Single X-ray Bursts and the Model of a Spreading Layer of Accreting Matter over the Neutron Star Surface

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Abstract — The excess of the rate of type I X-ray bursts over that expected when the matter fallen between bursts completely burns out in a thermonuclear explosion is explained in terms of the model of a spreading layer of matter coming from the accretion disk over the neutron star surface. Such excess is observed in bursters with a high persistent luminosity, \(4 \times 10^{36} \text{ erg s}^{-1} \lesssim L_X \lesssim 2 \times 10^{37} \text{ erg s}^{-1}\). In this model the accreting matter settles to the stellar surface mainly in two high-latitude ring zones. Despite the subsequent spreading of matter over the entire star, its surface density in these zones turns out to be higher than the average one by 2–3 orders of magnitude, which determines the predominant ignition probability. The multiple events whereby the flame after the thermonuclear explosion in one ring zone (initial burst) propagates through less dense matter to another zone and initiates a second explosion in it (recurrent burst) make a certain contribution to the observed excess of the burst rate. However, the localized explosions of matter in these zones, after which the burning in the zone rapidly dies out without affecting other zones, make a noticeably larger contribution to the excess of the burst rate over the expected one.

Keywords: X-ray bursts, neutron stars, X-ray bursts, thermonuclear explosion, accretion, boundary layer, spreading layer.

INTRODUCTION

Previously (Grebenev and Chelovekov 2017) we showed that the model of a spreading layer of accreting matter over the surface of a neutron star with a weak magnetic field (Inogamov and Sunyaev 1999, 2010) allows the origin of multiple type I X-ray bursts detected sometimes from the Galactic X-ray bursters to be successfully explained. By multiple bursts we mean double or triple ones with a recurrence time (total duration of the series of events) \(t_r \sim 400–1200 \text{ s (7–20 min)}\). This time is much shorter than the characteristic accumulation time \(t_a\) of the critical mass needed for a thermonuclear explosion to be initiated on the neutron star surface.

Indeed, if the matter coming from the accretion disk spreads uniformly over the stellar surface and burns out completely during the explosion, then \(t_a \simeq 4\pi \Sigma_c R_1^2 M_1^{-1} \simeq 1.7 \Sigma_{\text{He}} R_1^2 M_1^{-1} \) days. Here we substituted the critical surface density of the matter \(\Sigma_c = 1.7 \times 10^5 \Sigma_{\text{He}} \text{ g cm}^{-2}\), corresponding to explosive helium ignition (Tutukov and Ergma 1979; Ergma and Tutukov 1980; Fujimoto et al. 1981; Hanawa and Fujimoto 1982; Bildsten 1998). The total luminosity of the neutron star in the period between bursts corresponding to \(\dot{M} = 10^{17} \dot{M}_{17} \text{ g s}^{-1}\) is \(L_a = GM_\ast \dot{M}/R_\ast \simeq 1.6 \times 10^{37} (M_{1.4} \dot{M}_{17}/R_{12}) \text{ erg s}^{-1} \simeq 0.09 (M_{17}/R_{12}) L_{\text{Ed}}\).

As usual, \(M_\ast = 1.4 M_{1.4} M_\odot\) and \(R_\ast = 12 R_{12} \text{ km}\) are typical neutron star mass and radius, \(L_{\text{Ed}} \simeq 1.3 \times 10^{38} (M_\ast/M_\odot) \text{ erg s}^{-1}\) is the critical Eddington luminosity, and \(G\) is the gravitational constant.

The seemingly unresolvable discrepancy between the times \(t_r\) and \(t_a\) may be explained in the model of a spreading layer of matter over the neutron star surface. Inogamov and Sunyaev (1999) showed that at a high \((\dot{M} \gtrsim 10^{17} \text{ g s}^{-1})\) accretion rate the matter coming from the accretion disk and rotating with the Keplerian velocity can not entirely settle to the neutron star surface directly in the region of its contact with the disk. This is hampered by the pressure of the radiation emitted as the matter decelerates, which upsets the balance between the gravitational and centrifugal forces. According to Inogamov and Sunyaev (1999), the bulk of this radiation-dominated, levitating matter is displaced in a spiral toward the poles and settles to the stellar surface only at high latitudes in two ring zones. Despite the subsequent spreading of the matter already fallen to the stellar surface, its efficient accumulation occurs in these zones (Inogamov and Sunyaev 1999).

