

Application of advanced time-series methods to a multiple sectors TESS observation of a radio-loud Active Galactic Nucleus

Ashutosh Tripathi^{1,2}, Paul J. Wiita³, Ryne Dingler², Krista Lynne Smith², R. A. Phillipson⁴, Matthew J. Graham⁵, and Lang Cui¹

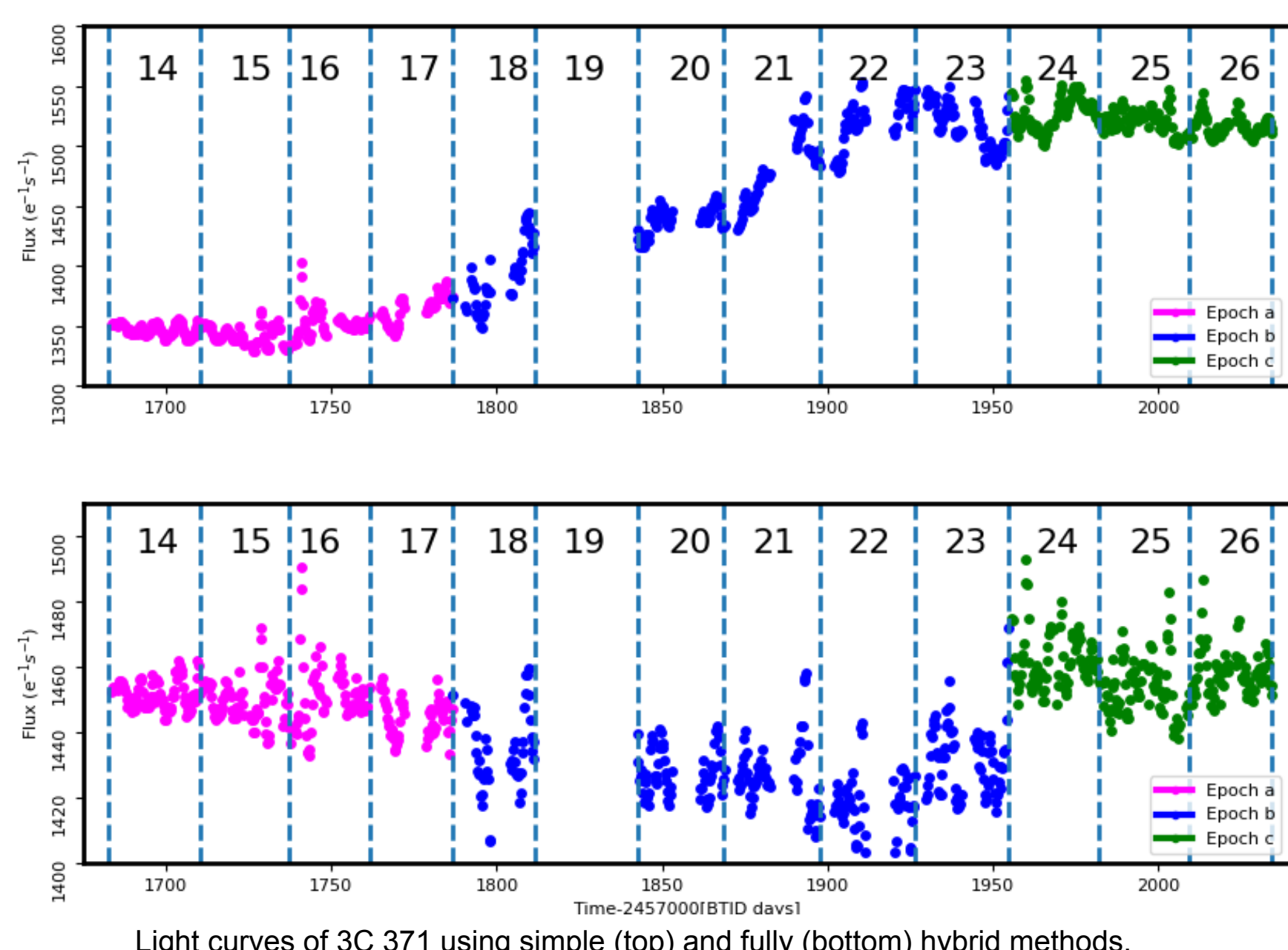
¹Xinjiang Astronomical Observatory, CAS, 150 Science-1 Street, Urumqi 830011, People's Republic of China, ²George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA, ³Department of Physics, The College of New Jersey, 2000 Pennington Rd., Ewing, New Jersey 08628-0718, USA, ⁴Department of Physics, Villanova University, Villanova, PA 19085, USA, ⁵California Institute of Technology, 1200 E. California Blvd, Pasadena, CA 91125, USA

