MULTIPLE X-RAY BURSTS AND THE MODEL OF A SPREADING LAYER OF ACCRETING MATTER OVER THE NEUTRON STAR SURFACE

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Submitted on September 26, 2016

We report the detection during the JEM-X/INTEGRAL observations of several X-ray bursters of series of close type I X-ray bursts consisting of two or three events with a recurrence time much shorter than the characteristic (at the observed mean accretion rate) time of matter accumulation needed for a thermonuclear explosion to be initiated on the neutron star surface. We show that such series of bursts are naturally explained in the model of a spreading layer of accreting matter over the neutron star surface in the case of a sufficiently high ($\dot{M} \gtrsim 1 \times 10^{-9} M_\odot \text{yr}^{-1}$) accretion rate (corresponding to a mean luminosity $L_{\text{tot}} \gtrsim 1 \times 10^{37} \text{erg s}^{-1}$). The existence of triple bursts requires some refinement of the model — the importance of a central ring zone is shown. In the standard model of a spreading layer no infall of matter in this zone is believed to occur.

DOI: 10.1134/S106377371709002X

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

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INTRODUCTION

In the period of the discovery of type I X-ray bursts (Belian et al. 1972, 1976; Babushkina et al. 1975; Grindlay et al. 1976; Heise et al. 1976) and their theoretical explanation as thermonuclear explosions of a mixture of hydrogen and helium on the surface of a neutron star with a weak magnetic field (Hansen and van Horn 1975; Woosley and Taam 1976; Maraschi and Cavaliere 1977), the question of precisely where the explosion occurred was not discussed specially. It was believed that the accreting matter spreads rapidly over the entire neutron star surface, and the explosion could begin in a more or less arbitrary place in which critical conditions favorable for this were accidentally created at a given time. But, most importantly, it was believed that after the initiation of an explosion the thermonuclear burning propagates over the entire stellar surface in fractions of a second with a supersonic (detonation wave) speed, \( v_{\text{det}} \sim 10^4 \text{ km s}^{-1} \gg a_s = (2kT/m_p)^{1/2} \approx 1200 \ (kT/10 \text{ keV})^{1/2} \text{ km s}^{-1} \); therefore, the specific place of ignition is of no importance (Joss et al. 1978; Fryxell and Woosley 1982a). Here, \( T \) is the temperature at the base of the neutron star atmosphere, \( a_s \) is the corresponding sound speed, and \( m_p \) is the proton mass. Except for the short (\( \leq 1 \text{ s} \)) X-ray flux growth stage, the observed exponentially decaying burst time profile is determined by the cooling time of the explosion-heated stellar atmosphere — the diffusion time (\( \approx 5 - 15 \text{ s} \)) of X-ray photons undergoing multiple Compton scatterings in it and free-free production-absorption (Paczinski 1983a, 1983b; Ebisuzaki et al. 1984; Ebisuzaki 1987; Sunyaev and Titarchuk 1986; London et al. 1986).

Subsequently, however, it became clear that the detonation wave in the neutron star atmosphere should rapidly decay and could not ignite an appreciable area of its surface (Timmes and Niemeyer 2000). The deflagration wave propagates too slowly (Fryxell and Woosley 1982b; Nozakura et al. 1984; Bildsten 1995), with a speed \( v_{\text{def}} \sim 0.01 - 0.1 \text{ km s}^{-1} \) (for conductive energy transfer from the burning region to the surrounding matter) or \( \sim 0.3 - 3 \text{ km s}^{-1} \) (for convective energy transfer). In this case, the flame propagation time is much longer than the observed burst duration. There were doubts that the explosion was capable of affecting the entire surface of the star.

The conclusion about fairly slow flame propagation was confirmed by the RXTE discovery of high-frequency (ms) coherent oscillations of the X-ray flux from bursters during bursts, which were explained by the neutron star spin with a frequency \( \Omega_s \sim 300 - 600 \text{ Hz} \).
(Strohmayer et al. 1996, 1997; Smith et al. 1997; Galloway et al. 2008). The flame speed \(v\) must be less than \(\pi R_\ast \Omega_s / N \sim 150 \Omega_s / (400 \text{ Hz})\) km s\(^{-1}\) \(< a_s\), where \(R_\ast\) is the neutron star radius, which is assumed here and below to be 12 km, and \(N \gtrsim 100\) is the number of successive pulsations needed for their reliable detection (\(T = N / \Omega_s \gtrsim 0.25\) s is the detection period). However, it is apparently still higher than the deflagration speed \(v_{\text{def}}\).

