Return of 4U 1730–22 after 49 yr Silence: The Peculiar Burst Properties of the 2021/2022 Outbursts Observed by Insight-HXMT

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Abstract

Staying in quiescence for 49 yr, 4U 1730–22 became active and had two outbursts in 2021 and 2022; 10 thermonuclear X-ray bursts were detected with Insight-HXMT. Among them, the faintest burst showed a double-peaked profile, placing the source as the seventh accreting neutron star (NS) exhibiting double-peaked type I X-ray bursts; the other bursts showed photospheric radius expansion (PRE). The properties of a double-peaked non-PRE burst indicate that it could be related to a stalled burning front. For the five bright PRE bursts, apart from the emission from the neutron star (NS) surface, we find the residuals both in the soft (<3 keV) and hard (>10 keV) X-ray bands. Time-resolved spectroscopy reveals that the excess can be attributed to an enhanced preburst/persistent emission or the Comptonization of the burst emission by the corona. We find, the burst emission shows a rise until the photosphere touches down to the NS surface rather than the theoretical predicted constant Eddington luminosity. The shortage of the burst emission in the early rising phase is beyond the occlusion by the disk. We speculate that the findings above are due to that the obscured part (not only the lower part) of the NS surface is exposed to the line of sight due to the evaporation of the obscured material by the burst emission, or the burst emission is anisotropic (ξ > 1) in the burst early phase. In addition, based on the fluxes of PRE bursts at their touchdown times, we derive a distance estimation as 9.0–12.4 kpc.

Unified Astronomy Thesaurus concepts: X-ray bursters (1813)

1. Introduction

Until 2022 June, there were three outbursts observed from 4U 1730–22: lasting ~6 months in 1972 detected by Uhuru (Cominsky et al. 1978; Forman et al. 1978), lasting 1 month in 2021 (Kennea et al. 2021; Kobayashi et al. 2021), and lasting 3 months in 2022, and all three with a peak flux of 100 mCrab in the soft X-ray band. In the interval between the first two outbursts, a bright X-ray emission in its quiescent state was observed by Chandra, which indicates its neutron star’s (NS) nature (Tom sick et al. 2007) and its distance estimation of ~10 kpc. In the second outburst, 49 yr after the first one, thermonuclear bursts were detected in 4U 1730–22 by NICER, which were identified as NS X-ray binaries (Bult et al. 2021). Its spin is around ν = 584.6 Hz (Li et al. 2022), based on the burst oscillation detection by NICER.

Type I X-ray bursts, also named thermonuclear X-ray bursts, are triggered by unstable thermonuclear burning of the accumulated accretion fuel from a low-mass X-ray binary (LMXB) hosting an NS (for reviews, see Lewin et al. 1993; Cumming 2004; Strohmayer & Bildsten 2006; Galloway et al. 2008). Bursting behavior is known to be extremely variable and violent, and most bursts manifest as a fast rise (seconds), an exponential decay (~10 s to minutes) and a peak luminosity up to the Eddington luminosity. Most bursts are single peaked, except the brightest ones that show photospheric radius expansion (PRE; due to radiation pressure).

For the PRE bursts, the radiation pressure of the burning exceeds the NS gravitational force in the photosphere, resulting in an increase of the photosphere radius and a decrease of the photosphere temperature in an adiabatic expansion; as the expansion ceases, the lifted photosphere drops on the NS surface and an increase of the photosphere temperature is shown in an adiabatic compression (Grindlay et al. 1980).

The above spectral shift causes a dip in the temperature, a spike in the radius, and a plateau in the luminosity in the PRE phase. In the light curves, a single-peaked structure is typically observed with soft X-ray instruments, e.g., Swift/X-ray Telescope, Chandra, XMM-Newton, NICER, AstroSat/Soft X-ray Telescope, and Hard X-ray Modulation Telescope (HXMT, also dubbed as Insight-HXMT)/Low Energy X-ray Telescope (LE), but a double-peaked structure is often seen with hard X-ray instruments because of the passband limitation, e.g., INTEGRAL, Swift/Burst Alert Telescope, RXTE/HETE, RXTE/Proportional Counter Array, AstroSat/LAXPC, Insight-HXMT/Medium Energy X-ray Telescope (ME), and Insight-HXMT/High Energy X-ray Telescope (HE).

The vast majority of the bursts with luminosity below the Eddington limit show a single peak in the light curves. Non-PRE bursts with double-peaked or triple-peaked structures
have been detected in several bursters, e.g., 4U 1636–536 (Bhattacharyya & Strohmayer 2006; Zhang et al. 2009; Li et al. 2021), 4U 1608–52 (Penninx et al. 1989; Jaisawal et al. 2019; Guver et al. 2021), GX 17+2 (Kuulkers et al. 2002), XTE J1709–267 (Jonker et al. 2004), MXB 1730–335 (Rapid Burster) (Bagnoli 2014), and GRS 1741.9–2853 (Pike et al. 2021). Potential explanations include multiple generations/release of thermonuclear energy, absorption/scattering from an accretion-disk corona, and flame spread stalling on the NS surface (e.g., ignites at high latitude but stalls on the equator; see Pike et al. 2021).

Since the bursts occur on the NS surface, the interplay between the NS surface emission and the accretion environment should be taken into account. In the past 10 years, among thousands of observed bursts from the 118 bursters,8 impacts on the accretion process by bursts have been observed, i.e., an enhancement/deficit (Worpel et al. 2013; Ji et al. 2014; Worpel et al. 2015; Bult et al. 2021) at the soft X-ray band, a shortage at the hard X-ray band (Maccarone & Coppi 2003; Chen et al. 2012; Ji et al. 2013), a bump peaking at 20–40 keV, and/or discrete emission by reflection from the accretion disk (Ballantyne & Strohmayer 2004; in’t Zand et al. 2013; Keek et al. 2014).

