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Insight-HXMT Research Progress in 2024–2026*

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Abstract Since the launch in 2017 June, Insight-HXMT has been in service smoothly in orbit and its scientific productivity has been particularly high since 2024. Among a total number of 425 papers published so far based on Insight-HXMT data, roughly 150 were published from April 2024 to June 2026, accounting for 35% of the total. These studies cover a variety of scientific subjects, including the basic properties of black holes and neutron stars, the outbursts of accreting black hole and neutron star X-ray binaries, thermal nuclear burst probes, quasi-periodical oscillations, cyclotron resonant scattering features, fast radio bursts and gamma-ray bursts, *etc*. This paper reviews the overall progress with a focus on some potential breakthroughs.

Key words Insight-HXMT, Black hole, Neutron star, Outburst

Classified index P17

1 Introduction

The Hard X-ray Modulation Telescope (HXMT) is China's first X-ray astronomy satellite and was launched in June 2017, dubbed as Insight-HXMT in honor of the Chinese scientist Prof. He Zehui. There are three slat-collimated instruments onboard Insight-HXMT. For the details of the three telescopes and the mission, please refer to Ref. [1–4].

So far, Insight-HXMT has been operating well, and its scientific outputs have accumulated to more than 400 papers. Discoveries derived during 2017–2024 provided clues for our understandings the neutron star merging by joining the global campaign of observing the historical event of the first event GW 170817[5], the properties of accretion matter (jet, corona and accretion disk) and Quasi Periodic Oscillations (QPO) with a series of discoveries from MAXI J1820+070 and improving a technique of the so-called Hilbert-Huang Transform (HHT)[5–8], the mechanism of Galactic Ultra Luminous Source (ULX) and properties of the magnetic poles by detecting the highest energy of the Cyclotron Resonant Scattering Feature (CRSF) at 146 keV from Swift J0243.6+6124 and four regimes (hence three critical luminosities) in evolution of the CRSF centroid energy against the accretion rate revealed in 1A 0535+262[9–11], and decoding the mysteries of a Fast Radio Burst (FRB) by identifying the first X-ray counterpart of FRBs[12]. See details for the previous progress reports in Ref. [13,14] and the references therein. In this paper, we review the state-of-art results of Insight-HXMT, which are either highly supplementary to those key issues as shown above or new breakthroughs and applications with Insight-HXMT.

2 Black Hole X-ray Binaries

2.1 Swift J1727.8-1613

Swift J1727.8-1613 is a newly discovered black hole X-ray binary system which underwent a huge outburst in

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2023 and was subsequently listed as one of a few samples observed by Insight-HXMT with high cadence. So far, there are 24 papers since 2024 with the data from the observations mainly based on Insight-HXMT. As a comparison, MAXI J1820+070 as Insight-HXMT's previous leading source in the number of publications both in normal and top-tier journals, so far 27 papers have been published with Insight-HXMT data since its huge outburst in 2018. This demonstrates that, Insight-HXMT has increasing impact in the high energy astrophysical society once there is new bright source for which Insight-HXMT will make high cadence observations with the best quality and quantity due to its advantages with wide energy coverage, high time resolution and the largest detection area at hard X-rays. Accordingly, Swift J1727.8-1613 with Insight-HXMT observations turns out to be another good laboratory to our further understanding ofthe basic physical process of accreting black hole X-ray system.

2.1.1 A Variety of Temporal and Spectral Features

In 2023, Swift J1727.8-1613 underwent an outburst with a typical evolution track in the Hardness-Intensity Diagram (HID). An investigation of the energy dependence of RMS of the Low-Frequency Quasiperiodic Oscillation (LFQPO) (*e.g.*, type-C QPO) shows a transition at the frequency around 3 Hz: while RMS increases continuously below 3 Hz, it drops at LE band but remains stable at ME and HE bands[15]. Positive correlation between QPO frequency and RMS was seen as well in GRS 1915+105 at frequency below 2 Hz[16], and the low-energy RMS drop at higher frequency is common in BHXRB outbursts. One interpretation could be that, during the initial phase of the outburst, the truncated inner disk moves toward the BH and the Lense-Thirring (L-T) precession strengthens with increasing precessing angle. The low energy QPO RMS may drop with more disk contribution, along with outburst evolving to the soft intermediate state. For probing the possible origin of QPO, an interesting trial of performing the bicoherence analysis indicates that the type-C QPO is coupled with noise rather than generated independently[17].

