Multi-frequency, broad-band variability study of the BL Lac object OJ 287

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Active Galactic Nuclei (AGN) / Blazars

- Super-massive black hole (SMBH; $> 10^8 M_{\odot}$), accreting matter from the **accretion disc**, producing highly collimated, magnetized, and relativistic outflows **“jets”**, terminating in extended **lobes** . Total kinetic jet power : $\sim 10^{44-48}$erg s^{-1}

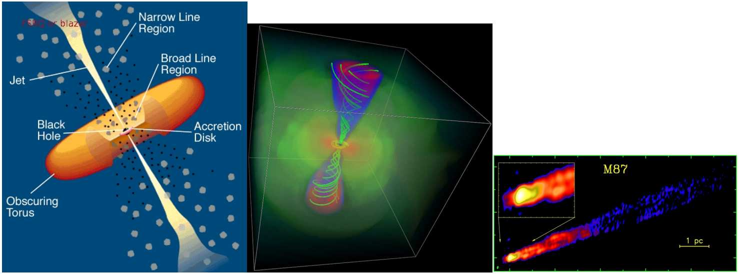


Figure 1: *left :* Unification scheme for radio-loud AGN by Urry and Padovani 1995; *middle :* 3D GRMHD simulation of the jet formation by McKinny et al., 2009; *right :* Inner radio jet in M87 radio galaxy from Kovalev et al. 2007)

Double peaked blazar Spectral Energy Distribution

- **Leptonic scenario :** Electron-positron pairs accelerated to high energies $\geq$ TeV) emit radio-to-optical/X-ray synchrotron emission and X-ray-to-very high energy $\gamma-$rays in the inverse-Compton (IC) process (e.g., Ghisellini et al. 1998).
- **Hadronic scenario :** Protons accelerated to ultra-high energies ($\geq$ *EeV*) produce $\gamma-$rays via either direct synchrotron emission or meson decay and synchrotron emission of secondaries in proton-photon interactions (Boettcher et al., 2013)

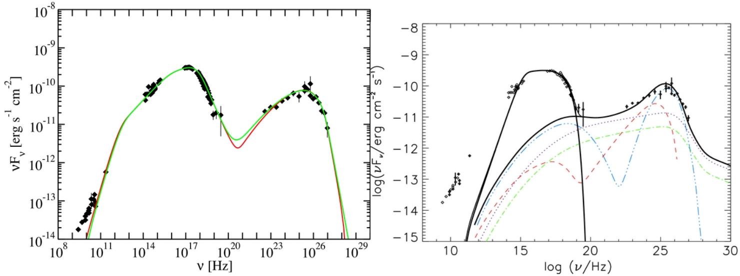


Figure 2: Spectral energy distribution (SED) of Mrk 421 (*left* : Leptonic scenario) and (*right* : Hadronic scenario)

Issues with the current SED modeling

1. Too simplified model set : “single spherically symmetric blob moving along the jet”.
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).

3C 279 : An example

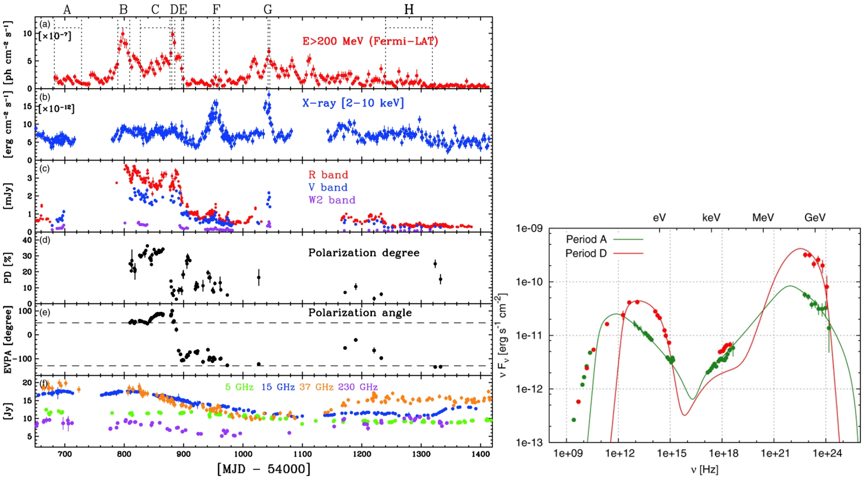


Figure 3: *left :* multi-frequency light curve of 3C 279. *right :* the corresponding single zone SED fitting (Abdo et al. 2010).

