Broad-Band Observations of Thermonuclear Bursts with Insight-HXMT (Postprint)

Authors: Chen Yupeng

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Since its successful launch in 2017, the Insight Hard X-ray Modulation Telescope (Insight-HXMT) has been operating continuously for over 8 yr, accumulating a vast amount of observational data. In observations targeting multiple thermonuclear burst sources, it has detected more than 200 thermonuclear burst events. Leveraging its excellent broad-band detection capability (1–250 keV) and large effective area (>5000 cm^2@20 keV), Insight-HXMT has systematically revealed the interaction mechanism between thermonuclear bursts and the accretion environment through in-depth analysis of the energy spectra and temporal variability characteristics of thermonuclear bursts, particularly investigating the radiation features in the hard X-ray energy band (>20 keV). Specific research achievements include: the first observation of the high-temperature corona cooling process induced by thermonuclear bursts in a single burst event, providing direct evidence for studying the interaction between thermonuclear bursts and the corona; the first discovery and confirmation of the correlation between neutron star surface radiation anisotropy and accretion rate, offering important clues for understanding the physical processes on neutron star surfaces; and systematic studies of the accretion radiation enhancement effect triggered by thermonuclear bursts, as well as the occultation effect of the accretion disk on thermonuclear bursts. These achievements not only expand our understanding of the physical processes of thermonuclear bursts, but also provide a new observational perspective for the study of neutron star accretion systems.

Full Text

Preamble

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Broad-band X-ray Observations of Thermonuclear Bursts by Insight-HXMT

CHEN Yu-peng
(Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049)

Abstract

Since its successful launch in 2017, the Insight Hard X-ray Modulation Telescope (Insight-HXMT) has been operating continuously for over eight years, accumulating a vast amount of observational data. During observations of multiple thermonuclear burst sources, it has detected more than 200 thermonuclear burst events. Leveraging its exceptional wide-band detection capability (1–250 keV) and large effective area (>5000 cm^2 at 20 keV), Insight-HXMT has conducted in-depth analyses of the spectral and temporal characteristics of thermonuclear bursts, particularly focusing on radiation features in the hard X-ray band (>20 keV), thereby systematically revealing the interaction mechanisms between thermonuclear bursts and the accretion environment. Specific achievements include: the first observation of high-temperature corona cooling induced by a thermonuclear burst in a single event, providing direct evidence for studying burst-corona interactions; the first discovery and confirmation of a correlation between neutron star surface radiation anisotropy and accretion rate, offering important clues for understanding physical processes on neutron star surfaces; and systematic investigations of the enhanced accretion radiation effect triggered by thermonuclear bursts, as well as the obscuration of bursts by the accretion disk. These results not only expand our understanding of the physical processes of thermonuclear bursts but also provide new observational perspectives for studying neutron star accretion systems.

Keywords: X-rays: binaries, bursts, stars: neutron, telescopes: Insight-HXMT
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1 Introduction

Stars derive their energy from nuclear fusion, while celestial bodies can also influence their surroundings through gravity. The process of attracting surrounding material via gravitational forces and releasing gravitational energy is known as accretion, a physical mechanism used to explain the outburst phenomena observed in X-ray binaries. Among X-ray binaries containing compact objects that are neutron stars, there exists an observational phenomenon whose energy source is nuclear fusion—thermonuclear X-ray bursts, also known as Type I X-ray bursts.

Thermonuclear bursts result from unstable nuclear fusion of material (mostly hydrogen or helium) accumulated on the neutron star surface through accretion.

They manifest as sudden, intense eruptions superimposed on the persistent accretion light curve, reaching the Eddington limit within seconds. Their spectra are generally blackbody-like, with burst timescales ranging from seconds to minutes, characterized by a fast rise and slow decay profile, accompanied by spectral softening during the flux decline phase. Theoretically, the peak luminosity of the brightest thermonuclear bursts reaches the Eddington luminosity, where radiation pressure can cause photospheric radius expansion (PRE). The radiating area corresponds to the neutron star’ s surface area, allowing constraints on the neutron star’ s mass, radius, distance, and spin from observed bursts. Simultaneously, thermonuclear bursts interact with the surrounding accretion environment, enabling their use as probes to study accretion disks, coronae, and other accretion structures.

Since the first detection of thermonuclear bursts in 3A 1820-30 in 1975, 120 Galactic X-ray binaries have been observed to produce thermonuclear bursts as of November 15, 2024. These bursts represent primary observational targets for X-ray telescopes such as RXTE (Rossi X-ray Timing Explorer), NICER (Neutron star Interior Composition Explorer), and Insight-HXMT.

