Research Progress on Quasi-Periodic Oscillation Phenomena Based on Insight-HXMT Satellite Observations (Postprint)

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Abstract

Quasi-Periodic Oscillation (QPO) phenomena are ubiquitously observed in the light curves of X-ray binaries. It is generally believed that QPOs originate from accretion flows in close proximity to the compact object, making them an important probe for testing general relativistic effects in strong gravitational fields and for investigating the evolution of accretion geometry near compact stars. Prior to the launch of the Insight-HXMT satellite, QPO studies were predominantly concentrated in the energy range below 30 keV. The Insight-HXMT satellite possesses a very large effective area in the high-energy band, thereby opening a new window for studying the high-energy properties of QPOs. This paper summarizes the progress achieved by the Insight-HXMT satellite in QPO research, including the observational characteristics of high-energy QPOs, their physical origins, and the corresponding evolution of accretion geometry, and offers an outlook on potential future breakthrough directions.

Full Text

Research Progress on Quasi-Periodic Oscillations Based on Observations from Insight-HXMT

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Abstract

Quasi-Periodic Oscillations (QPOs) are commonly observed in the light curves of X-ray binaries, and they are believed to originate from the innermost accretion flow around the compact object. Therefore, QPOs serve as powerful probes for testing general relativistic effects in strong gravitational fields and studying the evolution of accretion geometry near compact objects. Prior to the launch of Insight-HXMT (Insight Hard X-ray Modulation Telescope), research on QPOs primarily focused on the energy range below 30 keV. With its large effective area in the high-energy band, Insight-HXMT has opened a new window for investigating the high-energy properties of QPOs. This paper reviews the progress in QPO studies using Insight-HXMT data, including observational characteristics of high-energy QPOs, their physical origins, and the corresponding evolution of accretion geometry. We also discuss future directions for potential breakthroughs in this field.

Keywords: X-rays: binaries, accretion, accretion disks, black hole physics

1 Introduction

X-ray binaries are binary systems consisting of a compact object (a stellar-mass black hole or neutron star) and a companion star. The compact object accretes matter from its companion, releasing enormous gravitational potential energy during the infall process, which is converted into radiation primarily in the X-ray band. These objects provide extreme physical environments of gravity, magnetic fields, and density, offering excellent laboratories for studying the states and dynamics of matter under extreme conditions. Based on the mass of the companion star, X-ray binaries can be broadly classified into low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs). LMXBs include black hole X-ray binaries, neutron star X-ray binaries of the Z-source and Atoll-source types, while HMXBs can be further divided into Be X-ray binaries and supergiant X-ray binaries according to the companion type. The spatial scales of X-ray binary systems are extremely small and currently unresolvable, but timing characteristics provide an indirect method for measuring the accretion geometry around compact objects. The most prominent signals in the power spectra of X-ray binaries are narrow peaks known as Quasi-Periodic Oscillations (QPOs). QPOs are generally believed to originate from the accretion flow near the compact object, making them important probes for testing general relativistic effects in strong gravitational fields and studying the evolution of accretion geometry near compact objects.

Based on their centroid frequencies, QPOs in X-ray binary systems can be divided into three categories: mHz QPOs (<0.01 Hz), low-frequency QPOs (LFQPOs, ~0.01-60 Hz), and high-frequency QPOs (HFQPOs, >60 Hz). In black hole systems, LFQPOs can be further classified into three types (A, B, and C) according to their power spectral and cross-spectral properties (centroid frequency, full width at half maximum, amplitude, and time lag). Type-C and type-B QPOs have relatively strong amplitudes and narrow widths, while type-A QPOs have weaker amplitudes and broader widths. The centroid frequency of type-C QPOs (~0.1-30 Hz) increases as the energy spectrum softens, and the power spectrum contains strong broadband noise components and QPO harmonic features. Type-B QPOs have centroid frequencies concentrated around 4-6 Hz, with strong broadband noise components in the power spectrum and common secondary harmonic peaks. Type-A QPOs have centroid frequencies mainly around 6–8 Hz, accompanied by very weak broadband noise and generally no harmonics. Different types of LFQPOs appear in different spectral states: type-C QPOs primarily occur in the hard state and hard intermediate state, while type-B and type-A QPOs appear in the soft intermediate state and soft state, respectively.

