Possible hard X-ray shortages in bursts from KS 1731-260 and 4U 1705-44 (Research Note)

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ABSTRACT

Aims. A hard X-ray shortage, implying the cooling of the corona, was observed during bursts of IGR J17473-272, 4U 1636-536, Aql X-1, and GS 1826-238. Apart from these four sources, we investigate here an atoll sample, in which the number of bursts for each source is larger than 5, to explore the possible additional hard X-ray shortage during Rossi X-ray timing explorer (RXTE) era.

Methods. According to the source catalog that shows type-I bursts, we analyzed all the available pointing observations of these sources carried out by the RXTE proportional counter array. We grouped and combined the bursts according to their outburst states and searched for the possible hard X-ray shortage while bursting.

Results. We found that the island states of KS 1731-260 and 4U 1705-44 show a hard X-ray shortage at significant levels of 4.5 and 4.7σ and a systematic time lag of 0 ± 2.0 s with respect to the soft X-rays, respectively. While in their banana branches and other sources, we did not find any consistent shortage.

Key words. stars: coronae – X-rays: binaries – X-rays: bursts – stars: neutron

1. Introduction

Disc-accreting X-ray binaries (XRBs) are known to display distinct spectral states according to the variation of their accretion rate during the evolution of an outburst (Lewin et al. 1993; Remillard & McClintock 2006; Esin et al. 1997). At the high state, the spectrum is usually dominated by thermal components, and at the low state, significant non-thermal hard X-rays can be observed, which is thought to originate from the corona or the jet. Although XRBs have been discovered decades ago, the corona formation process is still unclear. In theory, it can result from evaporation (Meyer et al. 1994; Esin et al. 1997; Liu et al. 2000; Meyer & Pringle 2007).

A hard X-ray shortage, implying the cooling of the corona, was observed during bursts of IGR J17473-272, 4U 1636-536, Aql X-1, and GS 1826-238 (Maccarone et al. 2003; Chen et al. 2012; Ji et al. 2013, 2014, Chen et al. 2013). Apart from these four sources, we investigate an atoll sample here (Tables 1, 2), in which the number of bursts for each source is larger than 5, to explore the possible additional hard X-ray shortage during the Rossi X-ray timing explorer (RXTE) era. In this sample, we pay extra attention to the sources that show complete color–color diagrams (CCDs; see Table 1). According to the CCDs, we can identify outburst states at a time around the occurrence of each burst and categorize the bursts into hard and soft states, respectively. Finally, we find two atoll sources (4U 1705-44 and KS 1731-260) that showed corona cooling while bursting. In this paper, we focus on the results derived on these two sources.

The neutron star KS 1731-260 is a transient located near the Galactic center (l = 1.07°, b = 3.66°) with a mass less than 2.1 M⊙ and a radius R < 12.5 km ( Özel et al. 2012). It was discovered in 1989 (Syunyaev et al. 1990) and remained active until transitioning to quiescence in early 2001 (Chelovekov et al. 2006). The distance was estimated to be ~7 kpc (Muno et al. 2000). The neutron star 4U 1705-44 is a persistently bright XRB in the direction of the Galactic bulge. Christian & Swank (1997) derived a distance of 11 kpc from the peak flux of photospheric radius expansion (PRE) bursts. The kilohertz quasi-periodic oscillations were discovered using observations with RXTE by Ford et al. (1997). The spectral analysis and fluorescent iron line have been carried out by Di Salvo et al. (2005).

Section 2 introduces the data and the observations we analyze. Section 3 describes the results of the corona cooling and their intrinsic timescale of reheating. The summary and discussion of these results are provided in Sect. 4.

2. Observation and data reduction

According to the source catalog that shows type-I bursts and is provided by Galloway et al. (2008), we analyzed all the available pointing observations of these sources carried out by RXTE proportional counter array (PCA). Apart from those four for which the hard X-ray shortages were reported while bursting, we select the sources in which larger than 5 bursts were observed for the following analysis and present them in Tables 1 and 2. In Table 1, we have six atolls for which the complete CCDs are derived. In Table 2, we have eleven atolls that only parts of the CCDs are available from the observational data. Among the five co-aligned Xe multiwire proportional counter units (PCUs), only PCU2 was used due to its better calibration and longer coverage. We used the data of the Standard 2 mode when producing CCDs, while only the data from the E_125u_64M_1_s and the Goodxenon mode were adopted when studying the properties of...
bursts due to their high resolution. The data were filtered with the standard criteria: the elevation angle is larger than 10°, and the pointing offset is less than 0.02°. The background files were created using the program pcabackest with the latest bright source background model, and the detector breakdowns have been removed. We should note that PCA count rates are dominated by background model, and the detector breakdowns have been re-adapted using the program pcabackest with the latest bright source background model.