The recurrence time of thermonuclear bursts ranges from hours to days. During this interval, the ratio of accretion energy to thermonuclear burst energy is 40-200. Assuming no outflow and that all accreted material reaches the neutron star surface to participate in thermonuclear bursts, this ratio represents the efficiency ratio between gravitational energy release and nuclear energy release. This has long served as a criterion for identifying thermonuclear bursts and can also determine the composition of nuclear fuel (as hydrogen and helium have different nuclear energy conversion efficiencies), distinguishing them from Type II X-ray bursts. Since thermonuclear bursts were discovered earlier and Type II bursts later, they are termed Type I and Type II X-ray bursts, respectively.

Type II X-ray bursts exhibit similar light curve profiles to thermonuclear bursts but with shorter intervals between bursts, as short as tens of seconds, and non-thermal spectra. They often show a reduction in continuum emission before and after bursts, forming dip-like structures similar to binary outbursts, generally attributed to accretion instabilities. Currently, only two Galactic sources exhibit Type II bursts: Rapid Burster (MXB 1730—335) and Bursting Pulsar (GRO J1744—28), with thousands of Type II bursts detected from these sources. The former also shows thermonuclear bursts, while the latter does not, possibly due to its stronger magnetic field (~5.3×10^{11} G).

Most thermonuclear bursts last 10-100 s. Based on their total energy and nuclear energy conversion efficiency, the ignition column density on a 10 km neutron star surface is ~10^8 g cm^{-2}. Since helium fusion proceeds faster, short rise times (~1 s) are generally attributed to helium fusion, while long rise times (~10 s) indicate hydrogen fusion. After reaching peak flux, the decay timescale is ~10-100 s. Peak blackbody temperatures can reach 3 keV, decreasing during the decay until returning to pre-burst levels. However, some strong sources show no temperature decrease at the burst end, such as Cyg X-2, possibly due to high accretion rates causing burst photons to be scattered by the corona.

For the most luminous bursts, the luminosity reaches the Eddington limit, where radiation pressure lifts the neutron star' s photosphere, causing photospheric radius expansion. The photosphere can extend to tens of kilometers, accompanied by spectral softening and decreasing blackbody temperature. The light curve shows a single peak in soft X-rays and double peaks in hard X-rays, while spectral evolution exhibits a double-peaked blackbody temperature—highest at the beginning and end of PRE (reaching 3 keV), with the lowest temperature (<1 keV) when the photospheric radius is maximum. PRE bursts constitute ~20% of all thermonuclear bursts. Theoretically, for a given accreted composition, the Eddington luminosity depends only on neutron star mass, enabling mass determination from observed burst flux, while the measured blackbody area constrains the radius, thereby limiting the neutron star' s equation of state. Recent studies indicate that burst spectra contain not only blackbody components but also emission related to the accretion environment, which must be subtracted before measuring neutron star parameters.

Theoretically, in neutron star binaries, the accretion disk' s inner region rotates at Keplerian velocities far exceeding the neutron star' s surface spin, causing accreted material to decelerate and form a transition region near the equator known as a spreading layer or boundary layer. This region reaches temperatures of several keV and heights of several thousand meters, considered along with the corona as the source of non-thermal components in the high/soft (banana) state. For the corona, based on spectral fitting results of neutron star binaries and analogy with black hole binaries, typical temperatures range from several keV to over 100 keV, with optical depths of 1-10. However, its geometry remains uncertain, with proposed models including disk corona covering the disk, spherical corona covering the neutron star surface, "lamppost" models above the magnetic poles, relativistic jets, or hybrid models.

When analyzing the inner radius of accretion disks using the diskbb model in XSPEC, results are affected by absorption along the line of sight, particularly when disk temperatures are low and the telescope's effective area at low energies is limited. Additionally, disk emission is influenced by non-thermal corona or boundary layer emission, requiring corrections to the derived inner disk radius. Since thermonuclear bursts occur on the neutron star surface, they interact with surrounding accretion structures including the disk, corona, and boundary layer. Following the discovery of thermonuclear bursts, theorists in the 1980s predicted these interactions, including disk reflection of bursts and radiation-induced accretion rate increases. However, due to limited effective areas of tens to hundreds of cm^2, these effects were not observed until the launch of RXTE with ~6000 cm^2 effective area nearly two decades later.

Thermonuclear burst-accretion environment interactions include: (1) burst radiation causing coronal temperature reduction and Compton scattering by hot electrons in the corona; (2) burst radiation decelerating inner disk material via Poynting-Robertson drag, increasing accretion rate, followed by decreased post-burst accretion as viscous processes cannot immediately refill the cleared inner disk region; (3) burst radiation pressure clearing away the disk and corona, reducing accretion emission while changing disk obscuration of burst radiation; and (4) burst radiation reflecting off the accretion disk, producing reflection features such as iron fluorescence lines.

