FROM HARD TO SOFT: FOLLOWING THE EVOLUTION OF QPOS

H. Stiele[1,2] & A. K. H. Kong[2] MNRAS 522, 268

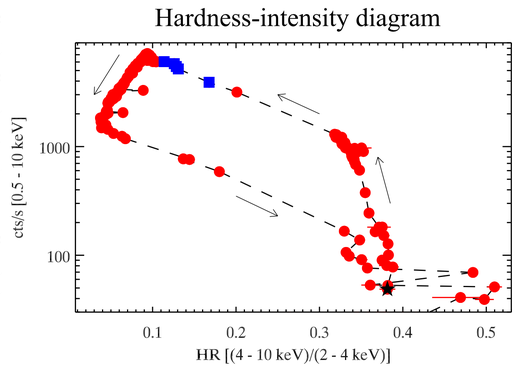
[1] Jülich Supercomputing Centre, Forschungszentrum Jülich, Jülich, Germany
[2] Institute of Astronomy, National Tsing Hua University, Hsinchu, Taiwan

In 2021, the Neutron star Interior Composition Explorer (*NICER*) onboard the International Space Station closely monitored an outburst of GX 339–4, the prime example of a low-mass black hole X-ray binary. The dense coverage of this outburst and the increased sensitivity of *NICER* compared to previous missions allowed us to study in detail the evolution of quasi-periodic oscillations (QPOs) and noise components in the intermediate states as the source transitions from the hard to the soft state.
The evolution between these states is a somewhat erratic process with multiple transitions. In our study, we were able to follow the emergence and disappearance of the different types of QPOs in more detail and gain further insight into their evolution. In addition to the power-density spectra, we also investigated the evolution of spectral parameters, but found only a strong correlation between the hardness ratio and the type of QPO observed.
We present the results of our study and discuss implications of our findings for the occurrence and coherence of type-B QPOs and their relation to changes in the accretion geometry of the system. We will also consider them in light of the comptonisation models for type-C and type-B QPOs.

NICER view of the 2021 outburst of GX 339–4

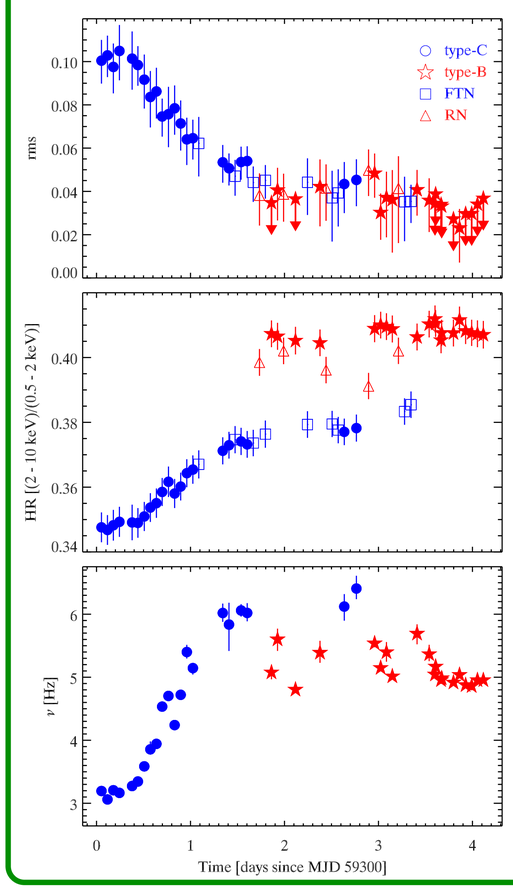
- Transient low-mass black hole X-ray binaries typically start and end their outbursts in the low-hard state, and can make a transition to the high-soft state, transiting through the hard and soft intermediate states
- The transition through the intermediate states is *not* a smooth process, *but* can show excursions to other states