In this work, using broad energy band capabilities of Insight-HXMT in 1–50 keV, we study 10 bursts from 4U 1730–22: one double-peaked burst and nine PRE bursts. The present paper focuses on the nature of these bursts and also examines the effect of the burst emission on the accretion environment using a variable persistent flux method and Comptonization of the burst emission by the surrounding hot electrons. We describe the observations and data reduction in Section 2. We present our analysis methods, spectral results on the outburst, and spectral/temporal properties of the bursts in Section 3. Finally, a discussion and understanding of the above results are given in Section 4.

2. Observations and Data Reduction

2.1. Insight-HXMT

The Insight-HXMT (Zhang et al. 2020) excels in its broad energy band (1–250 keV) and a large effective area in the hard X-ray energy band. It carries three collimated telescopes: the HE (Liu et al. 2020; phoswich NaI/CsI, 20,250 keV, ∼5000 cm²), the ME (Cao et al. 2020; Si pin detector, 5–40 keV, 952 cm²), and the LE (Chen et al. 2020; Swept Charge Device (SCD) detector, 112 keV, 384 cm²). Under the quick readout system of Insight-HXMT detectors, there is little pileup effect at the burst peak, e.g., the fraction of pileup events of Insight-HXMT/LE is ∼1% for the brightest sources such as Sco X–1 with a maximum count rate ∼18,000 cts s⁻¹ (>10 Crab at 1–10 keV; Chen et al. 2020). The dead times for ME and HE are <260×10⁻⁶ s and <10×10⁻⁶ s, respectively. Insight-HXMT Data Analysis software (HXMTDAS) v2.059 is used to analyze the data.

As shown in Figure 1, for the two outbursts in 2021 and 2022, Insight-HXMT has observed 4U 1730–22 with 74 observations ranging from P04140101001-20210707-01-01 to P051400200101-20220430-01-01 with a total observation time of 184 ks. These observations covered the peak/decay phase of the outburst in 2021 and the plateau of the outburst in 2022.

We note that the default good-time-interval (GTI) selection criteria of LE are very conservative because of the influence of light leaks. To obtain a complete sample of bursts, light curves are extracted without filtering GTIs. Burst-like fluctuations that may be caused by a sharp variation of the background, when the telescope passes the South Atlantic Anomaly (SAA), are excluded.

As shown in Table 1, 10 bursts are found in ME and HE data with a peak count rate ∼300–600 cts s⁻¹ and ∼100–200 cts s⁻¹; among them, 6 bursts are also found in LE data with a peak count rate ∼300–1200 cts s⁻¹. For each burst, we use the time of the ME count rate peak as a reference (0 s in Figure 3) to produce light curves and spectra. We extract time-resolved spectra of LE, ME, and HE with a bin size of 0.5 s starting from the onset of each burst. As a conventional procedure, the preburst emission (including the persistent emission and the instrumental background) is extracted, which is taken as the background when fitting the spectra during bursts. In practice, for each burst, we define the time interval between 70 and 20 s before the burst peak as the time window of the preburst emission, i.e., [−70 s, −20 s].

For the outburst in 2022, the last eight bursts are located at the plateau of the outburst. During this outburst, there are six near-simultaneous Insight-HXMT and NICER observations. Since these spectra are very similar and the derived model parameters are well consistent with each other, we chose the first near-simultaneous observation to show the result, i.e., P051400200102-20220430-01-01 (Insight-HXMT) and 4639010134 (NICER; see Section 2.2), respectively. Thus, we get 600 s and 2300 s GTI of LE and ME in this obsid. The HE spectrum is not involved in the joint spectral fitting of the persistent emission, since the HE detection falls below the systematic error of the background model. Please note that the HE spectra are involved in the burst analysis, since the peak fluxes of the burst detected by HE are much brighter than the persistent emission.

The other results, e.g., the persistent spectra, background, and net light curves are obtained following the recommended procedure of the Insight-HXMT Data Reduction, which are screened with the standard criterion included in Insight-HXMT pipelines: lepipeline, mepipeline, and hepipeline.

For the persistent emission spectral fitting of LE and ME, the energy bands are chosen to be 2–7 keV and 8–20 keV. The spectra are rebinned by the ftool fgrouppha optimal binning algorithm with a minimum of 25 counts per grouped bin (Kaastra & Bleeker 2016).

The LE background model works only in a certain temperature range (Li et al. 2020). This leads to some uncertainties below 2 keV caused by the electronic noise when the temperature exceeds this range after the middle of the year 2019. During a burst with a timescale of tens of seconds, the temperature fluctuation of LE is so small that it can be neglected. The resulting electronic noise of the preburst spectrum is the same as that of burst spectra. Therefore, the influence of the electronic noise can be canceled out when we take the preburst spectrum as the background of burst spectra. In this case, the energy band of LE can be extended to 1–10 keV in the burst analysis.

The ME and HE energy bands used in burst spectral fitting are 8–30 keV and 25–50 keV, respectively. The slices of burst

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8 https://personal.sron.nl/~jeanz/bursterlist.html
9 http://hxmtweb.ihep.ac.cn/
spectra of LE, ME, and HE are rebinned by ftool grppha with a minimum of 10 counts per grouped bin, based on the limited photons of the burst slice spectra due to the short exposure time. We added a systematic uncertainty of 1% to the Insight-HXMT spectra to account for the systematic uncertainties in the detector calibrations (Li et al. 2020).

