Insight-HXMT Observations of 4U 1636-536: Corona Cooling Revealed with Single Short Type-I X-Ray Burst

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Abstract

Corona cooling was detected previously from a series of short type I bursts that occurred during the low/hard state of an atoll outburst. Type I bursts are hence regarded as sharp probes used to better our understanding of the basic properties of the corona. The first Chinese X-ray satellite, Insight-HXMT, has a large detection area at hard X-rays that provides a unique opportunity to move further in this research field. We report the first detection of corona cooling by Insight-HXMT from a single short type I burst appearing during the flare of 4U 1636-536. This type I X-ray burst has a duration of ~13 s and hard X-ray shortage is detected with a significance of 6.2σ in 40–70 keV. A cross-correlation analysis by the light curves of the soft and hard X-ray band shows that the corona shortage lags the burst emission by 1.6 ± 1.2 s. These results are consistent with those derived previously from stacking a large amount of bursts detected by RXTE/PCA within a series of flares of 4U 1636-536. Moreover, the broad bandwidth of Insight-HXMT also allows, for the first time, one to infer the burst influence upon the continuum spectrum via performing the spectral fitting of the burst, which points to the finding that hard X-ray shortage appears at around 40 keV in the continuum spectrum. These results suggest that the evolution of the corona along with the outburst/flare of NS XRB, may be traced via analyzing a series of embedded type I bursts using Insight-HXMT.

Key words: stars: coronae – stars: neutron – X-rays: binaries – X-rays: bursts – X-rays: individual (4U 1636-536)

1. Introduction

A type I X-ray burst, also named a thermonuclear burst (hereafter burst), is caused by unstable burning of the accreted hydrogen/helium on the surface of a neutron star (NS) enclosed in an X-ray binary (XRB), and manifests itself as a sudden increase (typically by a factor of 10 or greater) in the X-ray luminosity followed by an exponential decay (for reviews, see Lewin et al. 1993; Cumming 2004; Strohmayer & Bildsten 2006; Galloway et al. 2008). The most luminous bursts are the photospheric radius expansion (PRE) events, for which the peak flux is comparable to the Eddington luminosity at the surface of the NS.

More and more observational examples and theory models on the burst’s influence on persistent/accretion emission have rapidly accumulated over recent years (Degenaar et al. 2018). Basically, there are three types of observational evidence and corresponding physical process initiation between the two kinds of emission: accretion rate change because of Poynting–Robertson drag induced by dynamic/light-pressure of the burst; disk or/and corona change both in structural or/and intrinsic categories owing to the burst cooling/heating; and enhancement emission resulting from reflection of the accretion disk. Among the observational evidence, most of them are from intermediate long burst/super-burst or stacking lots of normal bursts (Degenaar et al. 2018).

For the interaction between bursts and corona, the shortage in the hard X-ray of the continuum emission is reported on several XRB, i.e., IGR J17473-2721 (Chen et al. 2011, 2012), Aql X-1 (Chen et al. 2013; Maccarone & Coppi 2003), 4U 1636-536 (Ji et al. 2013), GS 1826-238 (Ji et al. 2014a), KS 1731-260 (Ji et al. 2014b), 4U 1705-44 (Ji et al. 2014b), and 4U 1728-34 (Kajava et al. 2017), based on RXTE/PCA and INTEGRAL observations. It is very hard to detect the deficit up to 5σ in some short burst because of the relatively small detection area of previous missions at hard X-ray, and hence these firm detection significances are aggrandized by stacked tens to hundreds of bursts. For example, for 4U 1636-536 the deficit detection is based on 36 burst results.
In the timing analysis zone, effects of X-ray bursts on kHz quasi-periodic oscillations (QPOs) are also revealed in several bursters such as Aql X-1 (Yu et al. 1999) and 4U 1636-536 (Peille et al. 2014), and often manifest as QPO frequency and persistent flux changes between the beginning and end of the burst. Such detections are interpreted as the burst blew away or pulled up the inner disk based on the different viscous timescales for QPO recovery.

4U 1636-536, a low-mass X-ray binary (LMXB), discovered with the 8th Orbiting Solar Observatory (OSO-8; Swank et al. 1976), it is a well-studied LMXB that holds an 18th magnitude blue star, V801 Ara in an orbit of 3.8 hr (van Paradijs et al. 1990). It is one of the few persistent X-ray sources in our Galaxy that undergoes regular transitions between the hard state and the soft state, in a repeating period of roughly 70 days, and many bursts accompanied. The properties of the burst oscillations of 579.3 Hz and superbursts with durations of hours have been detected and analyzed (see Galloway et al. 2008 for a review). From its color–color diagram (CCD), 4U 1636-536 traces a U-shape or C-shape as a typical atoll source (detailed CCD was shown in Zhang et al. 2011). Its distance was estimated as ~6 kpc (Galloway et al. 2006) by using the PRE burst.

