

Insight-HXMT Study of Weakly Magnetized Neutron Star Low-Mass X-Ray Binaries: Post-print

Authors: Bu Qingcui

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Abstract

Weakly magnetized neutron star low-mass X-ray binaries generally refer to low-mass X-ray binary systems where the primary star (neutron star) has a magnetic field strength below 10^{10} Gs. The neutron star accretes matter from the companion star via an accretion disk through Roche-lobe accretion, releasing a large amount of gravitational energy during the accretion process that is converted into X-ray radiation near the neutron star. Their X-ray radiation typically exhibits rapid variability on short timescales and is accompanied by evolution of spectral properties. Therefore, such celestial objects are of great significance for studying fundamental physics, particularly in testing general relativity and strong gravitational field effects, as well as studying the equation of state of superdense matter. This paper mainly summarizes the observational studies of weakly magnetized ($10^8 - 10^{10}$ Gs) neutron star low-mass X-ray binaries since the launch of the Insight-HXMT satellite, including primarily the research progress on kilohertz quasi-periodic oscillations, the origin of high-energy hard X-ray tails, and the evolution of accretion disk corona geometry with accretion state.

Full Text

Preamble

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Insight-HXMT Studies of Weakly Magnetized Neutron Stars in Low-Mass X-Ray Binaries

BU Qing-cui

Institute of Astrophysics, School of Physics Science and Technology, Central China Normal University, Wuhan 430079

Abstract

Weakly magnetized neutron star low-mass X-ray binaries (NS-LMXBs) refer to systems where the magnetic field strength of the primary neutron star is below 10^{10} Gauss. In these systems, the neutron star accretes matter from its companion via Roche lobe overflow through an accretion disk, releasing substantial gravitational energy that is converted into X-ray radiation near the neutron star surface. Their X-ray emission typically exhibits rapid temporal variability on short timescales, accompanied by spectral evolution. These objects are therefore of great significance for fundamental physics, particularly in testing general relativity and strong-field gravity effects, as well as in studying the equation of state of ultra-dense matter. This review summarizes observational studies of weakly magnetized (10^{8-10} G) neutron stars in LMXBs since the launch of the Insight-HXMT satellite, focusing on advances in kilohertz quasi-periodic oscillations, the origin of high-energy hard X-ray tails, and the evolution of accretion disk-corona geometry with accretion state.

Keywords: X-rays: binaries, compact objects: accretion, stars: neutron

1. Introduction

Weakly magnetized neutron star low-mass X-ray binaries (NS-LMXBs) are generally defined as systems where the primary neutron star has a magnetic field strength between 10^8 and 10^{10} Gauss. The companion star is typically a main-sequence star, white dwarf, or red giant with mass below one solar mass, and the orbital period is generally less than one day. Since the discovery of the first such system, Sco X-1, in 1962, more than 200 sources have been observed in the Milky Way. In these systems, the neutron star accretes matter from its companion through an accretion disk, releasing enormous gravitational energy that is converted into X-ray radiation near the stellar surface. Because the magnetospheric radius correlates positively with magnetic field strength and inversely with accretion rate, the inner edge of the accretion disk can approach the neutron star surface when the magnetic field is weak and the accretion rate is sufficiently high. In short, the accretion process in weakly magnetized NS-LMXBs is directly modulated by both the neutron star's magnetic field and the accretion rate, making these systems ideal laboratories for studying extreme physical processes near neutron stars under weak magnetic fields.

Based on their distinct patterns in color-color diagrams (CCD) and hardness-intensity diagrams (HID), weakly magnetized NS-LMXBs are classified into Z sources and Atoll sources. Atoll sources are either persistent or transient, with luminosities generally below 0.1 times the Eddington limit, and they trace a "C"-shaped track in CCDs. Z sources are typically persistent, with luminosities

at or above the Eddington limit, and exhibit a “Z” -shaped track in CCDs. Six Z sources have been identified to date, including the first discovered weakly magnetized NS-LMXB, Sco X-1. Both Atoll and Z sources display three main spectral states that roughly correspond to the hard, intermediate, and soft states observed in black hole systems. In Atoll sources, these are called the Island State (IS), Lower Banana (LB), and Upper Banana (UB); in Z sources, they are the Horizontal Branch (HB), Normal Branch (NB), and Flaring Branch (FB). Morphological transitions between Z and Atoll patterns observed in special sources such as XTE J1701-462 and IGR 17480-2446 suggest that the primary distinction between these classes is the average mass accretion rate, which is significantly higher in Z sources. While the overall trend shows increasing accretion rate from hard states (IS, HB) to soft states (UB, FB), the evolution of the accretion rate across individual branches remains controversial.