Quite recently, three-dimensional theoretical computations of an explosion on the surface of a neutron star (Simonenko et al. 2012; see also Gryaznykh 2013a, 2013b) have shown that the flame can propagate in a qualitatively different, three-dimensional way. These authors pointed out that the heat flux from the explosion along the stellar surface should weaken greatly, because the bulk of the explosion energy (radiative and kinetic) is carried away upward due to the atmosphere being exponential. The horizontal heat flux may turn out to be insufficient for direct ignition of the surrounding matter. In these conditions the flame will propagate through the inflow of matter expanding during the explosion onto the layer of the unperturbed atmosphere surrounding the place of explosion, its pressing and, thus, the creation of conditions for thermonuclear ignition at the base of the atmosphere. The speed of this process \(v_{3D}\) can exceed appreciably the deflagration speed \(v_{\text{def}}\), while during powerful explosions it can reach and even exceed the sound speed \(a_s\). Such a process allows the observed duration of ordinary bursts to be explained.

In this paper we discuss the detection of series of multiple (triple and double) type I X-ray bursts from a number of known bursters occurring with a recurrence time \(t_r \sim 400\)–600 s (7–10 min) in the data of JEM-X telescope (Lund et al. 2003) onboard the INTEGRAL observatory (Winkler et al. 2003). This time is much shorter than the characteristic time of matter accumulation \(t_a \sim 4\pi \Sigma_c R_\ast^2 \dot{M}^{-1} \simeq 5 \Sigma_8 \dot{M}_8^{-1} \text{ h}\) needed for a thermonuclear explosion to be initiated on the neutron star surface. Here, \(\Sigma_c = 10^8 \Sigma_8 \text{ g cm}^{-2}\) is the critical surface density of the accumulated matter (for explosive helium ignition), \(\dot{M} = 10^{17} \dot{M}_{17}\) g s\(^{-1}\) is the accretion rate corresponding to the total luminosity of the neutron star in the period between bursts \(L_X = GM_\ast \dot{M} / R_\ast \simeq 1.6 \times 10^{37} \dot{M}_{17}\) erg s\(^{-1}\), \(G\) is the gravitational constant, and \(M_\ast\) is the neutron star mass, which is assumed to be \(1.4 \ M_\odot\). The time \(t_a\) determines the mean frequency of ordinary bursts \(< \nu > = 1 / t_a\) observed from each specific burster, and, of course, most of the bursts from the bursters being discussed were detected precisely with this frequency. The detection of multiple bursts recurring on a time scale \(t_r \sim 10\) min \(< t_a\) from the same bursters seems surprising.
Multiple bursts were also detected previously, in particular, double bursts were observed by Murakami et al. (1980) and Ohashi et al. (1982) from the sources 4U 1608-522 and 4U 1636-536, more rare triple ones were observed by Boirin et al. (2007) from the transient burster EXO 0748-676 and by Keek et al. (2010) from several more sources. Sanchez-Fernandez et al. (2011) detected a triple burst from the burster 4U 1608-522 with the JEM-X telescope onboard the INTEGRAL observatory, the same one whose data are analyzed in this paper. In addition to bursts with a recurrence time \( t_r \sim 10 \text{ min} \), double bursts with \( t_r \sim 10 \text{ s} \) were detected. Bhattacharyya, Strohmayer (2006) observed such a burst from the source 4U 1636-536; they assure that the burst profile was formed without involving any photospheric expansion effects.

The nature of multiple bursts is not yet clear. Having studied the properties of such bursts detected during superlong (158 h) continuous observations of the burster EXO 0748-676 by the XMM-Newton satellite, Boirin et al. (2007) revealed: (1) a reduction in the exponential decay time of the profile for the recurrent events compared to the initial ones (which, in their opinion, is related to a decrease of the hydrogen abundance in the exploded matter) and (2) a decrease in the intensity of events in the series compared to the separate bursts from this source. Based on these properties of multiple bursts, they assumed that stepwise burning of the layers of stratified material with different chemical compositions (hydrogen, helium, and CNO abundances) is observed on the neutron star surface during them. Hydrogen burns out during the first flash, whereupon conditions for the ignition of helium are created etc. Indeed, the computations by Fujimoto et al. (1981) and Peng et al. (2007) show that at a sufficiently low accretion rate the hydrogen burning on the neutron star surface can be explosive and, at the same time, may not accompanied by the simultaneous ignition of helium. It is only unclear why the helium burning is resumed \( \sim 10 \text{ min} \) after the first flare and why triple events are observed.