In this work, we study the burst-corona interaction in the LMXB 4U 1636-536 using the first year of data collected with Insight-HXMT (Zhang et al. 2014). In Section 2, we present Insight-HXMT observations and the data analysis procedure in detail. In Section 3, the shortage in hard X-ray band are given based on the broadband spectrometry results. In Section 4, we present our interpretation of the detection and a comparison with a previous detection of the hard X-ray shortage during the burst.

2. Observations and Data Analysis

On 2017 June 15th, the Hard X-ray Modulation Telescope (HXMT, also dubbed Insight-HXMT, Zhang et al. 2014) was launched in the Jiuquan Satellite Launch Center. It excels in broad energy band (1–250 keV) detection ability and large effective area in the hard X-rays energy band. It consists of three slat-collimated instruments: the High Energy X-ray Telescope (HE), the Medium Energy X-ray Telescope (ME), and the Low Energy X-ray Telescope (LE), with collecting-area/energy-range in ~5000 cm² in 20–250 keV, ~900 cm² in 5–30 keV, and ~400 cm² in 1–10 keV respectively.

In this work, we analyze the brightest of three bursts, represent the time-resolved spectroscopy and give our interpretation on the uniqueness of observational behavior. By virtue of quick read-out time of Insight-HXMT detectors, there is little pile-up event at the PRE burst peak. HEASOFT version 6.22.1 and Insight-HXMT Data Analysis software (HXMDAS) v2.01 were used to process and analyze the data. Only the small fields of view (FoV) of LE and ME were used, because large FoV were easily contaminated by a nearby source and the bright earth. The good time intervals were filtered with the following criteria: (1) pointing offset angles <0.05 degree; (2) elevation angles >6 degree; and (3) the value of the geomagnetic cutoff rigidity >6.

Among its first years of observation, the total Insight-HXMT observation of 4U 1636-536 was ~370 ks, covering the time span between 2018 February 11th and July 1st. Eight type-I X-ray bursts are detected in 4U 1636-536. Among them, the first three bursts have low flux levels of persistence both in soft X-ray at ~40 mCrab and hard X-ray at ~15 mCrab. The other five bursts have high hard X-ray flux and relatively low flux in soft X-ray, indicating that they locate in the island state (similar to the low/hard state of black hole XRB). Most of them lack LE results because of optical pollution from the bright earth. From these eight bursts, we choose a burst that satisfies the good-time-interval selection criteria of LE, ME, and HE simultaneously, and locates at the island state with a high hard X-ray flux ~75 mCrab of its inhabited persistent emission. (Figure 1) The obsid number is P011465402801-20180701-01-01, with peak flux happening at MJD 58300.717896.

The light-curve profile of the burst, which is derived in time bins of 1 s in the full passband of LE and ME and 40–70 keV of HE with preburst emission subtracted, is shown in Figure 2, the top, middle, and bottom panels are for LE, ME, and HE respectively. From Figure 2, the light curves are stable before and after the burst, indicating little variation of the persistent and background emission.

We adopted the standard analysis procedure of the burst, i.e., we take preburst emission (including instrumental background and persistent/accretion flux of the neutron star system) as background to investigate the burst spectra evolution. We divide the burst into intervals of 1 s after the burst onset, and extract the spectra of LE, ME, and HE respectively. For the burst, we use the time of the bolometric flux peak as a reference (0 s in Figure 3) to produce the light curve/spectra. A blackbody model (bbbody in Xspec) with fixed absorption $0.41 \times 10^{22} \text{ cm}^{-2}$ as derived in Agrawal & Hasan (2016) is used to fit the burst spectra. To compromise the effective area calibration deviation, a constant is added to the model. At first attempt, for LE, the constant is fixed to 1, the others (ME and HE) are alterable during spectra fitting. But the fitting result indicates that most of the constants of HE are not convergent, owing to the low-significance of the HE detection. Under this situation, the constant of HE was fixed at 1 for the combined-spectra fitting, which was based on the combined-spectra fitting of Crab observations by the same detector selection. The unabsorbed bolometric flux of the spectra is estimated by the XSPEC model cflux, and the observed blackbody radius is estimated under the condition that the distance of 4U 1636-536 is 6 kpc. The fitting results are shown in Figures 3 and 4.
3. Results