We excluded bursts for which the peak flux are not 300 cts/s larger than the persistent emission. In 4U 1636-536 and Gs 1826-238, an energy band of 30–50 keV is used to study the properties of the corona because the temperature of type-I bursts is relatively low in these two bursters (Ji et al. 2013, 2014). However, the burst temperature in some sources (e.g. 4U 1728-34) in Tables 1 and 2, is much higher. Therefore, we took a narrower energy band of 40–50 keV to indicate the intensity of the corona to minimise the contaminations by the bursts, following Chen et al. (2013). Using the date of Standard 2 mode, the persistent flux for each burst is estimated as the average count rate of the whole observation ID at 40–50 keV during which the data at ~100 s around the burst is subtracted off. The persistent flux at energies of 3.6–18 keV and 40–50 keV shown in Tables 1 and 2 represents the averaged persistent flux for the bursts in a source or a sub-group. Following a standard approach, we took the flux at a window of 30 s prior to each burst as the background and subtracted it off to have the net lightcurve and spectrum (van Paradijs et al. 1986; Lewin et al. 1993). The cross correlation was calculated by CROSSCOR2, a standard software in XRONOS, which computes the coefficient normalized by the square root of the number of newbins with the fast Fourier transform (FFT) algorithm.

Notes. The columns denote the source name, number of bursts, averaged persistent flux at 40–50 keV and 3.6–18 keV, and peak flux of bursts at 3.6–18 keV for hard and soft states.

Table 2. The sources that have a burst number larger than 5 but show no complete CCDs.

| Source     | Number | Persistent flux at 40–50 keV (cts/s) | Persistent flux at 3.6–18 keV (cts/s) | Peak flux at 3.6–18 keV (cts/s) |
|------------|--------|------------------------------------|-------------------------------------|--------------------------------|
| 4U 0513-401| 11     | -0.033 ± 0.054                     | 34.89 ± 0.06                        | 1120.33 ± 10.28                 |
| x1735-444  | 8      | -0.026 ± 0.010                     | 228.46 ± 0.09                       | 2374.16 ± 18.75                 |
| 4U 1820-30  | 12     | 0.230 ± 0.009                      | 227.46 ± 0.06                       | 3906.67 ± 19.17                 |
| HETEJ1990.1-2455 | 10  | 0.203 ± 0.015                     | 60.76 ± 0.05                        | 5635.34 ± 27.54                 |
| 1M 0836-425 | 15     | 0.273 ± 0.011                     | 79.82 ± 0.04                        | 1030.44 ± 8.41                  |
| EXO 1745-248 | 16     | 0.478 ± 0.012                     | 215.18 ± 0.08                       | 1540.94 ± 11.48                 |
| 4U 1916-053 | 12     | 0.072 ± 0.009                     | 27.45 ± 0.02                        | 2031.05 ± 13.24                 |
| IGR J17511-3057 | 9     | 0.234 ± 0.008                     | 45.88 ± 0.03                        | 2945.85 ± 18.60                 |
| SXL 1744-300 | 8      | 0.089 ± 0.010                     | 82.29 ± 0.04                        | 779.84 ± 10.01                  |
| SAX J1750.8-2900 | 6       | 0.109 ± 0.019                    | 126.83 ± 0.09                       | 2965.07 ± 22.84                 |
| XTE J1759-220 | 6      | 0.045 ± 0.011                     | 25.47 ± 0.03                        | 695.87 ± 10.90                  |

Notes. The columns denote the source name, number of bursts, averaged persistent flux at 40–50 keV and 3.6–18 keV, and peak flux of bursts at 3.6–18 keV.
energies between 2–10 keV and 40–50 keV. The time delays and their errors are calculated by a throwing-dot method. In practice, we sample the lightcurves at energies between 2–10 keV and 40–50 keV by assuming that each point in lightcurves has a Gaussian distribution and then calculate the time delay with a cross-correlation method. By sampling the lightcurve a thousand times, we fit the resulted time delay and corresponding error with a Gaussian function. The resulted time delays in KS 1731-260 and 4U 1705-44 are 0.9 ± 2.1 and 2.5 ± 2.0, respectively.

4. Summary and discussion

We report on the hard X-ray shortage during bursts in KS 1731-260 and 4U 1705-44, suggesting the corona can be cooled by the shower of seed photons from type-I bursts. For all the six sources (the previous four and the two reported in this paper) so far showing corona cooling, the reheating timescale is ~seconds. However, a similar phenomenon cannot be observed for other sources in Tables 1 and 2.

