Long-term Optical Variability of Blazars

Characteristic Timescales from Power Spectral Densities

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Characteristic Timescales in Blazar Jets

Why long-term light curves?

Blazars: AGN with relativistic jets close to the line of sight, producing strong broadband variability. Optical synchrotron emission probes *inner* jet and accretion disc — baselines spanning decades give access to longest variability timescales, where central-engine physics is imprinted.

The key question

Can we extract a **characteristic relaxation timescale** τ from the stochastic optical variability, and connect it to physical properties of the jet and SMBH?

Physical drivers of τ:

Disc viscous	∼hundreds of days
Inter-shock	weeks – months
Reconnection	days – weeks

Artist's impression of a blazar jet. Image credit: DESY / Science Communication Lab.

Our approach

- PSD modelling of R-band light curves
- 10 blazars, baselines up to 130 yr
- Three stochastic models compared via Bayesian evidence

Sample & Homogenised Light Curves

Tuorla Blazar Monitoring Programme

- Started in 2001 by Kari Nilsson and Leo Takalo
- Provides the R-band photometric reference system used here

Selection criteria

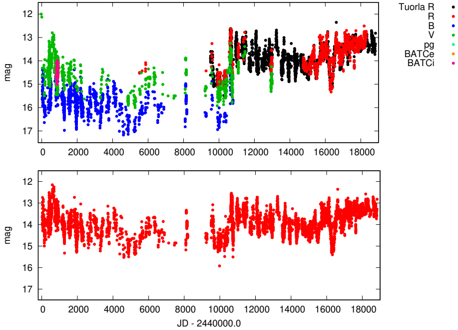
- Archival record $\gtrsim$ 50 yr; actively monitored by the Tuorla Blazar Monitoring Programme
- Broad subtype coverage: HBL, IBL, LBL, FSRQ
- Result: **10 targets**

Dataset statistics

- $>$ 80 000 R-band measurements; baselines 17–130 yr
- 5-day binning; accuracy $\lesssim 0.05\,\mathrm{mag}$

Homogenisation pipeline

- Empirical magnitude offsets from quasi-simultaneous pairs
- Galactic extinction correction + host-galaxy subtraction
- All data tied to the Tuorla R-band reference system



Three Stochastic PSD Models

M1 – Simple Power Law

$$P(f) = C\, f^{-\beta}$$

Null baseline. Scale-free, no preferred timescale. Single free parameter β.

Cannot provide a characteristic timescale — power diverges as $f \to 0$.

M2 – Broken Power Law

Break at f_B; slope flattens by -1 below.

Two free parameters: β, f_B.

Break timescale $t_B = 1/f_B$ *could* indicate a disc viscous or inter-shock scale.

But: highly susceptible to the 1-yr observing artefact.

M3 – Ornstein–Uhlenbeck

$$\dot{u} = -\theta\, u + \sigma\, \mathcal{N}(0, 1)$$

Mean-reverting stochastic process.

Relaxation timescale $\tau = 1/\theta$ is the *longest memory scale* of the jet.

Robust to annual sampling gaps.

Only M2 and M3 yield a timescale

Fitting method: PSRESP (Uttley et al., 2002)

M2 Reflects the Observing Calendar, Not Jet Physics

Key finding: M2 breaks are not physical

All 10 sources yield $f_B \approx$ 310–370 days — regardless of redshift, BH mass, subtype, or baseline length. **The characteristic OU timescale is ∼1 year, irrespective of source redshift.**

Why does this happen?

- Seasonal gaps of ∼3–4 months yr^{-1} modulate the *window function* at $f \approx 1\,\mathrm{yr}^{-1}$
- Creates a periodogram depression at $f \approx 3 \times 10^{-3}\,\mathrm{day}^{-1}$
- The M2 free break is captured by this window feature, not a physical disc or jet timescale

Conclusion: M3 (OU) is the preferred model

$\tau = 1/\theta$ is encoded in the *exponential ACF decay* — insensitive to the $1\,\mathrm{yr}^{-1}$ window artefact.