The X-ray continuum of weakly magnetized NS-LMXBs can generally be described by a soft thermal component and a hard Comptonization component. The soft component may originate as single-temperature blackbody radiation from the neutron star surface or boundary layer, or as multi-temperature blackbody radiation from the accretion disk. The hard component arises from inverse Compton scattering of soft photons in a hot plasma corona. These two components form the basis of two classic models known as the “Eastern model” and “Western model.” In the Eastern model, the soft component is described by a multi-temperature disk blackbody, while the hard Comptonization component originates from weak Comptonization near the neutron star surface or boundary layer. In the Western model, the soft component is a single-temperature blackbody from the neutron star surface or boundary layer, while the hard Comptonization component comes from a slab-like corona covering the accretion disk. X-ray continuum analysis is therefore crucial for understanding the physical properties and spatial geometry of accretion flows near neutron stars. The spectral characteristics of weakly magnetized NS-LMXBs vary significantly with position in the CCD/HID, accompanied by evolving timing features. In power spectra, besides common low-frequency quasi-periodic oscillations (QPOs) and broadband noise components, the discovery of kilohertz QPOs has revolutionized the field. These QPOs typically appear in pairs at frequencies ranging from hundreds to thousands of hertz, representing the fastest temporal variations ever observed from celestial objects (microsecond timescales). Their extremely short timescales imply that kilohertz QPOs likely originate from emission regions very close to the neutron star surface, providing the most direct observational evidence for accretion flow dynamics. Kilohertz QPO pairs have been observed in over 30 NS-LMXBs, and because their upper frequencies closely match the Keplerian frequency at the neutron star surface, they can be used to constrain neutron star mass and radius.

Over the past decades, successive X-ray telescopes have yielded important advances in our understanding of weakly magnetized NS-LMXBs. BeppoSAX and RXTE (Rossi X-ray Timing Explorer) provided broad energy coverage that helped elucidate accretion physics near weakly magnetized neutron stars.

RXTE' s high time resolution and large effective area enabled the discovery of kilohertz QPOs, offering new ways to constrain the neutron star equation of state. Chandra and XMM-Newton, with their high spectral resolution in soft X-rays, allowed detailed analysis of emission lines and absorption edges in X-ray continua, further constraining neutron star accretion physics in strong gravitational fields. However, several controversies persist, including the evolution of accretion rates along Z-source branches, the origin of hard X-ray tails, the physical nature of kilohertz QPOs, and the evolution of disk-corona geometry at different accretion rates. The successful launch of China' s first X-ray telescope, Insight-HXMT (Insight Hard X-ray Modulation Telescope), provides unprecedented opportunities to address these questions. As the first X-ray telescope combining wide energy coverage (1-250 keV), high time resolution, and large effective area, Insight-HXMT delivers high-quality observational data that was previously unavailable. The following sections highlight representative studies published in recent years using Insight-HXMT data.

2. Tracing the Origin of Kilohertz QPOs

The debate over the origin of kilohertz QPOs has persisted for nearly three decades. Current models primarily focus on their dynamical nature, including the beat-frequency model, relativistic precession model, and relativistic resonance model. These dynamical models generally assume that kilohertz QPOs arise from some form of oscillation in the accretion disk or corona surface. In contrast, theoretical studies of their radiation mechanisms have been relatively limited, focusing mainly on the emission location and X-ray radiation characteristics. Over the past 30 years, investigations of how kilohertz QPO parameters (frequency, time lag, amplitude) evolve with spectral state and energy have constrained their origin to regions outside the accretion disk—specifically, the neutron star surface or corona region—though their precise physical origin and radiation mechanism remain unclear and require further study.

Studying kilohertz QPOs requires satellites with both high time resolution and large effective area. Due to RXTE' s limited effective area above 20 keV, previous studies focused primarily on energies below 20 keV. Insight-HXMT is the first satellite since RXTE to detect kilohertz QPOs and has, for the first time, achieved 3σ detection capability for kilohertz QPOs in the 20-60 keV band, demonstrating its powerful hard X-ray detection capability. For example, in the Z source Sco X-1, Jia et al. [8] simultaneously detected low-frequency QPOs and kilohertz QPOs in the 20-60 keV band for the first time [FIGURE:3, left]. This discovery provides crucial observational evidence for constraining the origin of kilohertz QPOs, as such high-energy QPOs cannot originate from lower-energy regions like the accretion disk or neutron star surface, but more likely from higher-energy hard Comptonization regions.

The basic physical picture of weakly magnetized NS-LMXBs involves a transition layer (TL) between the accretion disk and neutron star surface, through which matter is accreted onto the neutron star. By fitting the evolution of kilo-

hertz QPO root-mean-square (rms) intensity with photon energy [FIGURE:3, right], Jia et al. [9] found that the rms spectrum of kilohertz QPOs is dominated by Compton scattering of photons from the inner boundary layer (dashed line in figure), thus localizing the origin of kilohertz QPOs to the inner region of the boundary layer. They also found that the rms spectral index of kilohertz QPOs is smaller (harder) than that of the continuum spectrum, suggesting that kilohertz QPOs likely originate from clumpy motions within the inner boundary layer.