The RMS spectrum of the type-C QPO evolves with outburst in a manner significantly different from other BHXRBs: the RMS spectrum has an obvious excess at energies above 40 keV and evolves gradually to a flatter one typical to the usual RMS spectral shape at high energies[18] (see Figure 1). Together with the spectral analysis reported by Peng *et al*.[19] that a strong power component shows up apart from the corona component; this peculiar RMS spectrum suggests again that the additional hard component comes from jet emission.

Xu *et al*.[20] found a rare anticorrelation between the unscattered disk emission and the QPO frequency at the early outburst phase when the QPO frequency is below 3 Hz, which may indicate the coupling between the inner hot flow and the inner disk. They proposed a possible scenario that the truncated inner disk can penetrate the corona, thus leading to a larger covering fraction of the corona and hence the decreasing unscattered disk emission (see Figure 2).

Ma *et al*.[21] tested the L-T procession origin of QPO by fitting the broadband energy spectrum with SSSED model, and found that the estimated truncated inner disk radius decreases from 45 R_g to 9 R_g. However, with this evolution of radius, the QPO frequency is systematically higher than the L-T prediction by a factor of a few, if assuming that the QPO originates from the L-T precession of the hot inner flow.

Diagnostics with cross and biphase spectrum, Bollemeijer *et al*.[22] investigated the QPO waveforms for both the fundamental and harmonic. They found that the phase lag between the fundamental and second harmonic QPO is highly energy dependent: the waveform changes to almost opposite at energies above 15–20 keV. Also, the time lag of the harmonic QPO extends to a broader frequency range and may be related to the broad band noise variabilities.

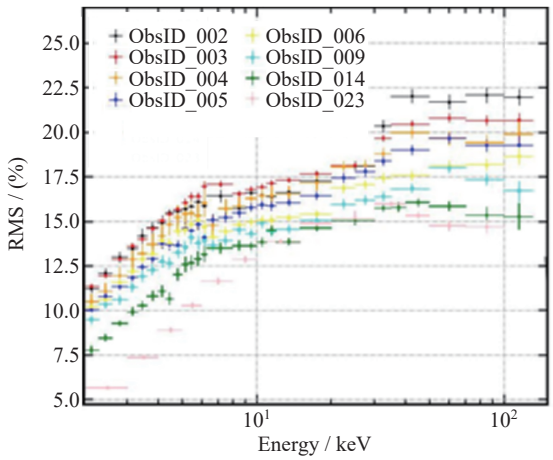


Fig. 1 Evolution of QPO RMS spectrum observed by Insight-HXMT during outburst of Swift J1727.8-1613 [18]

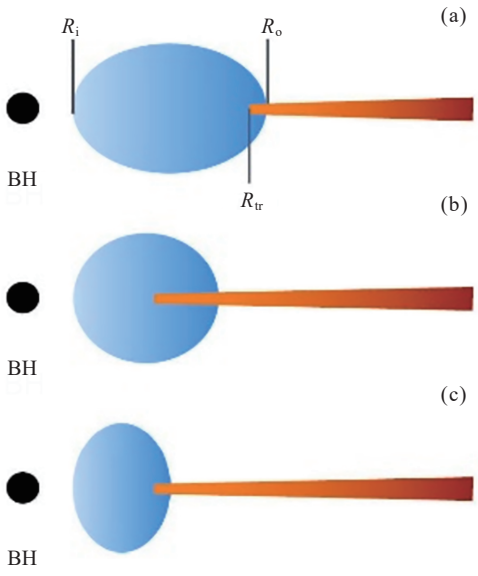


Fig. 2 Disk-corona connection introduced to explain the observed QPO frequency evolution[20]

2.1.2 Geometry of the Accretion Flow Revealed by HHT Technique

The most powerful diagnostics of the inner accretion flow were performed with HHT analysis[23]. The QPO phase-resolved spectra reveal that both thermal and nonthermal components of the spectrum exhibit strong variations along with the QPO phases. The spectral parameters of the disk temperature, spectral indices and reflection fraction modulate with QPO phases with significances above 5σ (see Figure 3). Notably, the variation of the disk temperature precedes the variations of the disk flux and normalization by 0.4–0.5 QPO cycles. Two nonthermal components have different QPO modulations: while the spectral index follows the QPO waveform which resembles that found in MAXI J1820+070[8] for one component, it shows the opposite modulation with respect to the QPO waveform for the other component. This clearly demonstrates the co-existence for precession of both hot corona and jet.