OU rest-frame timescales τ_{rest} (90% CI)

Source	z	τ_{rest} (d)
3C 66A	0.444	170–563
AO 0235+164	0.940	38–127
S5 0716+714	0.310	35–88
PKS 0735+178	0.424	255–770
OJ 287	0.306	175–637
Mrk 421	0.031	75–249
Mrk 501	0.034	232–639
3C 279	0.536	27–71
BL Lac	0.068	63–126
3C 454.3	0.859	26–66

Rest-frame range: ∼26–770 days. Source-to-source diversity is genuine (unlike the uniform M2 artefact). Consistent with disc viscous and inter-shock / reconnection timescales for $M_\bullet \sim 10^8\,M_\odot$.

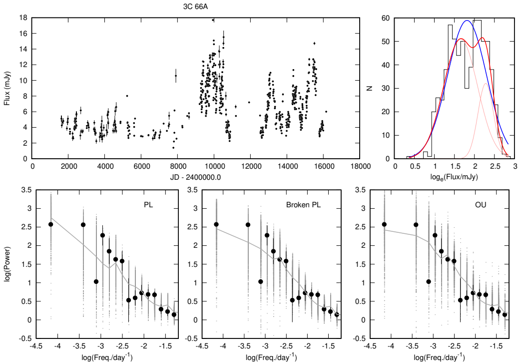
Flux Probability Density Distributions

Multiplicative variability ⇒ log-normal flux PDF:

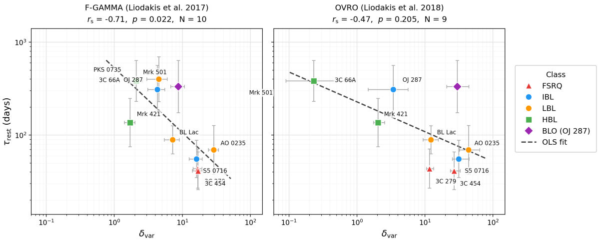
$$p(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}\,x}\exp\left[-\frac{(\ln x-\mu)^2}{2\sigma^2}\right]$$

Anderson–Darling (AD) test applied to all 10 sources:

- **9/10 sources** depart from a single log-normal ($p < 0.05$)
- **Two-component** fit significantly better ($\Delta\mathrm{AIC} > 2$)
- Bimodality implies *distinct jet emission states*
- **Exception:** PKS 0735+178 — single multiplicative process
- Most extreme: 3C 454.3 ($\Delta\mathrm{AIC} = 373$), OJ 287 ($\Delta\mathrm{AIC} = 104$)
- Two-component PDFs used as input to PSRESP simulations



Timescale vs. Doppler Factor — and Rejected Correlations


F-GAMMA (Liodakis et al. 2017)
r_s = -0.71, p = 0.022, N = 10

OVRO (Liodakis et al. 2018)
r_s = -0.47, p = 0.205, N = 9

τ vs. Doppler factor $\delta_{\rm var}$ (F-GAMMA):

- $r_s = -0.71,\ p = 0.022$: significant anti-correlation; lost with OVRO ($r_s = -0.47$, $p = 0.21$)
- Beamed FSRQs show shortest $\tau_{\rm rest}$; weakly beamed HBLs the longest
- Consistent with Doppler compression of timescales

Relations *not* established (small sample):

- **SMBH spin**: apparent $r_s = -0.82$ vanishes after Doppler de-boosting ($r_s = +0.15$, $p = 0.70$) — beaming artefact
- **SMBH mass**: no significant correlation; sample too small to separate mass and beaming effects
- Both require a larger, more uniform sample

Outlook

Expanding the sample: ∼220 blazars

- Apply OU analysis to the full Tuorla monitoring database (∼220 BL Lacs and FSRQs)
- τ **vs. SMBH mass:** test $\tau \propto M_\bullet^{0.35\text{–}0.50}$ (Chen et al. 2025, 2026)
- τ **vs. spin and Eddington ratio:** revisit with $N \sim 100\text{–}200$ and rigorous Doppler de-boosting
- **BL Lacs vs. FSRQs:** compare τ, $F_{\rm var}$, and PSD slopes

Flux statistics & multi-state behaviour

- **Flux distributions:** log-normality testing for all ∼220 sources; identify bimodal state populations
- **Bayesian-block duty cycles:** measure high/flaring state fractions; test correlations with $M_\bullet$, $\lambda_{\rm Edd}$, SED class
- **RMS–flux relation:** test multiplicative accretion-disc signature

Polarimetry & multi-wavelength

- Joint OU analysis of flux *and* optical polarisation light curves
- Optical + radio + γ-ray PSD comparison across wavelengths

Thank you!

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