4.1. Comparison between the sources showing the corona cooling

Here, we find two more atoll sources, which behaved as possible hard X-ray shortages. These, together with the previous four sources (Aql X-1, IGR J17473-2721, 4U1636-536, and GS 1826-238) constitute six sources exhibiting cooling of the corona during type-I bursts. However, the evolution of the outbursts in these sources and the position in the CCDs when the bursts occurred are quite different. The bursts in IGR J17473-2721 are embedded in a long-lived preceding hard state of a single outburst (Chen et al. 2012). The accretion rate in GS 1826-238 ranges from 5%\(L_{\text{edd}}\) to 9%\(L_{\text{edd}}\), which is remarkably stable. The luminosity of 4U 1636-536, KS 1731-260, and 4U 1705-44 is 3%–16%\(L_{\text{edd}}\), 6%–38%\(L_{\text{edd}}\), and 1.1%–70%\(L_{\text{edd}}\), respectively. The bursts in Aql X-1 are mostly located in the failed outbursts (the outbursts without state transitions). This implies that the cooling of the corona prompted by the bursts may be independent of the detailed accretion evolution. In addition, it seems that the different duration of the bursts (for example, ~30 s in 4U 1705-44 and ~100 s in GS 1826-238), which suggest the different proportion of hydrogen in accretion materials, do not greatly affect the reheating process because of their similar time delays. This result seems to suggest that the physical process dominating the corona is similar in different sources.

4.2. Cooling and reheating

By assuming the equipartition between the thermal and magnetic energy (\(\frac{1}{2}mkT \sim B^2/8\pi\)) or the balance condition (\(c_s^2 \sim B^2/8\pi\)) in typical ADAF models, the magnetic field in the corona is \(10^6\) G. Given that the relation of the cooling efficiency between Compton scattering and synchrotron radiation is \(\frac{\dot{E}_{\text{cool}}}{\dot{E}_{\text{acc}}} \approx \frac{\dot{E}_{\text{acc}}}{\dot{E}_{\text{cool}}}\), the corona cooling is dominated by the inverse Comptonization. Since an effective Compton cooling of a pure electron plasma takes \(~10^{-6}\) s, the discovered time lag of about a few seconds should be intrinsic to the corona recovery process.

In theory, evaporation models give a timescale of days, and it is usually used to explain the behavior of the corona evolution in long-term outbursts. Ji et al. (2014) proposed that the timescale the statistical fluctuation. With respect to the following simulation, the mean cross correlation coefficients are –0.55 and –0.51, respectively.
for evaporation while bursting could drop significantly after considering the additional angular momentum transfer mechanism. The detailed reheating model, however, remains unknown.

Alternative to the evaporation model, the corona can also be formed through a magnetic reconnection process, as was firstly proposed according to the similarity between the XRB disks and the solar corona. In a magnetic reconnection model, similar to what happens in Sun, magnetic turbulence and buoyancy can trigger magnetic flares and cause an intense heating (Zhang et al. 2000). Following the model by Liu et al. (2002), the energy balance in the corona between heating by magnetic reconnection and cooling by Compton scattering, is as follows:

\[ \frac{B^2}{4\pi} \approx \frac{4kT}{m_{\text{e}c^2}} n\sigma_T c U_{\text{rad}}, \]

where \( V_A \sim B/\sqrt{4\pi \rho_0} \) is Alfvén speed. Here, \( \rho_0 \) is the electron density, \( \sigma_T \) is the Thomson cross-section, \( U_{\text{rad}} \) is the soft photon field, and \( l \) is the characteristic length of the magnetic loops. We estimate the timescale of the reheating process in a magnetic reconnection model as \( t_{\text{c,rc}} \), where \( c_s \) is the sound speed and \( c_s \sim 10^4 T^{1/2} \text{km s}^{-1} \) (Frank et al. 2002). By assuming the \( l \sim 10 r_g \) and a characteristic temperature between \( 10^7 \) K and \( 10^9 \) K, the time delay ranges from 0.01 to 0.1 s.

4.3. The atoll sources without hard X-ray shortage

Except for KS 1731-260 and 4U 1705-44, we find no significant hard X-ray shortage in other sources listed in both Tables 1 and 2. During banana states for atoll sources enclosed in Table 1, there is no evidence of hard X-ray shortage probably because the persistent hard X-ray flux itself is too weak to be detectable. This could be the case as well for some sources listed in Table 2.

Apart from KS 1731-260 and 4U 1705-44, there are seven other sources in Tables 1 and 2 that have the 40–50 keV flux larger than 0.2 cts/s. However, we see no obvious hard X-ray shortage while bursting from these seven sources. One possibility that makes shortages invisible could be that, bursts with high temperature contribute hard X-rays that are not negligible while bursting to dilute the original shortage. For example, the mean temperature for 4U 1728-34 around the peak of the bursts is 2.8 keV, which leads to a contribution of 0.45 cts/s at 40–50 keV. As once discussed in Chen et al. (2012) in the case of the lacking shortage in the lagging low hard state of IGR J17473-2721, an additional possibility is that the corona may be located too far away from the neutron star to be effectively cooled off by the bursts. This occurs because in current observations the innermost radius of the accretion disk in the hard state cannot be well constrained due to the relative low luminosity and severely hardened spectrum. Another possibility could be that the hard X-rays are from the jet, which is usually hard to cool off under the soft X-ray shower of the bursts.

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