2.2. NICER

For the two outbursts, NICER also performed high-cadence observations on 4U 1730–22. Lu et al. (2023) reported 16 type I X-ray bursts from 4U 1730–22 observed by NICER, and most of them exhibited PRE. Unfortunately, there is no burst of 4U 1730–22 simultaneously detected by NICER and Insight-HXMT. There are two bursts detected by Insight-HXMT during the outburst in 2021, but there is no LE data for both of them. Without the LE data, the canonical blackbody model could fit the burst spectra well, and there is no need for adding another component during the fitting, e.g., the variable persistent emission. Under this condition, only the persistent spectra of the outburst in 2022 are extracted for fitting, and the derived parameters of the model are used to fit the burst spectra. Thus, the joint spectral fitting of the outburst in 2021 is not given in this work. For the outburst in 2022, since several bursts have LE data, the variable persistent emission has to be added in the burst spectral fitting. Thus, the joint spectral fitting results of the outburst in 2022 are given in this work. There are several NICER observations in the plateau of the outburst of 2022, and we choose an overlapped obsid of 4639010134.

![Figure 1. Top panel: daily light curves of 4U 1730–22 by MAXI (black) during the outbursts in 2021 and 2022 in 220 keV. The bursts are indicated by vertical lines. Bottom panel: light curves of 4U 1730–22 by LE (blue) and ME (red), which are rebinned by one obsid (~10,000 s).](image)

| No. | Obsid | Burst Peak Time | $F_{peak}$ | $E_{b}$ | PRE |
|-----|-------|-----------------|------------|---------|-----|
| 1   | P041401100410-20210709-02-01 | 59404.30775 | 3.4 ± 0.3 | 26.9 ± 1.0 | Y   |
| 2   | P041401100801-20210716-01-01 | 59411.72027 | 4.6 ± 0.4 | 56.6 ± 1.5 | Y   |
| 3   | P051400200102-20220430-01-01 | 59699.26105 | 4.2 ± 0.2 | 30.8 ± 0.5 | Y   |
| 4   | P051400200402-20220503-01-01 | 59702.29225 | 3.0 ± 0.2 | 25.3 ± 0.4 | Y   |
| 5   | P051400200601-20220505-01-01 | 59704.34837 | 2.9 ± 0.2 | 32.7 ± 0.5 | Y   |
| 6   | P051400200701-20220506-01-01 | 59705.15499 | 4.2 ± 0.2 | 33.5 ± 0.5 | Y   |
| 7   | P051400200801-20220507-01-01 | 59706.25535 | 4.9 ± 0.3 | 42.2 ± 0.8 | Y   |
| 8   | P051400200902-20220508-01-01 | 59707.34785 | 3.7 ± 0.4 | 27.0 ± 0.8 | Y   |
| 9   | P051400210103-20220509-01-01 | 59708.45082 | 1.7 ± 0.2 | 12.7 ± 0.4 | N   |
| 10  | P051400210102-20220510-01-01 | 59709.33134 | 3.9 ± 0.4 | 25.5 ± 0.8 | Y   |

Notes.

a The bursts were not detected by LE.
b The burst with a double-peaked profile.

![Table 1](image)

| Obsid | Start Time | GTI (s) |
|-------|------------|---------|
| 4639010134 | 59700.04657 (2022-05-01T01:02:20) | 453 |

![Table 2](image)
background is estimated using the tool nibackgen3C50 using ftool XSELECT to extract light curves and spectra. The \( \chi^2 \) values of the fit are given in the following sections based on the PRE bursts. The thcomp parameters of the electron temperature \( kT_e \) and optical depth \( \tau \) are \( 3.61^{+0.42}_{-0.57} \) keV and \( 7.8^{+1.0}_{-0.9} \). The scattered/covering fraction \( f_{sc} \) is derived as 0.929. However, when we extract the confidence region for \( f_{sc} \), the parameter is pegged at hard limit \( f_{sc} \). It is then frozen at 1; as expected, the results are consistent with each other within the parameter’s error bar. The derived hydrogen column density \( N_H \) is \( 0.53 \pm 0.01 \times 10^{22} \text{ cm}^{-2} \). The constants of LE and ME are \( 0.93 \pm 0.01 \) and \( 0.83 \pm 0.05 \), respectively. For the ME constant value, this large degree of deviation from unit is caused by the uncertainty of the background model. The Insight-HXMT background model is based on the spectrum of the blind detectors (Liao et al. 2020a, 2020b; Guo et al. 2020). If the source is very faint, e.g., fainter than \( 50–100 \) mCrab (just like this work, \( 40 \) mCrab in ME’s energy band), the source flux (in units of \( \text{erg cm}^{-2} \text{ s}^{-1} \)) is comparable with that of the blind detectors. Under this condition, the uncertainty will be magnified. The influence on the spectral shape is insignificant. Based on joint observations with NuSTAR or other telescopes (in a private communication with the Insight-HXMT team), the inferred bolometric flux in a 0.01–1000 keV band is \( 3.08^{+0.04}_{-0.03} \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \) corresponding to \( 20.5\% \) \( L_{\text{edd}} \) at distance of 10 kpc, with \( L_{\text{edd}} = 1.8 \times 10^{38} \text{ erg s}^{-1} \).

The other scenario, i.e., substituting the diskbb component with a blackbody component in the aforementioned convolution model, is also attempted. Taking this approach, spectral fits yield roughly the same thcomp parameters and reduced \( \chi^2 = 0.93 \) (the same d.o.f.). However, the derived blackbody radius is \( 80 \pm 3 \text{ km} \), which is far greater than the NS radius.

3. Analysis and Results

3.1. Fitting the Joint Insight-HXMT/NICER Spectrum of Persistent Emission

We fit the joint NICER and Insight-HXMT (LE and ME) spectra with an absorbed convolution thermal-Comptonization model (with input photons contributed by the spectral component diskbb), available as thcomp (a more accurate version of nthcomp; Zdziarski et al. 2020) in XSPEC, which is described by the optical depth \( \tau \), electron temperature \( kT_e \), and scattered/covering fraction \( f_{sc} \). The hydrogen column (thbs) in XSPEC accounts for both the line-of-sight column density and any intrinsic absorption near the source. The seed photons are in the shape of diskbb since the thcomp model is a convolution model, and a fraction of Comptonization photons are also given in the model. Normalization constants are included during fittings to take into account the intercalibrations of the instruments. We keep the normalization factor of the NICER data with respect to the LE and ME data to unity.