In this paper, based on the JEM-X/INTEGRAL observations of multiple events, we offer a different possible explanation of this phenomenon: the thermonuclear explosions producing successive flashes occur in physically separated regions on the neutron star surface in which the matter efficiently accumulates during its nonuniform (in the meridional direction) infall as it is accreted. Such infall of matter should be expected at a sufficiently high, though much lower than the Eddington level, accretion rate in the model of a spreading layer proposed by Inogamov and Sunyaev (1999, 2010). According to this model, falling from the accretion disk
into the boundary equatorial region of the star, the accreting matter has an excessively large (Keplerian) angular momentum, that completely compensates the gravitational attraction, which together with the radiation pressure does not allow it to immediately settle to the stellar surface. Continuing to rotate, the matter is displaced toward higher latitudes and only there, often in the immediate vicinity of the neutron star poles, does it slow down and settle to the stellar surface. Depending on the accretion rate, the ring regions where the infall of matter occurs can be at different distances from the equator and can have different widths. The bulk of the accretion energy of the infalling matter accounted for by the spreading layer is released and radiated in the zones of these regions more distant from the equator. Note that in the Newtonian approximation the luminosity of the spreading layer is equal to the luminosity of the entire accretion disk $L_b \simeq 0.5 \dot{M} R_\ast^2 (\Omega_K - \Omega_s)^2 \simeq 0.5 GM_\ast \dot{M} / R_\ast$ (Shakura and Sunyaev 1988; Kluzhniak 1988). Here, $\Omega_K = (GM_\ast / R_\ast^3)^{1/2}$ is the Keplerian angular velocity near the stellar surface.

Suppose that the subsequent spreading of the fallen matter from these regions over the stellar surface is much slower than its accumulation, so that a critical surface density $\Sigma_c$ is reached at some time. The amount of matter fallen in the northern and southern regions must be approximately the same. However, it is obvious that the explosion initially begins in one of them, let this be the northern region. After the explosive burnout of hydrogen and helium in it (for example, in the regime proposed by Simonenko et al. 2012), the flame slowly (as a deflagration wave) propagates over a less dense layer of matter with a speed $v_{\text{def}} \sim 0.01 \text{ km s}^{-1}$ until it reaches the boundary of the southern region, where a new flash begins. Let us examine how well this explanation agrees with the observed picture of the series of multiple bursts.

**OBSERVATIONS**

We revealed multiple events when working on the full catalog of X-ray bursts detected by the JEM-X telescope onboard the INTEGRAL observatory in 2003-2014 (Chelovekov et al. 2017). This is the final, third part of our investigation of thermonuclear X-ray bursts with the INTEGRAL telescopes. The first two parts (Chelovekov at al. 2006; Chelovekov and Grebenev 2011) were the catalogs of bursts detected by the IBIS/ISGRI telescope sensitive in a harder X-ray band ($\gtrsim 18 \text{ keV}$) than the JEM-X band (4–30 keV). Although it is clear
Fig. 1: JEM-X/INTEGRAL photon count rates (the 3–20 keV energy band) in the observing sessions on March 24, 2004 (top), and March 28, 2009 (bottom), during which triple thermonuclear X-ray bursts were detected from the X-ray bursters Aql X-1 and 4U 1608-522. In the inserts the burst profiles are shown with a better time resolution.
## Characteristics of multiple type I X-ray bursts detected by the JEM-X telescope onboard the INTEGRAL observatory in 2003–2014

