2$: Red/Brownian noise on timescales from 23 yrs to minutes (6 decades in temporal frequencies), intra-night psd slopes ranging from 1.5 to 4 (non-stationarity on intra-night time scales) !

PSDs : GHz band radio frequencies



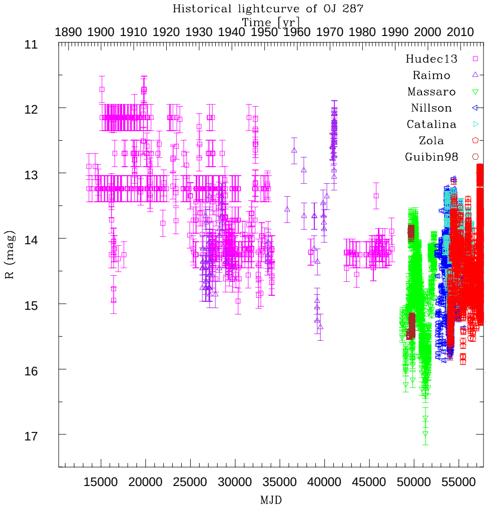
- $\beta \sim 2$: Red/Brownian noise on timescales from 30 yrs to weeks.

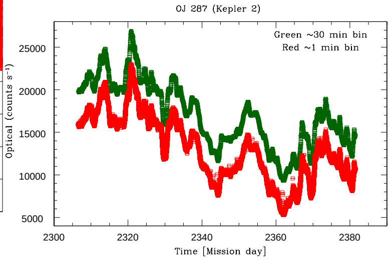
PKS 0735+178 : Multi-freqeuncy PSDs



- Increasingly large power at higher energies !

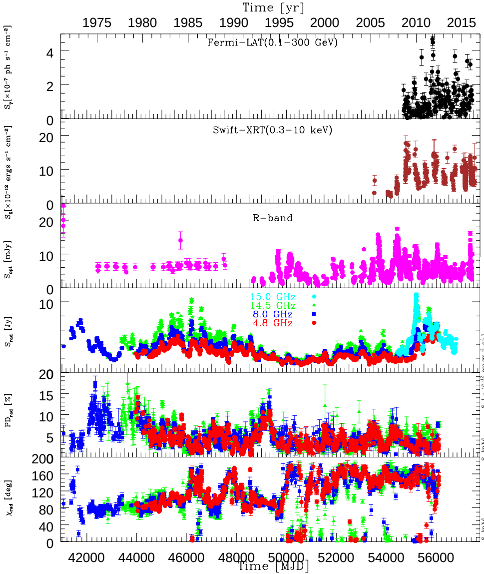
OJ 287 - Historical (117 yr) and Kepler light curves

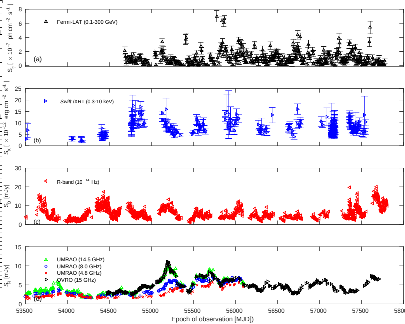




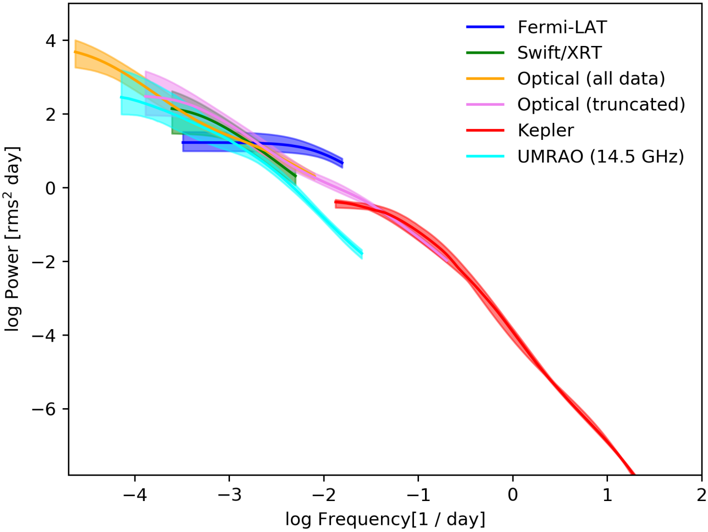
- Different Epochs/sites/observers

OJ 287 - Multiwavelength light curve





OJ 287 - Multi-frequency PSDs



Results

PKS 0735+178

- Featureless, single power-law forms of the power spectral densities over 4-5 decades in temporal frequency range
- Hints for non-stationarity on intra-night timescales at optical frequencies