Abstract

We present various time series analysis methods to analyze multiple-sector observations of bright AGN from the Transiting Exoplanet Survey Satellite (TESS) and examine whether issues such as gaps and noise in these data can be mitigated. We determine variability timescales and search for quasi-periodicity using these methods and assess any differences. We present an analysis of the ~ 300 -day TESS observation of a blazar 3C 371 using power spectrum density, structure-function, and weighted wavelet Z-transform approaches. To reduce the effect of gaps and noise, Continuous auto-regressive moving averages, and Bartlett periodogram methods are used. We have also used recurrence analysis to account for the nonlinearity present in the data and to quantify variability or periodicity as the recurrent state. When analyzing multiple sectors together, significant variability, which could be quasi-periodic oscillations (QPOs), of duration 3–6 days in individual segments, is detected. These may be attributed to the kink instabilities developed in the jet or the existence of mini-jets inside a jet undergoing precession. We find that these methods, when applied appropriately, can be used to study the variability in TESS data. The noise present in these TESS observations can be minimized using Bartlett's periodogram and wavelet decomposition to recover the real stochastic variability.

Introduction

- Blazars are known to display variability on timescales ranging from a few minutes and hours to weeks, months, and even a few years across the whole electromagnetic spectrum. Different timescales in different wavebands can correspond to different physical processes and emission mechanisms.
- TESS is a space-based optical telescope that provides very high-cadence data and are very suitable for investigating timescales of the order of a few hours to days and sometimes up to a few months.
- The Quaver pipeline provides three distinct methods to correct for the systematic effects affecting the TESS light curves; these are simple PCA, simple hybrid, and full hybrid methods. The simple hybrid light curves show remarkable agreement with simultaneous ground-based observations, which, however, are not as densely sampled as TESS light curves and preserves long-term variability. The fully hybrid method considers all systematics rigorously and removes them from the source flux itself. Specifically, the fully hybrid method is more suitable for studying rapid variability and quasi-periodicities but over-fits long-term variability of the order of the length of a TESS observation sector.



- The TESS data usually have gaps in the middle of each roughly monthly observation as well as the gaps between adjacent sectors. To analyze multiple sectors of TESS observations, it is important to treat the gaps with care so that they do not significantly affect the measurements of any variability timescales.

