Insight-HXMT Observation of 4U 1608–52: Evidence of Interplay between a Thermonuclear Burst and Accretion Environment

Yu-Peng Chen¹, Shu Zhang¹, Long Ji², Shuang-Nan Zhang¹,³, Ling-Da Kong¹,³, Peng-Ju Wang¹,³, Zhi Chang¹, Jing-Qiang Peng¹,³, Jin-Lu Qu¹,³, and Jian Li⁴,⁵, Zhi Chang¹

¹ Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing 100049, People’s Republic of China; chenyp@ihep.ac.cn, szhang@ihep.ac.cn
² School of Physics and Astronomy, Sun Yat-Sen University, Zhuhai, 519082, People’s Republic of China
³ University of Chinese Academy of Sciences, Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
⁴ CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, People’s Republic of China
⁵ School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, People’s Republic of China

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Abstract

A Type I burst could influence the accretion process through radiation pressure and Comptonization both for the accretion disk and the corona/boundary layer of an X-ray binary, and vice versa. We investigate the temporal evolution of a bright photospheric radius expansion (PRE) burst of 4U 1608–52 detected by Insight-HXMT in 1–50 keV, with the aim to study the interplay between the burst and persistent emission. Apart from the emission from the neutron star (NS) surface, we find residuals in both the soft (<3 keV) and hard (>10 keV) X-ray bands. Time-resolved spectroscopy reveals that the excess can be attributed to either an enhanced preburst/persistent emission or the Comptonization of the burst emission by the corona/boundary layer. The Comptonization model is a convolution thermal-Comptonization model (thcomp in XSPEC), and the Comptonization parameters are fixed at the values derived from the persistent emission. We find, during the PRE phase, after the enhanced preburst/persistent emission or the Comptonization of the burst emission is removed, the NS surface emission shows a plateau and then a rise until the photosphere touches down on the NS surface, resulting in a flux peak at that moment. We speculate that the findings above correspond to the lower part of the NS surface that is obscured by the disk being exposed to the line of sight due to the evaporation of inner disk by the burst emission. The consistency between the $f_a$ model and convolution thermal-Comptonization model indicates the interplay between thermonuclear burst and accretion environments. These phenomena do not usually show up in conventional blackbody model fittings, which may be due to the low count rate and narrow energy coverage in previous observations.

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

1. Introduction

Type I X-ray bursts, also called thermonuclear bursts, are triggered by the unstable thermonuclear burning of the accreted fuel from a low-mass X-ray binary (LMXB) hosting a neutron star (NS) (for reviews, see Lewin et al. 1993; Cumming 2004; Strohmayer & Bildsten 2006; Galloway et al. 2008). Since its first detection in 1975 from 3A 1820–30, so far there have been 116 Galactic X-ray binaries observed to produce thermonuclear bursts,° manifesting a sudden increase in the X-ray luminosity followed by an exponential decay and with a typical duration of about 10 s. The most luminous bursts are the photospheric radius expansion (PRE) events, for which the peak flux reaches the Eddington luminosity of the NS.

Among some of the thousands of observed bursts (Galloway et al. 2020), observations of bursts by RXTE (Ballantyne & Strohmayer 2004; in’t Zand et al. 2013; Worpe et al. 2013; Keek et al. 2014), INTEGRAL (Sánchez-Fernández et al. 2020), NICER (Keek et al. 2018a, 2018b), AstroSat (Bhattacharyya et al. 2018), and Insight-HXMT (Chen et al. 2018, 2019) revealed interactions between the burst emission and the accretion environment: The continuum spectrum was observed to have an enhancement at soft X-rays and/or a shortage at hard X-rays (Chen et al. 2012; Ji et al. 2013; Worpel et al. 2013, 2015). Such spectral deviations are considered to be burst-induced and might be relevant to disk reflection, accretion rate increase, and corona cooling (Ballantyne & Strohmayer 2004; Keek et al. 2014; Degenaar et al. 2018).