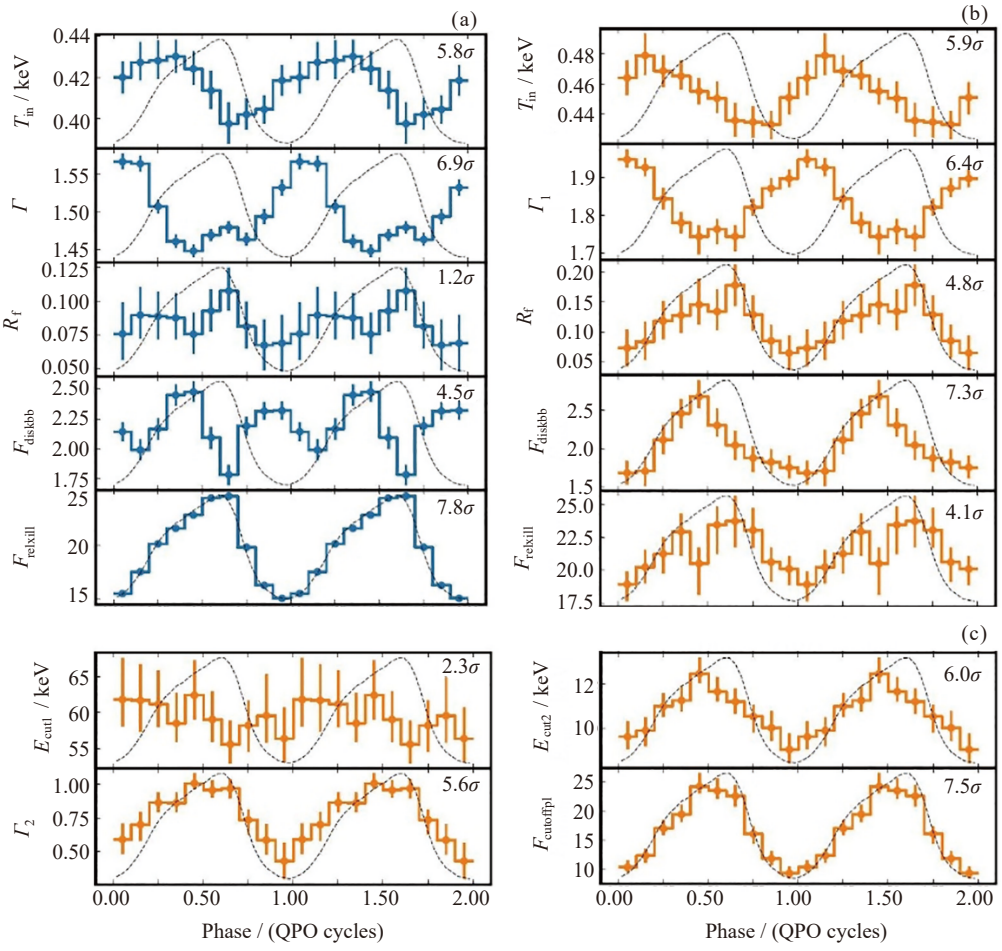


Fig. 3 Spectral parameters modulation with QPO phases derived with HHT [23]

2.1.3 New World Record of the Highest Energy of QPO

With a novel HHT-based QPO searching technique[24], significant QPO signals (above 5σ) at energies above 250 keV are detected by either NaI or CsI of HE[25]. At energies around 300 keV, QPO was detected with a significance level of 3σ. The previous QPO's highest energy was also from Insight-HXMT observations, but instead from MAXI J1820+070[6], which reached only above 200 keV.

2.1.4 A Scenario Tailored for a Series of Rare Flares

Swift J1727.8-1613 underwent a series of flares when the source started to enter the soft state. The properties of these flares were investigated in details by Cao *et al.*[26], where they found that the source stepped into very high state during the first flare, characterized by fast enhanced disk emission, a steep power law component, and weak reflection. These features can be understood in a scenario where during the flares, the jet is accelerated and hot inner flow contributed weak reflection (see Figure 4).

2.2 Other Sources

The excellent Insight-HXMT data on MAXI J1820+070 collected during the initial Insight-HXT phase keep bringing us more exciting discoveries and Insight-HXMT observations on some peculiar BHXRB outbursts shed light on understanding the evolution between different spectral states.

2.2.1 New Landscape for Shaping the Broadband Noise

Yang *et al.*[27] carried out the covariance spectrum of MAXI J1820+070 and investigated the nature of the inner accretion flow. There, they found that for both the long- and short-timescales the coherence at hard X-ray decreases with respect to the soft X-rays, while the electron temperature associated with the long-time variability is generally larger than that with the short-time variability. Accordingly, they introduced a two-Comptonization framework to make a possible interpretation. Interestingly, the broadband noise studied by Gao *et al.*[28] based on the same outburst revealed that, during the outburst evolution, the characteristic frequency of the low/high-frequency broad band noise decreases/increases against the increasing photon energy (see Figure 5). Both results require the corona to have an inhomogeneous temperature distribution and probably the inner hot corona responds less efficiently to the disk variability due to the block of the outer cooler corona located in between.