Using the model above, we find an acceptable fit: reduced \( \chi^2 = 0.91 \) (d.o.f. 160; Figure 2 and Table 3), with the inner disk radius \( R_{\text{diskbb}} \) and temperature \( kT_{\text{in}} \) found to be \(~ 19.3^{+1.6}_{-1.3} \text{ km} \)(with a distance of 10 kpc and an inclination angle of \( 0^\circ \)) and \( 0.68^{+0.39}_{-0.34} \text{ keV} \), respectively. Please note that the distance is given in the following sections based on the PRE bursts. The thcomp parameters of the electron temperature \( kT_e \) and optical depth \( \tau \) are \( 3.61^{+0.42}_{-0.57} \) keV and \( 7.8^{+1.0}_{-0.9} \). The scattered/covering fraction \( f_{sc} \) is derived as 0.929. However, when we extract the confidence region for \( f_{sc} \), the parameter is pegged at hard limit \(~ 1\). It is then frozen at 1; as expected, the results are consistent with each other within the parameter’s error bar. The derived hydrogen column density \( N_H \) is \( 0.53 \pm 0.01 \times 10^{22} \text{ cm}^{-2} \). The constants of LE and ME are \( 0.93 \pm 0.01 \) and \( 0.83 \pm 0.05 \), respectively. For the ME constant value, this large degree of deviation from unit is caused by the uncertainty of the background model. The Insight-HXMT background model is based on the spectrum of the blind detectors (Liao et al. 2020a, 2020b; Guo et al. 2020). If the source is very faint, e.g., fainter than \( 50–100 \) mCrab (just like this work, \( 40 \) mCrab in ME’s energy band), the source flux (in units of \( \text{erg cm}^{-2} \text{ s}^{-1} \)) is comparable with that of the blind detectors. Under this condition, the uncertainty will be magnified. The influence on the spectral shape is insignificant. Based on joint observations with NuSTAR or other telescopes (in a private communication with the Insight-HXMT team), the inferred bolometric flux in a 0.01–1000 keV band is \( 3.08^{+0.04}_{-0.03} \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \) corresponding to \( 20.5\% \) \( L_{\text{edd}} \) at distance of 10 kpc, with \( L_{\text{edd}} = 1.8 \times 10^{38} \text{ erg s}^{-1} \).

The other scenario, i.e., substituting the diskbb component with a blackbody component in the aforementioned convolution model, is also attempted. Taking this approach, spectral fits yield roughly the same thcomp parameters and reduced \( \chi^2 = 0.93 \) (the same d.o.f.). However, the derived blackbody radius is \( 80 \pm 3 \text{ km} \), which is far greater than the NS radius.

3.2. Burst Light Curves by Insight-HXMT

3.2.1. The Light Curve of the Double-peeked Burst

We show the LE/ME/HE light curves in Figure 3 with a time resolution of 0.5 s. The burst profiles exhibit a typical fast rise and slow (exponential) decay in the X-ray band. For the faintest burst, burst #9, there is a double-peeked structure with an interval between the peaks of \(~ 10 \text{ s} \). Both for the light curves of LE and ME, the peak flux of the first subburst is \(~ 2/3 \) of that of the second one. The rising rate of the two subbursts is similar for the ME: \( 50 \text{ cts s}^{-1} \) increases every 0.5 s, but the decay of the first subburst is much faster than the second one.

Some will doubt the reliability of burst #9, i.e., since the burst’s behavior is beyond the normal burst, the reason that we believe its authenticity is given here. For LE and ME, each of them contains three independent boxes, each with elongated rectangle fields of view (FoVs) and different orientations (differing by \( 60^\circ \)). For pointing observations, the target source is located at the center of the FoVs. If the X-ray emission is from the target source, the fluxes of the three boxes should be roughly the same; otherwise, they are from other nearby sources in the FoVs. If the detected signal is from some sort of background flare, e.g., charged particles, the ratio between the normalization constants of LE and ME derived from the spectral fitting will deviate significantly from unit (by a factor of 2 or much larger). In this work, for burst #9, roughly the
same count rates in three boxes of LE or ME and roughly the
same values of the normalization constants derived from the
spectral fitting denote that the emission is its X-ray’s origin and
should originate from 4U 1730–22.

3.2.2. The Light Curve of the PRE Burst

For the five bursts with detection of LE, bursts #3–#7, the
light curves of LE present a single-peaked structure. Moreover,
the hard X-rays (ME and HE) lag behind the soft X-rays (LE)
by ∼ 1 s; the peak times of the ME and HE light curves are
consistent with each other. The brightest burst, burst #7, shows
a double-peaked profile in ME and HE light curves, which is a
typical characteristic of a PRE burst. For other bright bursts,
e.g., bursts #1, #2, #4, and #6, there are only hints of
another peak at just the onset of the burst, i.e., marginal double-
peaked profiles. For bursts #8 and #10, these bursts lack LE
data; however, their ME and HE peak fluxes are higher/
comparable with the PRE bursts #4–#6. Accompanied by
the larger radii in the burst peak times, these bursts are identified as
PRE bursts.

3.3. Broadband Spectra of Burst Emission by Insight-HXMT

When we fit the burst spectra, we estimate the background
using the emission before the burst, i.e., assuming the persistent
emission is unchanged during the burst. To account for the
effective area calibration deviation, a constant is added to the
model. At the first attempt, for ME, the constant is fixed to 1,
the others are variable during spectral fitting. The fits indicate
that most of the constants of HE and some of the constants of
LE are not convergent, owing to the low-significance data.

Under this situation, the constants of LE and HE are fixed at 1
for the combined spectral fitting. Based on in-flight calibrations
and cross-calibrations with other X-ray telescopes, e.g., NICER
and NuSTAR, the effective areas of the three main payloads
(LE, ME, and HE) of Insight-HXMT are revised and reliable.