Moreover, the reflection spectrum, consisting of discrete lines and a hump peaking at 20–40 keV, is interpreted as the disk reflection of an illuminant from the corona/boundary layer. The burst emission could also serve as the illuminant of the disk, and a reflection component is correspondingly observed during the burst. However, so far, only the iron line is firmly detected during bursts, specifically during long-duration superbursts (Ballantyne & Strohmayer 2004; Keek et al. 2014). The observations above are the influence of the bursts on the accretion environment; however, there are few observational results reported related to the burst spectral change caused by the accretion disk/corona.

4U 1608–52 is a prolific burster located at the Galactic plane (Belian et al. 1976). More than 100 Type I X-ray bursts inhabiting its outbursts, which have a typical frequency of once every 1–2 yr since its discovery, have been regularly observed. The distance was estimated to be $D \approx 2.9\pm 4.5$ kpc based on the peak flux of PRE bursts, $\sim 1.2\times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$.

° https://personal.sron.nl/~jeanz/bursterlist.html

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Both bursts are detected by three payloads of Insight-HXMT. However, the second burst, which is only half as bright as the first one, is not located in the GTI.

In this present investigation, we provide a broadband spectral view of 4U 1608–52 during its 2020 outburst observed by NICER and Insight-HXMT, both for its outburst and burst emission. We first describe the data reduction procedure of NICER and Insight-HXMT in Section 2. We then present an in-depth spectral analysis and model parameters of its outburst emission in Section 3.1, and its burst lightcurves and spectral evolution in Sections 3.2 and 3.3. Finally, we summarize our results and discuss their implications in Section 4.

2. Observations and Data Reduction

2.1. Insight-HXMT

The Hard X-ray Modulation Telescope (HXMT, also dubbed as Insight-HXMT; Zhang et al. 2020) excels in the broad energy band (1–250 keV) and a large effective area in hard X-rays energy band. It carries three collimated telescopes: the High Energy X-ray Telescope (HE; position NaI/CsI, 20–250 keV, \( \sim5000\) cm\(^2\)), the Medium Energy X-ray Telescope (ME; Si pin detector, 5–40 keV, 952 cm\(^2\)), and the Low Energy X-ray telescope (LE; SCD detector, 1–12 keV, 384 cm\(^2\)). Under the quick read-out system of the Insight-HXMT detectors, there is little pileup effect at the PRE burst peak. Insight-HXMT Data Analysis software (HXMTDAS) v2.04 is used to analyze the data. The data are reduced following the recommended procedure of the Insight-HXMT Data Reduction Guide v2.04 \(^5\) and are screened in the standard criterion include in Insight-HXMT pipelines: lepipe-line, mepipeline, and hepipeline.

Two bursts were detected by three payloads of Insight-HXMT from 4U 1608–52 during its 2020 outburst, as shown in Table 1. However, the second burst, which is only half as bright as the first one, did not fall into the good time interval (GTI) of the LE; thus, we only analyzed the first burst that occurred at MJD 59069.770768 in this work.

The persistent spectra adapted from the GTI exclude the time span before the burst peak time, 100 s, and after the burst peak time, 200 s. The persistent spectra in the LE are rebinned using ftool grppha with a minimum of 100 counts per grouped bin. For the ME, the spectra are binned up by a factor of 20 because its background is comparable with the source emission.

For the burst, we perform time-resolved spectroscopy with a time resolution of 0.25 s and define the time of the bolometric flux peak as a time reference (0 point in Figures 1 and 3). The burst spectra are rebinned by ftool grppha with a minimum of 10 counts per grouped bin.

In the calibration experiments on ground and the first two years in orbit, the recommended energy band for the spectral fitting of LE is 1–10 keV, except for very bright sources with flux brighter than several Crab. After the midyear of 2019, the recommended band shrunk to 2–10 keV, which is mostly due to the poor background estimation because of an increase in detector temperatures and other factors. However, in the burst spectral analysis, we take the preburst emission as the background, so we extend the energy band to 1–10 keV in the burst spectra fitting, but still adapt 2–10 keV in persistent emission spectral fitting. We notice that the LE spectral residuals of the persistent emission have rather complex structures in the energy band <1.5 keV, where the bursts only have a few data points. We also use the

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\(^5\) http://hxmtweb.ihep.ac.cn/SoftDoc.jhtml
Figure 2. The spectral fit results of the persistent emission by LE (black), ME (red), and NICER (green) with model cons*tabs*thcomp*diskbb. The embedded panel shows the background level for ME (red) and HE (blue).