| Date UTC | Time UTC | $\delta t$ | $C_{b}(C_{c})$ | $P_{b}$ | $P_{c}$ | $\Delta T_{1}$ | $\Delta T_{2}$ | $\Delta t$ | Source burst |
|----------|----------|------------|----------------|--------|---------|----------------|----------------|-----------|--------------|
| 1        | 2        | 3          | 4              | 5      | 6       | 7              | 8              | 9         | 10           |
| 2004-02-23 | 23h20m44s | 16 | 166 (8) | 1.6 ± 0.9 | 25.2 ± 1.0 | 1.9 | 1.6 | 4U 1636-536 |
| 2004-03-24 | 17h03m31s | 19 | 273 (7) | 1.5 ± 1.4 | 17.6 ± 1.4 | 830 | 2.6 | Aql X-1 |
| 2004-08-08 | 18h30m11s | 30 | 197 (7) | 3.0 ± 0.8 | 19.4 ± 1.5 | 8.7 | 1.6 | 4U 1636-536 |
| 2004-08-22 | 23h52m34s | 7  | 299 (33) | 3.5 ± 2.2 | 67.8 ± 3.2 | 7.6 | 2.6 | * | GX 3+1 |
| 2005-04-15 | 03h37m46s | 6  | 289 (28) | 4.2 ± 1.8 | 66.8 ± 2.1 | 15.3 | 2.6 | * | GX 3+1 |
| 2005-04-26 | 10h15m03s | 39 | 256 (11) | 3.8 ± 1.9 | 23.2 ± 1.3 | 11.0 | 2.6 | Aql X-1 |
| 2005-04-29 | 09h00m36s | 22 | 263 (7) | 5.2 ± 1.5 | 21.6 ± 1.3 | 36.1 | 2.6 | Aql X-1 |
| 2005-08-27 | 17h40m25s | 13 | 144 (8) | 1.8 ± 1.3 | 18.6 ± 1.0 | 26.2 | 1.6 | 4U 1636-536 |
| 2005-10-10 | 23h54m04s | 9  | 155 (5) | 3.4 ± 1.6 | 4.4 ± 1.9 | 94 | 16.5 | * | XTE J1739-285 |
| 2006-03-12 | 23h26m54s | 14 | 196 (6) | 1.5 ± 1.1 | 5.6 ± 1.8 | 19.6 | 11.8 | SAX J17470-2853 |
| 2006-03-21 | 21h34m48s | 6  | 157 (7) | 2.6 ± 1.6 | 3.6 ± 2.4 | 41 | 16.5 | XTE J1739-2885 |
| 2009-03-28 | 20h10m38s | 24 | 359 (13) | 7.9 ± 3.1 | 30.7 ± 1.7 | 221 | 1.6 | 4U 1608-522 |
| 2010-02-24 | 23h35m49s | 21 | 135 (6) | 1.7 ± 1.1 | 17.9 ± 1.8 | 5.0 | 1.6 | 4U 1636-536 |
| 2010-04-02 | 11h22m57s | 11 | 305 (31) | 6.7 ± 3.0 | 72.3 ± 3.1 | 86 | 2.6 | * | GX 3+1 |
| 2010-04-13 | 15h47m07s | 7  | 283 (29) | 4.7 ± 4.0 | 68.9 ± 4.6 | 130 | 2.6 | * | GX 3+1 |

a Date and time (UTC) of the peak count rate in the burst.
b The burst duration.
c The peak $C_{b}$ and mean $C_{c}$ count rate of photons from the source in the 3–20 keV band.
d The peak flux in the 3–20 keV band.
e The persistent flux from the burster during several previous exposures in the 3–100 keV band.
f The time from the first burst in the series to the nearest burst not from the series $\Delta T_{1}$.
g The minimum time between ordinary bursts from this burster for the entire sample $\Delta T_{2}$.
h The interval between the bursts in the series exceeds 30 min.
that it is better to observe type I bursts in the standard X-ray band, the search for bursts in
the IBIS/ISGRI data made sense due to the larger field of view of this telescope (exceeding
the JEM-X field of view by a factor of \( \sim 8 \)) and better corresponded to the main goal of
our investigation, i.e., revealing hitherto unknown bursters. Two such bursters have indeed
been discovered (see Chelovekov and Grebenev 2007, 2010).

The full catalogue of bursts detected with JEM-X is accessible at
\(<http://dlc.rsdc.rssi.ru>\). The main characteristics of the series of double and triple
events selected from this catalog are given in the table. It provides the date of observation,
the time of the peak count rate \( T \) and the duration \( \delta T \) of each burst in the series, the
peak and observation-averaged \( (\sim 1 \, \text{h}) \) count rates of events from the source \( C_b \) and
\( C_c \), the recorded peak flux in the burst \( F_b \), and the mean flux \( F_c \) from the source in
several consecutive previous exposures (for more details, see Chelovekov et al. 2017).
The fluxes in the bursts were measured in the 3–20 keV band; the persistent flux was
measured in the 3–100 keV band. Note that the characteristic persistent flux from the
bursters being discussed \( F_c \sim 1 \times 10^{-9} \, \text{erg s}^{-1}\text{cm}^{-2} \) corresponds to an X-ray luminosity
\( L_X \sim 1.2 \times 10^{37} \, \text{erg s}^{-1} \) under the assumption that the source is near the Galactic center at
a distance of 8 kpc, i.e. these are all sources with a fairly high accretion rate.