Methodology

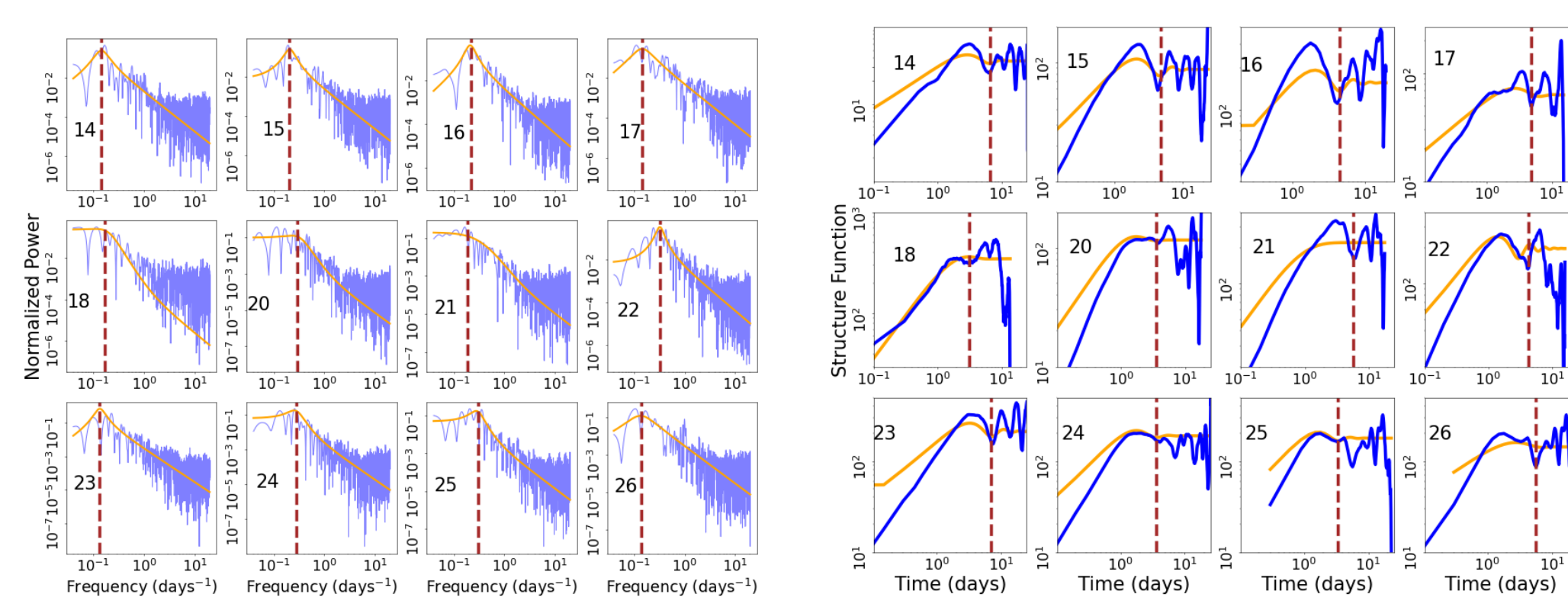
- The variability observed in AGNs across the electromagnetic spectrum is believed to originate in the outflows, jets, and the accretion disk of the system. The resultant variable emission can interact with various phases of the plasma surrounding the central engine, which can make the observed variability more complex and non-linear in nature. Therefore, including non-linear dynamics in the analysis could provide a better model to explain the observed variability.
- C-ARMA processes directly probe the possible correlation structure present in the observation in the form of a stochastic differential equation which defines the temporal evolution of data.
- We used C-ARMA (2,1) process, commonly known as the Damped Harmonic Oscillator (DHO), which is a second-order differential equation. The motivation behind using this model is the ability of second-order differential equations to explain many physical systems.

$$\frac{d^2C(t)}{dt^2} + \alpha_1 \frac{dC(t)}{dt} + \alpha_0 C(t) = \beta_1 \frac{d\epsilon(t)}{dt} + \beta_0 \epsilon(t),$$