2–10 keV band to analyze the burst spectra and obtain roughly consistent results within the parameters’ error bars. We extend the ME band to 8–30 keV and the HE band to 25–50 keV in the burst spectra fitting following similar considerations. In short, for the persistent emission spectra fitting of LE and ME, the energy bands are limited to 2–10 keV and 10–20 keV for the burst spectra fitting of LE, ME, and HE, the energy bands used are 1–10 keV, 8–30 keV, and 25–50 keV, respectively.

During fittings of the persistent emission, the LE data in 2–10 keV and the ME data in 10–20 keV are used, while ME data >20 keV and the HE spectra are not used for fitting because of a faint source flux and strong background. As shown in Figure 2, the persistent emission detected by ME in 20–30 keV and HE in 25–100 keV is very weak compared with the background. Most of these spectral channels are close to or fainter than the systematic uncertainty of the background (1%); e.g., for the count rate detected by HE in 30–50 keV, the background of \( \sim 120 \text{cts s}^{-1} \) is comparable to the detected count rate of \( \sim 123 \text{cts s}^{-1} \). Thus, the persistent emission has a count rate of \( \sim 3 \text{cts s}^{-1} \), which is close to the systematic uncertainty of the estimated background. In addition, we added a systematic uncertainty of 1% to the persistent spectra to account for systematic uncertainties in the detector calibrations (Li et al. 2020).

2.2. NICER

On 2020 August 8, within the same day when Insight-HXMT detected the burst from 4U 1608–52, NICER also observed the same source. The OBSID is 3657026501 (as shown in Table 2), with a GTI of \( \sim 2 \text{ks} \), and a count rate of \( \sim 900 \text{cts s}^{-1} \) in the 0.3–12 keV band. However, NICER missed the Type-I X-ray burst because of an observation gap.

The NICER data are reduced using the pipeline tool nicer2 in NICERDAS v7a with the standard NICER filtering and using fiool XSELECT to extract lightcurves and spectra. The background is estimated using the tool nbackgen3C50 (Remillard et al. 2022). Focal Plane Module (FPM)Nos. 14 and 34 are removed from the analysis because of increased detector noise. The response matrix files (RMFs) and ancillary response files (ARFs) are generated with the ftool nicerrmf and nicerarf. The spectra are rebinned using the ftool figrouppha (Kastra & Bleeker 2016) optimal binning algorithm plus a minimum of 25 counts per grouped bin. Other rebinning methods, e.g., a minimum of 100 counts per grouped bin by ftool grppha, are adapted. As expected, the fit results are consistent with each other within the parameters’ error bar.

For the ISM absorption, we use tbabs in the spectral model and Wilms abundances (Wilms et al. 2000). To erase residuals <1 keV, three absorption edges are added in spectra fitting: 0.56 keV, 0.71 keV, and 0.87 keV. We added a systematic uncertainty of 1% to the NICER spectra. From NICER and Insight-HXMT lightcurves, the nonburst/persistent emission is stable in our observations. We jointly fit the persistent spectra observed with NICER and Insight-HXMT, as shown in Figure 2. The joint fit of the spectra covers the energy bands of 0.4–10 keV, 2–10 keV, and 10–20 keV for NICER, LE, and ME, respectively.

The spectra are fitted with XSPEC v12.11.1 and the model parameters are estimated with a 68% confidence level (1\( \sigma \)).

### 3. Analysis and Results

#### 3.1. Nonburst/Persistent Emission Detected by NICER and Insight-HXMT

The joint NICER and Insight-HXMT data in the broader energy range 0.4–20 keV give us an opportunity to utilize a more physically meaningful model to fit the persistent emission, rather than the simplified models, i.e., a simple photon power law, a power law with a high-energy exponential rolloff (cutoffpl in xspec), and a broken power law (bknpow in xspec). We fit the joint NICER and Insight-HXMT (LE and ME) spectrum with an absorbed convolution thermal Comptonization model (with an input seed photon spectrum diskbb) available as thcomp (a more accurate version of nthcomp) (Zdziarski et al. 2021) in XSPEC, which is described by the optical depth \( \tau \), electron temperature \( kT_e \), and scattered/covering fraction \( f_{sc} \).