Although many models have been proposed to explain LFQPOs (for an introduction to QPO models, see reference [1]), the physical origin of QPOs remains controversial. Recent observational evidence suggests that the flux modulation of QPOs arises from geometric effects, with Lense-Thirring precession as predicted by general relativity being a possible generation mechanism. HFQPOs in black hole systems are generally weak and have only been detected with significant signals in a few sources such as GRS 1915+105, GRO J1655–40, and XTE J1550–564.

The most prominent signals in the power spectra of Z-sources and Atoll-sources are pairs of kilohertz QPOs. Current theoretical models for interpreting kHz QPOs include the beat-frequency model and the precession model. Compared to black hole systems, LFQPO phenomena in neutron star systems are generally weaker. Depending on the evolutionary track branch, LFQPOs in Z-sources can be classified as Horizontal Branch Oscillations (HBOs), Normal Branch Oscillations (NBOs), and Flaring Branch Oscillations (FBOs), corresponding to type-C, type-B, and type-A QPOs in black hole systems, respectively. QPO phenomena with power spectral shapes similar to HBOs and FBOs have also been observed in Atoll-sources. It is generally believed that LFQPOs in black hole and neutron star systems have similar physical origins. Additionally, mHz QPO phenomena are also common in neutron star systems.

Before 2017, observational studies of QPOs primarily relied on the Rossi X-ray Timing Explorer (RXTE). Although this satellite was decommissioned in 2012, it achieved fruitful results in QPO research. However, RXTE had a very small effective area in the high-energy band (>30 keV), limiting previous studies. In 2017, China launched its first X-ray astronomy satellite, Insight-HXMT, which has a very large effective area in the high-energy band, opening a new window for studying the high-energy properties of QPOs. This paper introduces the scientific achievements of Insight-HXMT in the study of QPO phenomena.

2.1.1 Observational Characteristics of High-Energy QPOs

During the RXTE era, the highest-energy QPOs detected through direct methods were around 40 keV. During its more than eight years of operation, Insight-HXMT has detected low-frequency QPOs above 50 keV in multiple black hole X-ray binaries [2–8], demonstrating that high-energy QPOs are a common phenomenon in these systems. In particular, Insight-HXMT detected type-C QPOs above 200 keV in the black hole X-ray binary MAXI J1820+070, which represents the highest-energy QPO phenomenon detected to date [3]. Figure 1 [Figure

1: see original paper] shows the type-C QPOs observed by Insight-HXMT in different energy bands in MAXI J1820+070, along with a schematic diagram of the jet precession model.

Over the 1-250 keV range, the centroid frequency of type-C QPOs remains essentially constant with energy. The observed frequency variations with energy in some observations [2, 8] may be caused by the simultaneous presence of two QPO components with different frequencies [9]. The typical amplitude spectrum of type-C QPOs can be approximated by a broken power law: at low energies, the QPO amplitude increases with energy; above a certain break energy, the amplitude remains roughly constant or shows a slight decreasing trend [10]. Figure 2 [Figure 2: see original paper] shows the typical amplitude and lag spectra for different types of QPOs in black hole X-ray binaries. The break energy gradually increases as the energy spectrum softens, reaching ~10–20 keV in the intermediate state. The QPO amplitude at high energies (up to 20%) is significantly higher than at low energies, indicating that the QPO modulation primarily originates from the Comptonization process. The hot corona or jet base are possible generation regions, while the accretion disk component, which dominates at low energies, contributes little to the amplitude. In some cases, the reflection component also makes a significant contribution to the QPO flux modulation [12]. Regarding temporal evolution, as the energy spectrum softens and the QPO frequency increases, the amplitude of low-energy QPOs typically decreases while that of high-energy QPOs increases [6, 13].

