Recurrence plot analysis of blazar gamma-ray light curves: exploiting the time-domain capabilities of Fermi-LAT

Fermi satellite
Credit: NASA

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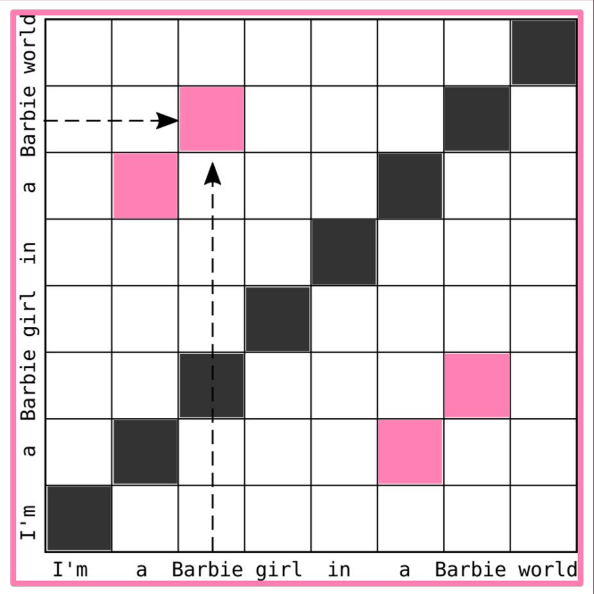
The statistical methods often used to characterize the measured time variability (e.g., techniques based on the Fourier transform) rely on the underlying assumption that the time series data is stationary, with mean and variance remaining constant over time. However, this is not the case for blazar light curves. We present a different approach to characterize the flux variability observed in bright gamma-ray blazars using the recurrence plot analysis technique - to gain insight into the non-linear and stochastic behavior of blazar jets at γ-ray energies.

What are recurrence plots?

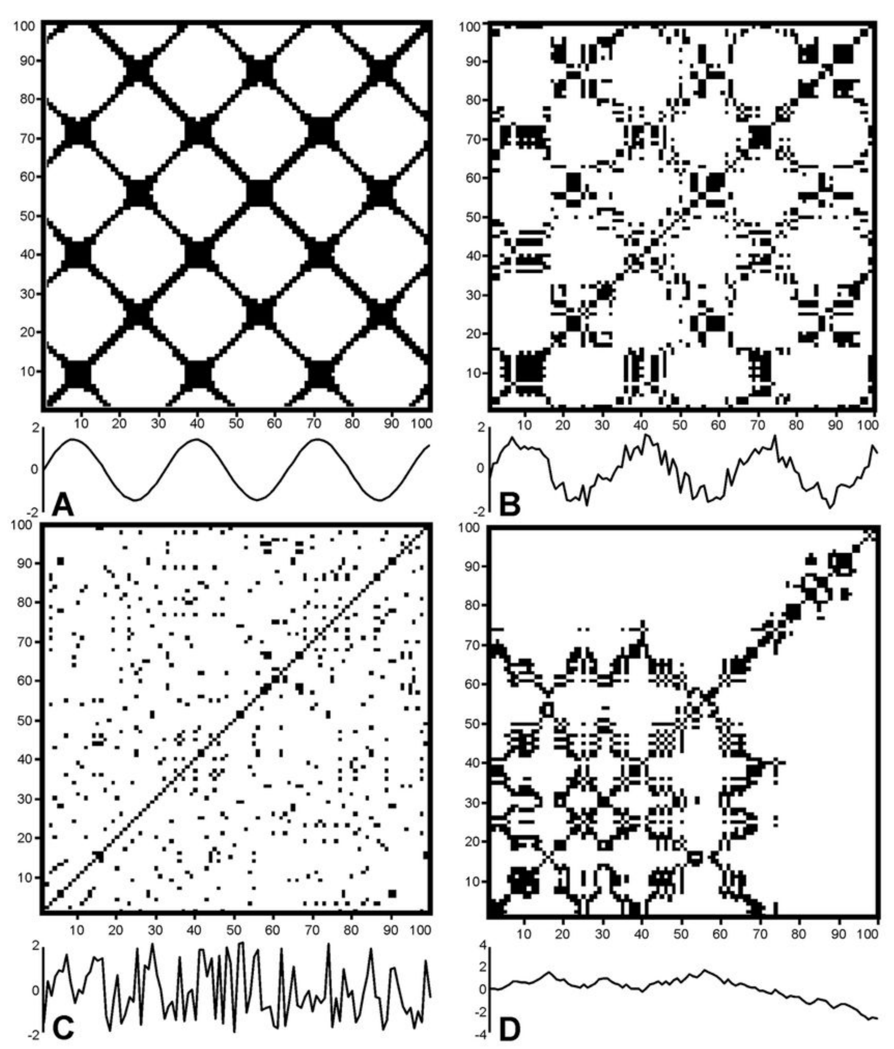
- Recurrence plots are a visualization of dynamical trajectories in phase space that are built from one-dimensional time series (e.g., light curves)
- Recurrence plots look like two-dimensional binary matrices: if a point at position *j* in the time series is in the neighbourhood of a point at position *i*, this is marked by a black dot in the recurrence plot.