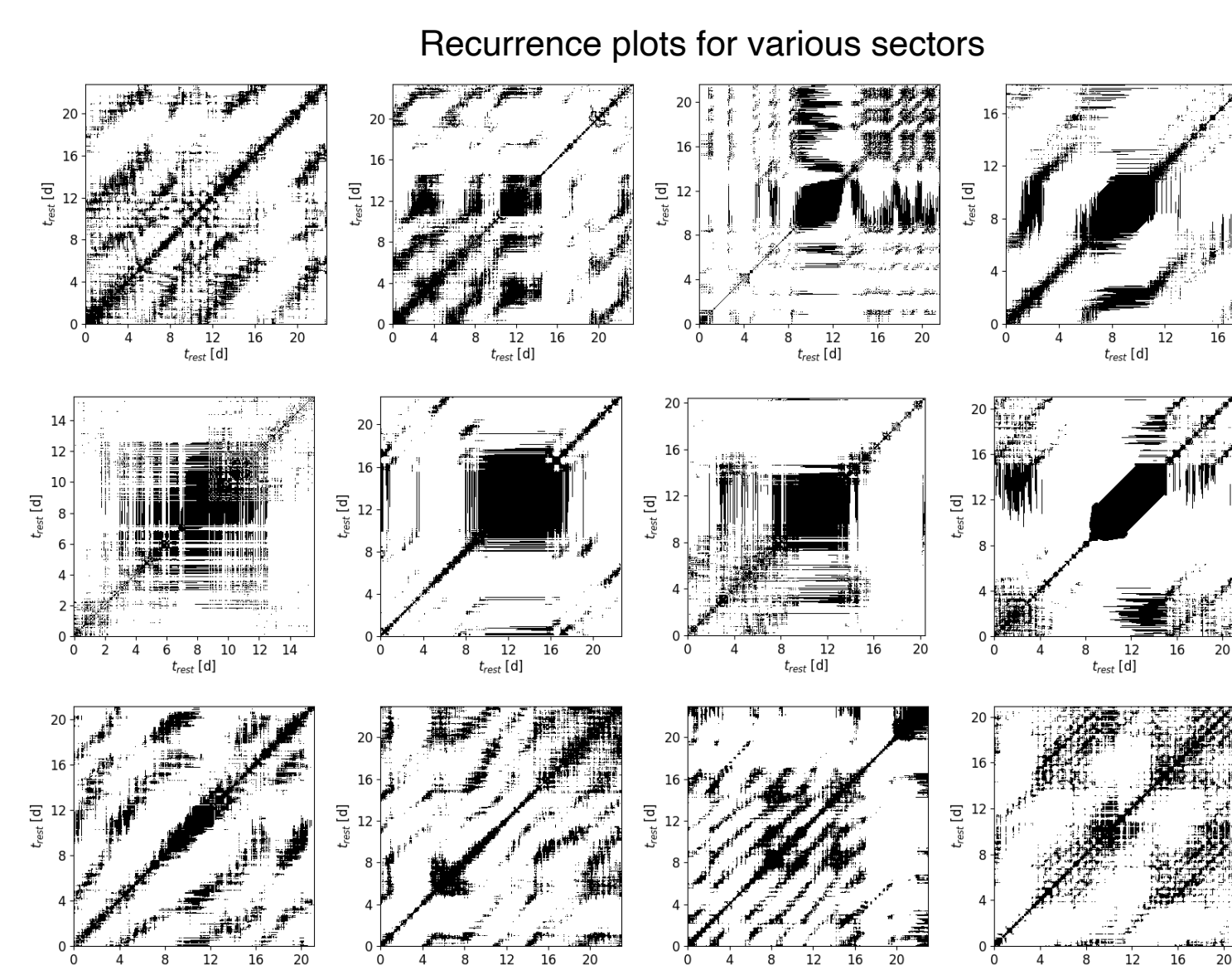
where α_1 and β_1 are the autoregressive and moving average coefficients, respectively. The coefficients are defined such that α_2 is equal to unity. Here, $\epsilon(t)$ is the Wiener process that provides stochasticity in the behavior of $C(t)$ which is essentially a perturbation around the steady flux state for the observed state $C(t)$.

- The variability of stochastic processes, as observed in AGNs, is often described in terms of the power spectral density (PSD) and structure function (SF). PSD measures the variability amplitude per temporal frequency, while the SF estimates the variability amplitude as a function of timescale.

