An AstroSat Anticipated ToO: observing the state transition of 4U 1630-47

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Abstract

Following two ISSI-BJ workshops in 2015 and 2016 on rapid multi-wavelength variability in compact objects, we developed an anticipated AstroSat Target-of-Opportunity programme to trigger on outbursts of known black-hole X-ray binaries. In March 2023, 4U 1630-47 satisfied the trigger criteria during its 2022–2024 outburst, leading to a long (~10 day) AstroSat observation with contemporaneous NICER coverage. The campaign captured a continuous flux evolution through the steep-power-law state. Flux-resolved spectral-timing analysis reveals strong type-C-like QPOs evolving from 3.6 to 6.1 Hz, a transient ~30 mHz quasi-regular modulation, and at higher flux two simultaneous non-harmonically related QPOs at ~4.6 and ~13 Hz. The higher-frequency component is strongly correlated with disk-related spectral parameters, while the ~4.6 Hz QPO follows different trends, indicating distinct variability mechanisms or emitting regions. In the final segment the lower-frequency QPO disappears and the higher-frequency feature persists near 12.2 Hz. Energy-dependent rms and phase-lag behaviour further separates the variability into distinct regimes. These observations show how the anticipated-ToO strategy can capture rapid changes in disk-corona coupling and probe the changing inner accretion flow during a black-hole transient outburst.

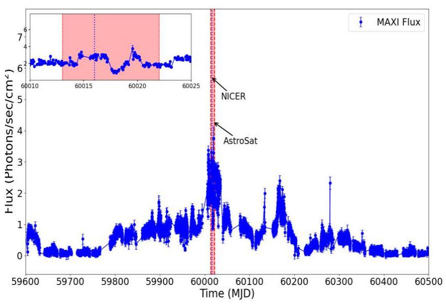
1. Motivation & Anticipated ToO

The results presented originated from ISSI-BJ workshops on rapid multi-wavelength variability in accreting compact objects, organized by Tomaso Belloni and Dipankar Bhattacharya.

Three identical anticipated AstroSat ToO proposals targeted 15 known black-hole X-ray binaries, with triggering when a source entered outburst with a flux >0.4 Crab.

In March 2023, during AstroSat cycle A12 one of the targets, 4U 1630-47, finally satisfied the trigger criteria when it was detected to be in outburst by MAXI. The resulting long AstroSat observation, together with contemporaneous NICER coverage, captured the evolution during the 2022-2024 outburst.

In Figure 1 we present the light curves from MAXI, AstroSat and NICER during the outburst.

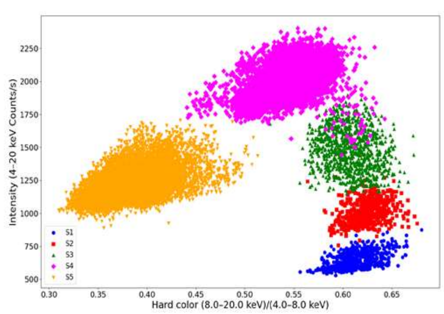


MAXI 2–20 keV outburst light curve showing the AstroSat and NICER observing intervals.

2. Observations & Flux Evolution

AstroSat observed 4U 1630-47 on 10–12 and 15–19 March 2023 using LAXPC and SXT. NICER provided simultaneous soft-X-ray observations during part of the campaign.

The LAXPC hardness-intensity diagram was divided into five flux-resolved segments (S1–S5), with S1 further split according to QPO-frequency evolution.



Hardness-intensity diagram defining the time-resolved segments used in the analysis.

3. Spectral-Timing Method

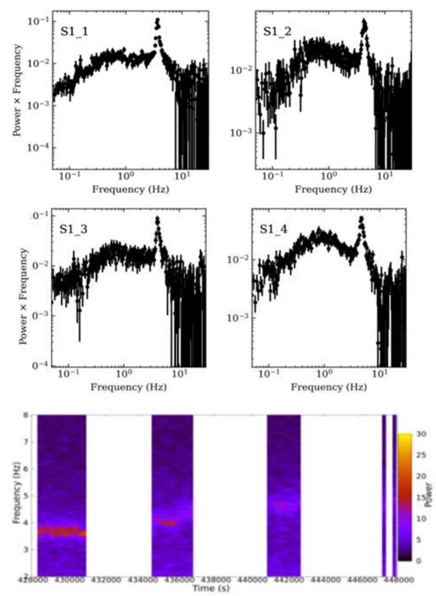
Power-density spectra (PDS) and cross spectra (CS) were calculated in two energy bands.

Following Mendez et al. (2024), the two PDS plus the real and imaginary parts of the CS were fitted simultaneously with multiple Lorentzians. This constrains centroid frequencies, widths, rms amplitudes and phase lags consistently, and can reveal components that are weak or hidden in the PDS alone.