The hydrogen column (tbabs in XSPEC) accounts for both the line-of-sight column density as well any intrinsic absorption near the source. The seed photons are in the shape of diskbb, because the thcomp model is a convolution model and the fraction of Comptonization photons is 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 LE data with respect to the ME and NICER data to unity.

Using the model above, we find an acceptable fit: \( \chi^2 / \nu = 0.95 \) (degrees of freedom, d.o.f. 846; Figure 2 and Table 3), with the inner disk radius \( R_{\text{diskbb}} \) and scattered/covering fraction \( f_{sc} \) found to be \( \sim 11.6_{-0.6}^{+0.7} \) km (with a distance of 4 kpc and inclination angle 40°) and \( 0.77_{-0.03}^{+0.05} \), respectively. The derived hydrogen column density \( N_H \) is \( \sim 1.3 \times 10^{22} \text{cm}^{-2} \), which agrees with values in the range of 0.9–1.5 \( \times 10^{22} \text{cm}^{-2} \).
previously reported (Penninx et al. 1989; Armas Padilla et al. 2017). The thcomp parameters $\tau$ and $kT_e$ are well consistent with a previous outburst in the soft state of 4U 1608–52 (Armas Padilla et al. 2017), the parameters of which were derived with the nthcomp model. The inferred bolometric flux in 1–100 keV is $7.33^{+0.06}_{-0.05} \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$. The constant of ME and NICER is 0.93 ± 0.02 and 1.05 ± 0.01, respectively.

Using the model of cons’tabbs’(diskbb+nthcomp) to fit the spectra, i.e., a nonconvolutional Comptonization model, we get similar results for both the corona and the disk temperatures but with a smaller normalization of the disk. The shortage in the disk normalization compared to the convolution model corresponds to the missing part of the disk emission, which is supposed to be scattered in the corona.

We also assumed that the seed photons of the Comptonization are from the NS surface, i.e., the diskbb component is substituted by a blackbody component in the aforementioned convolution model. Taking this approach, spectral fits yield roughly the same thcomp parameters but with $\chi^2 = 1.12$ (the same d.o.f) and soft residuals $< 2$ keV. Furthermore, the derived blackbody radius is $34.1 \pm 1.0$ km, which is far greater than the NS radius. A hybrid model (Armas Padilla et al. 2017), i.e., a three-component model (diskbb+thcomp*bb or bb+thcomp*diskbb), is not attempted because the above two-component model is able to fit the data.

Because there is no iron emission line or reflection bump above 10 keV, no reflection model is used for the spectrum fitting.

### 3.2. Burst Lightcurves by Insight-HXMT

We show the LE/ME/HE lightcurves in Figure 1 with a time resolution of 0.1 s. The burst profiles exhibit a typically fast rise and slow (exponential) decay in the soft X-ray band, and manifest a plateau in soft X-ray band (LE) and two peaks in hard X-ray band (ME and HE), which are typical characteristics of a PRE burst.

In the middle of the PRE phase with a constant luminosity $L_{Edd}$, the burst emission has the lowest blackbody temperature, which could cause a dip in the HE lightcurves. However, interestingly, there is a peak/excess in the HE lightcurves. For the six highest points in the HE lightcurves in its whole energy band (20–250 keV), the hard excess is $222.3 \pm 39.3$ cts s$^{-1}$ with a 5.6$\sigma$ detection; meanwhile, the burst emission for HE (for a blackbody with a temperature of 2.0 keV and a bolometric flux of Eddington luminosity) should be less than 35 cts s$^{-1}$ in this energy band. The hard excess in 30–50 keV is $71.5 \pm 18.0$ cts s$^{-1}$ with a 4$\sigma$ detection; meanwhile, the burst emission should be negligible with <0.1 cts s$^{-1}$ in this energy band.

