A STATE-DEPENDENT INFLUENCE OF TYPE I BURSTS ON THE ACCRETION IN 4U 1608–52?

LONG JI1, SHU ZHANG1, YUPENG CHEN1, SHUANG-NAN ZHANG1, DIEGO F. TORRES2,3, PETER KRETSCHEMAR4, and JIAN LI1

1 Laboratory for Particle Astrophysics, Institute of High Energy Physics, Beijing 100049, China
2 Institució Catalana de Recerca i Estudis Avançats (ICREA), 08010 Barcelona, Spain
3 Institute of Space Sciences (IEEC-CSIC), Campus UAB, Torre C5, 2a planta, 08193 Barcelona, Spain
4 European Space Astronomy Centre (ESA/ESAC), Science Operations Department, Villanueva de la Cañada (Madrid), Spain

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ABSTRACT

We investigated the possible feedback of type I bursts on the accretion process during the spectral evolution of the atoll source 4U 1608–52. By fitting the burst spectrum with a blackbody and an adjustable, persistent spectral component, we found that the latter is significantly state-dependent. In the banana state, the persistent flux increases along the burst evolution, while in the island state this trend holds only when the bursts are less luminous and start to reverse at higher burst luminosities. We speculate that, by taking into account both the Poynting–Robertson drag and radiation pressure, these phenomena may arise from the interactions between the radiation field of the type I burst and the inner region of the accretion disk.

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

Online-only material: color figures

1. INTRODUCTION

Type I bursts are nuclear explosions triggered by unstable burning on the surface of neutron stars (for details see, e.g., Lewin et al. 1993; Galloway et al. 2008 and references therein). The burst spectrum is usually morphologically described as a pure blackbody, assuming that the persistent emission remains unchanged and can be subtracted off during bursting (see, e.g., van Paradijs & Lewin 1986; Kuulkers et al. 2003). Generally, the persistent emission for a neutron star X-ray binary (XRB) mainly consists of the spectral components of a multicolor blackbody, a blackbody, and a power law that is believed to have origins in an accretion disk, a boundary layer (between the accretion disk and the neutron star surface), a corona, or a jet (see e.g., Belloni 2010; Muñoz-Darias et al. 2014 and references therein). In this Letter, we investigate a well-known XRB 4U 1608–52. According to the spectral and timing properties, 4U 1608–52 was classified as an atoll source (Hasinger & van der Klis 1989), for which the typical outburst evolution experiences so-called island and banana states.

Theoretical predications for the possible deviations of the burst spectrum from a blackbody have been made using different mechanisms. For instance, the reflection of the burst emission by the accretion disk was considered in Ballantyne et al. (2004). In addition, the radiation of the boundary layer may also be affected by type I bursts (in’t Zand et al. 2013). Walker (1992) proposed that the radiation torque may induce a substantial increase of the accretion rate during a type I X-ray burst, likely resulting from the effect of Poynting–Robertson drag. On the contrary, Kluzniak (2013) predicted an ejection under the radiation pressure of a large part of optically thin gas orbiting the neutron star.

