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Temperature measurement during thermonuclear X-ray bursts with *BeppoSAX*

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HIGHLIGHTS

- Temperature measurement of thermonuclear X-ray bursts using hardness ratio.
- Observation with BeppoSAX show temperatures as high as 3 keV in different spectral states.
- High temperatures indicate the possibility of deviation from a true blackbody.

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ABSTRACT

We have carried out a study of temperature evolution during thermonuclear bursts in LMXBs using broad band data from two instruments onboard *BeppoSAX*, the MECS and the PDS. However, instead of applying the standard technique of time resolved spectroscopy, we have determined the temperature in small time intervals using the ratio of count rates in the two instruments assuming a blackbody nature of burst emission and different interstellar absorption for different sources. Data from a total of twelve observations of six sources were analyzed during which 22 bursts were detected. We have obtained temperatures as high as ~3.0 keV, even when there is no evidence of photospheric radius expansion. These high temperatures were observed in the sources within different broadband spectral states (soft and hard).

1. Introduction

Thermonuclear X-ray bursts due to unstable nuclear burning of hydrogen and/or helium (Joss, 1977; Lamb and Lamb, 1978; Lewin et al., 1993; 1995; Strohmayer and Bildsten, 2006; Bhattacharyya, 2010) have been observed in nearly 80 neutron star low mass X-ray binaries (Liu et al., 2007; Galloway et al., 2008). These bursts offer a useful tool for the measurement of neutron star parameters (Bhattacharyya, 2010). Time resolved spectroscopy during bursts have been performed for many sources for the determination of neutron star radius by assuming that the entire surface emits in X-rays (e.g., van Paradijs, 1978; Galloway et al., 2008; Güver et al., 2012b). The background subtracted continuum spectra during these bursts are often fit using Planck (blackbody) function. The persistent emission prior to the burst is subtracted as background (Galloway et al., 2008; Bhattacharyya, 2010). In time resolved spectroscopy of the photospheric radius expansion bursts, when the photosphere falls back to the neutron star surface, the temperature has the highest value and the blackbody normalization has the lowest value, which is also called the touchdown (e.g., Damen et al., 1989; Kuulkers et al., 2003). Time resolved spectroscopy during the cooling phase after the touchdown is the most widely used method for neutron star radius measurement (e.g., Lewin et al., 1993; Özel, 2006; Galloway et al., 2008; Özel et al., 2009; Güver et al., 2010a; 2010b; 2012a; 2012b). The scattering of photons by the electrons and frequency dependence of the opacity in the neutron star atmosphere harden the spectrum, and shift it to higher energies (London et al., 1984; 1986; Syunyaev and Titarchuk, 1986; Ebisuzaki and Nakamura, 1988; Titarchuk, 1994; Madej et al., 2004; Majczyna et al., 2005; Bhattacharyya, 2010). Therefore, it is believed that the effective temperature is substantially smaller than the temperature obtained from the blackbody fit (e.g., Ebisuzaki et al., 1984; Galloway et al., 2008). The observed color temperature and flux is associated with the blackbody radius through $R_\infty = (F_\infty/\sigma T_\infty^4)^{1/2} d$ (Lewin et al., 1993). Here, F_∞ is the observed flux, T_∞ is the blackbody temperature measured at infinity and d refers to the source distance. The neutron star radius is estimated from the blackbody radius (R_{BB}) via the following equation:

$$R_{BB} = R_\infty {f_c}^2/(1+z) \quad (1)$$

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Table 1
Log of observations used in this work.

Sourcename	Obs-ID	Observation date	Number of bursts	N_H (10^{22}) cm^2
4U 1702-429	21224001	2000-08-24	3	1.8[b]
4U 1702-429	21224002	2000-09-23	2	1.8[b]
X 1724-308	20105002	1996-08-17	1	1.11[e]
4U 1728-34	20674001	1998-08-23	3	2.5[a]
SAX J1747-2853	21032001	2000-03-16	1	8.8[c]
SAX J1747-2853	210320013	2000-04-12	1	8.8[c]
SAX J1748.9-202	20549003	1998-08-26	1	0.82[d]
SAX J1748.9-202	21416001	2001-10-02	3	0.82[d]
GS 1826-238	20263003	1997-10-25	1	0.11[f]
GS 1826-238	21024001	1999-10-20	1	0.11[f]
GS 1826-238	21024002	2000-04-18	3	0.11[f]
GS 1826-238	20269001	1997-04-06	2	0.11[f]

References: N_H values were taken from: (a) Di Salvo et al. (2000), (b) Church et al. (2014), (c) Natalucci et al. (2004), (d) in 't Zand et al. (1999b), (e) Guainazzi et al. (1998), (f) in 't Zand et al. (1999a).

