Simulated Observations of High-Frequency Variability in X-ray Binaries

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Abstract

We develop an end-to-end simulation pipeline to evaluate the detectability of high-frequency quasi-periodic oscillations (HFQPOs) in signals from black hole X-ray binaries with various space observatories. Light curves (LC) from analytic (Karas, 1996) and ray-traced (Bakala et al., 2007, 2015) hotspot models are combined with the global flux of microquasar `GRS 1915+105`; and photon events with SIXTE (Dauser et al., 2019), using SIMPUT (Schmid et al., 2013), for XRISM (Tashiro, 2022) and the planned *new*ATHENA (Cruise et al., 2024) are generated. We analyze power density spectra (PDS) of observed LC to recover the fundamental and harmonic frequency peaks across models and signal-to-background ratios. The study benchmarks simulated performance against RXTE and LOFT to validate the capabilities of new missions to observe HFQPOs. We found that WFI detector onboard *new*ATHENA robustly recovers the HFQPO fundamental and harmonics for the tested setups; XRISM/Resolve (GV closed) recovers only strong fundamentals in short exposures, with harmonics generally below detectability.

Introduction / Context

HFQPOs with frequencies of tens to a few hundred Hz probe the innermost accretion flow near compact objects. Their detectability depends on instrument timing and effective area. We target a BH microquasar `GRS 1915+105`, and test whether current (XRISM) and future (newATHENA) missions recover QPO signatures. Goals: (i) construct a QPO→SIMPUT→SIXTE pipeline; (ii) simulate observations; (iii) quantify detectability thresholds vs. mission/instrument.

Methodology

Modeling: Generate QPO light curves (analytic and ray-traced) at centroid frequencies relevant to `GRS 1915+105`; mix with the global source flux approximated by fitted functions with ratio $n \in \{0.25, 0.5, 0.75\}$.
Instrument simulation: Convert LC and spectral energy distribution (SED) to SIMPUT (SRC_CAT, TIMING, SPECTRUM) and simulate with SIXTE using mission configurations for XRISM Resolve (GV closed) and newATHENA WFI Fast.
Timing analysis: Compute Leahy-normalized PDS, locate peaks at expected radial frequency (ν_r), keplerian frequency (ν_K), and periastron frequency (ν_p) and their harmonics; estimate significance/width; track detectability across models and n.
Benchmarking: Compare to RXTE and LOFT tested performance reported in Bakala et al. (2014).