Simple example for what a recurrence plot shows, shown here for the lyrics of the song 'Barbie girl' by Aqua.



Check out "SongSim" by Colin Morris for more matrices of popular songs (colinmorris.github.io/SongSim)

- Depending on the time series, a recurrence plot can show different patterns:



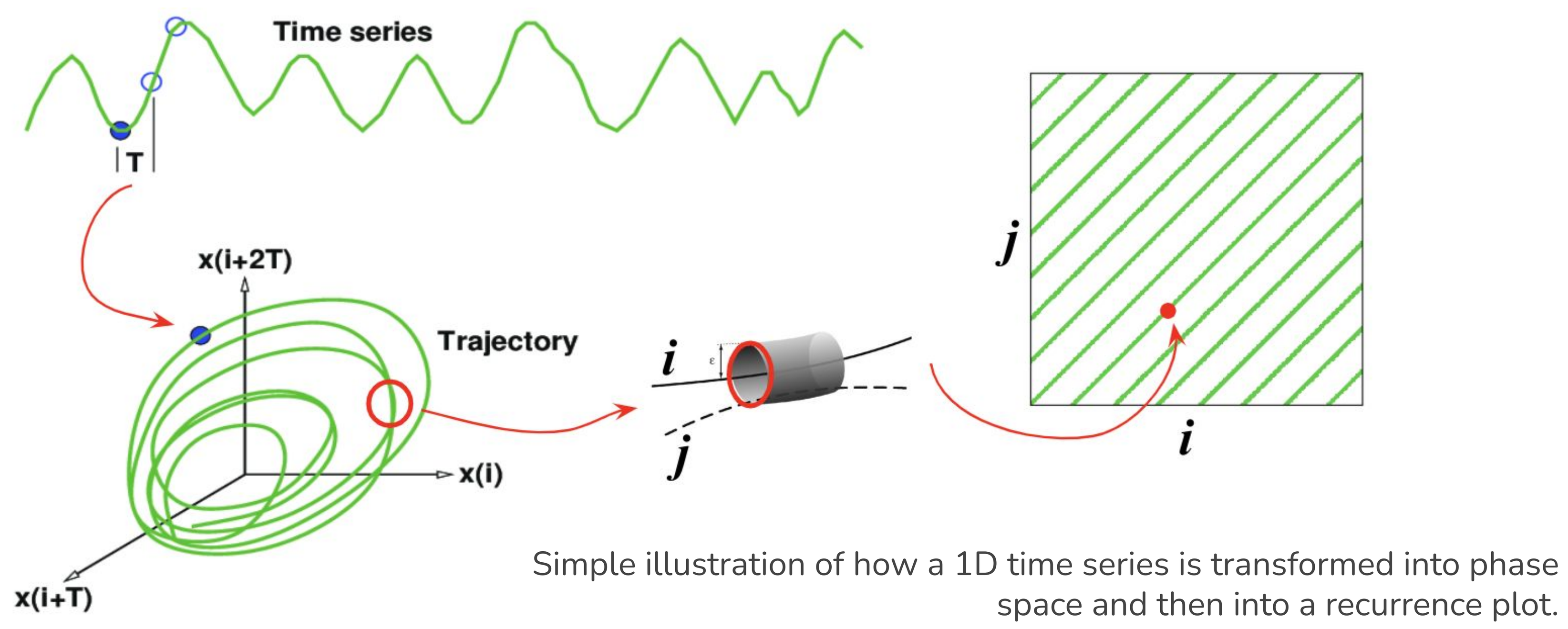
Different time series with their respective recurrence plots:

