Deterministic Aspect of the γ-ray Variability in Blazars

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ABSTRACT

Linear time series analysis, mainly the Fourier transform based methods, has been quite successful in extracting information contained in the ever-modulating light curves (Lcs) of active galactic nuclei, and thereby contribute in characterizing the general features of supermassive black hole systems. In particular, the statistical properties of γ-ray variability of blazars are found to be fairly represented by flicker noise in the temporal frequency domain. However, these conventional methods have not been able to fully encapsulate the richness and the complexity displayed in the light curves of the sources. In this work, to complement our previous study on the similar topic, we perform non-linear time series analysis of the decade-long Fermi/LAT observations of 20 γ-ray bright blazars. The study is motivated to address one of the most relevant queries that whether the dominant dynamical processes leading to

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Motivation

- **To** characterize the general features of supermassive black hole systems
- γ-ray light curves can provide insight into innermost regions of BH systems
- use "novel" non-linear analysis methods on the astronomical data
  - γ-ray variability of blazars are found to be fairly represented by flicker noise
- explore the deterministic/stochastic nature of observed γ-ray variability
- Connect the result to possible implication of strong disk-jet connection in blazars which could prove to be significantly useful in constructing models that can explain the rich and complex multi-wavelength observational features in active galactic nuclei
- "Novel approach" of Recurrence Quantification Analysis (RQA), which provides more accurate measures of determinism predictability, and entropy, is discussed in detail
- In addition we estimate the dynamical timescales of the γ-ray light curves

Data I

Fermi Gamma-ray Space Telescope (FGST) by NASA

- launched 2008
- observations of celestial gamma-ray sources
- in the energy band extending from 10 MeV to more than 100 GeV
- The Large Area Telescope (LAT) detects individual gamma rays

Blazars

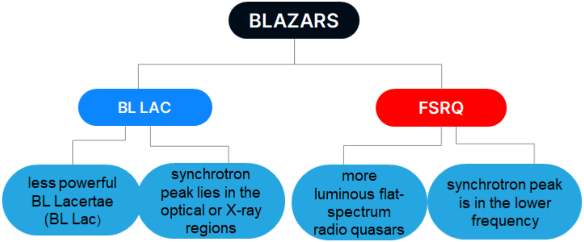
- extra-galactic, supermassive black hole systems
- display relativistic jet closely pointed towards the Earth
- flat-spectrum radio quasars (FSRQ), the more luminous kind that shows emission lines over the continuum
- BL Lacertae (BL Lac) sources, the less powerful objects which show weak or no such lines

Model

- plasma material swirls inward close to the supermassive black holes of the masses in the order $\sim 10^9 \mathrm{M}_\odot$, the magnetic field in conjunction with the fast rotation of the supermassive black hole contributes to the launching of the bi-polar relativistic jets which then travel up to Mpc scale distance (Blandford et al. 2019; Blandford, & Znajek 1977).

Data II

- data collected within 10 years
- 7 days binning
  - $\rightarrow$ data time series length should be ~ 513 but the average is ~ 430
  - $\rightarrow$ some of the data have gaps (missing values) $=$ uneven sampling



Sources

- PKS 1502+106
- 4C+38.41
- W Comae
- 4C+21.35
- 3C 279
- AO 0235+164
- PKS 1424−418
- 3C 454.3
- BL Lac
- TON 0599
- PKS 0454−234
- 3C 273
- CTA 102
- 1ES 1959+65
- Mrk 421
- ON+325
- S5 0716+714
- Mrk 501
- 3C 66A
- PKS 2155−304

Linear analysis

- Power Spectrum Density (PSD) analysis is one of the most powerful tools in characterizing the statistical nature of the observed variability.
- Is limited to second-order moments of the flux distribution
- Linear methods fail to incorporate the information about the inherent non-linearity and non-stationarity which is contained in the higher order moments and which directly reflect into the dynamical nature of the black hole systems (see Shoji et al. 2020, Zbilut & Marwan 2008, Green et al. 1999)

Non-linear time series analysis (NLTSA)