In observations, the possible influence of the bursts upon the accretion disk is mostly investigated with so-called photospheric radius expansion (PRE) bursts. For PRE bursts, the X-ray luminosity reaches the local Eddington limit and is strong enough to lift up the outer layers of the neutron star (Galloway et al. 2008). in’t Zand et al. (2013) detected a PRE burst from SAX J1808.4–3658 in an observation campaign of Chandra and the Rossi X-Ray Timing Explorer (RXTE), and found spectral deviations from a blackbody at both low and high energies. In addition, by assuming that the shape of the persistent spectrum remains stable throughout the burst and involving a dimensionless quantity “fa” to account for the change in normalization of the persistent emission (hereafter fa model), Worpel et al. (2013) analyzed 332 PRE bursts born out of 40 atoll sources. They found that the majority of the best-fit values of fa are significantly greater than 1, suggesting an enhancement of the persistent flux during these bursts. Since the changes in the structure of the accretion disk, i.e., the transitions between the standard disk and the advection-dominated accretion flow (ADAF), are expected to influence the burst spectrum, the variability of the persistent flux observed in PRE bursts may have a dependence on the spectral states. However, most of the PRE bursts are located in the banana state (Watts 2012) and the influence of the island non-PRE bursts on the accretion process is less known. In order to study the bursts’ influence thoroughly, one also needs to account for the non-PRE bursts occurring mostly in the island state. To this end we studied the well-known XRB 4U 1608–52, which was first detected by Vela-5 and subsequently observed with Uhuru, HEAO-1, RXTE, and other satellites (Belian et al. 1976; Tananbaum et al. 1976; Fabbiano et al. 1978; Galloway et al. 2008). The distance to 4U 1608–52 was estimated as ~3.2 kpc with PRE bursts when their luminosities reach the Eddington limit, under the assumption of a canonical neutron star with M = 1.4M⊙, R = 10 km, and X = 0.7 (Galloway et al. 2008).

2. OBSERVATIONS AND DATA ANALYSIS

We analyzed all RXTE Proportional Counter Array (PCA; Jahoda et al. 1996) observations of 4U 1608–52 and found 46 bursts, 19 of which exhibited PRE. The PRE bursts have been identified by Poutanen et al. (2014). The Standard 2 mode data were used when studying the persistent spectra because of their better calibration and the Event mode data were adopted when studying detailed properties of bursts because of their high resolution. There are five co-aligned Xe multiwire proportional
counter units (PCUs) on board RXTE, and all active ones were used for the following analysis.

The spectral fits were performed using XSPEC version 12.7.1, during which a multiplicative model component (wabs in XSPEC) was employed to correct for the effects of interstellar absorption and the hydrogen column density was fixed to $10^{22}$ atoms cm$^{-2}$ (Keek et al. 2008). The instrumental background of PCA was estimated with the latest bright source models and generated using the pcabackest version 3.8, heasoft release 6.12. In the spectral fits, the Levenberg–Marquardt algorithm was used to find the local best-fit values and their corresponding confidence intervals. Because the effective area of PCA drops off rapidly above 20 keV, sometimes only a few counts are observed in higher energy bands. To ensure that we could get an unbiased estimate of the parameters, we have used the likelihood method, namely, the command “statistic cstat” in XSPEC. The fitted energy range was in principle 3–25 keV but could get an unbiased estimate of the parameters, we have used the likelihood method, namely, the command “statistic cstat” in XSPEC. The fitted energy range was in principle 3–25 keV but

3. RESULTS

First, we produced light curves for each burst with a time resolution of 1/8 s. We then performed time-resolved analysis for those time intervals in which the count rate exceeds 25% of the burst peak. To improve the statistics, we summed up the time intervals so that the total counts can exceed 35,000 photons. This means that, in order to have balance in statistics, the bin size has to gradually increase toward the burst tail. For the spectral fits, we employed two different models: the standard approach (see, e.g., Lewin et al. 1993; Kuulkers et al. 2003, wabs*bbodyrad in XSPEC) in which the preburst emission is regarded as a background, and the “$f_a$” model (Worpel et al. 2013; in’t Zand et al. 2013, wabs*(bbodyrad+$fa\times$persistent flux) in XSPEC) in which the “persistent spectrum” is estimated by multiplying the pre-burst spectral shape with a normalization factor “$f_a$.” Obviously, the two approaches are equivalent when $f_a$ equals 1. Since the type I bursts are located in different spectral states, it is hard to estimate the persistent emissions with an exclusive model. The models we employed to fit the persistent flux were “wabs*(gauss+bbody+compt)” and “wabs*(gauss+bbody+diskbb)” (Zhang 2013), and the Gaussian component was set at 6.4 keV (Gierliński & Done 2002). It turned out that these two models can describe the persistent data well, and resulted in an averaged reduced $\chi^2 \sim 1.01$ (44df).