A. Periodic signal
B. Periodic signal with noise
C. White noise
D. Random walk

Credit: A. Spiridonov, 2017, J. Geol. 125, 381-398

What can we do with recurrence plots?

- Recurrence plots are ideally suited to study (blazar) light curves, because:
  - they can retrieve the same information embedded in power spectral densities but without making assumptions about stationarity,
  - they can additionally probe non-linearity, and
  - they provide distinctions between stochastic and deterministic behaviour in a source



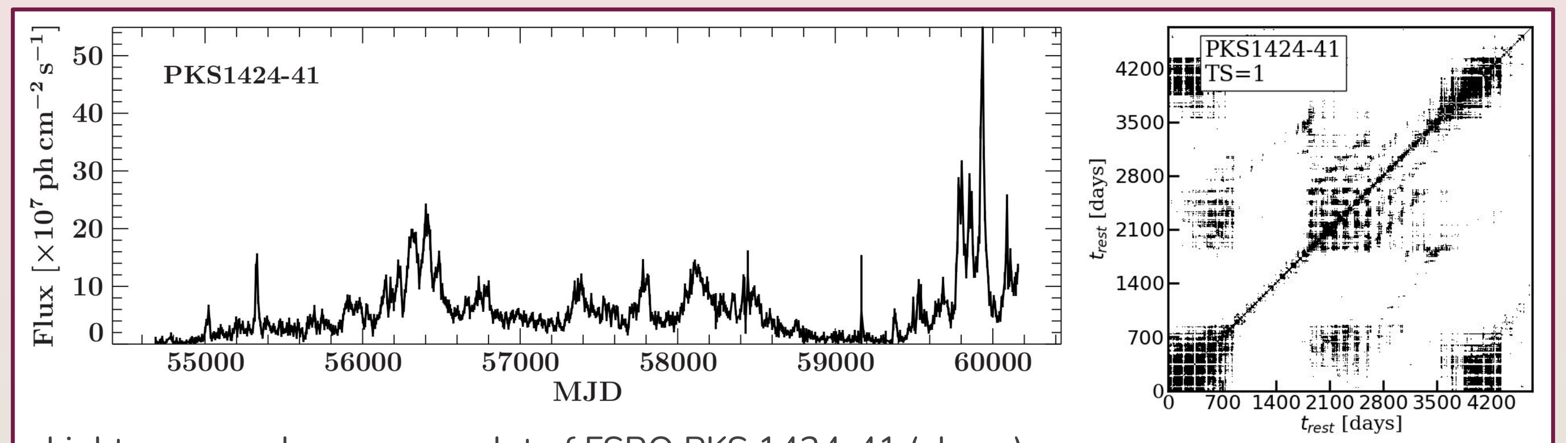
Simple illustration of how a 1D time series is transformed into phase space and then into a recurrence plot.