Table 3

| N_{HT} (10^{22} cm^{-2}) | τ     | kT_1 (keV) | f_{lc} | kT_{bc} (keV) | N_{diskbb} | χ^2 \_d.o.f |
|-------------------------|-------|------------|--------|----------------|------------|-------------|
| 0.53^{+0.01}_{-0.01}   | 7.8^{+1.9}_{-0.9} | 3.61^{+0.22}_{-0.57} | 0.929^{+0.12}_{-0.01} | 0.68^{+0.39}_{-0.34} | 370^{+340}_{-62.8} | 146.1/160   |

Figure 3. Light curves with preburst emission subtracted of the 10 type I X-ray bursts detected in the Insight-HXMT observation of 4U 1730–22 with a time bin of 0.5 s by LE (black), ME (red), and HE (green). The light curves of LE and ME are in their full energy bands; the HE light curves result in 20–50 keV.

We follow the classical approach to X-ray burst spectroscopy by subtracting the persistent spectrum and fitting the net spectrum with an absorbed blackbody, as shown in Figure 4. For bursts detected by LE, ME, and HE (bursts #3–#7), the d.o.f. are 35–100; for bursts that lack the LE data (bursts #1, #2, #8, and #10), the d.o.f. are 20–40. In the decay phase, such a spectral model generally results in acceptable goodness of fit, with a mean reduced $\chi^2_r \sim 0.5–1.5$ (d.o.f. 20–50) and a null hypothesis probability of $>5 \times 10^{-2}$. However, we also note that significant residuals are shown below 3 keV and above 10 keV, as shown in Figure 5, particularly for some of the spectra in the PRE phase with reduced $\chi^2_r > 1.5$ (with d.o.f. up to 60–80).

From the fitting results by the absorbed blackbody, among the 10 bursts, 9 bursts are PRE bursts with peak radii 12–40 km, peak temperatures $\sim 3$ keV, and peak bolometric fluxes $3–5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. The model parameters of the bursts...
without LE detection, i.e., bursts #1, #2, #8, and #10, show greater errors than those of the bursts with LE detection, which prevents us from adopting other models. A similar situation exists in the faintest burst, burst #9.

### 3.3.2. Fit of the Spectra of Bursts by the \( f_a \) Model

To reduce the residuals, we first consider the \( f_a \) model to fit the bright bursts that were detected simultaneously by LE, ME, and HE: burst #3–#7. Following Worpel et al. (2013) we then include an additional component for fitting the variable persistent emission. We assume that during the burst the spectral shape of the persistent emission is unchanged, and only its normalization (known as the \( f_a \) factor) is changeable. As reported earlier by RXTE and NICER, the \( f_a \) model provides a better fit than the conventional one (absorbed blackbody). We compare the above two models using the F-test. In some cases, the \( f_a \) model significantly improves the fits with a \( p \)-value $\sim 10^{-5}$.

As shown in the left panels of Figures 6, 7, 8, 9, and 10, the spectral fitting results from these two models have differences mainly around the PRE phase. By considering an additional factor \( f_a \), the burst blackbody flux tends to slightly decrease, and the temperature becomes higher but the radius shrinks. Using the fluxes of the touchdown time of the five bursts $2.07 \pm 0.22$–$3.93 \pm 0.22 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$, and assuming the empirical Eddington luminosity of $3.8 \times 10^{38} \text{ erg s}^{-1}$.

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**Figure 4.** Results of the spectral fits of time-resolved spectra of the 10 bursts detected from 4U 1730–22 during its 2021 and 2022 outbursts. All of the bursts except the second-to-last burst show photospheric radius expansion.
parameters are fixed at the persistent emission fit results. The inverse Compton scattering process on the burst photons by the corona was also used to fit the stacked burst spectra of Chandra and RXTE in 0.5–40 keV from GS 1826–238 (Thompson et al. 2005). In their approach, the seed photons’ temperature of the Compt model is tied with the temperature of the blackbody/burst emission. The updated Comptonization model is also used in the burst spectral fitting in 4U 1608–52 (Chen et al. 2022). Thus, the convolution thermal-Comptonization model (with an input seed photon spectrum of blackbody) has the same d.o.f. as the canonical blackbody model and more d.o.f. than the $f_a$ model. The bb and thcomp represent the burst emission from the NS photosphere and a corona influence on the burst emission. This model allows us to evaluate the contribution from both the photons upscattered by the corona and direct from the NS surface. In the burst results from GS 1826–238 (Thompson et al. 2005), by stacking six bursts of Chandra and three bursts of RXTE, the burst spectra were fit with two Comptt models (one from the corona and another from the boundary layer, BL) and a blackbody model; assuming the first Comptt component (the corona) was unchanged during the burst, the parameters of the blackbody and the second Comptt model (the BL) were derived. However, in this work, the faintness of the burst emission prevents us from allowing the change of thcomp’s parameters or from distinguishing the emission from the corona and the BL. Thus, we use the corona to present the Compton emission.

As shown in the right panels of Figures 6, 7, 8, 9, and 10, in the PRE phase, this model provides the best fit and yields physically acceptable spectral parameters; the obtained best-fit parameters are given in the right panels. We find that this convolved thermal-Comptonization model provides equally good results as the $f_a$ model. As mentioned above, the free/unfixed parameters include the blackbody temperature $kT_{bb}$ and the normalization $N_{bb}$. The trend of the parameters is similar to the $f_a$ model, but with a greater change. Compared to the $f_a$ model results, the maximum radius $R_{bb}$ is up to 83.7$^{+10.4}_{-8.2}$ km, and the minimum temperature $kT_{bb}$ is lowered to 0.81 ± 0.05 keV. From the convolved thermal-Comptonization model, the source distance is estimated as 11.2 kpc with the average flux of 2.51 ± 0.08 $\times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ derived at the touchdown time of the five bursts. Other scenarios, i.e., burst reflection by the disk and NS atmosphere model carbatm/hatm (Suleimanov et al. 2011, 2012, 2018) in XSPEC, are also tried to fit the burst spectra, as we did in Chen et al. (2019). However, neither could alleviate the residuals at soft X-ray and hard X-ray bands simultaneously.