3.1. Light Curves of Burst Emission in Soft and Hard X-Ray Bands

As shown in Figure 2, the HE flux is mostly negative during the burst and around zero elsewhere. This deficit is $12.4 \pm 2.0 \text{ cts s}^{-1}$, and its significance is $6.2\sigma$, which is estimated by the ratio of the deficit area and the sum of the error bars with a duration of 32 s. The preburst emission of HE is $\sim140 \text{ counts s}^{-1}$ in 40–70 keV, which include the background $\sim125 \text{ counts s}^{-1}$ and persistent emission $\sim15 \text{ counts s}^{-1}$. From Figure 2, the hard X-ray decrement reaches a maximum of $16.1 \pm 5.5 \text{ cts s}^{-1}$ at the soft-X-ray burst peak. Considering the two values above, we conclude that almost all of the persistent emission in 40–70 keV is crippled at the burst peak time.

A cross-correlation analysis is attempted between the LE light curves in 1.1–12 keV and the re-extracted HE light curve in 40–70 keV with a bin size of 1 s, as shown in Figure 2. The minimum of the cross-correlation value appears at $1.6 \pm 1.2$ s, indicating that the hard X-ray deficit delays the burst emission. The value is derived from Gaussian-fitting of Figure 2.

3.2. Broadband Spectra of Burst Emission

The time-ordered burst spectra fitting results are as shown in Figure 3, the peak bolometric flux is $2.6 \pm 0.4 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$, which is roughly half of the Eddington luminosity $6.0 \pm 0.6 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ obtained from the PRE bursts of obsid P011465400301-20180213-01-01. The reduced $\chi^2$ of the jointed spectra fitting are roughly at 1, with most of the degrees of freedom being more than 50. The duration of the bursts is also estimated from the ratio of the bolometric flux to the peak flux, $\sim13.1 \text{ s}$.

In the process of fitting 1 s exposure jointed spectra, by taking preburst emission as background, while the residual of LE and ME are roughly around 0, a marginal deficit appears for HE. For easy reading, all the time-ordered spectral fitting results in Figure 3 are merged into one graph, which is shown in Figure 4, a clear deficit is visible around 40–50 keV. To further investigate the deficit, a jointed spectra with 32 s exposure time is extracted and fitted with a two-blackbody model (with absorption fixed). The consideration of one more blackbody spectral component is to account for the temperature evolution in the case of handing the entire burst. The embedded HE spectra of Figure 4 shows that the negative values appear at...
40–70 keV, the significance of this deficit in 40–70 keV from the spectra is 6.8σ. This value is estimated based on the different counts of the bursts and preburst emission from the spectra, i.e., 4012 counts for the burst and 4465 counts for preburst emission at the same energy band. From the above analysis, the significance of the deficit derived from the spectra and light curves are consistent with each other.

4. Discussion

So far, observations of Insight/HXMT, provide us with the best opportunity to study the effects of type-I X-ray bursts on continuum emission of NS XRB, thanks to the large detection area and wide bandwidth of the Insight-HXMT. Here with the Insight-HXMT we find for the first time the hard X-ray deficit/shortage via the single short type-I burst showing up during the flare of 4U 1636-536. The hard X-ray shortage is detected with a significance of 6.2 in 40–70 keV, and a cross-correlation analysis between the light curves of soft and hard X-ray bands, shows that the corona shortage lags the burst emission by 1.6 ± 1.2 s. These results are consistent with those derived previously from stacking a large amount of bursts detected by XTE/PCA within a series of flares of 4U 1636-536. Moreover, the broad bandwidth of Insight-HXMT also allows us for the first time to infer the burst influence upon the continuum spectrum via performing the spectral fitting of the burst, which ends up with the finding that hard X-ray shortage appears at around 40 keV in the continuum spectrum. These results suggest that the evolution of the corona along with the outburst/flare of NS XRB may be traced via looking into a series of embedded type-I bursts by using Insight-HXMT.

Our previous work has revealed the deficit of the hard X-rays in six sources using RXTE/PCA data, by constructing a sample with tens of bursts for each source (e.g., Chen et al. 2012; Ji et al. 2013, and reference therein). Since all of these reports are based on the RXTE/PCA observations, a suspicion may arise for the dead time concerning which may have influence upon the significance of observing a hard X-ray shortage accompanied with the type-I burst. Although, later on, INTEGRAL observations also confirmed such a deficit in 4U 1728-34 (Kajava et al. 2017), through stacking a sample of 123 bursts in the low/hard state, but they reported detection significances of 3.4σ in the 40–50 keV band and 1.8σ in the 50–80 keV band. In this work, benefitting the broad energy coverage of three different detectors, this phenomenon is also detected for the first time with a single burst of 4U 1636-536.