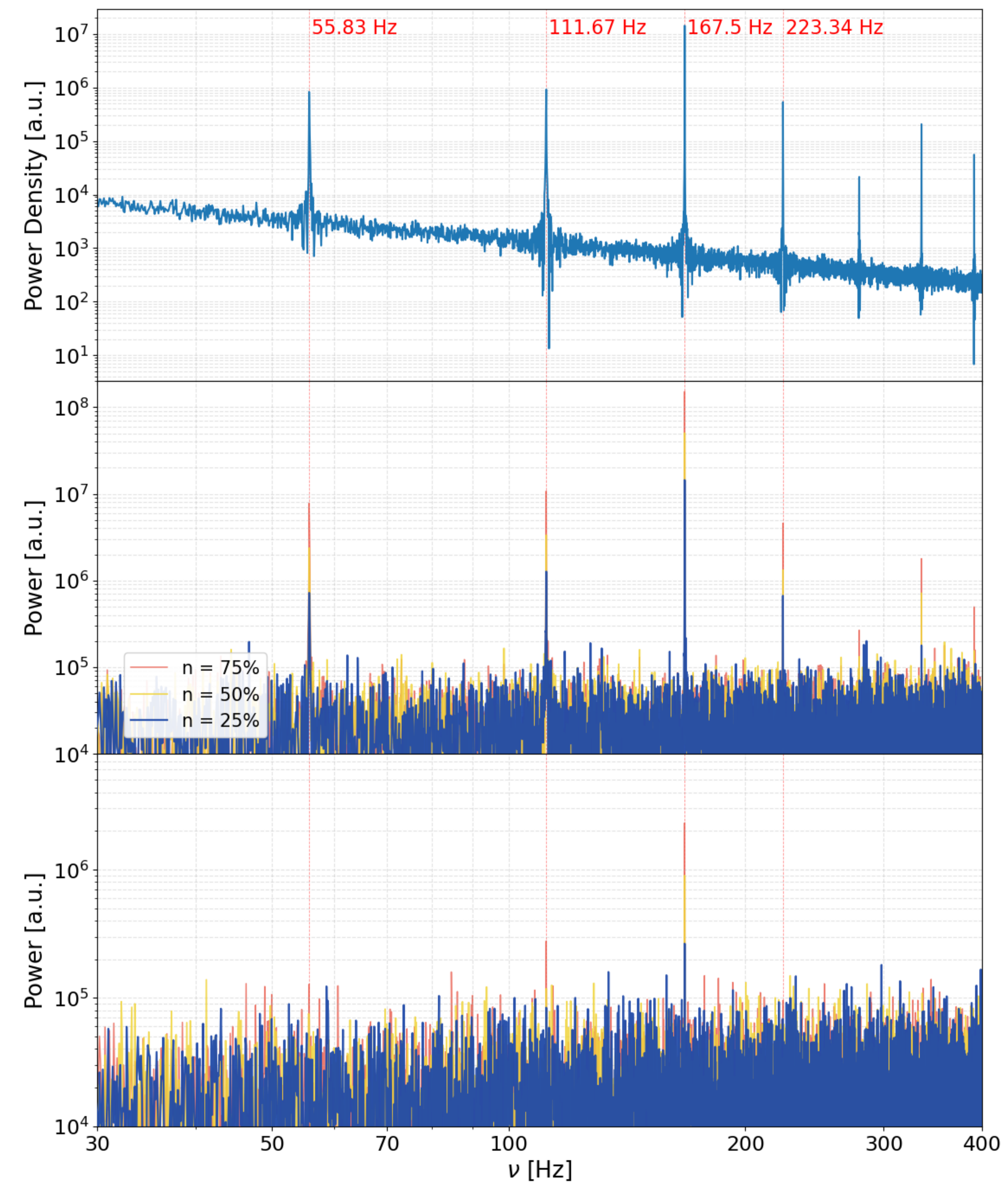
Detector and observation setup

Instrument	Detector	Config	Timing resolution	Observation time	Time step
newATHENA	WFI Fast	fd_wfi_df35mm	80 μs	10 s	1 ms
XRISM	Resolve	GV closed	∼10–12 μs timing	10 s	1 ms

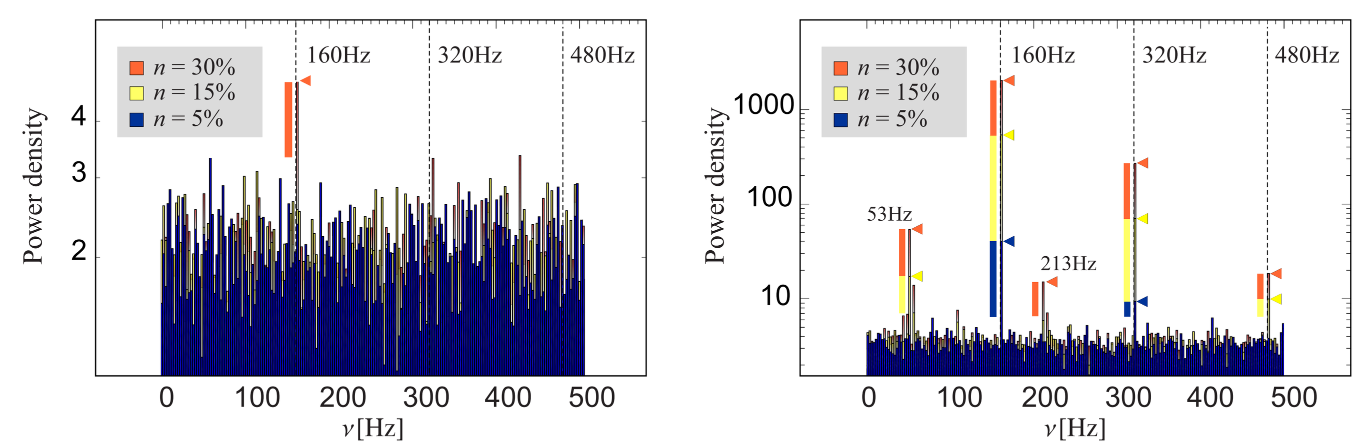
Key Results

WFI Fast: Detects the fundamental HFQPO and harmonics for the raytraced single-spot model across all tested n; the multi-spot, time-varying case remains detectable in short exposures.
Resolve (GV closed): Recovers the fundamental only for strong n; harmonics and weaker peaks are generally suppressed, and multi-spot cases are not recovered in short exposures.
Consistency with literature: Trends agree with RXTE/LOFT results: RXTE marginal/partial; LOFT strong. WFI Fast meets or exceeds RXTE for many settings.

Results for simulated single hotspot



Top: PDS of the combined signal before using SIXTE for $n = 25\%$. Middle: Leahy normalized PDS for the single spot with new*ATHENA*. Bottom: Leahy normalized PDS for the single spot with *XRISM*. Marked frequencies are $\nu_r = 55.83$ Hz, $\nu_K = 167.5$ Hz and $\nu_p = 111.67$ Hz with the harmonic at 223.34 Hz, corresponding to the total mass of BH 11M$_\odot$, radius of the hot spot of 6.75M and spin $a = 0$ for the simulated hot spot with raytraced data.
By putting the unprocessed data to the comparison with the processed ones, we can determine the accuracy of used mission and detector for these observation, as well as ability to visualize the possibly occuring shift of frequencies.



The same hotspot setup for *RXTE* (left) and *LOFT* (right). Observation capabilities of the single spot setup from (Bakala et al., 2014). Frequency difference is caused by slightly different values of mass for the source `GRS 1915+105`. As can be seen by comparison of the 2 figures, new`ATHENA` is comparable with the proposed `LOFT` mission in the ability to detect several key frequencies.

Discussion

Closed gate valve on Resolve shifts the effective band and reduces soft response, limiting timing capabilities of XRISM. Short exposures emphasize differences; longer integrations would improve both missions. The pipeline generalizes to other sources and models and can incorporate future response files as missions evolve.

Conclusion

We demonstrate an end-to-end simulation pipeline from QPO models to realistic observations. For the tested setups, newATHENA/WFI Fast robustly detects HFQPOs (including harmonics), while XRISM/Resolve (gate valve closed) detects only the strongest peaks. The approach is ready to extend to additional missions, exposure times, and source states.

Main references

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Author and thesis information

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