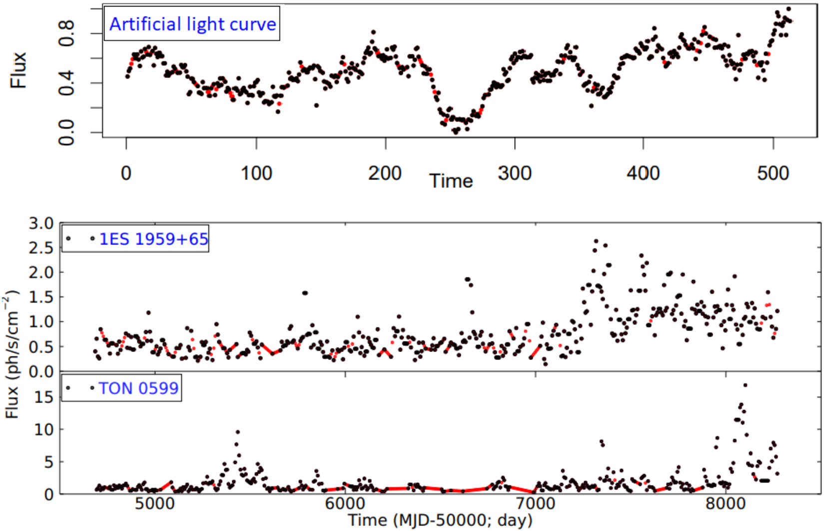
- powerful apparatus which can directly probe into the dynamical states of a deterministic systems
- provides a framework for the inverse problem – restoring eqs. of motion of the underlying system
- Based on mathematical theorems as (Takens 1981) – simplified, one variable reflects the dynamics of the whole system (all degrees of freedom)
- Chaos analysis of scalar time series can be approached following several methods e.g. invariant methods such as fractal dimensions (box counting, correlation dimension) or numerically calculated Lyapunov exponents (see Kantz, H., Schreiber, T. 2003), ML..
- Theorems are considering infinite amount of data (Takens 1981)
- There are only estimates of the relations e.g. $N > 42^{D_2}$, where N is amount of data needed and D_2 is the correlation dimension (Smith 1988)
- Problems lke : Unevenly spaced data (see Bradley & Kantz)
  - Interpolation adds artificial dynamics
  - Noise to signal ratio

Analysis

In order to further explore the nature of variability in γ-ray light curves of the sample blazars, we adopted a number of approaches to the chaos study.
The main goal is to sort the data according to their deterministic signal content.

- emphasis is given to use algorithms with small amount of inputs
  - the less parameter, the easier is the physical interpretability
  - the algorithms handling NL phenomena are sensitive to the inputs
- to obtain most unbiased results we test several natural inputs of the algorithms
  - the choice of τ-time delay, m-embedding dimension, lmin, maxRR-Reccurance rate (RQA parameters) where to average, and their combinations
- The testing is made with the assumption, that the artificially produced data - Artificial light curves (ALC) mimic the real data
  - the ALCs are produced with the package "RobPer" (Thieler et al., Journal of statistical software) in R, func. "tsgen" has 15 parameters
  - we analyze both data structures, with "gaps", so as interpolated ones
  - high red noise content is assumed

Light curves



Algorithms - Construction of embedding

The main algorithm for the non-linear analysis is the reccurance quantification analysis (RQA)

- for NLTSA it is essential to embedded the studied time series which is an input for RQA into higher dimension (Takens 1981)

Embedding: The m dimensional delayed vector $\vec{X}(t)$ constructed from m samples of the $\vec{y}(t)$ with the delay τ is defined as:

$$\vec{X}(t) = [\vec{y}(t), \vec{y}(t-\tau), \vec{y}(t-2\tau), \ldots, \vec{y}(t-(m-1)\tau)] \tag{1}$$

Estimation of m and τ:

Average mutual information - Mutual information, a measure of the information shared between two random variables, suitable for nonlinear data.

$$\mathrm{AMI}_\epsilon(\tau) = \sum_{\mathrm{i,j}} \mathrm{p_{ij}}(\tau) \ln \mathrm{p_{ij}}(\tau) - 2 \sum_{\mathrm{i}} \mathrm{p_i} \ln \mathrm{p_i}. \tag{2}$$