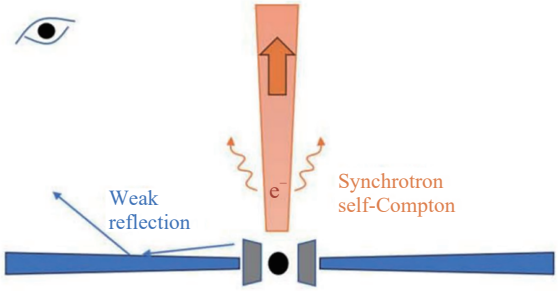


Fig. 4 A jet-disk-corona scenario introduced to match the flare properties observed in Swift J1727.8-1613 [26]

2.2.2 Unified Disk-corona Configuration Across Huge BH Mass Range

Constrained by the limited detection area of the previous hard X-ray telescopes and the extremely short time scale of the time lags caused by coronal X-rays reflecting off the disk, previous measurements of reverberation lags for stellar-mass BHs are limited to energies below 10 keV. A breakthrough was made by You *et al.*[29] by detecting for the first time the Compton hump reverberation, peaking at about 30 keV, from the X-ray binary MAXI J1820+050 as observed by Insight-HXMT. The accompanying detection of an iron line feature at about 6.4 keV confirms the X-ray reverberation scenario and provides strong evidence that accretion flows in AGNs and X-ray binaries are governed by a ubiquitous process.

2.2.3 Condition for Disk Transition to Slim One

Peng *et al.*[30] made a spectral analysis of the outbursts of 4U 1630-472 observed by Insight-HXMT in 2022 and 2023. They found that the disk temperature - flux relation is roughly consistent with that of a standard disk by taking the hardening factor into account. With the p-free model, although the standard disk cannot be excluded, the evolution of decreasing p with disk temperature is visible. These findings may suggest that the previously reported apparently standard regime may not be fully relevant to a slim disk but instead implies an evolution toward a slim disk. The formation of a slim disk may be influenced, apart from the accretion rate, as well by the disk/corona properties (*e.g.*, nonthermal fraction) in the

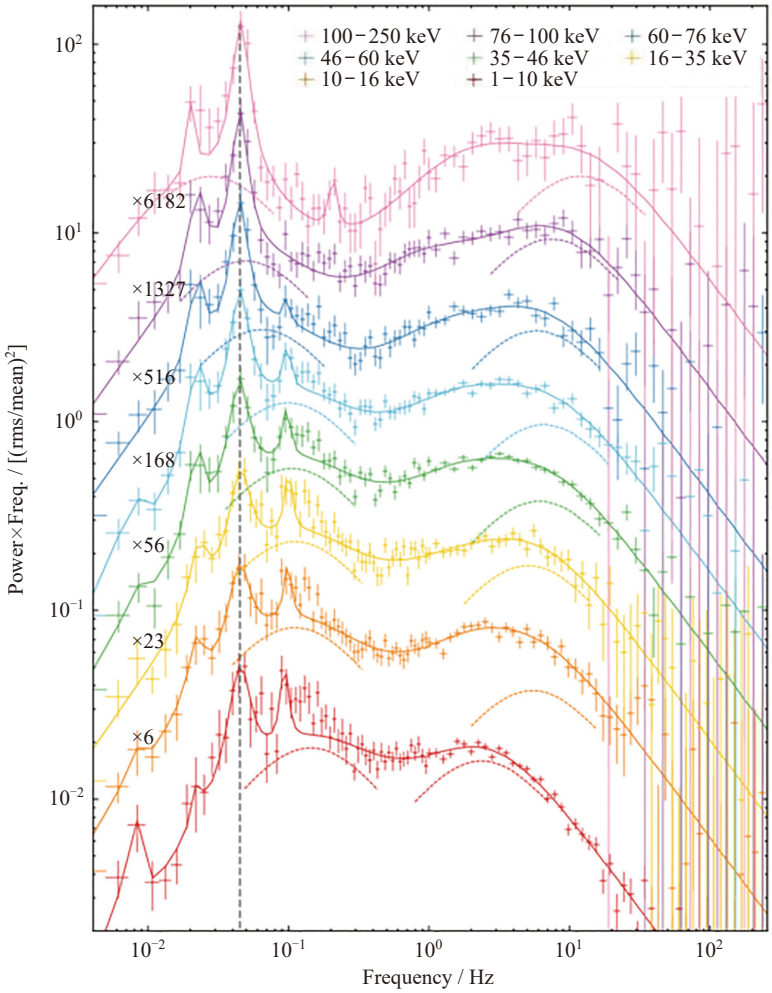


Fig. 5 Simultaneous PDS in different energy bands obtained from the Insight-HXMT observation carried out during 27 March 2018 [27]

HSS. A slim disk may be less likely to form with the presence of the dominant nonthermal emission in the HSS. The existence of a hot corona may help to ionize the outer part of the disk in the vertical direction and hence hinder the formation of a slim disk by reducing the optical depth (see Figure 6).