This high X-ray excess in the lightcurve suggests that it has another provenance, but not the burst, which is also visible during the burst spectra analysis below.

### 3.3. Broadband Spectra of the Burst Emission from 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 LE, the constant is fixed to 1; the others are variable during spectra fitting. The fits indicate that most of the constants of HE and some of the constants of ME are not convergent, owing to the low-significance data. Under this situation, the constants of ME and HE are fixed at 1 for the combined-spectra fitting.

We follow the classical approach to X-ray burst spectroscopy by subtracting the persistent spectrum and fitting the net spectrum with an absorbed blackbody. In the decay phase, such a spectral model generally results in an acceptable goodness of fit, with a mean reduced $\chi^2 = 1.0$ (d.o.f. 20–60). However, we note that there are significant residuals below 3 keV and above 10 keV, as shown in the left panel of Figure 4; specifically for the spectra in the PRE phase, the reduced $\chi^2$ are above 1.5 (d.o.f. 60–80).

To erase the residuals, we first consider the $f_a$ model. Following Worpel et al. (2013) we then include an addition 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 a $f_a$ 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 left panel of Figure 3, 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. The $f_a$ factor reaches a maximum of $6.5^{+1.3}_{-1.1}$ when the radius reaches its peak. During the PRE phase, the radius is up to $10.8^{+1.2}_{-1.0}$ km, which is two times larger than the radius measured at touchdown time $5.1^{+0.3}_{-0.2}$ km (assuming a distance of 4 kpc). This is typical for a moderate photospheric expansion with a bolometric burst peak flux $F_{bb} 15.3^{+0.8}_{-0.5} \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ in 0.1–100 keV.

Because the burst photons could also be affected by the coronaboundary layer, we thus check if the model used in the persistent emission could be same as that for the burst emission. By taking the preburst emission as the background emission, the burst spectra are fitted by the model thcomp*bb, in which the thcomp parameters are fixed at the persistent emission fit results. Thus, the convolution thermal-Comptonization model (with an input seed photon spectra 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

| $N_H$ ($10^{22}$ cm$^{-2}$) | $\tau$ | $kT_e$ (keV) | $f_{bb}$ | $kT_{bb}$ (keV) | $N_{bb}$ ($10^{22}$ cm$^{-2}$) | $\chi^2$ |
|--------------------------|---------|-------------|--------|----------------|-----------------------------|--------|
| 1.33$^{+0.01}_{-0.01}$   | 10.2$^{+0.3}_{-0.4}$ | 3.02$^{+0.08}_{-0.08}$ | 0.76$^{+0.05}_{-0.05}$ | 0.68$^{+0.01}_{-0.02}$ | 8.38$^{+0.03}_{-0.96}$ | 802/846 |
represent the burst emission from the NS photosphere and the influence of the corona/boundary layer on the burst emission. This model allows us to evaluate the contribution from both photons upscattered by the corona/boundary layer and direct photons from the NS surface.

In the PPE phase, this model provides the best fit and yields physically acceptable spectral parameters; the obtained best-fit parameters are given in the right panel of Figure 3. We find that this convolved thermal-Comptonization model provides equally good results with the 1 model but with more d.o.f. and is statistically preferred to the 1 model for the middle of the PRE phase (which has the coolest blackbody temperature). However, in the rising and decaying parts, such a model—and even the canonical blackbody model—has a bigger reduced $\chi^2$ than the 1 model, which may indicate that the burst emission suffers low Comptonization during this phase.

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 with that of the 1 model, but with greater change. Compared to the 1 model results, the maximum radius $R_{bb}$ is up to $29.5^{+2.9}_{-2.5}$ km, and the minimum temperature $kT_{bb}$ is as low as $1.19^{+0.06}_{-0.05}$ keV.

We also tried other scenarios, i.e., burst reflection by the disk and NS atmosphere model carbatm/hatm (Suleimanov et al. 2011, 2012, 2018) in Xspec, to fit the burst spectra, as we did in Chen et al. (2019). However, neither could alleviate the residuals at the soft X-ray and hard X-ray bands simultaneously.