Characteristics of blazar light curves

•Blazars displays strong continuum emission variability from radio to $\gamma-$rays on timescales raging 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)

OJ 287

•Typical low-frequency peaked BL Lac object (3FGL catalog; Ackermann et al. 2015)

•Redshift = 0.305

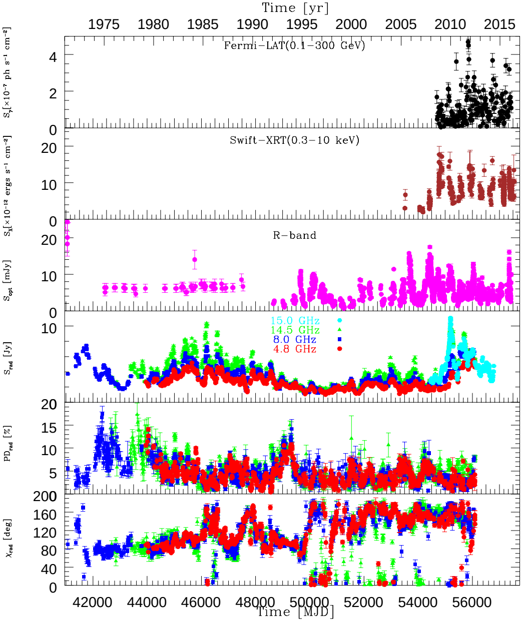
•Optically bright (average R band magnitude $\sim$ 14.5)

•Good quality long-duration multi-frequency data exist

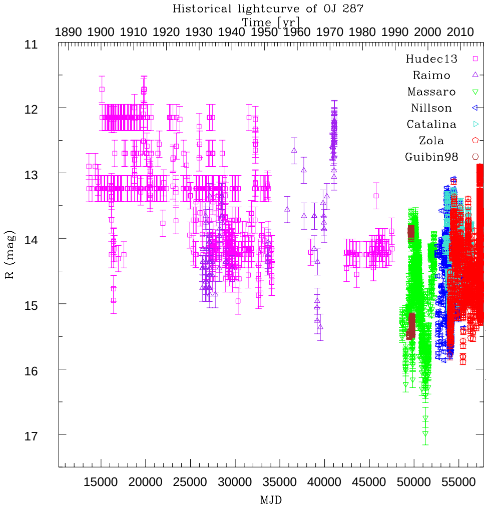
•One of the few blazars with $\geq$ 100 yr long optical light curve (Hudec et al. 2013)

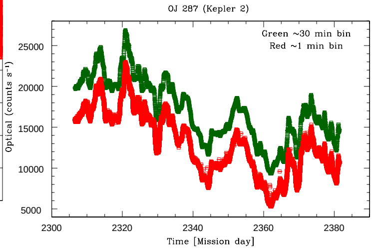
=> Therefore, ideal for characterizing the statistical properties of processes generating multi-frequency over extremely broad temporal frequency range !

Multi-wavelength light curve



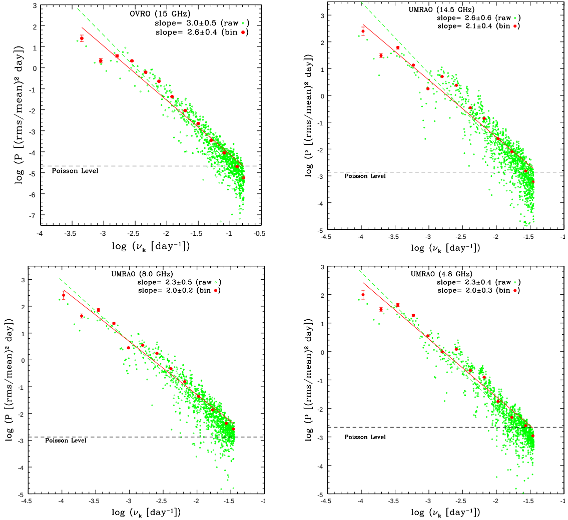
Historical (130 yr) + Kepler 2 mission light curve