3 Neutron Star X-ray Binaries

Insight-HXMT archival data of the high-cadence observations of two bright sources, Swift J0243.6+6124 and 1A 0535+262, have enabled more than 20 publications, and additional interesting results derived in the last two years are introduced in what follows.

3.1 Rapid Quasi-periodic Reconfiguration of the Accretion Column

CRSF is a probe of the emission site of the accretion column of the accretion neutron star system and long-term CRSF-luminosity correlations reflect changes in column geometry driven by variations in the mass accretion rate. So far, it remains a puzzle for CRSF properties on a short time scale of such as a few seconds. Kong *et al.*[31] found that, during a giant outburst of the X-ray pulsar 1A 0535+262, X-ray QPO is accompanied by synchronized oscillations of the cyclotron line energy, with amplitudes exceeding those expected from simple accretion-rate fluctuations. The anti-correlation between cyclotron energy and apparent flux provides direct spectral-timing evidence for rapid changes in the line-forming region, which is interpreted as a geometric reconfiguration of the accretion column. The CRSF modulation therefore reflects an intrinsic, dynamical reconfiguration of the accretion column geometry on timescales of tens

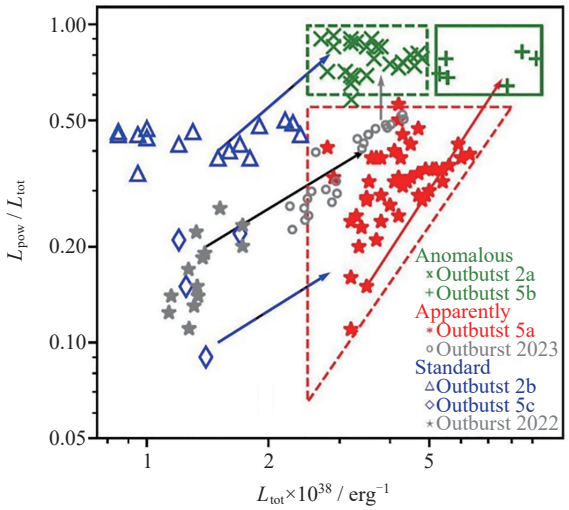


Fig. 6 Evolution of the luminosity ratio of the nonthermal to the total luminosity against the total luminosity for different outbursts from 4U 1630-472[30]

of seconds, linking the emergence of high-energy QPOs to the formation of a radiation-supported column with rapid geometric restructuring.

3.2 Hunting the Highest Energy of Pulsation from PULX

Pulsating Ultraluminous X-ray (PULX) sources are generally thought to have its apparent high luminosity relevant to relativistic or geometric beaming effect. The discovery of > 130 keV pulsation from PULX RX J0209.6-7427[32] reveals that the emission should be in fan mode but not pencil beaming. The breakthrough of measuring the highest energy of 146 keV CRSF from the Galactic PULX Swift J0243.6+6124[10] provides the first evidence that the high luminosity is accompanied with the real super-Eddington accretion. Here, with a novel pulse-profile-correlation technique, the highest energy of pulsation observed by Insight-HXMT in the outburst of Swift J0243.6+6124 is found to have positive correlation with accretion rate, with the highest one reaching around 200 keV, which is the new world record in accretion pulsar systems and serves as additional evidence that PULXs have non-beaming emission[33].

3.3 Diagnostic of the Radiation Regime of PULX at Low Luminosity

The discovery of the 146 keV CRSF and no propeller effect during outburst tail suggests that the PULX Swift J0243.6+6124 holds an NS with multiple-B structure. However, consolidation of this scenario needs more detailed exploration of the source properties at low-luminosity periods. Chen *et al.*[34] performed a detailed spectral analysis of Swift J0243.6+6124 in its sub-Eddington regime, with observations from Insight-HXMT and NICER during a series of outbursts, and found a new transition at $L_t \sim 4.5 \times 10^{37}$ erg·s^{-1}, which is the fifth transition luminosity identified so far, accompanied by significant turnover of the blackbody normalization. They proposed a scenario by introducing a multipolar magnetic field configuration, where weak (~2.8×10^{12} G) and strong (~1.6×10^{13} G) magnetic poles govern the emission at different accretion rates. Such a magnetic field configuration is equivalent to a relatively weak pure dipole magnetic field of ~6.6×10^{12} G on the scale of the magnetospheric radius, and allows the local magnetic field of the neutron star to exceed 10^{13} G (see Figure 7).