For the hard X-ray excess detected in the lightcurve during the PRE phase, we calculate and find that the persistent emission does not have enough flux to build the enhancement. We fake the HE spectra using the aforementioned model parameters of the persistent emission; the HE flux of the persistent emission model in 20–250 keV and 30–50 keV is 3 and 0.7 cts s$^{-1}$. Taking the factor 1 into account, this model predicted an enhancement flux only equivalent to 1/10 of the hard excess. The spectra residuals in the hard X-ray band are also visible in the middle panel of Figure 4 (1 model to fit the burst spectra in the PRE phase). The hard X-ray excess also disfavors the reflection model because of the faint persistent emission in the hard X-ray band.

Figure 3. Spectral fitting result of the burst with time bin 0.25 s with a pure blackbody model (black), 1 model (the left panel, red), and convolution thermal-Comptonization model (the right panel, red), including the time evolution of the blackbody bolometric flux $F_{bb}$, the temperature $kT_{bb}$, the observed radius $R$ of the NS surface at 4 kpc, the goodness of fit $\chi^2$. The bolometric flux of the blackbody model $F_{bb}$ is in units of $10^{-8}$ erg cm$^{-2}$ s$^{-1}$. 5
two geometrically distinct regions to generate the X-ray emission (see the review by Done et al. 2007): in the accretion disk and the boundary/spreading layer (BL/SL) (similar to the corona in the case of an accreting black hole). The BL is supposed to spread over a large radial extent in the disk midplane, whereas the SL has a narrower spread but spreads over a considerable height from the equatorial plane to higher stellar latitudes. There are established judging criteria for the BL and SL based on temporal (Gilkis et al. 2003) and spectral (Greivenev & Sunyaev 2002; Suleimanov & Poutanen 2006) characteristics.

In the burst review, during the decaying part of the burst, the burst emission is well fitted by a blackbody and no strong Comptonization/upscattered emission is detected. Thus, the hot electron plasma should not have a significant coverage for the NS surface. Add that into the consideration of a big scattering factor $f_{sc}$ 0.77$^{+0.05}_{-0.05}$ (the hot electron plasma on the disk in the persistent emission), the corona-like geometry of the BL is favored.

We find that the persistent emission is 4.8% $L_{\text{Edd}}$ and the corona/boundary-layer temperature is $3.02^{+0.08}_{-0.08}$ keV, which is in the range of Comptonizing temperatures expected for NS LMXBs in the soft state (Armas Padilla et al. 2017). Meanwhile, the scattering factor $f_{sc}$ is $0.77^{+0.05}_{-0.05}$, which is too large for the corona/boundary layer with a lamp-post geometry. Given those above, we prefer the corona/boundary layer with a slab/sandwich geometry, as shown in Figure 7. Because the temperature and optical depth deviate from the corona’s canonical value, we also prefer another corona pattern—a so-called warm layer (Zhang et al. 2000) with temperature $\sim$2–3 keV and optical depth $\sim$5–10, which is produced by the magnetic reconnection. The outburst spectral evolution and our understanding of it will be given in our forthcoming paper.

4. Discussion

In this work, we have presented the spectral analysis of a PRE burst and persistent emission from 4U 1608–52 during its 2020 outburst observed by NICER and Insight-HXMT. The persistent emission is well fitted by an absorbed convolution thermal-Comptonization model, in which 77% of the disk emission is upscattered by the corona/boundary layer. 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. This excess is consistent with the burst emission being upscattered by the corona/boundary layer and only the part of the burst emission without Comptonization is detected, which mimics the Comptonization of the disk emission in the persistent emission.

4.1. X-Ray Continuum

Based on LE and ME lightcurves and spectral fitting results, the burst is located in the high/soft state (banana state). Previous works have attempt to fit the spectra with a thermal (diskbb or/and blackbody) plus a Comptonization model, rather than a convolution thermal-Comptonization model, which will cause an underestimation of the thermal emission. In this work, adopting the thermal-Comptonization model thcomp in XSPEC, the fit results indicate that most of the disk emission is involved in Compton upscattering.