The evolution of QPO time lags with time and energy is more complex, and the calculation methods and physical interpretations of lags have remained controversial. The traditional method uses the average lag within half the full width at half maximum (FWHM/2) centered on the QPO frequency in the cross-spectrum as the QPO lag, but this approach does not account for the influence of broadband noise. Insight-HXMT discovered that at high energies, the phase lag within the low-frequency plateau noise range is large and approximately constant. The QPO structure in the cross-spectrum is superimposed on the noise continuum, so calculating QPO lags requires consideration of broadband noise effects [3, 8, 14].

Ma et al. [3] proposed a new method for calculating QPO lags by subtracting the average phase lag within the low-frequency plateau noise range from the average phase lag within the QPO range, thereby obtaining the intrinsic phase lag of the QPO. Using this method, they obtained consistent QPO phase lag spectra across different observations of MAXI J1820+070. Both low-energy and high-energy photons arrive earlier than photons around 10 keV. The QPO lag spectrum obtained by extracting the instantaneous QPO light curve using the Hilbert-Huang transform and calculating lags for different energy bands is essentially consistent with the intrinsic QPO lag spectrum obtained by Ma et al. [15]. Similar QPO phase lag spectra have also been observed in the new source Swift J1727.8-1613 during its 2023 outburst [8]. QPO lags may result from either time delays caused by different propagation paths for photons of different energies or phase differences between QPO waveforms in different energy bands. In MAXI J1820+070, the time delay between the highest-energy band and low-energy bands reaches the order of seconds. If the lag were entirely due to time delays, the corresponding physical size would be about $10^4 R_g$, which is inconsistent with known physical pictures. Therefore, phase differences likely dominate the QPO lags.

2.1.2 Relationship Between Type-C QPOs and Noise

Fitting the power spectra of black hole X-ray binaries typically employs multiple Lorentzian functions, which assume that QPO and broadband noise components are additive in the time domain, i.e., $f_{tot}(t) = n(t) + q(t)$, where $n(t)$ and $q(t)$ represent the light curves of the noise and QPO components, respectively. This model further assumes that QPOs and noise are uncorrelated, so the total power spectrum in the frequency domain is the sum of their individual powers. However, bispectrum studies reveal strong phase coupling between QPOs and noise, which cannot be produced under the additive assumption [16].

Ma et al. [3] found a linear relationship between the phase lags of different power spectral components and the total component phase lags, suggesting that the intrinsic phase lag of QPOs can be obtained through linear correction. The traditional additive model between QPOs and broadband noise is therefore unsuitable for extracting the intrinsic phase lags of QPOs. Zhou et al. [14] proposed a model where QPOs and broadband noise are related by convolution in the time domain, i.e., $f_{tot}(t) = n(t) \otimes q(t)$, and mathematically demonstrated that the intrinsic phase lag of QPOs can be extracted under this model. According to the convolution theorem, power spectra must be fitted using a multiplicative model under this framework. Compared with the traditional additive model, the multiplicative model yields similar QPO centroid frequencies and widths but slightly smaller QPO amplitudes. This work provides a new perspective for studying the coupling relationship between QPOs and broadband noise components.

2.1.3 Physical Origin of Type-C QPOs

Statistical analysis based on RXTE data revealed a strong correlation between type-C QPO amplitude and inclination angle, with QPO amplitudes in high-inclination systems significantly higher than in low-inclination systems [17]. Using phase-resolved spectral analysis of Insight-HXMT observations, Shui et al. [18] found that the parameters of the Comptonization and reflection components are strongly modulated with QPO phase, while accretion disk parameters show little modulation. Figure 3 [Figure 3: see original paper] shows the variation of different spectral parameters with QPO phase. The modulation of the reflection component and iron line centroid energy can be well explained by geometric effects. The most commonly used theoretical model for explaining QPO phenomena through geometric effects is the Lense-Thirring precession model [1], where the precessing region could be either a hot inner flow or the base of a small-scale jet. The hot inner flow precession model is based on the truncated disk assumption, where precession of the hot inner flow between the accretion disk and the central compact object produces the observed QPOs, while changes in the truncation radius lead to the evolution of QPO properties (frequency, amplitude, and lag) during outbursts. However, in MAXI J1820+070, no significant changes in the inner disk boundary were found during periods of rapid QPO frequency variation [19], indicating that the hot inner flow precession model cannot explain the QPO phenomenon in this source, at least.