Having noted that the conditions favorable for thermonuclear ignition are created precisely in these ring zones.

1Some fraction of the matter, nevertheless, must fall in precisely here to slow down the radial flow velocity in the disk (Grebenev and Chelovekov 2017).
Fig. 1. (a) Rate of X-ray bursts from bursters reconstructed from observations versus the accretion luminosity. The dashed lines indicate the predictions of the model of complete burning in a burst of the matter fallen to the neutron star surface since the previous burst. The upper and lower lines correspond to the different presumed helium abundances. The thick solid line indicates the prediction with allowance made for the spreading layer. (b) Mean burst duration versus the accretion luminosity. (c) Mean fluence in a burst (in counts) versus the burster luminosity.
zones, Grebenev and Chelovekov (2017) suggested the following scenario for the formation of multiple bursts. The explosion that began in one of the ring zones rapidly burns out hydrogen and helium in it, forming the first burst in the source’s X-ray light curve. Then, the thermonuclear flame slowly, with a deflagration wave speed \( v_{\text{def}} \sim 10 - 100 \, \text{m s}^{-1} \) (Fryxell and Woosley 1982; Nozakura et al. 1984; Bildsten 1995), propagates through matter with a lower surface density to the opposite ring zone and initiates a new explosion there (the last burst in the source’s light curve). If a sufficient amount of matter was accumulated in the equatorial zone, then a middle burst is formed in the light curve when the flame front passes through it. This event is always weaker than the first and last ones. A triple burst is observed in this case. If there was little matter in the equatorial zone, then a double burst is observed. In such a way \( t_{\nu} \) is the time of flame propagation over the neutron star surface while \( t_{\mu} \) is the time between this series of events and the nearest burst not included in it.

In this paper we show that the model of a spreading layer allows another puzzle of X-ray bursts to be explained equally successfully — the excess of the burst rate observed for sources with a moderately high persistent luminosity, \( 4 \times 10^{36} \, \text{erg s}^{-1} < L_X < 2 \times 10^{37} \, \text{erg s}^{-1} \), over that predicted in the model of complete burning of the matter fallen to the neutron star surface upon accretion during the explosion.

**OBSERVATIONS AND RESULTS**

A catalog of type I X-ray bursts from a large number of bursters based on the sky observations by the JEM-X and IBIS/ISGRI telescopes onboard the INTEGRAL observatory in 2003–2015 is presented in Chelovekov et al. (2017). This paper continues the investigation of thermonuclear X-ray bursts with the INTEGRAL telescopes begun in 2006 (Chelovekov et al. 2006; Chelovekov and Grebenev 2011). The full catalog of detected bursts is accessible at [http://dlc.rsdc.rssi.ru](http://dlc.rsdc.rssi.ru). The large size of the sample of bursts (2201 events) allows one to carry out various statistical studies, in particular, to find the dependence of the mean rate of bursts from bursters on their accretion luminosity (accretion rate).

This dependence is indicated in Fig. 1a by the thin solid line (histogram). On the whole, it is consistent with the analogous dependence derived by Galloway et al. (2008) from RXTE data, though even surpasses it in the number of events used. Note that no event was recorded at luminosities \( L \lesssim 2 \times 10^{35} \, \text{erg s}^{-1} \). Four bursts corresponding to a separate peak in the range of super-Eddington luminosities were detected from the same source, GX 17+2; they all belong to the group of superlong bursts associated with explosive burning of matter with a large CNO abundance (Cumming and Bildsten 2001; in’t Zand et al. 2004).

The dashed straight lines in the figure indicate the expected change in the burst rate under the assumption that the matter fallen to the stellar surface after the previous burst burns out completely. The upper and lower lines correspond to cases of helium and hydrogen burning, respectively.