Also, taking the brightest burst (burst #7; Figure 10), for example, the nine data points in the PRE phase; for the thcomp model, seven data points of the derived reduced $\chi^2$ of the thcomp model are smaller than that of the blackbody model. Thus, most of the fits by the thcomp model are more improved than the blackbody model in the PRE phase.

3.3.4. No Cooling between the Subbursts of the Double-peaked Burst

As shown in Figure 4, for the first subburst of the double-peaked burst (burst #9), the temperature and the radius of the blackbody reach 1.9 ± 0.1 keV and 9.5 ± 1.4 km. After that, the radius drops but the temperature stays at a high value: we average the eight data points (4 s) during the flux dip, and get an average temperature of 1.9 ± 0.1 keV and an average radius of 5.5 ± 0.6 km. For the second subburst, it reaches peak flux

(Kuulkers et al. 2003), we derive the source distance of 9.0–12.4 kpc. For simplicity, we use a distance of 10 kpc to calculate the luminosity and blackbody radius.

Taking the brightest burst (burst #7; Figure 10) for example, the nine data points are in the PRE phase; using the F-test common in XSPEC to calculate the F-statistic values and probabilities (the blackbody and the $f_a$ model) and we get F-statistic values 0.11, 21, 2.5, 17, 19, 8.9, 15, 1.2, and 2.2 and the probabilities 0.7, $3 \times 10^{-5}$, 0.11, $9 \times 10^{-5}$, $3.7 \times 10^{-5}$, $4 \times 10^{-3}$, $2 \times 10^{-4}$, 0.3, and 0.14, with d.o.f. 43–78. Thus, more than half of the fits by $f_a$ model are significantly improved than that of the blackbody model.

The $f_a$ factor reaches a maximum of 6 ± 1 when the radius reaches its peak, as shown in Figure 11. The large error bars of $f_a$ prevent us from further analysis. During the PRE phase, the radius is up to ~30 km, which is 4 times larger than the radius measured at touchdown time ~8 km (assuming a distance of 10 kpc). This is typical of a moderate photospheric expansion.

3.3.3. Fit of the Spectra of Bursts by the Convolution Thermal-Comptonization Model

Since the burst photons could also be affected by the corona, we thus check if the model used in the persistent emission could be the same as the burst emission. By taking the preburst emission as the background emission, the burst spectra are fitted by the model $\text{thabs}^{*}\text{thcomp}^{*}\text{bb}$, in which the thcomp

![Figure 5](image-url)
up to 30% brighter than the first one. After that, the burst decays with temperature dropping, e.g., \( T_{bb} = 1.0 \pm 0.2 \text{ keV} \) at \(-7.5 \text{ s} \) at the end of the burst (which is not shown in Figure 4). The lack of temperature dropping between the two subbursts is reminiscent of the lack of measured cooling in the decay phase of Cyg X–2, GX 17 + 2, and IGR J17480–2446 (Linares et al. 2011), which is caused by the loss of sensitivity when persistent emission is high and the NS photosphere cools down during the tails of the bursts, but by an amount below the detection limit. However, their ratios (\( \beta \)) between peak-burst and persistent luminosities are \(<1\); for burst \#9 of this work, \( \beta \) is \( \sim 6 \), which is much larger than that of the three sources above. Accompanied by the cooling detected in the decay phase, it is unlikely that the high persistent emission causes the lack of temperature dropping between the two subbursts.

3.4. Rising Bolometric Flux during the PRE Phase

In Figure 12, we explore the relation between the bolometric flux, \( F_{bb} \), and the blackbody temperature, \( kT_{bb} \), using the parameters derived from the \( f_x \) model for the five bursts. If the whole NS surface emits as a single-temperature blackbody and a constant color correction factor, the burst flux \( F \) should scale as \( T_{bb}^4 \) in the flux–temperature diagram, and the slope represents the emitting area in the double logarithmic coordinates (Guver et al. 2012). The diagram for the convolution thermal-Comptonization model is not given, since the trend is very similar to the \( f_x \) model. The diagonal line in the plot represents the line of constant radius, \( R_{bb} = 6.9 \ \text{km} \), assuming a distance \( d = 10 \ \text{kpc} \) to the source, which is derived from the fitting of the decay phase of the bright burst (burst \#7) in the diagram of \( F_{bb} \) versus \( T_{bb} \) by a model \( F_{bb} \propto R_{bb}^2 T_{bb}^4 \).

From the diagram, in the decay phase (gray points in Figure 12), it is apparent that the bursts follow the expected relation \( F_{bb} \propto R_{bb}^2 T_{bb}^4 \) with a fixed \( R_{bb} = 6.9 \ \text{km} \). In the PRE phase, i.e., the photospheric radius larger than the NS radius (blue points in Figure 12), the bursts depart from the \( F_{bb} \propto R_{bb}^2 T_{bb}^4 \) relation and are located to the left of the line of \( R_{bb} = 6.9 \ \text{km} \), which indicates larger radii. There are two junctions between the blue points and the red line: the upper one corresponds to the touchdown time, and the lower one corresponds to the time when the photosphere is just lifted from the NS surface. We notice that the fluxes of the two junctions are different, i.e., the upper one is at least twice as bright as the lower one, e.g., the two fluxes for burst \#3 are \( 0.7 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( 2 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \), which should be the same value since both of them are the values of the Eddington limit. We notice that the time bin (0.5 s) in the time-resolved spectroscopy is much coarser than the rise timescales, and thus would cause the underestimation of the flux of the first data point since the onset of the burst should much fainter than the Eddington limit. In the comparison between the fluxes of the lift-up and the touchdown time of the photosphere, if we replace the first data points by the second data points, the ratios between the fluxes of the lift-up
and the touchdown time are <2, which falls within the range of the disk occlusion.