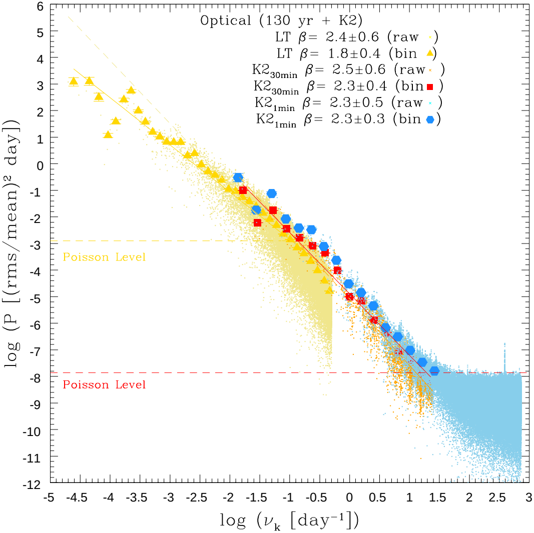
- Different Epochs/sites/observers

GHz band radio PSDs



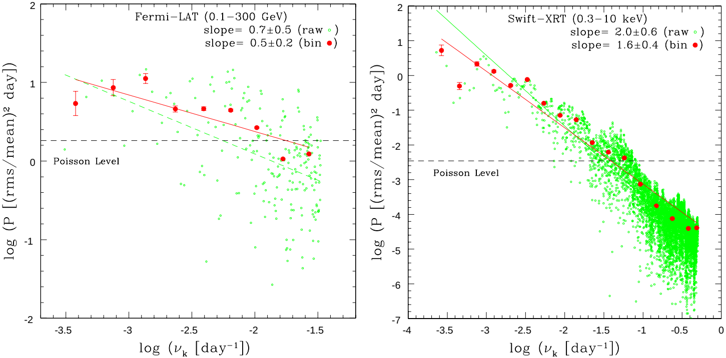
- $\beta \sim 2$: Red/Brownian type on timescales $\sim$ 10000 to weeks (4 decades in temporal frequencies) !

Optical frequencies



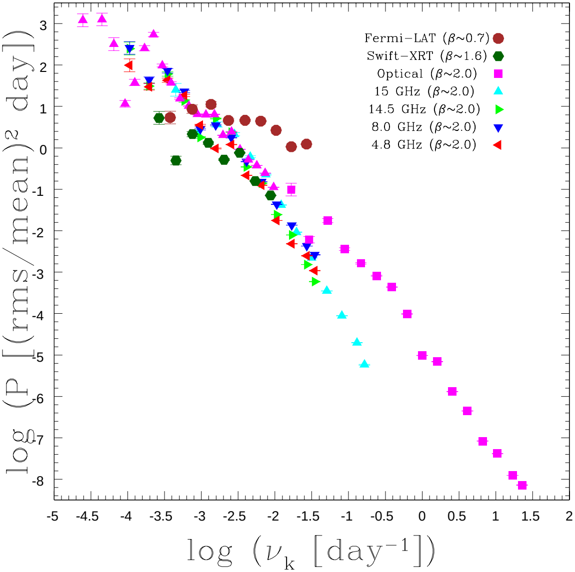
• $\beta \sim 2$: Red/Brownian noise on timescales $\sim$ 100 yrs to minutes (6 decades in temporal frequencies) !

$\gamma-$ray and X-ray



• $\beta \sim 1$: Flicker/pink noise at high energies on timescales $\sim$ 3000 to 50 days (2 decades in temporal frequencies) !

Normalization of PSDs



- Increasingly high power at higher energies !

Results

•Strongly variable in optical and radio fluxes on timescales on **days/months/years/decades** .

•Featureless, single power-law power spectral density over the extremely broad variability frequency range

•Statistical character of $\gamma-$ray and X-ray variability (flicker/pink) is different than that of optical and radio (red/Brownian).

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. 2016, submitted): synchrotron emission is produced in the same *extended region* of the jet, which is however highly inhomogeneous/turbulent ; synchrotron variability is driven by a single stochastic process with the relaxation timescales $\tau_{\rm long} \gtrsim$ 1,000 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 $\tau_{\rm long} \gtrsim$ 1,000 days and $\tau_{\rm short} \lesssim$ 1 day (-> pink noise for the variability timescales between $\tau_{\rm long}$ and $\tau_{\rm short}$, and red noise for the variability timescales shorter than $\tau_{\rm short}$).

Different relaxation timescales !

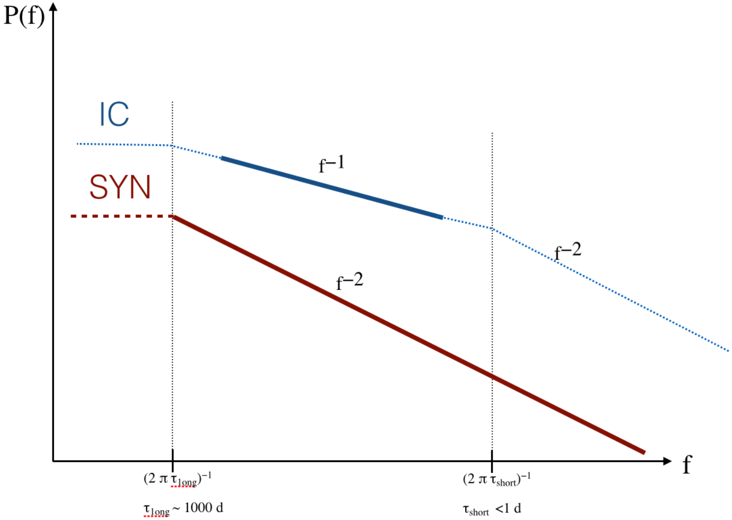


Figure 4: Leptonic scenario #2.