According to Bildsten (1998, 2000; see also Ergma 1983; Strohmayer and Bildsten 2006), the following regimes of burning/explosion on the neutron star surface are possible, depending on the local rate of accretion \( \dot{M} \):

1. at \( \dot{M} < 0.16 \, \text{g s}^{-1} \) (a low accretion rate corresponding to the luminosity \( L_{\alpha} = GM\dot{M}/R_{\ast} \), in units of \( 10^{36} \, \text{erg s}^{-1} \), \( L_{36} < 2.6 \)) there is simultaneous explosive burning of a mixture of hydrogen and helium caused by the explosion of hydrogen (the bursts occur rarely, but are characterized by a large power and duration);

2. at \( \dot{M} < 0.72 \, \text{g s}^{-1} \) (a higher accretion rate corresponding to \( L_{36} < 11.6 \)) hydrogen in the matter fallen to the neutron star surface has time to burn into helium in a stationary regime and, therefore, the explosion occurs in helium-rich matter (the bursts occur more frequently, but they are less powerful and shorter);

3. at \( \dot{M} < 12 \, \text{g s}^{-1} \) (an even higher accretion rate corresponding to \( L_{36} < 190 \)) hydrogen has no time to burn completely into helium and, therefore, helium explodes in a hydrogen-rich medium (an H/He mixture if, of course, the normal star in the system is not a helium dwarf) (the bursts turn out to be more powerful than those in the case of purely helium bursts);

4. at \( \dot{M} > 12 \, \text{g s}^{-1} \) (\( L_{36} > 190 \)) only simultaneous stationary burning of hydrogen and helium is possible.

Note that the given values of \( L_{36} \) relate to the total luminosity of the source in the whole energy range, with taking into account the emission of both the accretion disk and the boundary or spreading layer. It is unlikely that the disk emission contributes significantly to the X-ray flux in the 3–20 keV band. Therefore the luminosity should be decreased by a factor of 2 when the regimes of burst generation are compared with Fig. 1.

Given the above picture, the luminosity dependence of the accretion rate observed in Fig. 1a could be modeled as indicated by the thick (blue) solid line. The transition from hydrogen explosive burning to helium one is qualitatively confirmed by the dependences of the burst duration and fluence (in counts) on the burst continuum luminosity presented in Figs. 1b and 1c. Indeed, there is an obvious decrease of the mean burst duration\(^2\) and fluence in them in the range \( L(3–20 \, \text{keV}) \gtrsim 1.5 \times 10^{36} \, \text{erg s}^{-1} \).

\(^2\)Actually there are two burst populations observed below this threshold of luminosities, more or less short ones and long ones, thus the term of the mean burst duration is rather arbitrary.
along with the step-wise increase in the burst rate. However, the observed dependence of the burst rate on the luminosity (accretion rate) is consistent with the described picture only at luminosities \( L \leq 4 \times 10^{36} \text{ erg s}^{-1} \). At higher luminosities, in the range \( 4 \times 10^{36} \text{ erg s}^{-1} \leq L \leq 2 \times 10^{37} \text{ erg s}^{-1} \), the observed burst rate exceeds the expected one by several times.

The enhanced burst rate in this luminosity range can be explained in terms of the model of a spreading layer of accreting matter over the neutron star surface. As has been said above, at such high luminosities the matter falls to the stellar surface in two high-latitude ring zones and it has no time to spread over the entire surface during the characteristic time interval between bursts. The accumulation of matter occurs in these zones, each of which can be responsible for its burst.