Based on Insight-HXMT results for MAXI J1820+070, Ma et al. [3] proposed a jet precession model (schematic shown in Figure 1). This model suggests that QPOs originate from the precession of a small-scale jet, with Doppler and solid-angle effects during precession producing flux modulation. The strength of QPO amplitudes is primarily determined by the jet velocity. QPOs at different energies originate from different regions of the jet: high-energy photons are produced at the jet base, while low-energy photons are produced at the jet top. Since the jet is curved, different regions of the jet face the observer at different QPO phases (producing maximum flux), resulting in phase differences between low-energy photons from the jet top and high-energy photons from the jet base. This model can well explain the QPO amplitude and lag spectra observed by Insight-HXMT. Additionally, QPOs have been detected simultaneously in the optical and X-ray bands with the same frequency [20–21], and the rapid optical variability likely originates from the jet, supporting the jet precession model.

Notably, wavelet analysis based on Insight-HXMT data [22–24] reveals significant short-term intensity variations in QPOs. In MAXI J1820+070, QPOs typically remain significantly detectable for timescales of about five QPO cycles, with this duration correlating with the QPO quality factor. No significant differences are found between the energy spectra during periods of strong and weak QPO presence. The short-term intensity variations of QPOs may be caused by changes in jet velocity, and modulation of jet velocity can also produce broadband noise components.

Furthermore, QPOs can serve as probes for studying the evolution of accretion geometry. By simultaneously fitting the time-averaged spectrum, QPO amplitude spectrum, and lag spectrum, Zhang et al. [25] found evidence for the gradual evolution from an extended hot corona to a radial jet in the intermediate state of MAXI J1535-571, corresponding to the transition of radio jets from steady to transient states.

2.2.1 Observational Characteristics of High-Energy QPOs

Insight-HXMT has observed type-B QPOs in sources such as MAXI J1348-630 and GX 339-4, with centroid frequencies concentrated in the 4–6 Hz range. The properties of type-B QPOs appearing in a single outburst are very similar. In MAXI J1348-630, type-B QPOs above 100 keV were detected, representing the highest-energy type-B QPO phenomenon observed to date [5, 26]. The centroid frequency of type-B QPOs does not vary with energy. The amplitude spectrum of type-B QPOs is similar to that of type-C QPOs in the hard intermediate state before the spectral state transition: below ~10 keV, the QPO amplitude increases with energy; above ~10 keV, the amplitude remains essentially constant with energy, reaching up to 15% at high energies [5]. The lag spectrum of type-B QPOs typically shows a "V" shape, with photons at low energies (<2 keV) and high energies (>3 keV) both lagging behind photons around 2-3 keV. At high energies around 7 keV, the lag spectrum shows a clear break (see Figure 2).

2.2.2 Transient Nature of Type-B QPOs

A characteristic feature of type-B QPOs is their sudden disappearance/reappearance, with this transition occurring on very short timescales, typically within tens of seconds. Insight-HXMT observed multiple instances of sudden QPO disappearance/reappearance in MAXI J1348-630. Broadband spectral comparisons show clear differences between the energy spectra during periods with and without QPOs [5, 26]. During QPO presence, the flux of the high-energy Comptonization component increases significantly, while the low-energy accretion disk component becomes notably weaker.