Observationally, burst-accretion interactions were first discovered in superbursts with hour-long durations. Typical thermonuclear bursts last seconds to minutes, intermediate bursts last minutes to 40 minutes, and superbursts last hours, with the latter two rare long bursts attributed to sudden fusion of helium or carbon. For tens-of-seconds bursts, RXTE and Chandra observations of the strongest burst from the accreting millisecond pulsar SAX J1808.4-3658 revealed an additional component beyond neutron star blackbody radiation. This component had a spectrum identical to the persistent emission but with 20× increased flux during the burst, accounting for 60% of the burst peak flux. The spectral model blackbody + f × persistent, where f represents the accretion spectrum enhancement, became the mainstream model for explaining deviations from blackbody spectra during bursts. This matches theoretical predictions from 1989 that burst radiation increases accretion rates via Poynting-Robertson drag, with the enhanced accretion luminosity L = (8/3)(1−)L_b/ , where L_b is burst flux and is the mass-to-energy conversion efficiency. For a 10 km neutron star radius (= 0.2), L = 0.6L_b, consistent with observations, though the predicted post-burst accretion decrease was not observed.

An alternative explanation suggests the flux increase originates from burst radiation reflected by the optically thick disk and subsequently scattered by the optically thin corona, with reflected photons mostly below 0.5 keV. Similar soft X-ray excesses during bursts have been found using RXTE, NuSTAR, NICER, AstroSat, and Insight-HXMT data for sources including Aql X-1, 4U 1608-52, 4U 1636-536, 4U 1730-22, and MAXI J1816-195.

From Insight-HXMT observations of approximately ten accreting neutron stars, we have identified a sample of about 200 bursts, as shown in Table 1 . Benefiting from HXMT’ s large detection area and broad energy coverage, we have obtained burst spectral evolution and studied their interactions with the accretion environment.

2 Effect of Burst Radiation on Accretion Emission: Hard X-ray Deficit During Bursts

For thermonuclear bursts lasting tens of seconds, the first indication of burst-accretion interactions came in 2003 when RXTE observed a flux decrease in the 30–60 keV band during a burst from Aql X-1, though with only 2σ significance. In 2005, combining Chandra and RXTE observations of multiple bursts from GS 1826-238, spectral fitting of 0.5–40 keV data revealed coronal temperature decreasing from 20 keV to 3 keV during bursts. In 2012, stacking dozens of bursts from IGR J17473-2721, we discovered a significant hard X-ray deficit in the 30-50 keV RXTE/PCA light curve with ~50% amplitude. Subsequently, in sources with sufficiently bright persistent hard X-ray emission (Swift/BAT flux >100 mCrab), hard X-ray deficits have been observed during bursts in sources including IGR J17473-2721, Aql X-1, 4U 1636-536, GS 1826-238, KS 1731-260, 4U 1705-44, 4U 1728-34, and 4U 1724-30, as summarized in Table 2 .

Prior to Insight-HXMT, X-ray telescopes had relatively small hard X-ray detection areas, making 5σ deficits difficult to detect in individual bursts. Significance was achieved by stacking dozens to hundreds of bursts—for example, the hard X-ray deficit in 4U 1636-536 resulted from stacking 36 bursts observed by RXTE/PCA.

After HXMT' s launch, we detected hard X-ray deficits in individual bursts from 4U 1636-536, as shown in Figure 1 [Figure 1: see original paper]. During the 2018 outburst, a single short thermonuclear burst exhibited a 6.2σ deficit in the 40-70 keV band, consistent with previous RXTE/PCA stacking results. Furthermore, HXMT enabled the first wide-band spectral fitting of bursts to study their impact on accretion emission, revealing that the hard X-ray deficit appears in the persistent emission spectrum above 40 keV.

Table 2 presents hard X-ray deficits detected during bursts across various sources, instruments, and energy bands. Theoretically, if the corona cools from higher to lower temperatures during bursts, the deficit fraction should increase with energy. For example, a 10% temperature decrease (from 10.8 keV to 9.7 keV) would produce 50% and 30% flux reductions in the 50-60 keV and 30-40 keV bands, respectively. This estimate matches observations of MAXI J1816-195, where stacking HXMT burst light curves revealed a 15.7σ hard X-ray deficit in the 30-100 keV band. As expected, the deficit fraction is energy-dependent, being larger at higher energies (40-50 keV). Notably, the deficit fraction saturates at ~50% above 50 keV, possibly indicating another hard X-ray production region—accretion columns at the neutron star poles unaffected by bursts.