Once an explosion has occurred in one zone (for more details see, e.g., Grebenev and Chełovek 2017), the thermonuclear burning can propagate with a deflagration wave speed through less dense matter to another zone and initiate an explosion there. In this case, the bursts form a series of close events, multiple bursts. In Fig. 1 all recurrent bursts in the recorded series were removed; only the initial bursts were left. The removed bursts of the series are indicated in the figure by the dotted histogram. They are not too many. The rarity of such multiple bursts shows that the flame front by no means always manages to reach another zone; in most cases, the burning in the zone rapidly dies out without affecting other zones. However, as a result, the number of bursts doubles or even triples (if an appreciable fraction of the matter settles to the surface directly in the equatorial zone of the neutron star, in the place of contact of the star and the accretion disk; see Grebenev and Chełovek 2017) compared to the number of bursts expected in the case of complete uniform spreading of matter over the neutron star surface.

The thick (blue) solid line in Fig. 1a shows how such doubling/tripling of the number of bursts at such high luminosities (accretion rates) of bursters allows the observations to be explained. Note that at even higher luminosities \( L \geq 2 \times 10^{37} \text{ erg s}^{-1} \) the burst rate expectedly (see Lewin et al. 1993; Bildsten 1998) drops in view of the gradual transition of thermonuclear burning to a continuous regime or a noticeable rise in the radiation pressure and, along with it, the critical surface density of matter needed for an explosion to be initiated on the neutron star. However, this is already a completely different problem.

The possibility of burst generation at high latitudes (near the poles of the neutron star) at rather high accretion rates (corresponding to \( 0.19L_{\text{ed}} < L_a < 0.34L_{\text{ed}} \)) was theoretically predicted previously by Cooper and Narayan (2007). They did not consider spreading the matter over the neutron star surface but investigated stability of thermonuclear burning at different latitudes. In particular, they showed that the probability of matter ignition is maximal near the equator when the rate corresponds to \( L_a < 0.16L_{\text{ed}} \) (see also Spitkovskiy et al. 2002). Thus the bursts in Fig. 1 at low luminosities can actually arise at the near-equatorial region (note that at such luminosities the matter settles to the surface near this region and has enough time for spreading over the broader region). While the accretion rate increases till the level corresponding to \( L_a \sim 0.19L_{\text{ed}} \), the probability of explosion at high latitudes increases and becomes dominant at \( L_a > 0.19L_{\text{ed}} \). Moreover, thermonuclear burning at low latitudes (near the equator) is stabilized and bursts could not arise at all in this region at the rates corresponding to \( L_a > 0.30L_{\text{ed}} \). The burning becomes stable over the whole surface of the neutron star at \( L > 0.34L_{\text{ed}} \) as it is well seen in Fig. 1.

CONCLUSIONS

The previously obtained representative sample of thermonuclear X-ray bursts detected by the JEM-X and IBIS/ISGRI telescopes onboard the INTEGRAL observatory allowed the dependence of the rate of X-ray bursts generated by the bursters on their persistent X-ray luminosity (accretion rate indicator) to be reproduced. It follows from its analysis:

1. in the range of high luminosities, \( 4 \times 10^{36} \text{ erg s}^{-1} \leq L \leq 2 \times 10^{37} \text{ erg s}^{-1} \) the observed rate exceeds by several times that rate expected in the model of complete burning during a burst of the fuel that fell to the neutron star surface upon accretion after the previous burst;
2. the observed excess of the burst rate can be explained in terms of the model of a spreading layer of accreting matter over the neutron star surface (Inogamov and Sunyaev 1999), according to which the accreting matter is accumulated on the stellar surface in two or three separate ring zones, each of which can be responsible for its burst;
3. the cases where a burst in one of the zones initiates the propagation of a flame over the stellar surface capable of igniting the thermonuclear fuel in other zones that were described in detail by Grebenev and Chełovek (2017) (see also Keek et al. 2010) are realized quite rarely, in a few percents of all similar events;
4. the burst rate in the model of a spreading layer can rise also due to the fact that the matter spreading over the surface of the neutron star occupies a limited area (two high-latitude ring zones) compared to the surface of the entire star. Correspondingly, the critical surface density necessary to begin the explosion is reached earlier than in the spherically symmetric model. The area of the ring zones...
is defined by their width and latitude and, finally, by the accretion rate.

We will investigate these and other consequences of the model of a spreading layer in our subsequent papers.

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