Hardness-intensity diagram



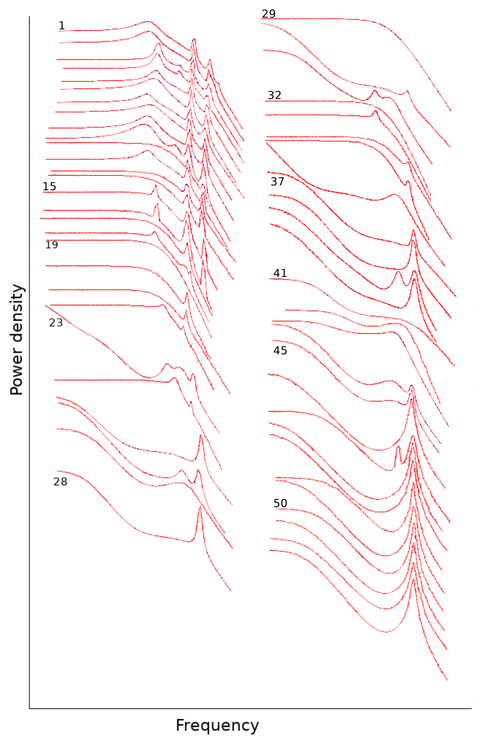
- In the hard intermediate state (HIMS) type-C QPOs are typically observed, while the soft intermediate state (SIMS) is defined by the presence of type-B QPOs
- *NICER* followed the 2021 outburst of GX 339–4 from January 20 to November 03
- Focus on five observations that cover the transition from the hard to the soft intermediate states and into the soft state (blue squares in the hardness-intensity diagram)
- These five observations were taken between March 27 and 31, Obs. ids. are 413301010X, where X = 4, …, 8
- Poissonian noise subtracted, Leahy normalised power-density spectra covering the total energy range and the 6.1×10^{-3} to 50 Hz frequency range
- *NICER* observation may contain more than one contiguous pointing at the target, due to the orbit of the International Space Station and visibility constraints. A contiguous pointing is known as a snapshot
- To follow the evolution of the noise components and the QPOs with sufficient statistics, we averaged the individual PDS of each snapshot: In total, we analysed 53 snapshots
- This allows us to follow the evolution of the evolution of different types of QPOs and their associated noise properties on hours- to minutes-long time-scales
- For the snapshots hardness ratio are derived from the 2 – 10 keV and 0.5 – 2 keV bands

Evolution of the rms, hardness ratio, and characteristic frequency of the fundamental QPO



- The characteristic frequency of the fundamental type-C QPO increases from ~3 to ~6 Hz
- The type-B QPO appears at a characteristic frequency of ~5–5.5 Hz, close to the lastly seen characteristic frequency of the type-C QPO
- The return of the type-C QPO happens at a characteristic frequency of 6–6.5 Hz, continuing the increase in frequency seen before the appearance of the type-B QPO
- The type-B QPO is again found in the 5–5.5 Hz range
- Red noise and type-B QPOs appear at hardness ratios above a value of 0.39, while band-limited noise and type-C QPOs are observed at lower hardness ratio values ➜ transition between these two states is related to a change in the accretion geometry that shows up in a transition of the spectral properties

Evolution of the power density spectra



- Best fits to the PDS of the individual snapshots to get an impression of the overall evolution of the different components of the PDS, especially the QPOs
- Increase in the characteristic frequency of the QPO is not visible here, as we aligned the QPOs to plot the PDS more compactly
- For the first 16 snapshots, the PDS can be well described by a band-limited noise (BLN) component, a peaked noise (PN) component, and a QPO and its upper harmonic. In some of the snapshots, a lower harmonic is also present.
- Throughout these snapshots, we observe an increase of the characteristic frequency of the fundamental QPO from ~3 to ~5 Hz
- In the next few snapshots first the upper harmonic and then the fundamental QPO disappear; the fundamental QPO reappears again
- Some dramatic change takes place in snapshot 23 where the BLN seen up-to-now is replaced by red noise and several features are visible between ~2 and 6 Hz
- In snapshot 24 the BLN together with the PN component returns
- The next three snapshots show red noise and a type-B QPO that 'decays' into a broad feature, indicating some strong decoherence in the process that causes this feature
- After a gap of ~10 ks the type-B QPO is found again
- Snapshot 29 shows again BLN, followed by two snapshots that are dominated by red noise
- In snapshot 32 and the then following three snapshots GX 339–4 returns a state where the power density spectra show BLN and in the third and fourth the type-C QPO is found one more time
- Then the red noise returns and snapshots 37–40 show again a type-B QPO
- GX 339–4 returns for one last time to state where the power density spectra are dominated by BLN before it finally settles into the soft intermediate state where the power density spectra are dominated by red noise and show a type-B QPO