L. Cao algorithm from: Practical method for determining the minimum embedding dimension of a scalar time series (from 1997, cited 1738 times)

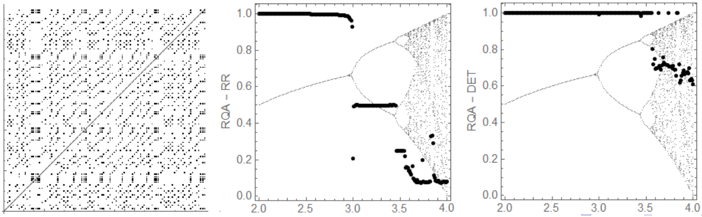
$$a(i,m) = \frac{\left\| y_i(m+1) \; - \; y_{n(i,m)}(m+1) \right\|}{\left\| y_i(m) \; - \; y_{n(i,m)}(m) \right\|}, \quad E(m) = \frac{1}{N - m\tau} \sum_{i=1}^{N-m\tau} a(i,m)$$

Recurrence Quantification Analysis RQA

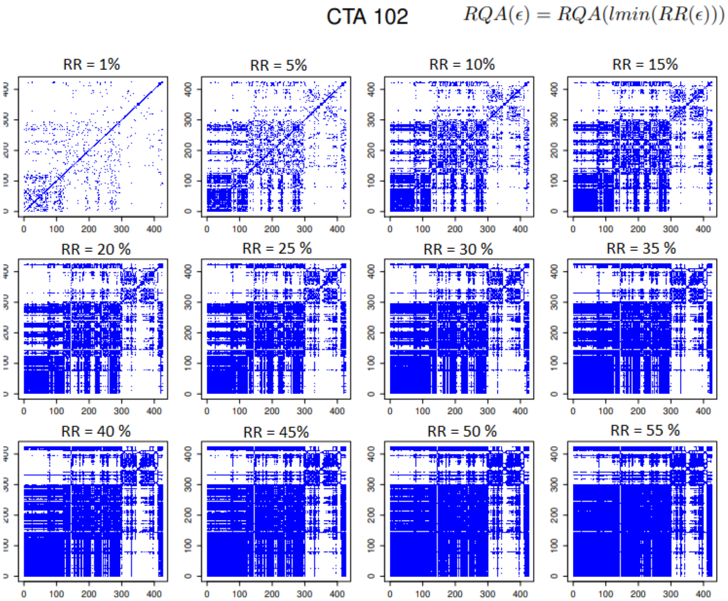
- Recurrence plot is a graphical tool for observing periodicity of phase space trajectories(Eckmann et al.in 1987). $R_{i,j} = H(\epsilon - \|x_i - x_j\|\ |) \quad i,j = 1, ..., N.$
- RQA tools quantifies number and duration of recurrences of a dynamical system (1992 by Zbilut, Webber Jr. and Marwan).

$$RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{i,j}, \qquad DET = \frac{\sum_{l=l_{min}}^{N} lP(l)}{\sum_{i,j=1}^{N}, R_{i,j}}, \quad LL, ENTR \dots \tag{4}$$

  - RR - The recurrence rate, measures density of recurrence points. RR reflects the chance that some state of the system will recur.
  - DET - Determinism is rate of recurrence points which build diagonal lines (l), it say how much deterministic/stochastic the system is ($P(l)$ frequency of l).



Reccurance plots of CTA102 for various RR



Averaged RQA - search of optimal parameters

- table(left) showing the ability of some configuration of RQA to sort the signals according the deterministic content - mD

	SNR	Len	τ	m	$\boxed{\text{mD}}$	mL	mEN
1	3.000	352	3	8	0.789	52.25	0.12
2	5.000	446	4	5	0.785	86.24	0.11
3	0.500	265	5	8	0.581	105.21	0.05
4	0.750	302	4	6	0.530	142.22	0.15
5	2.000	332	5	9	0.414	122.14	0.14
6	1.500	375	6	4	0.412	110.87	0.15
7	1.000	362	3	5	0.358	75.66	0.08
8	0.025	380	3	7	0.342	120.45	0.09
9	0.005	402	5	7	0.152	140.54	0.05
10	0.010	245	2	10	0.144	88.14	0.07