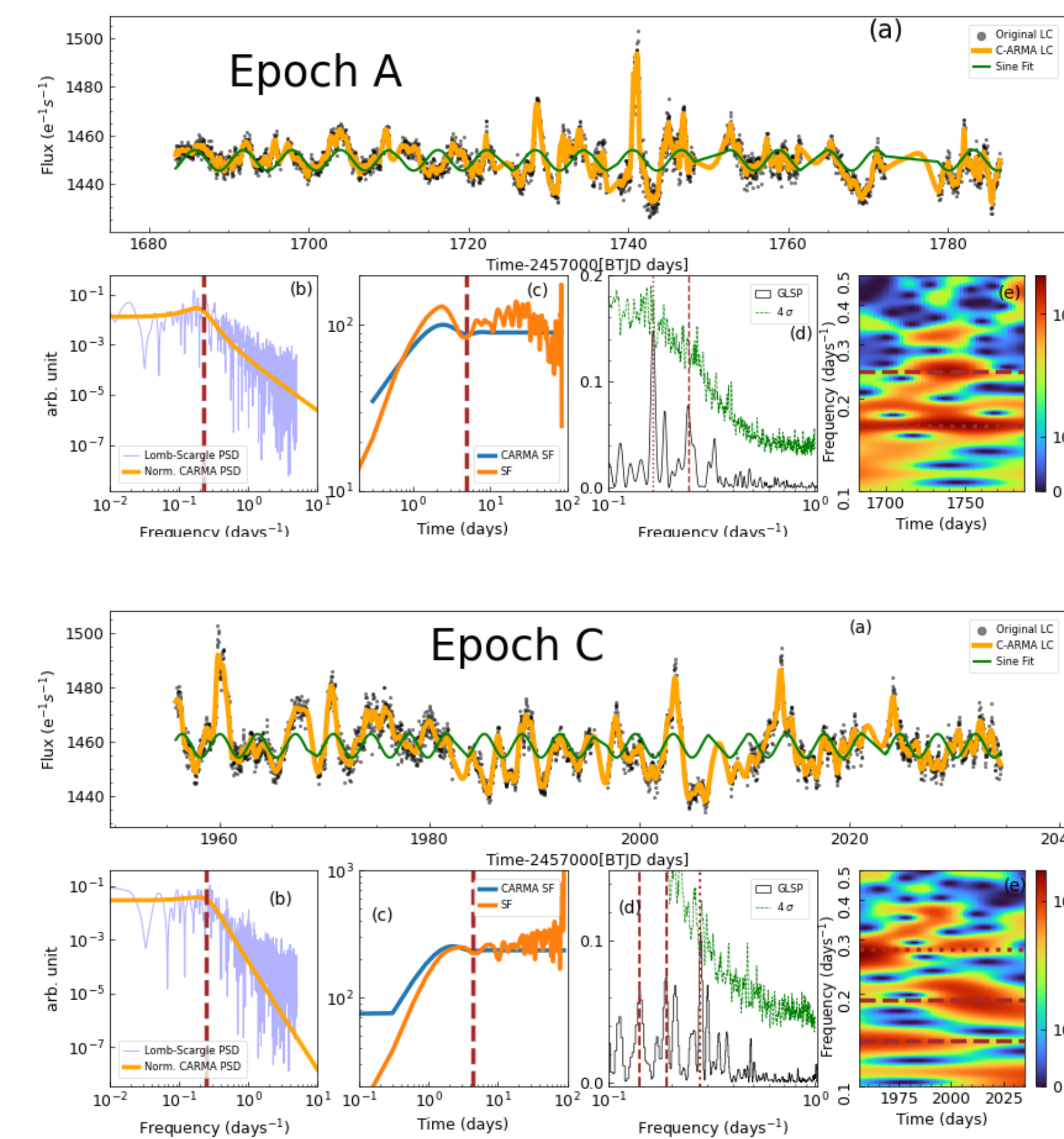
Comparison of PSD and SF calculated using CARMA and original LC