OJ 287

- Detection of relaxation timescale of $\sim$ 600 days in $\gamma-$rays
- Featureless, power-law forms of the power spectral densities from radio to X-rays

•Statistical character of the $\gamma-$ray variability (**flicker**/**pink**) is different than that at lower (synchroton) frequencies (**red**/**Brownian**) (in agreement with the previous analysis of other blazar sources by Sobolewska et al. 2014 – γ-rays; Isobe et al. 2015 – X-rays; Kastendick et al. 2011 – optical; Max-Moerbeck et al. 2014 – radio).

Possible interpretation

•**Leptonic scenario** $\#1$: synchrotron emission is produced in different *regions* of the jet than $\gamma-$rays
(but then why exactly red vs. pink ?)

•**Hadronic scenario** : different acceleration & emission sites and processes for electrons and protons
(but then why exactly red vs. pink ?)

•**Leptonic scenario** $\#2$ (Goyal et al. 2017): synchrotron emission is produced in the same *extended region* of the jet, which is however highly inhomogeneous/turbulent (Marscher 2014); synchrotron variability is driven by a single stochastic process with the relaxation timescales $\tau_{\rm long} \gtrsim$ 10,000 days (-> red noise for the variability timescales shorter than $\tau_{\rm long}$), while $\gamma-$ray variability is driven by a superposition of two stochastic processes with relaxation timescales $\tau_{\rm long} \gtrsim$ 10,000 days and $\tau_{\rm short} \lesssim$ 1 day (-> pink noise for the variability timescales between $\tau_{\rm long}$ and $\tau_{\rm short}$, and black/red/pink noise for the variability timescales shorter than $\tau_{\rm short}$).

Different relaxation timescales and non-stationarity !

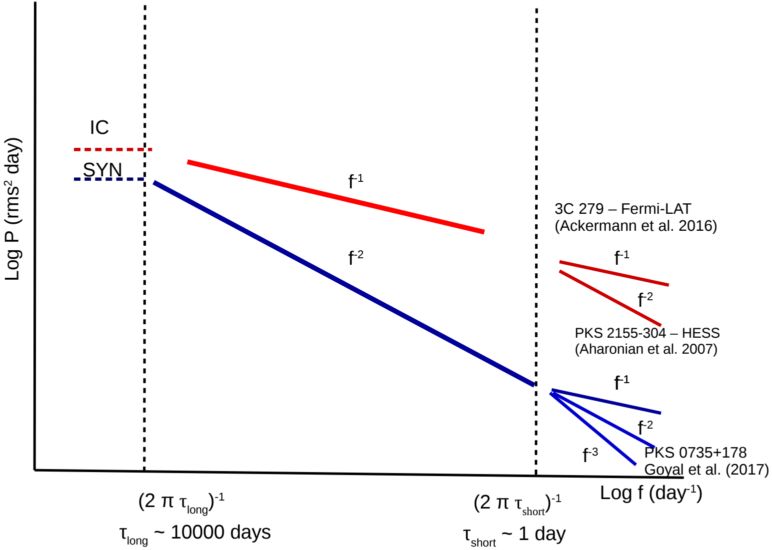


Figure 1: Leptonic scenario #2.

OJ 287 - core and the stationary knot

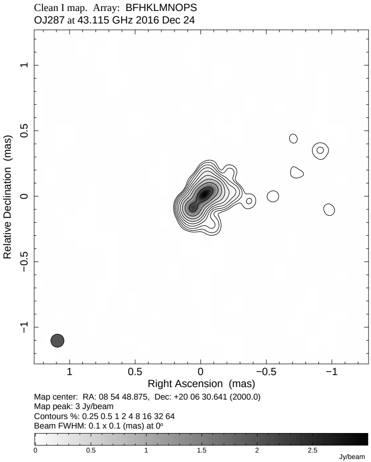


Figure 2: Total intensity VLBA image (BU Blazar programme)