- table(right) average of more different generators of light curves

RR	Part A				
%	lmin#	emb#	tau#	measure1	measure2
1	6	2	3	12.43	26.67
2	**7**	**3**	**3**	**10.35**	**25.00**
3	7	3	3	11.72	26.33
4	7	3	3	11.72	27.00
5	6	2	2	13.99	29.33
10	2	3	3	13.12	31.33
15	1	2	3	12.48	28.00
20	1	3	3	12.43	30.67
25	1	1	3	11.98	28.00
30	1	1	3	11.97	27.33
35	2	3	3	12.27	30.67
40	2	2	3	12.27	28.00
45	2	2	1	12.27	28.00
50	2	1	1	12.27	28.00
55	2	1	1	12.27	28.00
60	2	1	1	12.27	28.00
65	2	3	1	12.61	29.33
70	2	3	1	12.27	28.67
75	2	3	1	12.27	28.67
80	2	3	1	12.27	28.67
85	2	3	1	12.27	28.67
90	2	3	1	12.61	29.33
95	2	3	1	12.27	28.67

Final results - table

	source	Len	tau	m	mD	mL	mEN	msD	msL	msEN
1	W Comae	208	2	8	0.6507	118.0000	0.0000	20.0	12.5	1.0
2	3C 454.3	462	9	9	0.5169	7.8129	1.2666	19.0	1.5	17.5
3	AO 0235+164	273	4	7	0.4178	183.0000	0.0000	16.0	13.5	2.0
4	4C+21.35	373	3	9	0.4086	12.8359	1.2823	17.0	5.5	16.5
5	CTA 102	425	6	6	0.4060	10.8766	1.1721	16.0	3.0	16.5
6	3C 279	502	8	7	0.3966	10.9338	1.7201	16.0	4.5	20.0
7	PKS 1424-418	473	7	9	0.3526	9.6935	1.2379	14.0	2.5	17.5
8	PKS 1502+106	384	6	8	0.3326	17.7432	0.8783	13.5	8.0	13.0
9	TON 0599	355	7	11	0.2911	178.3333	0.3183	10.5	13.0	7.0
10	4C+38.41	462	7	9	0.2816	15.1153	0.7943	11.0	7.5	13.5
11	3C 273	363	3	9	0.2808	273.0000	0.0000	9.5	15.0	3.5
12	BL Lac	475	3	11	0.2784	12.1855	0.6458	10.5	4.5	13.0
13	PKS 0454-234	472	3	9	0.2588	23.2762	1.1288	8.5	9.5	15.5
14	1ES 1959+65	420	5	8	0.2318	330.0000	0.0000	7.0	16.0	4.5
15	Mrk 421	509	6	10	0.2186	19.3333	0.1606	6.0	8.5	10.0
16	ON+325	447	3	9	0.2164	357.0000	0.0000	5.5	17.0	5.5
17	S5 0716+714	490	4	10	0.2029	47.0549	0.3407	3.5	11.0	11.0
18	Mrk 501	461	2	8	0.2001	371.0000	0.0000	3.5	18.0	6.5
19	3C 66A	494	3	9	0.1886	404.0000	0.0000	2.0	19.0	7.5
20	PKS 2155-304	507	6	7	0.1850	417.0000	0.0000	1.0	20.0	8.5