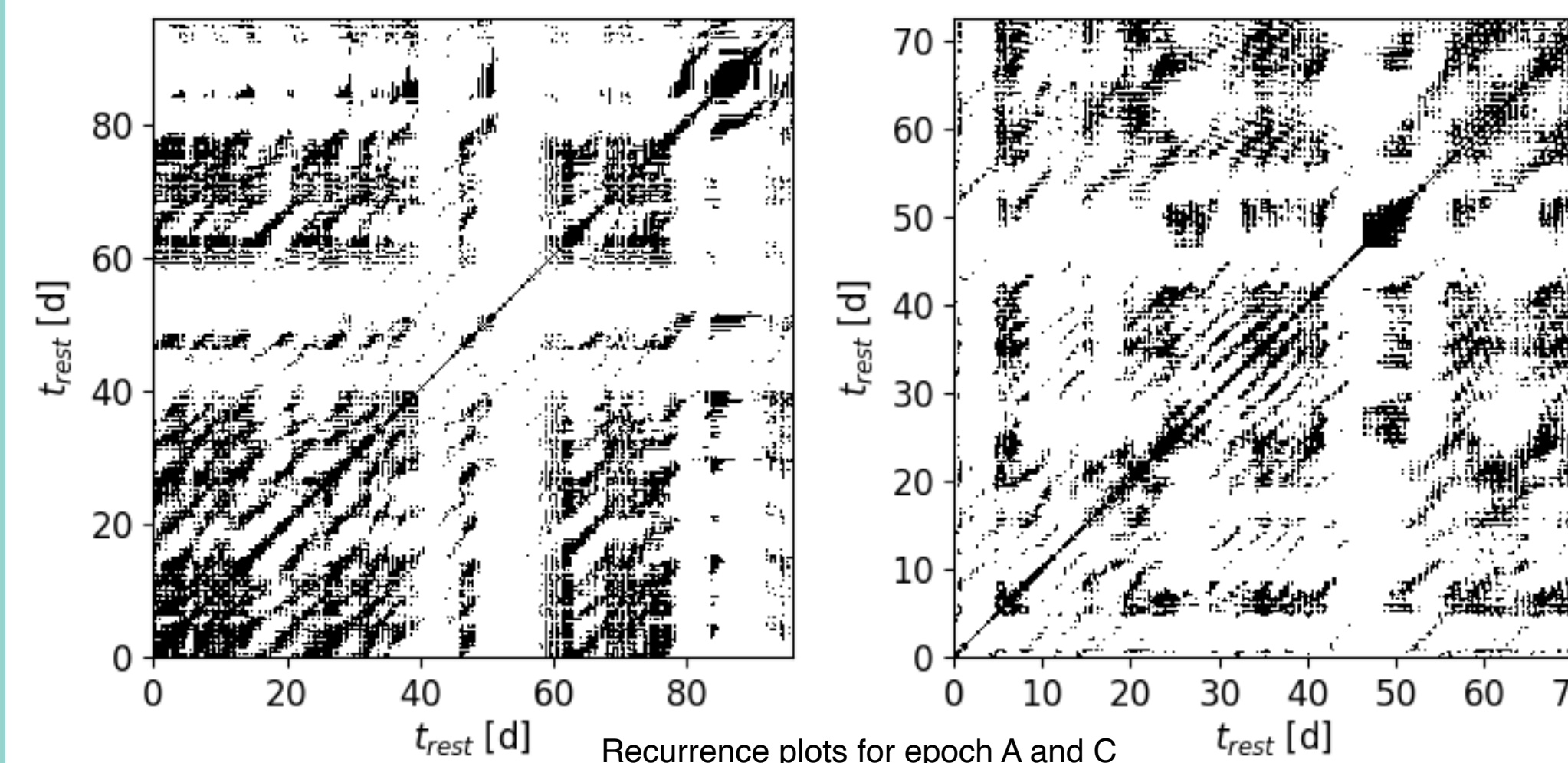
- Recurrence analysis is a method that correlates positions in time to nearby positions in the phase space of a dynamical system, compiled into a square matrix. The resultant matrix can be visualized as a "Recurrence Plot" (RP) with patterns unique to different dynamical systems. For example, repeating patterns in an RP is an indication of the presence of deterministic variability, possibly including quasi-periodicity, in the observation. RPs fundamentally probe the higher-order, non-linear patterns of variable sources and enable one to distinguish a stochastic process from a deterministic process as responsible for the observed variability.