3. Unveiling the Origin of High-Energy Hard X-Ray Tails

Broadband spectral analysis of weakly magnetized NS-LMXBs reveals that in soft states, their continua often exhibit a hard X-ray tail dominated by a power-law component around 20–30 keV, with photon indices typically between 1.9 and 3.3. The flux of this hard component decreases with increasing accretion rate. Hard X-ray tails are generally common in Atoll sources, with only a few detections in Z sources. The observed properties of hard X-ray tails evolve significantly with source position in the CCD, particularly pronounced in Z sources where the tail intensity is highest on the HB (photon index ~ 2.3) and can decrease to 1/20 of that value on the NB. The origin of hard X-ray tails in neutron stars remains controversial, with mainstream models falling into two categories: (1) non-thermal Comptonization by relativistic electrons in local outflows or coronal regions, or bulk motion of accreting matter near the neutron star surface, where the corona is a hybrid of thermal and non-thermal electrons (note that at high accretion rates, radiation pressure from the neutron star surface slows the bulk motion, suppressing bulk Comptonization); and (2) synchrotron radiation from relativistic electrons escaping from jets. In this model, since jets originate from and are powered by hot electron coronae, radio and X-ray fluxes are positively correlated—a relationship observed not only in NS-LMXBs but also in black hole binaries, providing additional constraints on the physical origin of hard X-ray tails.

Studying hard X-ray tails requires large effective area in the hard X-ray band, making Insight-HXMT ideally suited for such observations. Insight-HXMT has detected high-energy hard X-ray tails in the Z sources Sco X-1, GX 17+2, and GX 349+2. Ding et al. [11] analyzed Insight-HXMT observations of Sco X-1 [Figure 4: see original paper] and found that the spectral characteristics of the hard X-ray tail evolve significantly along the Z track, with flux decreasing markedly from the HB through the NB to the FB. Through detailed broadband spectral analysis from 2–240 keV, they found that the hard X-ray tails on the HB and NB can be well explained by the COMPTB model (thermal and bulk Comptonization of a seed blackbody-like spectrum), suggesting that these high-energy photons likely originate from inverse Compton scattering between soft photons from the neutron star surface and boundary layer and hot electrons flowing toward the neutron star.

4. Tracking the Evolution of Disk-Corona Geometry

X-ray continuum analysis is crucial for understanding the physical properties and spatial geometry of accretion flows near compact objects. However, due to strong degeneracies inherent in continuum fitting of weakly magnetized NS-LMXBs, spectral analysis alone is often insufficient to reveal the complete picture of disk-corona geometry. Timing or polarization analysis can provide additional dimensions that help break these degeneracies. For example, combining spectral analysis with Fourier-resolved spectroscopy allows investigation of different spectral components at characteristic frequencies, thereby constraining disk-corona geometry. Furthermore, since polarization of photons produced by Compton scattering is highly sensitive to the geometry of scattering material, different geometries and viewing angles produce different polarization degrees (PD) and polarization angles (PA). Therefore, joint spectral and polarization analysis offers a more direct way to study the geometric properties of emission regions.

Combined observations with Insight-HXMT and IXPE (Imaging X-ray Polarimetry Explorer) can provide three complementary dimensions—spectral, timing, and polarization—to better study accretion geometry around neutron stars. Seed photons become polarized after inverse Compton scattering in the corona, which is considered a primary source of photon polarization. In this scenario, PD depends strongly on accretion flow geometry and source spectral state. For a slab-like corona, seed photons mainly originate from the accretion disk, whereas for a spherical shell corona, they come primarily from the neutron star surface. Consequently, different accretion geometries produce distinct evolutionary patterns of PD and PA with energy for the same source. Studying these polarization properties as functions of energy and spectral state can thus constrain the accretion geometry.

Recently, Yu et al. [12] used joint observations with Insight-HXMT, NuSTAR, and IXPE to study the evolution of disk-corona geometry along the Z track in XTE J1701–462. They found that PD decreases significantly from the HB to the NB and even disappears [Figure 5: see original paper], while the Comptonized flux also drops substantially, indicating that the coronal scale shrinks considerably from the HB to the NB and may vanish entirely on the NB. Their results also show that the polarization in this source mainly originates from reflection components, ruling out a spherical corona geometry. These findings demonstrate that joint polarization-spectral analysis can effectively break degeneracies in spectral fitting and provide meaningful constraints on the accretion geometry of neutron star systems.

5. Summary

Research over the past six years has demonstrated that Insight-HXMT has made significant progress in addressing key questions about weakly magnetized NS-LMXBs, including the origin of hard X-ray tails, the physical nature of

kilohertz QPOs, and the evolution of disk-corona geometry. These achievements highlight the satellite's observational advantages in broadband coverage, high time resolution, and high photon statistics. Combined observations with other satellites have also proven that multi-messenger, multi-dimensional analysis will be a major and effective approach for studying weakly magnetized NS-LMXBs. In the future, Insight-HXMT will continue its observational strategy for these sources, expanding the sample of kilohertz QPO detections and exploring their energy limits. By combining spectral and polarization evolution, we can further constrain neutron star disk-corona geometry, while joint timing and spectral evolution studies will investigate hard X-ray tails on the FB branch.

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