Broadband LAXPC, SXT and NICER spectra were fitted jointly to follow changes in disk and Comptonized emission.

4. Evolving QPO Phenomenology

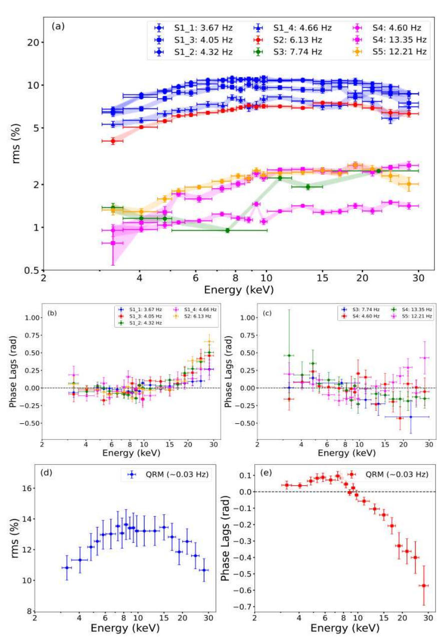
Early observations (S1) show strong type-C-like QPOs at 3.6–6.1 Hz. In S3 a ~30 mHz quasi-regular modulation emerges. At higher flux (S4), two non-harmonically related QPOs appear simultaneously at ~4.6 and ~13 Hz.



Power spectra and dynamical power spectra showing the QPO-frequency evolution.

5. Energy-dependent Variability

The rms and phase-lag spectra separate the variability into distinct regimes. The early type-C-like QPOs have high rms and increasingly hard lags at higher energies, while the later ~13/12.2 Hz and ~4.6 Hz components are much weaker and show different lag behaviour.



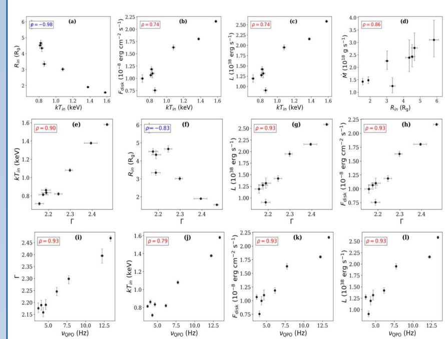
Energy-dependent rms and phase lags for the principal QPO/QRM components.

6. Disk Evolution & QPO Correlations

Over the course of the observation the disk becomes hotter and moves inward, indicating an increasing disk contribution as the source evolves. The QPO frequency is strongly correlated with disk-related spectral parameters: it increases with photon index and disk temperature and decreases as the inferred inner disk radius becomes smaller.

These correlations are driven principally by the higher-frequency (~13 Hz) component. When the ~4.6 Hz QPO is included, the correlations become much weaker.

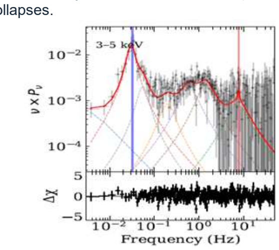
This suggests that the ~13 Hz oscillation is more directly coupled to changes in the inner disk, whereas the ~4.6 Hz QPO is less tightly linked to the disk emission and may trace a more global process in the accretion flow.



The ~13 Hz QPO is more closely coupled to the inner accretion flow than the ~4.6 Hz component.

7. Interpretation

- The appearance of a ~30 mHz (~30 s) Quasi Regular Modulation (QRM) in S3 (see below, marked with blue line) appears as the disk moves inward and becomes hotter. Its slow quasi-regular variability is consistent with a radiation-pressure instability in which the inner disk periodically inflates and collapses.



- In S4 the QRM disappears and two significant, non-harmonically related QPOs appear simultaneously at ~4.6 and ~13 Hz. Their different correlations with the spectral parameters argue for two distinct variability mechanisms or regions rather than a single oscillation and its harmonic.
- The ~13 Hz component is more closely associated with the inner disk; the ~4.6 Hz QPO may instead involve geometrical modulation or coronal dynamics.
- In S5 the ~4.6 Hz component disappears, while the higher-frequency oscillation persists near ~12.2 Hz, reinforcing the picture of changing disk-corona coupling as the source evolves.

8. Summary & Conclusions

- The anticipated ToO strategy successfully captured ~10 days of continuous spectral-timing evolution of 4U 1630-47 during its 2023 outburst. Simultaneous fitting of the PDS and the real and imaginary parts of the cross spectrum reveals variability components that are not always obvious in the PDS alone.
- The sequence from 3.6-6.1 Hz type-C-like QPOs, through a transient ~30 mHz QRM, to the high-flux ~4.6/~13 Hz twin-QPO state and the later ~12.2 Hz QPO demonstrates that several variability mechanisms coexist as the inner accretion flow and disk-corona coupling evolve.