An example of the time-resolved analysis is shown in Figure 2, in which the $f_a$ model was used. In Figure 2, the blue line shows the count rate against the burst time, for which we define the time with the maximum count rate as time zero. The red and green regions represent the 1σ confidence interval of $f_a$ and temperature, respectively. Thus, for each burst we can get a series of best-fit parameters along with the evolution of $f_a$ and temperature.
bursts. Because the purpose of this Letter is to distinguish the possible spectral differences between different spectral states, we divided the spectra into island and banana groups according to the positions of bursts in the CCD (see Figure 1). Here we used the reduced $\chi^2$ to describe the quality of the fits. Figure 3 shows histograms of the reduced $\chi^2$ for different spectral groups when using the standard approach. Clearly, the two distributions are significantly different and the Kolmo- gorov–Smirnov test gives a $p$-value of $1.07 \times 10^{-24}$. The average reduced $\chi^2$ are 1.32 (21 dof) and 1.71 (21 dof) for the spectra in the island and banana states, respectively. This result indicates that the fits are generally poor in the banana state. In general, once the $f_a$ model was introduced, the average reduced $\chi^2$ are 1.14 (20 dof) and 1.23 (20 dof) for the island and the banana states, respectively, showing largely improved fits for both.

Since $f_a$ was reported in in’t Zand et al. (2013) to evolve strongly with burst luminosity, we studied this trend as well but aimed at uncovering their possible dependence on the spectral states. Here we estimated the burst luminosity at the surface of the neutron star as $L = (1 + z)^4 \pi \sigma T^4 ND^2$, where $\sigma$ is the Stefan–Boltzmann constant, $D$ is the distance to the source in the units of 10 kpc, and $T$ and $N$ are the color temperature and normalization derived from the spectral fits with the XSPEC model “bbodyrad,” respectively. The factor $1 + z = (1 - 2GM/Rc^2)^{-1/2} \sim 1.31$ represents the gravitational redshift correction at the surface of the neutron star. The result is shown in Figure 4. The distribution of $f_a$ differs significantly between the island and banana states: although both have a peak around 2.5, the profile is much broader for the latter. The average $f_a$ for the island and the banana states are $3.2 \pm 0.1$ and $6.8 \pm 0.3$, respectively. A Kolmogorov–Smirnov test shows that the possibility of having a consistent distribution of $f_a$ in the two spectral states is $5.33 \times 10^{-27}$.

To have a clearer trend of the $f_a$ evolution against luminosity, we binned the points in Figure 4 in a bin size of $1.5 \times 10^{37}$ erg s$^{-1}$, and within each bin we calculated the weighted average of $f_a$. The result is illustrated in Figure 5. The red and blue lines represent the weighted average for the bursts in the banana and island states, respectively. We found that the $f_a$ increases gradually with the burst luminosity in the banana state, which is consistent with the report of in’t Zand et al. (2013). However, the bursts in the island state show a very different behavior. When the burst luminosity is smaller than around $1.8 \times 10^{38}$ erg s$^{-1}$ the $f_a$ is similar to that in the banana state; otherwise the $f_a$ shows an opposite tendency, i.e., decreases with increasing burst luminosity.

As shown in Figure 1, most of bursts in the island state are non-PRE bursts, while in the banana state the PRE bursts are appreciable. Considering that the photosphere is lifted up when the burst luminosity reaches the Eddington limit, it is natural to speculate if the different behaviors as shown in Figure 5 are caused by photospheric expansion. To this end we calculated the weight averaged $f_a$ for both the PRE bursts and non-PRE bursts. We note that there is no non-PRE burst having a luminosity larger than $1.8 \times 10^{38}$ erg s$^{-1}$ in the banana state. Hence, the weight averaged $f_a$ in the banana state when the luminosity is larger than this value is actually the contribution from PRE bursts. In addition, we found that in the island state there are 10 bright bursts (5 PRE and 5 non-PRE) that have peak luminosities larger than $1.8 \times 10^{38}$ erg s$^{-1}$. We therefore calculated the weight averaged $f_a$ for both types and the result is shown in the lower panel of Figure 5. It is obvious that the overall trends are consistent for both types of bursts in the island.