Yang et al. [26] conducted a systematic study of the transient phenomenon of type-B QPOs in three sources, finding an obvious anti-correlation between the flux changes of the accretion disk component and the Comptonization component in the 0.5-10 keV range during the transition. This indicates that the essence of the QPO transient phenomenon is the reallocation of accretion energy between the accretion disk and the Comptonization region: QPOs appear when more accretion energy is injected into the Comptonization region, and disappear when more energy is injected into the accretion disk. The study also found that type-B QPOs only appear when the fraction of Comptonization flux (Comptonization component flux/total flux) exceeds a certain critical value, which varies among different sources. The factors determining this critical value require further investigation. Figure 4 [Figure 4: see original paper] shows the ratio of energy spectra during periods with and without type-B QPOs, as well as the relationship between flux changes in the Comptonization and disk components during the transition.

2.2.3 Physical Origin of Type-B QPOs

The first appearance of type-B QPOs during an outburst occurs very close to the time of large-scale transient jet ejection, leading to the belief that type-B QPO generation is related to large-scale jets [27]. By fitting the QPO amplitude and lag spectra, García et al. [28] found that the variable spectrum of QPOs requires description by two physically related Comptonization regions: a small-scale region (size ~25 R_g) with strong feedback to the accretion disk, likely corresponding to an extended hot corona; and a large-scale region (size ~1500 R_g) with weaker feedback to the disk, likely corresponding to a radial jet. Yang et al. [26] proposed that type-B QPOs may originate from the joint precession of an extended hot corona and jet, while the sudden disappearance of QPOs may be caused by the Bardeen-Petterson effect aligning the inner accretion flow normal with the black hole spin axis, preventing precession.

2.3 Millihertz QPO Phenomena

In black hole systems, mHz QPOs are extremely rare and typically appear in spectrally hard accretion states. During the RXTE era, simultaneous detection of mHz QPOs and type-C LFQPOs suggested different physical origins [29]. Insight-HXMT observed a 60 mHz QPO during the rising phase of the 2021 outburst of the black hole candidate 4U 1630–47. Leveraging Insight-HXMT' s advantages of high-energy coverage and large effective area, Yang et al. [11] extended studies of black hole mHz QPOs to 100 keV for the first time. The study found that the amplitude of this mHz QPO increases with energy, indicating that the QPO modulation originates from the hot corona. Additionally, the observations show that soft photons lag behind hard photons, with the lag timescale increasing with energy (see Figure 2). Spectral analysis reveals that the optical depth of the hot corona decreases during mHz QPO presence, possibly due to an increase in coronal size. The increased coronal size would enhance its coupling with the accretion disk. The observed mHz QPO may arise from instability processes triggered by the interaction between the hot corona and the accretion disk. Insight-HXMT only detected mHz QPOs within a specific luminosity range, suggesting that the generation of this instability is related to changes in the accretion rate.

3.1 QPO Phenomena in Neutron Star Low-Mass X-Ray Binaries

Insight-HXMT conducted high-cadence monitoring of the Z-source Sco X-1, obtaining a complete evolution track and observing both low-frequency QPOs and kHz QPOs on different branches [30]. NBOs (~6 Hz) and FBOs (~16 Hz) appear at the end of the normal branch and the beginning of the flaring branch, respectively, when the energy spectrum is soft. These QPOs were only detected in the LE and ME data, with no significant signals in the HE data. In contrast, HBOs (~40 Hz) and kHz QPOs (~800 Hz) appear simultaneously on the horizontal branch when the spectrum is hard, with QPOs only significant in the ME and HE bands. For all types of QPOs, the centroid frequencies do not vary with energy, while the amplitudes increase with energy, suggesting that QPO modulation more likely originates from the Comptonization process. Notably, Insight-HXMT detected kHz QPOs from Sco X-1 above 20 keV for the first time. The mainstream model for kHz QPOs posits that they originate from the inner edge of the accretion disk and are dominated by thermal radiation, making it difficult to reach such high energies. The Insight-HXMT observations challenge the mainstream kHz QPO models. By comparing the time-averaged spectrum with the QPO amplitude spectrum, Jia et al. [31] localized the generation region of the upper kHz QPO to the inner region of the transition layer.