Results



Timing analysis for epoch A and C. The light curve is plotted in (a) along with the C-ARMA generated light curve and a sine fit with a period of 6 days. (b) and (c) respectively show the PSD and SF calculated directly from the observations and from the C-ARMA fit. (d) shows the GLSP results. The brown dotted correspond to a possible quasi-periodicity. WWZ color-color diagram is plotted in panel (e).



- Bartlett's method is an approach to computing the periodogram of a time series by averaging the periodogram of equal segments of the light curve, resulting in smoothing of the periodogram. One of the most common issues with multi-sector TESS data is how to perform careful treatment of the gaps between the sectors and also, sometimes, within the sector. The multiple-sector observation can be treated as a time series comprising many sectors separated by gaps.

Conclusion

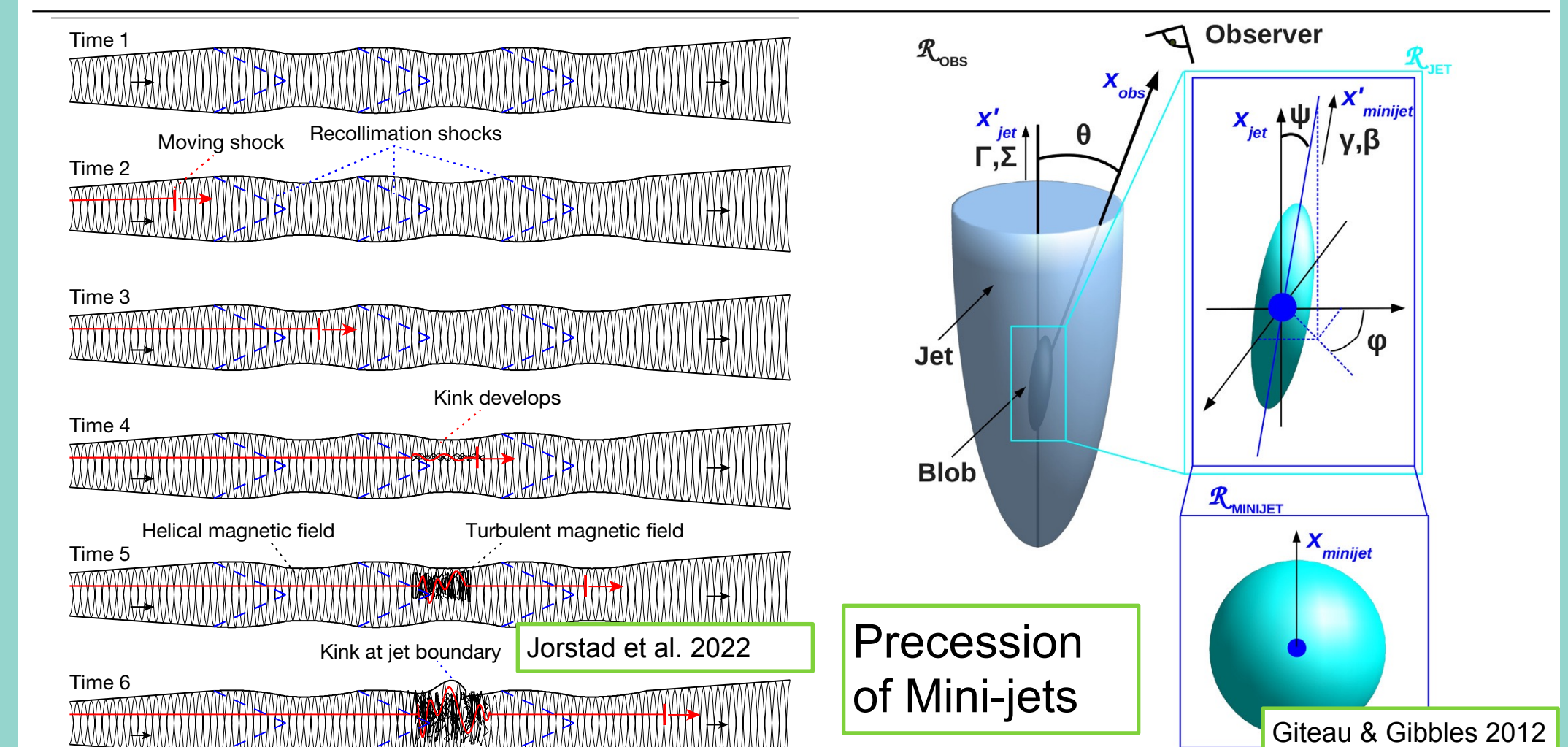
- The interaction between the instabilities and the toroidal magnetic field leads to magnetic reconnection and the formation of a kink at the center of a jet, which is quasi-periodic in nature. The temporal growth of the kink instability from the center of the jet to its boundary is manifested in the light curves as a variable quasi-periodic signature.