- Examples of parameters we can measure with recurrence plots:
  - Recurrence rate (RR): % of recurrence points in the plot
  - Determinism (DET): % of points forming diagonal lines
  - Laminarity (LAM): % of points forming vertical lines
  - Average diagonal line length (L_{mean})
  - Trapping time (TT): Average length of vertical lines
  - Longest diagonal line (L_{max}) / Longest vertical line(Vmax)
  - Entropy (ENTR): Entropy of prob. dist. of diagonal line lengths

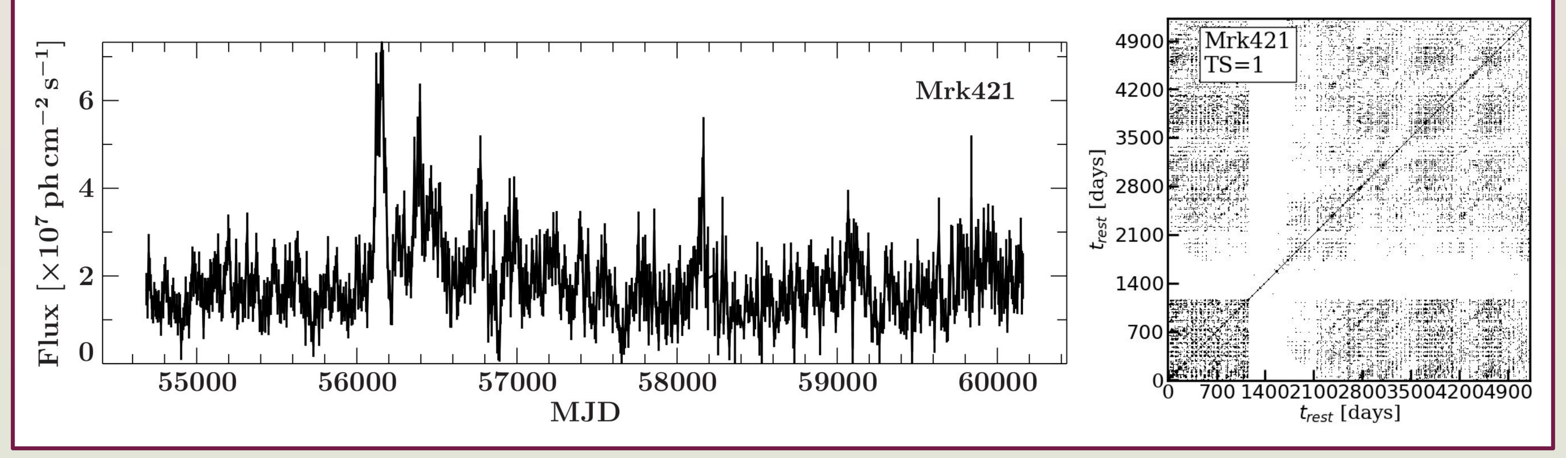
- For an extensive review on 'Recurrence plots for the analysis of complex systems', see Marwan et al., 2007, *Physics Reports*, 438(5–6), 237–329
- Conversion of a time series into phase space, 'Embedology', is described in detail by Sauer et al., 1991, *Journal of Statistical Physics*, 65, 579–616
- For a recent application of recurrence analysis to AGN X-ray light curves collected with *Swift*/BAT, check out the work by Phillipson et al., 2023, *MNRAS*, 518(3), 4372–4390 →

Our Fermi Blazar Sample

- Using long-term monitoring capabilities of *Fermi*-LAT
- Selecting bright blazars with ≤ 7% missing bins in light curve (TS threshold of ≥ 1)
  → 59 sources: 29 are FSRQs and BL Lacs each, plus one classified as BCU



Light curve and recurrence plot of FSRQ PKS 1424-41 (above) and the BL Lac-type blazar Mrk 421 (below).



- Comparing the recurrence plot parameters of different source classes for entire sample
- Plan to use surrogates to draw statistically sound conclusions

	PKS 1424-41	Mrk 421
DET	0.502	0.247
LAM	0.639	0.353
ENTR	0.642	0.328
L_{mean}	2.583	2.160
TT	2.939	2.253
Lmax	11.0	7.0

We will probe processes such as quasi-periodic oscillations, dynamics of energized plasma in the blazar jet and jet precession on time scales of weeks to several years.

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