As discussed in previous papers, the deficit in hard X-rays likely indicates a cooling of the corona by the burst, which provides an intense shower of the soft X-rays to cool the hot corona via Comptonization. The time lag between the burst at soft X-rays and the deficit at hard X-rays for the continuum emission is considered as the timescale of the corona reheating/reformation. So far, all the time-lags of the deficits detected in the above sources are within several seconds, indicating a similar mechanism for corona production during outburst/flare of NS XRBs.

As shown in Table 1 and Figure 1, apart form the burst with a hard X-ray shortage clearly seen, there are three other bursts detected during the soft state of the 4U 1636-536. Two of them are the short type-I bursts, and one is the PRE burst. No hard X-ray shortages are detected for the continuum emission during these bursts, due to the continuum hard X-ray emissions being too weak. As shown in the Swift/BAT observations, the source stayed at roughly the ~15 mCrab level above 15 keV at the time around these three bursts. The spectral analysis of the

| No. | obsid              | Time (MJD) |
|-----|--------------------|------------|
| 1*  | P011465400301-20180213-01-01 58162.871091 |
| 2   | P011465400401-20180215-01-01 58164.733723 |
| 3   | P011465400505-20180217-01-01 58166.117179 |
| 4   | P011465402301-20180626-01-01 58295.087021 |
| 5   | P011465402701-20180630-01-01 58299.489308 |
| 6   | P011465402801-20180701-01-01 58300.717896 |
| 7   | P011465403101-20180704-01-01 58303.959479 |
| 8   | P011465403201-20180705-01-01 58304.808113 |

Note.
* Burst shows photosphere radius expansion.
these bursts shows no obvious significant residual detected in LE and ME spectra fitting results. Although a hint of excess appears below $\sim 2$ keV for the burst showing up in the hard state of the flare, it becomes invisible by setting the absorption parameter free during spectra fitting. Usually, the persistent emission changes are detected in RXTE/PCA and NICER, and the degree of enhancement is proportional to the burst flux. The faintness of the burst peak flux probably prevents us from detecting the effects of the bursts on the disk emission. Clear residuals below $\sim 2$ keV are detected at the PRE burst of obsid P011465400301-20180213-01-01, which is detected with faint persistent emission, and also indicate the state-dependence of the persistent emission enhancement induced by the burst. The PRE burst results will be reported by an upcoming paper.

The physical origin of QPOs at kHz is thought to be the dynamical timescale of the inner part of the accretion disk and hence to provide another way to diagnose the burst influence upon the accretion disk corona. For 4U 1636-536, QPO frequency changes during the burst are detected (Peille et al. 2014). One interpretation is that the inner part of the disk is puffed up by the burst, which suppresses the QPO generation (Ballantyne & Everett 2005). If the disk curls up to higher latitude, the deficit will become unremarkable because of cloaking the burst photons by the taller disk, since the disk is optically thick. The other interpretation of the QPO suppression is the backward/regression of the inner disk, i.e., the X-ray burst blows away the disk to behave as if it has a bigger inner disk radius. However, the disk emission is detected to increase during burst by RXTE (Ballantyne & Strohmayer 2004; int Zand et al. 2013; Worpel et al. 2013; Keek et al. 2014) and NICER (Keek et al. 2018), which indicates a smaller inner disk radius induced by the burst. Unfortunately, no QPO is detected from 4U 1636-536 by the Insight-HXMT, probably due to its relatively small detection area at soft X-rays. An increase of disk temperature might reconcile this contradiction; in other words, the burst heats the disk.

The deficit energy covers a range of roughly 40–70 keV and extends to $\sim 70$ keV, within which HE has the largest effective area. Considering the effective area of HE decreases in higher energy and low count rates of the preburst emission for the continuum emission at hard X-rays, the deficit might extend to both lower and higher energies. More observations of the low/hard state of 4U 1636-536 and target of opportunity (ToO) observations of brighter bursters, such as Aql X-1, may provide us with a better chance to thoroughly investigate both the time and spectral evolution of corona along with the outburst flare via investigating an individual type-I burst with the unique capability of the Insight-HXMT. The upscattering photons of bursts by the continuum emission, should affect the shape/amplitude of blackbody spectra, joint observations of bursters by NICER or AstroSat and Insight/HXMT may give us an opportunity to test the coronal cooling interpretation.

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