$$T_{kink} = \frac{R}{\langle v_{tr} \rangle \delta},$$

T_{kink} is the ratio of the distance traversed by the kink from the center of the jet to its boundary, R , with the velocity of propagation, $\langle v_{tr} \rangle$ and δ is the Doppler factor. Putting values for a typical blazar in the above equation estimates the growth time to be 1--10 days, which is consistent with the QPO found in this work.

- As these optical emissions of such small timescales are believed to originate in the jets, multiple timescales could arise from different processes related to plasma instabilities or the presence of sub-structure within a jet, or "mini-jets"

Method	Epoch A	Epoch B	Epoch B1	Epoch C	Cycle 2
LSP	0.24 ± 0.02	0.23 ± 0.02	0.23 ± 0.02	0.30 ± 0.04	0.23 ± 0.04
CARMA PSD	0.21 ± 0.02	0.17 ± 0.03	0.14 ± 0.03	0.24 ± 0.02	0.15 ± 0.03
SF (1/day)	0.22 ± 0.02	0.24 ± 0.02	0.2 ± 0.03	0.23 ± 0.03	0.23 ± 0.03
CARMA SF (1/day)	0.2 ± 0.01	0.17 ± 0.01	0.19 ± 0.02	0.23 ± 0.02	-
Bartlett's PSD	0.18 ± 0.03	0.24 ± 0.01	0.24 ± 0.03	0.28 ± 0.01	0.24 ± 0.06
WD	0.16 ± 0.02	0.23 ± 0.03	0.23 ± 0.02	0.28 ± 0.04	0.23 ± 0.05



TESS has proved exceptionally useful for the study of AGNs as well as for its primary purpose of exoplanet detection. The high-cadence, regularly sampled data make it an excellent tool for probing short-term variations in many AGNs. To take advantage of such high-quality data, the inevitable gaps present within the sectors or between them and the noise affecting the AGN variability should be treated carefully. Our study concludes that the methods presented in this work are indeed effective in countering these issues and could certainly be used to analyze multiple-sector TESS observations of other blazars as well as Seyfert galaxies in future work.

References and Acknowledgements

- Tripathi, A. et al. Application of time-series analysis methods to a multiple-sector TESS observations: the case of the radio-loud blazar 3C 371. MNRAS, 545, issue 3 (2026). <https://doi.org/10.1093/mnras/staf2211>
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- Contact : E-mail: ashutosh31tripathi@yahoo.com