3.4 Diagnostic of the Accretion with Type-I Burst Probe

Type-I bursts are the thermal nuclear burning on the surface of a neutron star, and the interactions of the soft X-ray shower with the surrounding environment leave the footprint of either the enhancement of the disk emission due to the Poynting-Robertson (PR) dragging or the shortage of the hard X-ray emission due to the corona cooling. Accordingly, the frontier researches are led by different international groups. For example, the latter is led by the Insight-HXMT team due to Insight-HXMT's large detection area at hard X-rays. Previous researches show large difference for the hard X-ray shortage induced by type-I bursts: almost 100% hard X-ray shortage observable for the atoll source[35], while only roughly shortage visible for the millisecond accretion pulsar[36]. This implies that the non-cooling part comes from the accretion site of the magnetic pole where the hard X-ray pulsation originates, while for atoll sources, the hard X-rays are mainly contributed by the corona and hence are short of the emission from the sites around magnetic poles. The type-I burst influence upon the polar cap of the millisecond pulsar MAXI J18160195 is investigated by Ji *et al.*[37]. Apart from the burst-induced hard X-ray shortage, the properties of the pulsation within bursts shows no difference compared to those observed in the non-burst period. This provides evidence supporting that only the surrounding corona can be

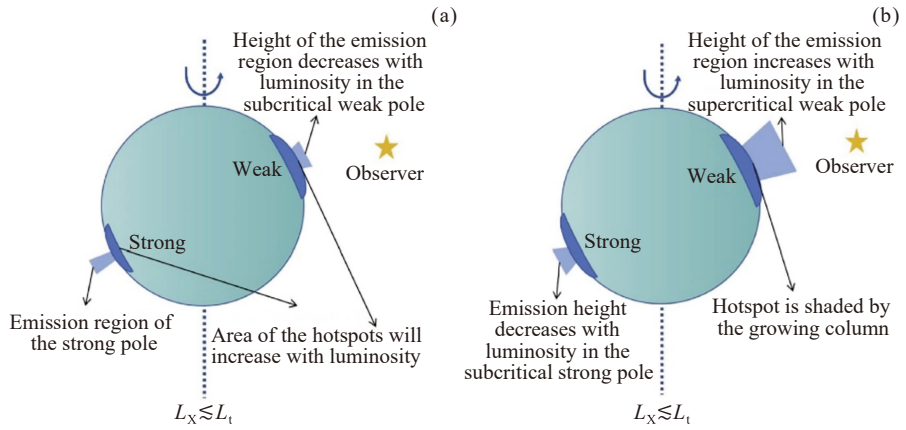


Fig. 7 Sketch of the two zones defined by the discovery of an additional critical luminosity during the sub-Eddington regime of Swift J0243.6+6124[34]

cooled off, and emissions from the polar cap are less influenced. Pulsations were also studied by Li *et al.*[38] for the accretion millisecond pulsar SRGAJ144459.2-604207, where a significant time lag with respect to the non-burst period shows up mainly at low energies. Such a time lag may be induced by the PR effect: during a type-I burst the highly enhanced accretion rate alters the local geometry of the site around the polar cap.

4 Extremely Violent Events

4.1 Gamma-ray Bursts

4.1.1 GRB Catalogues

GRB study is one of the Insight-HXMT core sciences. Owning to its largest detection area at hundreds keV to a few MeV and good time resolution, Insight-HXMT contributes to the GRB community, together with the joint observations of other GRB detectors in service, by precise measurement of the BAND function and improvement of the spectral break locations. Accordingly, so far two Insight-HXMT catalogues are released, namely the first Insight-HXMT GRB catalogue (also the first GRB catalogue in China), which hosts the GRB samples observed in the first 4 years[39], and the refined locations for the Short GRB (SGRB)[40]. For the former, noting that Insight-HXMT can detect more than 80 GRBs per year, the statistics of BAND function parameters will be largely improved for years to come. For the latter, by taking a localization method of so-called LI-CCF[41], the localization accuracies of 72 SGRBs are improved by 59% (3σ level), compared to that with Fermi/GBM alone. A series of research will benefit from this refined location catalogue, for example, the search for the GW counterpart, GRB association with neutrinos and so on.