where z is the gravitational redshift and f_c is the color correction factor which is defined as the ratio of color temperature (T_c) and the effective temperature (T_{eff}) of the star (London et al., 1986; Madej et al., 2004; Majczyna et al., 2005; Suleimanov et al., 2011a; 2012). Color correction factor varies as a function of effective temperature and also depends on effective gravitational acceleration, which determines the density profiles of the atmospheric layers (Güver et al., 2012b). It has been found that X-ray burst cooling properties are dependent on the accretion rate and the spectral states (Suleimanov et al., 2011b; Kajava et al., 2014). Though a color correction factor close to 1.4 has often been used (Madej et al., 2004; Majczyna et al., 2005), the most recent calculations by Suleimanov et al. (2012) suggest that f_c is in range of 1.8–1.9 when the luminosity is close to Eddington luminosity (L_{Edd}) and its value decreases to a range of 1.4–1.5 with the subsequent fall to $\sim$ 0.5 L_{Edd}. Assuming a constant value of color correction factor may lead to systematic change in inferred apparent surface area (Güver et al., 2012b). Hence, this is one of the sources for systematic uncertainty while measuring the radius of a neutron star from X-ray bursts.

Even if a blackbody model provides a good fit for the time resolved burst spectrum that is often measured with the proportional counters, Nakamura et al. (1989) have reported deviations from a blackbody. The authors observed a high energy tail during bursts and have interpreted it as a result of comptonization of the burst emission by hot plasma surrounding the neutron star. For a peak temperature close to 2.5 keV, the emission peaks at 2.8 $\times$ kT, i.e 6–7 keV. Therefore, in addition to the *RXTE*-PCA we expect to detect the bursts even with high energy instruments like *BeppoSAX*-PDS, *Suzaku*-PIN, *NuSTAR*. However, simultaneous data at energies below 10 keV with sufficient time resolution is also required to measure the temperature evolution and this is possible with the MECS of *BeppoSAX* and also with *NuSTAR*. Barrière et al. (2014), using *NuSTAR* data have reported a Type-I burst in GRS 1741.9-2853 that was found to be 800 s long with mild Photospheric radius expansion (PRE). The peak temperature of this burst was found to be 2.65 $\pm$ 0.06 keV.

A large fraction of all the burst temperature studies have been done with *RXTE-PCA* in the energy range of 3–25 keV. We have estimated the temperature evolution in short intervals during bursts that were observed with *BeppoSAX*. We performed studies of bursts using the two instruments MECS and PDS on-board *BeppoSAX*. Since *BeppoSAX* data have lower count rates than *RXTE-PCA* we have used a new technique for measuring the temperature evolution. If a blackbody spectrum with a fixed absorption column density is fitted to the time resolved spectra, the temperature obtained is a function of the ratio of the count rates in two energy bands. Therefore, instead of a spectral fit of data with low statistical quality, we have used the hardness ratio (HR) to determine the temperature evolution. The paper is organized as: the second section describes the observations and data reduction procedure, the third and fourth sections describe the calibration and timing studies performed. The last section is dedicated to the implications of the results achieved.

2. Observations and data reduction

BeppoSAX had four co-aligned narrow field instruments (NFI) (Boella et al., 1997) and a Wide Field Camera (WFC) (Jager et al., 1997). The four NFIs are: (i) the Medium-Energy Concentrator Spectrometer (MECS) that consists of three grazing incidence telescopes each with an imaging gas proportional counter that work in 1.3–10 keV band (Boella et al., 1997), (ii) the Low-Energy Concentrator Spectrometer (LECS), consisting of similar kind of imaging gas scintillation proportional counters but with an ultra-thin (1.25 μm) entrance window and working in the energy range of 0.1–10 keV (Parmar et al., 1997), (iii) the High Pressure Gas Scintillation proportional Counter (HPGSPC, 4–120 keV; Manzo et al. (1997)) and (iv) the Phoswich Detection System (PDS, 15–300 keV; Frontera et al. (1997)). The HPGSPC and PDS are non-imaging instruments. The PDS detector is composed of 4 actively shielded NaI(Tl)/CsI(Na) phoswich scintillators with a total geometric area of 795 cm^2.

Bursts were clearly detected over the entire energy range of 1.8–10 keV of MECS while in the case of PDS, most of the bursts were noticeable only up to 30 keV, i.e. in the energy range of 15–30 keV. Therefore, we selected these two energy bands for estimating the hardness ratio.

We considered only those sources and observations for which bursts were observed simultaneously in MECS and PDS. We have found a total of 22 bursts in 6 sources. The log of observations is given in Table 1. Since MECS 2 and MECS 3 data were available for all sources considered, we merged data from both these MECS. *HEASOFT-6.12* and *SAXDAS* (version 2.3.3) were used for reduction and extraction purposes.

Subsequently, the merged MECS event data files were used for extraction of light curves with a binsize of 0.5 s using the ftools[1] task *xselect*. The source radius of 4′ corresponding to $\simeq$ 95 % of the instrumental Point Spread Functions was selected and appropriate good time intervals (GTI) were applied. The light curves were restricted to the energy band 1.8–10 keV using appropriate energy filters. In case of PDS, the SAXDAS programs *saxpipe* and *pdproducts* were used for creating the light curves with a bin time of 0.5 s. Fig. 1 shows the time series for all the sources including about 100 s of data before and after the bursts. It is evident from the light curves shown in Fig. 1 that the persistent emission is stable before and after the burst.

[1] http://heasarc.gsfc.nasa.gov/ftools/.