This saturation phenomenon, also observed in 4U 1636-536, 4U 1608-52 (Figure 2 [Figure 2: see original paper]), and Aql X-1, suggests that thermonuclear bursts only affect a portion of hard X-ray emission. This implies either a multilayered corona (e.g., sparse and dense components, with bursts affecting only the former) or a jet component. Given MAXI J1816-195's nature as an accreting millisecond pulsar, we favor a jet origin for the unaffected hard X-ray emission. Do bursts affect the pulsed signal from polar caps? By stacking HXMT hard X-ray data from MAXI J1816-195 bursts—difficult with RXTE due to the scarcity of hard X-ray bright sources with many Type I bursts and soft X-ray band dead-time issues—we detected persistent accretion-powered pulsations during bursts with unchanged intensity and no phase drift. This demonstrates that pulse radiation is essentially unaffected by bursts, successfully decoupling the two hard X-ray components: ~50% from the hot corona and ~50% from polar cap (jet) emission. This hard X-ray deficit saturation in non-pulsating sources like 4U 1608-52 and 4U 1636-536 suggests the universality of these two hard

X-ray components in accretion emission.

3 Effect of Accretion Emission on Burst Radiation: Scattering by the Corona

For low/hard or high/soft state low-mass X-ray binaries, the persistent emission spectrum can be fitted with an absorbed thermal Comptonization model (with diskbb seed photons), described in XSPEC using thcomp (a more precise version of nthcomp), including optical depth τ, electron temperature kT_e, and scattering/covering fraction f_s.

Since burst photons may also be affected by the accretion region, we investigated whether the same model could fit burst spectra. By treating persistent emission as background, we fitted burst spectra with tbabs*thcomp*bb, where tbabs accounts for neutral hydrogen absorption along the line of sight, and thcomp parameters are fixed at values derived from persistent emission fitting. This convolution model has the same degrees of freedom as the f model but more than a simple blackbody model, where bb and thcomp represent burst radiation from the neutron star photosphere and the effect of the accretion region on burst radiation, respectively. This approach enables assessment of contributions from corona-scattered photons versus direct photons from the neutron star surface.

During the PRE phase of bursts from 4U 1608-52 and 4U 1730-22, this model provides the best fit with physically acceptable parameters, performing as well as the f model but with more degrees of freedom and statistically superior during the PRE phase (lowest blackbody temperatures), as shown in Figure 3 [Figure 3: see original paper]. For soft-state bursts, the convolution thermal Comptonization model fits well assuming constant coronal parameters, i.e., burst photons scattered by a static corona. However, for higher-statistics observations like those from NICER, this model underperforms relative to the f model, possibly because coronal parameters vary during bursts—for instance, coronal temperature decreasing from tens to a few keV in low/hard states, with potential changes in optical depth τ or covering fraction f_s. Such variations would imply density and geometric evolution of the corona during bursts, requiring wide-band, large-area observations (e.g., joint NICER-HXMT) that are currently lacking.

4 Effect of Accretion Emission on Burst Radiation: Disk Obscuration and Accretion-Rate-Dependent Anisotropy

In observations of PRE burst spectra, peak flux generally reaches a local maximum near the radius peak, as theoretically predicted. However, for PRE bursts from 4U 1608-52 and 4U 1730-22 detected by HXMT, burst flux differs between photospheric lift-off and touchdown, with peak flux not coinciding with maximum photospheric radius. The flux deficit during the PRE rise phase is interpreted as the disk obscuring part of the neutron star surface, as illustrated in Figure 4 [Figure 4: see original paper]. Without bursts, the accretion disk near the neutron star surface obscures the lower hemisphere, leaving only the upper hemisphere visible. During bursts, the inner disk radius increases, revealing the previously obscured lower hemisphere.

Theoretically, burst radiation anisotropy should depend on accretion state, as the disk in low/hard states is thought to be truncated at larger distances, but no observational evidence supported state-dependent anisotropy before 2022. Since low/hard and high/soft states have different accretion environments (e.g., inner disk radii), bursts in these states should exhibit different anisotropy levels: flux deficits during PRE bursts should be observed in high accretion rate states but not in low accretion rate states. This prediction was confirmed by HXMT observations of 4U 1608-52 bursts, as shown in Figure 5 [Figure 5: see original paper]. PRE bursts in the high/soft state show disk obscuration, while those in the low/hard state do not. However, only one PRE burst was observed in the low/hard state, requiring further verification of this conclusion' s universality.

5 Summary and Outlook

Current Insight-HXMT scientific results on thermonuclear bursts primarily focus on broad-band spectral analysis, yielding numerous results on burst-accretion environment interactions. Timing results, such as burst oscillations and millihertz quasi-periodic oscillations, have been detected but remain limited. For example, HXMT detected 614 Hz burst oscillations in 4U 1608-52 bursts with low significance. Over the past two years, irradiation-induced difficulties in background estimation and calibration below 2 keV for HXMT' s low-energy telescope have emerged. Following the successful launch and normal operation of the Einstein Probe (EP), joint observations with EP' s follow-up telescope and HXMT will provide broad-band (0.5-250 keV), high-statistics spectral and timing results, advancing thermonuclear burst research.

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