4. Discussion

In this work, we have presented a spectral analysis of 10 bursts and persistent emission from 4U 1730–22 in its 2021 and 2022 outbursts observed by NICER and Insight-HXMT. For the persistent emission in the outburst of 2022, the joint spectra are well fitted by an absorbed convolution thermal-Comptonization model, almost the whole of the disk emission is upscattered by the corona, the BL, or the spreading layer (SL). In this work, the derived thcomp’s parameters cannot distinguish the emission from the corona, the boundary layer, or the spreading layer. Thus, we use the corona to present the Compton emission. The faintest burst shows a double-peaked structure and no cooling in the interval between the two subbursts. For the PRE bursts, the X-ray burst shows a significant spectral deviation/excess both at <3 keV and >10 keV from an absorbed blackbody in the PRE phase. The residuals could be flattened by the $f_{\gamma}$ model and the convolution thermal-Comptonization model. For the PRE bursts, the bolometric flux of the touchdown time is about twice as bright as that of the rising part of the PRE phase.

4.1. Stalled Propagation of the Hot Area during the Faint Burst

The faint burst, burst #9, which is not a PRE burst, does not adhere to the canonical fast-rise and exponential-decay structure of most type I X-ray bursts, instead showing a double-peaked structure. As the bolometric flux and radius exhibit the same double-peaked profile, the temperature instead shows a plateau between the two subbursts. These features are different from the double-peaked burst with about 1 s or 4 s dips with an amplitude of 25% or 40% detected from 4U 1608–52 in 1984 (Penninx et al. 1989) and 2017 (Guver et al. 2021), or the double-peaked burst with the radius increasing monotonically with time from GRS 1741.9–2853 (Pike et al. 2021) and 4U 1636–536 (Bhattacharyya & Strohmayer 2006), or the double-peaked burst with the temperature decreasing monotonically with time during the interval of the two subbursts from GX 17 + 2 (Kuulkers et al. 2002), or the triple-peaked burst with a temperature dip during the interval of the subbursts (Zhang et al. 2009).

Since there is an absence of temperature dip, but with a dip in the radius between the two subbursts, it is natural to consider that it is due to a stalled propagation of the hot area, which still burns in the stalled location, e.g., ignites on high latitude and stalls in the equator (Bhattacharyya & Strohmayer 2006). Along with the stalling of the burning front, the NS surface is cooled very fast (e.g., the helium-rich burning material has a fast cooling timescale) except the stalled area where the material still burns. From a distant observer, there is only one hot area burning between the two subbursts, i.e., a small radius and a high temperature. The other scenario is that the first peak of burst #9 is a precursor. The precursor only burns part of the material, and for some reason stops the burning. It may also be a failed PRE burst, since the sum of the two peaks has a count rate comparable to that of the PRE. In such a scenario, the entire power is released in two steps: first by partial burning of
the fuel, leading to the preceding subburst, and then by burning of the entire NS surface.

4.2. Evidence of Obscured NS Surface during Outbursts

In theory, for the PRE bursts, there are at least two moments that the hot spot just covers the whole NS surface: the photosphere lift-up point and the touchdown point (Shaposhnikov et al. 2003). Because of the fasting rise on the onset of PRE bursts, particularly most of them with a large portion of helium, which causes a much shorter timescale of the rising phase; the latter is usually used to derive the NS radius, but the former is difficult to use to derive the NS radius due to the short rising time, i.e., the rising time is too short to accumulate enough photons for a spectral fitting. The fast-rising timescale and the lack of the just lifting-up time is also detected in XTE J1702–462 (Lin et al. 2009), which is similar to the bursts of 4U 1730–22.

Assuming the photosphere emission is isotropic, the Eddington luminosity measured by a distant observer is dependent on the burning material, effective temperature, and radius of the photosphere, e.g., Equation (7) of Galloway et al. (2008). Based on this equation, for the pure helium burning at the NS surface, i.e., at just the lift-up time and the touchdown time of the photosphere, the observed bolometric flux should be the same. In the PRE phase, the flux observed should be higher than the above two values due to the redshift correction, e.g., the observed bolometric flux with $R = 30$ km is $\sim 20\%$ higher than that with $R = 10$ km. In the observations of the time-resolved spectral of 246 PRE bursts by RXTE (Galloway et al. 2008), the vast majority of the fluxes reached their maximums close to the times of peak radii, which does follow the equation above. However, for the PRE bursts of 4U 1730–22, the fluxes reached their maximums close to the touchdown times, rather than the times of peak radii, which is different with the behavior of the PRE burst samples (Galloway et al. 2008) and violates the model’s prediction above.

The above results are based on the assumption that the emission is isotropic, e.g., absence from obscuration by the accretion disk or Comptonization by the corona. Please note that, here, the burst emission’s anisotropy is caused by the obscuration by the disk or other structures around the NS surface, rather than the anisotropy caused by the nonuniform temperature on the NS surface. However, in theory, Poynting–Robertson drag could drain the inner accretion disk by taking away the momentum of the accretion matter, hence enlarging the local accretion rate (in’t Zand et al. 2013; Worpel et al. 2013, 2015), which is faster than it is being refilled (Stahl 2013; Fragile et al. 2020). Assuming that a dynamical evolution of the disk geometry causes this phenomenon, i.e., the lower NS hemisphere that is obscured before the burst (the burst PRE phase) and appears from the disk after the burst–disk interaction, as shown in Figure 1 of Shaposhnikov et al. (2003) and Figure 7 of Chen et al. (2022), the inclination angle is derived from the equation $\frac{F_{\text{rise}}}{F_{\text{rise}}^{\text{obs}}} = (1 + \cos i)/2$ (Shaposhnikov et al. 2003; Shaposhnikov & Titarchuk 2004), in which $F_{\text{rise}}$ and

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**Figure 8.** Same as Figure 6, but for burst #5.
\( F_{\text{decay}} \) are the blackbody fluxes detected at the rising phase and decaying phase, respectively.