Broadly speaking, in an accreting low-magnetic-field NS, except for the emission from the NS surface, there are at least two geometrically distinct regions to generate the X-ray emission (see the review by Done et al. 2007): in the accretion disk and the boundary/spreading layer (BL/SL) (similar to the corona in the case of an accreting black hole). The BL is supposed to spread over a large radial extent in the disk midplane, whereas the SL has a narrower spread but spreads over a considerable height from the equatorial plane to higher stellar latitudes. There are established judging criteria for the BL and SL based on temporal (Gilkis et al. 2003) and spectral (Greivenev & Sunyaev 2002; Suleimanov & Poutanen 2006) characteristics.

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4.2. Enhanced Persistent Emission up to 50 keV

In several bursters, during the low/hard state, a decrease/deficit in the hard X-ray band (30–50 keV) has been observed in short-duration bursts, which happen in the low-hard state (Chen et al. 2012 and references therein). It is expected that the burst emission (2–3 keV), which is relatively cooler than the corona (tens keV), causes the change in the corona structure or temperature.

In this work, conversely, an enhancement in the hard X-ray emission is observed during a short-duration burst, which was first reported in GS 1826–238 by BeppoSAX in 30–60 keV (in’t Zand et al. 1999). However, these two sets of bursts are located in different spectral states of LMXBs. In both cases, the soft X-ray showers of the burst may manifest as an enhancement of the input seed photons but they are not sufficiently cooler in the corona.

Compared with the disk component of the persistent emission, the count rate of the burst at the PRE phase is four times more. The emergent photons of the burst could be upscattered to higher energies by the corona/boundary layer. For the Comptonization of the burst during the PRE phase, i.e., a blackbody with a temperature of 1.22 keV and normalization 1.33, and a hot corona with a temperature of 3 keV, optical depth 10.2, and covering factor 0.76, we fake a spectrum induced by the inverse Compton scattering of the blackbody emission and get a count rate of 289 cts s$^{-1}$ in the energy band of 30–50 keV. Thus, the upscattered photons of the burst do cause an enhancement in the hard X-ray emission.
Based on the burst spectra fit results, the enhancement of the hard X-ray emission could be related to the upscattering of the burst emission by the corona/boundary layer, just like the situation in the persistent emission, rather than an enhancement in the accretion rate manifesting itself as elevated persistent emission with an unaltered spectral shape (Worpel et al. 2013, 2015).

4.3. Dynamical Evolution of the Disk Geometry

As is common knowledge, the burst emission has an increasing and decreasing area during its rise and decay phases, which correspond to the hot spot spreading in the NS surface. Meanwhile, there are at least two moments when the hot spot covers that whole NS surface: during the photosphere lift-up point and the touchdown point for the PRE burst. As shown in Figure 1 of Shaposhnikov et al. (2003), the hot spot spreads on the NS surface and then lifts up the photosphere, i.e., from stage “a” to stage “b” in the figure. There should be a moment when the hot spot covers the entire NS surface during the rise phase and vice versa during the decay phase. However, there are some PRE bursts with a short increase time, i.e., the increase time is too short for the telescope to accumulate enough counts in the first moments when the hot spot covers the entire NS surface.

In practice, the latter is usually used to derive the NS radius. As shown in Figure 5, at the touchdown point, the burst emission reaches its peak flux, both for the $f_{\text{a}}$ model and convolution thermal-Comptonization model. A dynamical evolution of the disk geometry could cause this phenomenon, i.e., the lower NS hemisphere, which is obscured before the burst (the burst PRE phase), appears from the disk after the burst–disk interaction, as shown in Figure 1 of Shaposhnikov et al. (2003) and Figure 7 in this work.

In theory, the Poynting–Robertson drag could drain the inner accretion disk by taking away the momentum of the accretion matter, hence increasing the local accretion rate (in’t Zand et al. 2013; Worpel et al. 2013, 2015), which is faster than the rate at which the inner accretion disk is being filled (Stahl et al. 2013; Fragile et al. 2020). At this moment, the inner part of the disk is hollowed out by the burst emission.