4.1.2 Peculiar GRB Samples

Insight-HXMT also detected peculiar GRBs which are helpful for understanding the underlying GRB mechanism. The latest news from Insight-HXMT observations on the BOAT (brightest of all time) GRB 221009A is that, after the deadtime and saturation corrections, ME and LE lightcurves of the secondary particles induced by the interaction of the primary GRB photons with detectors are consistent with those from GECAM which are free of saturation problem. With the ME lightcurve, the minimum variability timescale of the main burst episode is measured as 0.1 s for the first time for GRB 221009A[42]. As a long-duration GRB associated with strong precursor and Kilonova (KN), GRB 211211A provides chance to investigate the pre-merger status. Although the precursor is rather rare for SGRBs, the detection of a non-thermal spectrum (cutoff power law) and a QPO (3σ level, so far the highest one among precursors) (see Figure 8) make this GRB extremely unique[43]. The authors proposed that either the premerger magnetosphere interaction or magnetar crust oscillation could be at work for possible explanations of this peculiar precursor. GRB 240825A is another peculiar GRB with three spectral components (see Figure 9), which is rather rare for GRB, measured jointly with a series of GRB telescopes[44]. The bulk Lorentz factor estimated from the spectral components other than the band function favors jet penetration scenario, and the multi-segment broken

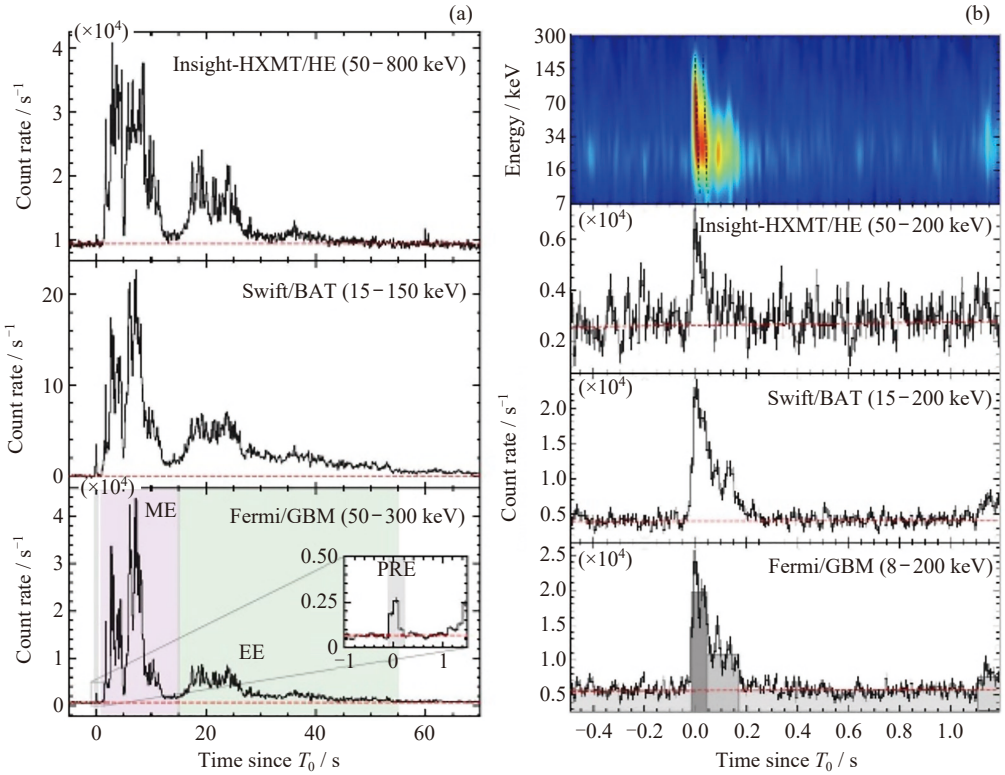


Fig. 8 Precursor and main burst of GRB 211211A recorded by different telescopes[43]