BL LAC FSRQ

Final results - graphically

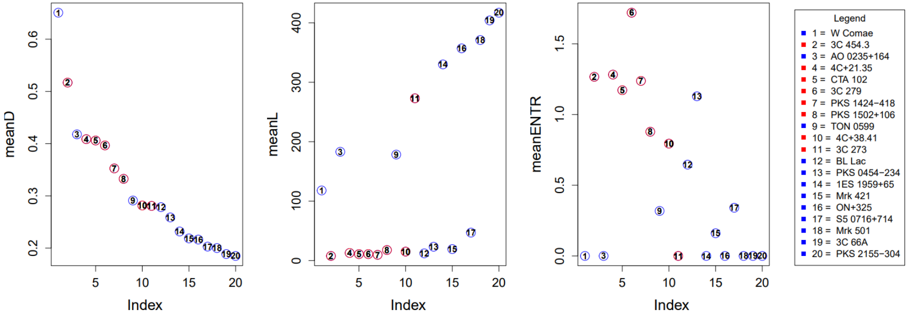


Figure: The distribution of the averaged DET, L and ENTR as derived from the recurrance analysis and as presented in the previous Table are shown in the left, middle and right panel, respectively. The sources FSRQs and BL Lacs are distinguished by the red and blue colors, respectively

Astrophysical conclusions I

- FSRQ are likely disk dominated, therefore, jets possibly are less magnetized and consequently provide less favorable conditions to stochastic process, e. g., rampant shock and/or magnetic reconnection events. Whereas BL Lacs jet have been found to be abundant with streaming particles that can contribute to the enhanced stochasticity (Zhang et al. 2014).
- The results that the dominant physical processes in FSRQs are more of deterministic nature can be interpreted in the widely accepted scenario that jets are powered through the extraction of the rotational energy of supermassive Kerr black hole surrounded by magnetically arrested accretion disk.
- The processes in AGN system could consist of both deterministic and stochastic nature.

Astrophysical conclusions II

- The authors F. Tavecchio, G. Bonnoli, G. Galanti, in article "On the distribution of fluxes of gamma-ray blazars: hints for a stochastic process?" are fitting the timing signal with stochastic DE. arxiv.org/abs/2004.09149

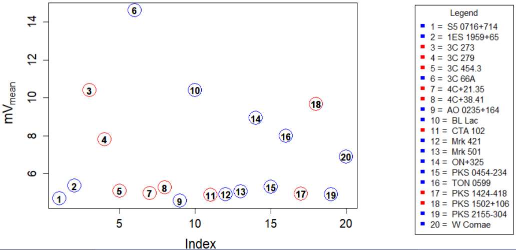
$$\frac{d}{dX}[\theta(\mu - X)p(X)] - \frac{d^2}{dX^2}\left[\frac{\sigma^2 X^2}{2}p(X)\right] = 0,$$

Source	σ	μ	θ	λ
PKS 1222+216	0.35 ± 0.05	2.1 (1.8-2.6)	0.04 (0.03-0.05)	0.15±0.1
CTA 102	0.39 ± 0.05	–	–	0.2 ±0.15
3C 273	0.44 ± 0.05	3.6 (2.9-5.5)	0.025 (0.015-0.03)	0.6±0.16
3C454.3	0.23 ± 0.05	–	–	0.1 (fixed)
PKS 1510-089	0.46 ± 0.04	6.3 (5.3-7.9)	0.04 (0.03-0.05)	0.1 (fixed)
3C279	0.44 ± 0.04	5.5 (4.0-9.0)	0.03 (0.015-0.04)	0.7±0.1

Table: σ-stochastic term, μ-deterministic drift

Astrophysical conclusions - Timescales

- The timescales are derived from the vertical distribution of the points in the RP are in range of 5 - 15 weeks
- For a typical black hole mass of $\sim 10^9 \mathrm{M}_\odot$ with gravitational radius $R_g = \frac{GM}{c^2}$, the size corresponding to 15 weeks corresponds to 0.5 pc, which is comparable to the size of the inner accretion disk; and 10 weeks represents a few thousands of gravitational radii, within which most of the gravitational potential energy is converted into the radiation energy. In such interpretation, the inner accretion disk might be treated as the main component of a dynamical state of an AGN, and the modulations driven by various instabilities e.g. radiation pressure, viscous instabilities (Janiuk & Czerny 2011; Janiuk et al. 2002)



Summary

Deterministic Aspect of the γ-ray Variability in Blazars

- We have analyzed the non-linear properties of 20 Blazars
- We used the novel appraoch of RQA
- The optimal inputs of algorithms have been extensively tested
- The pattern of distinguishing 2 groups of Blazars is visible

Any questions ?

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Thank you for your attention !