However, in this case, for the bright bursts \#3, \#4, \#6, and \#7, the ratio \( \frac{F_{\text{rise}}}{F_{\text{decay}}} \) is equal to or less than 0.5, e.g., in Section 3.4, for burst \#3, the flux ratio is 0.7/2 = 0.35, which is out of the allowed range 0.5–1. Please note that the small values of the ratio could be related to the underestimation of the flux of the first data point since the onset of the burst should be much fainter than the Eddington limit. Since the disk could only obscure at most half of the burst emission, another structure between the NS surface and our line of sight should be considered if the ratio were less than 0.5.

In theory, under a higher accretion rate, i.e., \( \sim 0.1–1 \) \( L_{\text{Edd}} \), hydrogen accretes faster than it can be consumed by steady burning, so that helium ignites unstably in a H/He environment (Galloway et al. 2008). Since the persistent emission when the bursts occurred is \( \sim 20\% \) \( L_{\text{Edd}} \) and the fast-rising timescale indicates a helium-rich material at the ignition time. The characteristics of bursts (e.g., the fast-rising timescale) in this work and the ratio (\( \sim 116–178 \)) of the persistent flux between bursts to the bolometric fluence of the burst (Lu et al. 2023, based on 16 bursts detected by NICER) conform to the helium-rich burning. However, we also notice that there is a large spread (2 times) for the touchdown fluxes of the PRE bursts. Moreover, the flux of the brightest touchdown point (the top blue point of burst \#7 in Figure 12) is roughly 4 times brighter than that of the faintest lift-up point (the bottom blue point of burst \#4 in Figure 12). Since the Eddington luminosities of the pure helium burning is only 2 times brighter than that of the pure hydrogen burning, the 4 times spread of the fluxes in the PRE phases above indicates there is another mechanism accounting for another 2 times spread of the fluxes.

We also notice that the decay phase obeys \( F \propto kT_{\text{bb}}^4 \) with the radius obtained from the touchdown time, which indicates the obscuring material is not refilled during the decay part of the burst. Since the following burst also shows the emission shortage during the rising PRE phase due to the obscuration, we speculate that the obscuring material has been rebuilt between the bursts.

Another possibility causing a different bolometric flux in the PRE phase is the different burning material, e.g., a larger portion of helium causes a higher bolometric flux of the Eddington limit. However, the fast-rising timescale already indicates pure helium burning in the rising phase (Fujimoto et al. 1987), and thus a higher helium portion is not possible. Yet another possibility is that the burst emission is intrinsic anisotropic (\( \xi > 1 \), different from the aforementioned anisotropic caused by the accretion disk or other structure, this anisotropy is caused by the uneven temperatures or the density inhomogeneity of the NS photosphere; Kuulkers et al. 2002) in the burst early phase, i.e., only part of the NS photosphere is lifted up and the rest of the photosphere is affixed to the NS surface. To a distant observer, this can create the illusion as if all of the photosphere were lifted up. However, it is hard to explain that the flux of the burst when the photospheric radius reaches its peak is still lower than that of the touchdown time. In particular, in theory, a smaller redshift correction when the
photospheric radius reaches its peak would cause a higher flux than that of the touchdown time.

Furthermore, another interpretation, derived from superbursts, the burst emission causes the inner disk to puff up and the increase of the inner disk’s vertical height could also block the NS surface (He & Keek 2016). However, the puffed-up inner disk could be there during the entire burst duration, which conflicts with the decreased obscuration at the touchdown time.

Since the effective area of the X-ray telescopes in orbit is not big enough to detect the rebuilding of the obscuring material or the process of obscuring the NS surface, a larger detection area may be satisfied by the next generation of Chinese mission of the so-called enhanced X-ray Timing and Polarimetry (eXTP; Zhang et al. 2019) or by stacking the light curves/spectra of the interval between bursts under the circumstances of enough bursts and relatively smooth persistent emission.

4.3. Comptonization of the Burst Emission by the Corona

Regarding that the temperature and optical depth deviate from the corona’s canonical values (Dove et al. 1997; Done et al. 2007; e.g., $T_e > 10$ keV and $\tau < 1$), we prefer another corona pattern, the so-called warm layer (Zhang et al. 2000) with temperature $\sim 2$–$3$ keV and optical depth $\sim 5$–$10$ in the high/soft state, which is produced by the magnetic reconnection. The Comptonization of the burst emission by the corona, by adopting the convolution model (with an input seed photon spectrum of blackbody) with the parameters derived in the persistent emission fitting, was first adopted in the burst detected from 4U 1608–52 (Chen et al. 2022). Similar to our previous work (Chen et al. 2022), the scenario is also applied to the five bursts from 4U 1730–22, resulting in an equally good fit compared with the $f_\alpha$ model during the bright/PRE phase. Under this scenario, the radius of the photosphere is underestimated with the canonical blackbody model or the $f_\alpha$ model.

5. Summary and Conclusion

In summary, from Insight-HXMT observations on 4U 1730–22, we present here one non-PRE burst with the double-peaked profile and no cooling between the two subbursts and nine PRE bursts with the flux shortage during the rising phase, which can be attributed to a stalled burning front at the equator and occlusion by the material in our line of
sight or an anisotropic emission in the burst early phase, respectively.

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Figure 12. Burst flux vs. blackbody temperature of bursts #3–#7. The blue points and gray points indicate the data points before and after the touchdown times. The dashed lines correspond to $R_{\text{BH}} = 6.9$ km under the distance of 10 kpc.
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