4. DISCUSSION AND SUMMARY

In this Letter, we investigated the spectral deviations from a blackbody during type I bursts in different spectral states. We found that these spectral deviations exist significantly in both the banana and the island states. To study whether such deviations are derived from the scattering of a neutron star in the atmosphere as expected by London et al. (1986), Madej et al. (2004), and Suleimanov et al. (2011, 2012), we fitted the time-resolved spectra using a more accurate model burstatmo provided by Suleimanov, during which the persistent flux was

**Figure 3.** Solid (dashed) blue and red histograms show the distributions of the reduced $\chi^2$, derived from the wabs*bbodyrad (wabs*burstatmo) model for the spectra in the island and banana states, respectively.
(A color version of this figure is available in the online journal.)
Figure 3. Clearly, the feedback of bursts in the accretion process behaves as a function of the distance between the neutron star and the accretion disk.

In the banana state, since the inner radius of the accretion disk is close to the neutron star, the Poynting–Robertson effect is overwhelming the radial radiation pressure and leads to an increased accretion rate. While in the island state the accretion disk is close to the neutron star, the Poynting–Robertson effect will be suppressed or enhanced. If the latter is more important, more material will fall onto the neutron during bursts, and lead to an increased accretion rate; while if the former is dominant, the material will be blown to infinity and become unbounded, resulting in a suppressed accretion process.

The quantitative calculation has been carried out by Mishra et al. (2014) and Stahl et al. (2013). They proved that during type I bursts a test particle near the innermost stable circular orbit (ISCO) was likely to fall onto the central neutron star. By contrast, when the particles are located at the outer part, say, at a distance of around 20 $R_G$ or more, they will be hurled out to infinity by a bright burst and be captured by a fainter burst (for details, please see Figure 5 from Mishra et al. 2014).

Their calculations can naturally explain phenomena that we found if we assume spectral deviations arise from the interactions between the radiation field of type I bursts and the accretion disk. According to the unified model proposed for outbursts in the low mass XRBs, a geometrically thin and optically thick accretion disk (a so-called “standard disk”) extends closer to the compact star in the banana state and is truncated at a larger radius in the island state, during which the corona or jets appear (see, e.g., Esin et al. 1997; Fender et al. 2004 and references therein). Although both the Poynting–Robertson effect and the radiation pressure diminish with distance, the former is more sensitive. As a result, the minimum luminosity required to eject the material to infinity, is monotonically decreasing with the increasing distance (Mishra et al. 2014; Stahl et al. 2013). Therefore, the feedback of bursts in the accretion process behaves as a function of the distance between the neutron star and the accretion disk.

In the banana state, the inner radius of the accretion disk is close to the neutron star, the Poynting–Robertson effect is overwhelming the radial radiation pressure and leads to an increased accretion rate. While in the island state the accretion disk is truncated at an outer radius and the escape luminosity is relatively small, the particles in the accretion disk will be ejected out to infinity when bursts are luminous and will be dragged onto the neutron star when bursts are less luminous. The lower panel of Figure 5 shows that for the non-PRE bursts the $f_a$ drops back to 1 at a luminosity $L \sim 2.2 \times 10^{38}$ erg s$^{-1}$, which corresponds to around 75% of the Eddington luminosity.
Based on Figure 5 from Mishra et al. (2014), we can deduce that the innermost radius of the accretion disk in the island state is around $16 R_G$, where $R_G = GM/c^2$.

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