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Spectral-timing made easy with Stingray

*Eleonora Veronica Lai, Matteo Bachetti, Daniela Huppenkothen,
Matteo Lucchini, Guglielmo Mastroserio
and the Stingray community*

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- **Stingray** is an open-source Github-based software package designed to perform time series analyses and related task on astronomical light curves.
- **Great performance** (*Lai et al. in prep.*)
- **Complicated spectral-timing analyses in a simple way:**
 - Check your results
 - Get acquainted with such methods



Spectral-Timing made easy with Stingray

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Rationale

Stingray is an open source GitHub-based Python library for time series analysis of astronomical light curves. It provides a range of the commonly used Fourier techniques, alongside dedicated tools for pulsar studies, simulating data sets, and statistical modelling. Stingray is designed to be both extensible and easily integrated into existing workflows and pipelines, making it a flexible resource for the astrophysics community.

History

Stingray was conceived at the 2016 workshop *The X-ray Spectral-Timing Revolution*, when a group of X-ray astronomers and developers joined forces to create a shared, open-source platform for timing analysis in Python. At the time, most X-ray timing relied on custom or proprietary tools. The aim was to merge existing efforts into a package that followed modern open-source practices, offered both scripting and graphical interfaces, and provided a solid statistical foundation for advanced spectral-timing techniques. Stingray's ultimate goal is to provide the community with a package that eases the learning curve for advanced spectral-timing techniques, with a correct statistical framework. Subsequent developments included **HENDRICS**, extending functionality for pulsar searches and command-line use, and **DAVE**, a graphical interface project. For a more complete overview of spectral-timing and Stingray's design, see Huppenkothen et al. (2019, *A&A*, 881, 39).

Ongoing development

Stingray is designed to provide advanced tools tailored to the needs of the high-energy astrophysics community, while remaining flexible and extensible through general-purpose classes and methods. Ongoing work, supported by the Italian National Recovery and Resilience Plan, focuses on boosting performance via GPUs and parallel computing. Future developments will include a major redesign of the modelling subpackage, integrating cutting-edge optimisation, sampling algorithms, and probabilistic programming techniques.

Application example (Lai et al. 2022, *MNRAS*, 512, 2671)

Spectral-timing analyses of XMM-Newton data in the hard state of Cyg X-1 highlights the impact of the stellar wind on variability properties of the source. In particular, the **power spectrum** shows enhanced fractional rms at low frequencies (~0.1–1 Hz) due to the presence of the stellar wind and suppressed high-frequency power, consistent with scattering or absorption in a denser medium.

Time lags between a hard (2-10 keV) and a soft (0.3-1 keV) energy band are reduced in amplitude, while pronounced soft lags emerge at low frequencies during intervals of strong absorption due to the wind. The **coherence** between the same energy bands, usually close to unity, drops significantly in the presence of the stellar wind, reflecting a more complex and non-linear variability coupling. These results demonstrate how such analyses can disentangle intrinsic accretion variability from environmental effects—precisely the type of studies enabled by Stingray!

Current capabilities

- 1. Data handling and simulation**
 - Loading event lists from FITS files (and generally good handling of OGIP-compliant missions, like RXTE/PCA, NuSTAR/FPM, XMM-Newton/EPIC, NICER/XTI)
 - Constructing light curves and time series from event data
 - Operations on time series (e.g. addition, subtraction, joining, and truncation)
 - Simulating realistic light curves and event lists
 - Good Time Interval operations
 - Filling gaps in light curves with statistically sound fake data
 - Dead time modelling
- 2. Fourier methods**
 - **Periodograms and Cross spectra** with different techniques (single, Bartlett, Multi-Taper, Lomb-Scargle) and different normalisations (Leahy, fractional rms, absolute rms, ...)
 - **Dynamical periodograms** and cross spectra
 - Maximum-likelihood fitting of periodograms
 - **Time Lags and Coherence**
 - Variability-Energy spectra, like covariance/lag spectra
 - **Bispectra**
 - (Bayesian) quasi-periodic oscillation searches
 - Power Colours
- 3. Other time series methods**
 - Pulsar searches with Epoch Folding and Z_2^2
 - Gaussian Processes for GPD studies
 - Cross correlation functions

... And Much More! See the documentation

A growing community

Stingray has benefited over time by code contributions and maintenance help from many people, especially young researchers and students.

Contacts and references

Our documentation can be found at docs.stingray.science. We created extensive walkthroughs through Jupyter notebooks that can be executed and adapted to the user's own necessities. Do you have an issue or a feature request? Do you want to contribute? Or maybe you are just curious about the details of the code? You can do this and more at <https://github.com/stingraysoftware/stingray>. Don't know where to start? [Ask for a tutorial!](#)

Acknowledgements

We especially thank the Astropy community for continued "infrastructure" support, the Google Summer of Code for providing a stipend to develop the *Stingray* package, the INFN INFN-PD for providing a PhD fellowship for funding, the Italian Research Center on High Performance Computing (C4HPC), project leader by European Union - NextGenerationEU - and National Recovery and Resilience Plan (NRRP) - Mission 4 Component 2 within the activities of Supercomputing and Quantum Computing.

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Need help?
Look for me during coffee breaks.
For sure you will find me close to the pistacchio sweets!

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Figure 1: Power vs Frequency for Cyg X-1 data. The plot shows a clear peak at approximately 100 Hz, indicating a periodic signal. The legend indicates DPS (red) and RMS (blue) data.

Figure 2: Coherence vs Frequency for Cyg X-1 data. The plot shows a clear peak at approximately 100 Hz, indicating a periodic signal. The legend indicates DPS (red) and RMS (blue) data.

Figure 3: Log(s) vs Frequency for Cyg X-1 data. The plot shows a clear peak at approximately 100 Hz, indicating a periodic signal. The legend indicates DPS (red) and RMS (blue) data.

The background of the image is a collage of various photographs of people, mostly young adults, smiling and posing in different settings. The photos are of various sizes and are arranged in an overlapping manner. In the center, the text "Thank you!" is written in a large, bold, black font. To the right of the text, there is a white square icon containing a black outline of a megaphone with a green arrow pointing upwards and to the right.

Thank you!