The flux–temperature diagram of the burst also indicates that the inner disk radius change causes a bigger visible part of the NS surface, as shown in Figure 7. If the whole NS surface shows up as a single-temperature blackbody and a constant color correction factor, the burst flux $F$ should scale as $kT_{bb}^4$ in the flux–temperature diagram, and the slope represents the emitting area in the double logarithmic coordinates (Güver et al. 2012). As shown in Figure 6, the rising phase and decaying phase obey different $F \propto kT_{bb}^4$. We fit the two sets with $F = \frac{k^4}{m} \sigma T^4$, and the blackbody radius of the rising and decaying phase is $5.4 \pm 0.14$ km and $6.6 \pm 0.062$ km with $D = 4$ kpc.

Assuming the NS radiates at the Eddington limit in the PRE phase and the disk reaches the NS surface before the PRE phase, the blackbody flux ratio detected at the rising phase $F_{\text{rise}}$ and decaying phase $F_{\text{decay}}$ is positively associated with the inclination angle $i$, i.e., $\frac{F_{\text{rise}}}{F_{\text{decay}}} = (1 + \cos i)/2$ (Shaposhnikov et al. 2003; Shaposhnikov & Titarchuk 2004). The inclination angle $i$ is estimated to be $\sim 70^\circ$. However, this result is bigger than the value of $\sim 30^\circ$–$40^\circ$ derived from the spectral fit results on an outburst of 4U 1608–52 by a reflection model (Degenaar et al. 2015).

4.4. Corona/Boundary Layer Reacting on the Burst

The interaction between the burst and inhabited persistent emission was first studied from the super expansions in 4U 1820–30 and 4U 1636–536 (Ballantyne & Strohmayer 2004;
which the inner part of the disk is swept away by the burst in the PRE phase. Keek et al. (2014) (a factor of \(\sim 10^4\) increase in emission area). Then, in short-duration bursts, this interaction was mainly observed as a persistent spectral change, rather than a burst spectral change, i.e., enhancement of the accretion rate, deficit at the hard X-ray band, reflection by the disk, and driven outflow. A Type 1 X-ray burst happens on the NS surface, which is also in the accretion environment. In principle, the burst spectrum may be influenced by the Comptonization of the burst photons by the surrounding corona/boundary layer (Chen et al. 2019). A Comptt component was reported in bursts of 4U 1608–52 from RXTE observations above 3 keV (Kajava et al. 2017). However, their approach resembled the \(f_R\) model because the Comptt component is added in the spectra fitting. In this work, the persistent emission is well fitted by a convolution thermal-Comptonization model. As a result, given the similarity, for the burst, adapting the convolution model with the parameters in the persistent emission fitting but with a blackbody emission, this could also fit the short-duration burst spectra in the PRE phase. The goodness of the fit is comparable with the \(f_R\) model, but with a colder \(kT\) and larger \(R\) in the middle of the PRE phase. If this is the case, the radius of the photosphere is underestimated with the canonical blackbody model or the \(f_R\) model.

In principle, the interaction between the burst and accretion environment might be expected to give rise to spectral evolution for both the burst emission and accretion emission during the burst, with the spectral shape deviating from a pure blackbody and the model of the preburst emission. The short duration and rapid spectral change limits the accumulated time and photon counts, which in turn requires a larger detection area and broadband energy coverage, which may be satisfied by the next generation Chinese mission, the so-called eXTP (enhanced X-ray Timing and Polarimetry mission) (Zhang et al. 2019), or a contemporary joint observation of the burst by NICER and Insight-HXMT.

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ORCID iDs

Yu-Peng Chen https://orcid.org/0000-0001-8768-3294
Shuang-Nan Zhang https://orcid.org/0000-0001-5586-1017
Ling-Da Kong https://orcid.org/0000-0003-3188-9079
Peng-Ju Wang https://orcid.org/0000-0002-6454-9540
Zhi Chang https://orcid.org/0000-0003-4856-2275
Jin-Lu Qu https://orcid.org/0000-0002-9796-2585
Jian Li https://orcid.org/0000-0003-1720-9727

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Figure 7. Illustration of the central region of an NS XRB before the PRE phase (left), in the PRE phase (middle), and after the PRE phase (right) during a burst, in which the inner part of the disk is swept away by the burst in the PRE phase.
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