3.2 QPO Phenomena in Accreting Pulsars

Insight-HXMT discovered mHz QPO phenomena during the 2020 outburst of the massive X-ray pulsar 1A 0535+262, with centroid frequencies varying in the 35–95 mHz range and positively correlating with source flux [32-33]. The QPOs were significantly detected only in the 25–120 keV range, with the highest significance in the 50–65 keV band. Notably, this marks the first detection of mHz QPOs above 80 keV in a neutron star system. The study found that the mHz QPO amplitude first increases and then decreases with energy, reaching a maximum at 50–65 keV. Furthermore, during the outburst peak, the mHz QPO exhibited a double-peaked structure, with a frequency difference of approximately 0.02 Hz between the two peaks—twice the neutron star' s spin frequency in this system. Previous theoretical models for mHz QPOs in neutron star systems, such as the beat-frequency model, Keplerian frequency model, and neutron star precession model, cannot explain the energy evolution of the mHz QPO amplitude in 1A 0535+262. The Insight-HXMT results suggest that the origin of mHz QPOs may be related to variations in non-thermal radiation, with resonance between the accretion column and the accretion disk or neutron star being a possible mechanism.

mHz QPOs have also been detected in the X-ray pulsar Cen X-3, with frequencies around 40 mHz [34]. Unlike in 1A 0535+262, the mHz QPO frequency in Cen X-3 does not correlate with X-ray flux but varies with orbital phase. The QPOs appear below 20 keV, and their amplitude gradually decreases with increasing energy. Similarly, beat-frequency and Keplerian frequency models cannot explain the evolution of this mHz QPO' s frequency and amplitude. The QPO may originate from instability processes when the accretion disk is truncated at the corotation radius.

RX J0440.9+4431 is a massive X-ray pulsar with a 205 s period that experienced its brightest recorded outburst in late 2022, with a peak flux exceeding 2 Crab. In the supercritical accretion state, short-timescale strong flares frequently appeared at the peaks of the high-energy pulse profile. Insight-HXMT discovered quasi-periodic modulations in flares at five pulse profile peaks [35]. The QPO frequencies varied among different pulses, ranging from 0.2–0.5 Hz and independent of source flux. The QPOs appeared in the 10–130 keV energy range and were not significant below 10 keV. Additionally, the QPO amplitude increased with energy. The Insight-HXMT observations suggest that QPOs in pulse flares may be related to instabilities in the accretion flow.

4 Summary and Outlook

This paper summarizes the important achievements of Insight-HXMT in QPO research over the past eight years. Insight-HXMT has discovered QPO phenomena above 100 keV in multiple black hole X-ray binaries, with the amplitude and lag properties at high energies suggesting an origin in the precession of small-scale jets. Leveraging Insight-HXMT' s large effective area, detailed spectral and timing analyses of short-term QPO variations reveal that QPO transient phenomena are likely related to the reallocation of accretion energy. Furthermore, Insight-HXMT observations of QPO phenomena in neutron star systems pose stricter challenges to existing models. These results highlight the advantages of Insight-HXMT in studying high-energy radiation from accretion systems.

Although Insight-HXMT observations have been crucial for constraining existing QPO models and establishing new theoretical frameworks, many questions regarding the physical origin of QPOs remain unresolved. For example: Does the precession model apply to all types of QPOs? What is the relationship between QPOs and noise? How are harmonic and subharmonic components generated?

Future next-generation X-ray astronomy satellites, such as the enhanced X-ray Timing and Polarimetry mission (eXTP), will have larger effective areas and higher energy and time resolution, allowing more precise testing of existing theoretical models. Additionally, polarization measurements will impose stricter constraints on QPO physical models. For instance, precession models predict clear modulation of polarization angle and degree with QPO phase, but recent results based on Imaging X-ray Polarimetry Explorer (IXPE) data have not found such modulation [36], challenging the precession models. Moreover, the introduction of unconventional methods (such as wavelet transforms and Hilbert-Huang transforms) has greatly aided our understanding of QPO properties, particularly their short-term characteristics.

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