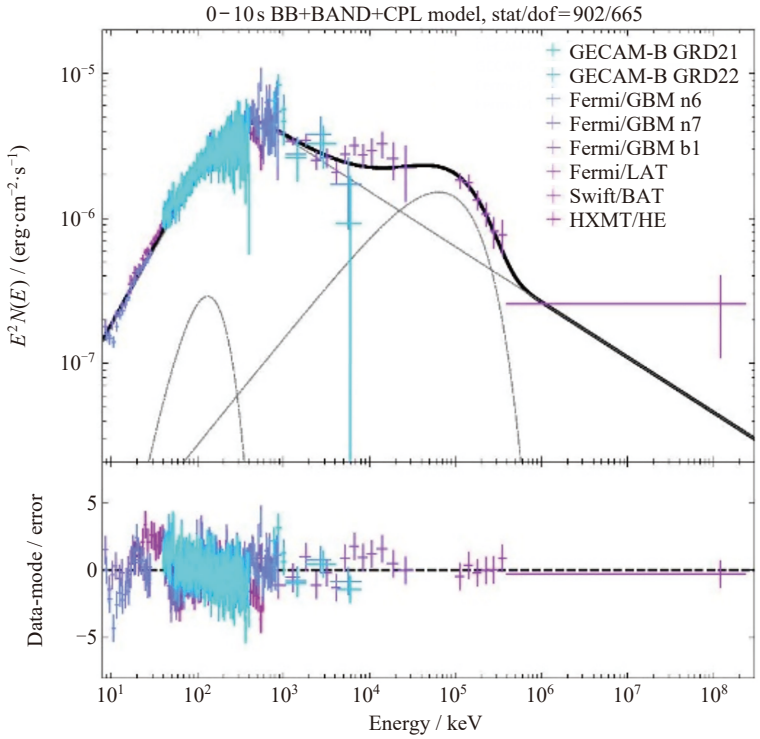


Fig. 9 Energy spectrum of GRB 240825A with three components [44]

power-law feature observed in the lightcurves suggests the presences of an early afterglow and a possible two-jet structure: a narrow early one followed by a latter broader one.

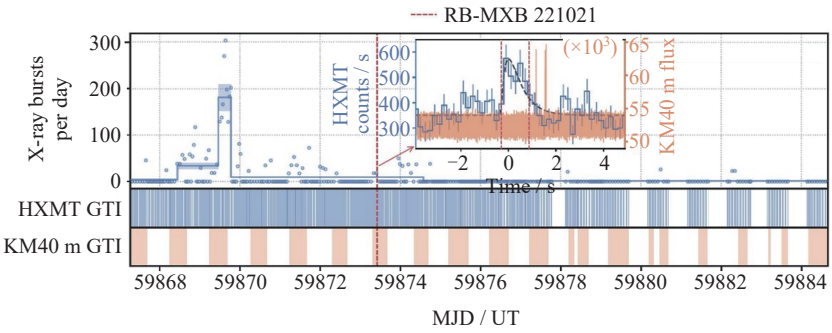


Fig. 10 Association of X-ray burst with radio bursts observed by Insight-HXMT at X-rays and KM40 m at radio band [45]

4.2 Fast Radio Bursts

Following the first FRB identification with a magnetar SGR 1935+2154[5], Insight-HXMT detected another X-ray burst, namely MXB 221021, associated with a radio burst measured by KM40 m radio telescope[45] on 21 October 2022. As shown in Figure 10, the X-ray burst is accompanied by three radio bursts with fluence ranging between 13–37 Jy·ms. Different from MXB/FRB200428, in this X-ray/radio association, the radio lags X-ray by roughly 1 second and the radio-to-X-ray fluence ratio is orders of magnitude lower. They noticed that such a radio burst is not likely the giant pulse of radio pulsar; otherwise the association with the X-ray burst would require a power far beyond the rotational energy budget. This association event may bridge the phenomenological gap between the normal radio emission and the FRB-like radio burst.

5 Insight-HXMT Applications

Insight-HXMT can also be used to observe the Terrestrial Gamma-ray Flash (TGF) and measure the density of the Earth's atmosphere, which is highly relevant to the living environment of human being. By comparing the large sample of TGF collected with Insight-HXMT and the lightning events recorded by the World Wide Lightning Location Network (WWLLN), close connection between TGF and the most intense lightning is confirmed[46]. By taking the Earth osculation data collected by Insight-HXMT observations of Crab, the atmospheric densities at altitudes spanning from 55 to 130 km are precisely measured, which indicates that the NRLMSIS (Navy Research Laboratory Mass Spectrometer Incoherent Scatter Radar Exosphere) model overestimates atmospheric density at altitudes 90–95 km and 100–120 km by 15%–20%[47].

6 Summary and Outlook

Insight-HXMT still keeps bringing us interesting and exciting results with more observations, new ideas and novel techniques developed for exploring the data archive. In near future, the joint eXTP and Insight-HXMT will build the most powerful constellation in probing the fundamental physical laws under different extremes. The Insight-HXMT mission is currently still operating quite well and will be available to the world-wide community for years to come. Please visit hxmt.org for further information about Insight-HXMT and downloading data.

Conflict of Interests The authors declare that there is no conflict of interests

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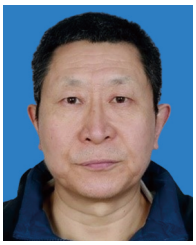
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