Discussion

- Attribute type-C QPO to Lense-Thirring precession of a hot inner flow in a truncated accretion disc geometry (Stella & Vietri 1999; Ingram et al. 2009): hot inner flow (that drives the type-C QPO) + thin accretion disc + transitional region where a passive disc is imbedded in the outer, non-thermal corona
- Characteristic frequency of the type-C QPO is anti-correlated to the radial extent of the combined comptonised emission region
- Type-C QPO gets quenched when the accretion disc has moved inward far enough that the hot flow region gets too small to produce detectable type-C QPOs, while the energy spectra can still show comptonised emission that comes from the region where the outer corona interacts with the accretion disc (Kubota et al. 2023).
- Temporary increase of the radius of the combined comptonised emission region will lead to a reappearance of the type-C QPO at a frequency close to the one where it was last seen before the transition to the SIMS, in agreement with the evolution of the characteristic frequency of the type-C QPOs seen in this study
- Several different mechanisms are under debate for type-B QPOs: either related to some type of instability (Tagger & Pellat 1999; Titarchuk & Osherovich 1999; Lamb & Miller 2001) or they are somehow connected to the relativistic jets (Fender, Homan & Belloni 2009; Miller-Jones et al. 2012)
- Our study shows that the transition from the HIMS to the SIMS is a gradual process that is intermitted by excursions back to the HIMS, implying that changes of QPO type is an interplay between two processes
- Mastichiadis, Petropoulou & Kylafis (2022) suggest a model based on radiative feedback between a hot electron population in the corona and soft radiation emerging from the accretion disc, due to reprocessing of the hard corona radiation
- In this model damped oscillations identified with type-C QPOs are observed
- Type-C QPOs are quenched when the corona shrinks and the outflow becomes continuously narrower as the source evolves from the hard to the soft states causing electrons to escape quickly from the corona
- In the SIMS, the outflow is narrow enough to show type-B QPOs that, according to Kylafis, Reig & Papadakis (2020), can be explained quantitatively as precession of the outflow
- Furthermore, an increase in soft disc radiation supports the suppression of type-C QPO activity in the SIMS
- In light of the results presented here, the shrinking of the corona *cannot* be a uni-directed process and/or there must be fluctuations in the soft disc radiation. To study this further, one would need to investigate whether the changes in the corona size and soft disc radiation can occur on the timescales observed here.
- We observe a continuous evolution and increase of the characteristic frequency of the type-C QPOs after the first appearance of type-B QPOs. If the evolution of type-C QPOs is driven by an increase in accretion rate, this increase may in some part counteract the shrinking of the corona and hence explain the reappearance of the type-C QPOs.
- Two-component comptonisation models where two comptonisation regions with different sizes are located at different distances from an accretion disc have been suggested to explain type-B QPOs (Karpouzas et al. 2020; García et al. 2021; Peirano et al. 2023)
- Karpouzas et al. (2021) proposed a similar model for the type-C QPOs in GRS 1915+105, where the corona and disc size are anti-correlated for frequencies ≳2 Hz and correlated for lower frequencies
- The large size of the corona at high type-C QPO frequencies makes it quite challenging to find in this model an explanation for the rather fast 'oscillations' between type-C and B QPOs that we report here
- Even if the corona that is responsible for the type-C QPO shrinks in size, as is assumed in the other models mentioned above, there remains the following point; If both type-C as well as type-B QPOs are due to a two-component corona, then the evolution observed in our study needs to be explained by an evolution of the two comptonisation regions that allows the system to kind of 'oscillate' between the two states when it transits from the HIMS to the SIMS.
- Independent of its exact composition, a successful model of the origin of QPOs should be able to reproduce this 'oscillating' behaviour between the two states and the related spectral and timing properties.

- Fender, Homan & Belloni 2009, MNRAS, 396, 1370
- García et al. 2021, MNRAS, 501, 3173
- Ingram et al. 2009, MNRAS, 397, L101
- Karpouzas et al. 2020, MNRAS, 492, 1399
- Karpouzas et al. 2021, MNRAS, 503, 5522
- Kubota et al. 2023, arXiv:2302.08314
- Kylafis, Reig & Papadakis 2020, A&A, 640, L16
- Lamb & Miller 2001, ApJ, 554, 1210
- Mastichiadis, Petropoulou & Kylafis 2022, A&A, 662, A118
- Miller-Jones et al. 2012, MNRAS, 421, 468
- Peirano et al. 2023, MNRAS, 519, 1336
- Stella & Vietri 1999, Phys. Rev. Lett., 82, 17
- Tagger & Pellat 1999, A&A, 349, 1003
- Titarchuk & Osherovich 1999, ApJ, 518, L95