The data from the table allow us to estimate the mean time interval between single
bursts (or a single burst and a series of bursts) \( t_a \simeq 0.24 \alpha \Sigma(\delta T F_b) / F_c \) using the so-called
parameter \( \alpha \sim 40 \) (Lewin et al. 1993), which characterizes the efficiency of energy release
during accretion compared to explosive helium burning. Here, the factor 0.24 allows for
the deviation of the measured burst duration \( \delta T \) from the exponential time and \( \Sigma \) denotes
summation over the bursts of the series. In particular, for the known bursters Aql X-1 and
4U 1608-522 \( t_a \simeq 1.6 – 2.4 \, \text{h} \). The table provides the time interval \( \Delta T_1 \) from the first burst
in the series to the nearest burst from this burster not from this series and the minimum
interval \( \Delta T_2 \) between ordinary bursts from this burster for the entire sample. These intervals
allow one to judge the mean frequency of bursts \( \langle \nu \rangle = t_a^{-1} \) from a given burster at the
current and mean accretion rates, respectively. Since the INTEGRAL observations of each
specific source were generally episodic, though they could last tens of hours, some bursts
must have undoubtedly been missed; therefore, these intervals should be considered only as
upper limits on the time \( t_a \). For this reason, we, in particular, used a fairly stringent criterion
for the inclusion of bursts in the series: the interval between them should not exceed 30 min.
Fig. 2: JEM-X/INTEGRAL photon count rates (the 3–20 keV energy band) in the observing sessions on April 29, 2005 (top), and March 12, 2006 (bottom), during which double thermonuclear X-ray bursts were detected from the X-ray bursters Aql X-1 and SAX J17470-2853. In the inserts the burst profiles are shown with a better time resolution.
The asterisks in column 9 of the table mark several possible double bursts that did not pass this criterion. These were detected from the known bursters GX 3+1 and XTE J1739-285; the interval between them was 40–70 min, while the time $\Delta T_2$ for these sources was 2.6 and 16.5 h, respectively. It is unclear whether these bursts are events similar to the remaining multiple events in the table and their long recurrence time $t_r$ reflects some of their unique physical properties or these are ordinary single bursts distinguished by an unusually short accumulation time $t_a$ of the critical matter density. Estimates based on the data from the table similar to those given above for the bursters Aql X-1 and 4U 1608-522 show that this is possible at least for the source GX 3+1. On the other hand, in this case, it is most likely insufficient for the source to have an enhanced accretion rate compared to other bursters; it is also necessary that at such an accretion rate the explosive development of a flash does not pass into continuous burning (see, e.g., Strohmayer and Bildsten 2006).

As an example, Fig. 1 shows the light curves of the triple events observed from the known bursters Aql X-1 and 4U 1608-522; Figs. 2–4 show those of the double events observed from the mentioned burster Aql X-1 and the equally known bursters SAX J17470-2853, 4U 1636-536, and XTE J1739-285. The insets present the profiles of individual bursts with a better time resolution demonstrating a fast rise to the maximum and a long exponential decay, which is characteristic for type I (thermonuclear) bursts. The burst duration varied between $\sim 5$ s and $\sim 15$ s, i.e., it was also typical for such bursts. In all the observed cases of triple events, the second burst was noticeably fainter than the first and third bursts and was located almost halfway between them (closer to the third burst by $\sim 50 – 70$ s). The third burst was slightly fainter than the first one. The total duration of the shown series of triple events was $\sim 800$ s ($\sim 13$ min). In the double events in Figs. 2–4 the second burst was, as a rule, fainter than the first one; in some cases, the bursts had a comparable intensity. As a rule, the duration of the second burst was shorter than that of the first one. For a number of sources the time interval between the double bursts was comparable to the duration of the triple events ($\sim 12 – 13$ min, cf. Figs. 1 and 2); for others it was noticeably longer ($\sim 20 – 25$ min for the burster 4U 1636-536, Fig. 3). It is important that the duration of the triple and double series of bursts for the source Aql X-1 was the same, suggesting that in the latter case the intermediate burst was too faint to be detected. The double bursts from 4U 1636-536 in Fig. 3, along with other series of bursts from this source (see the table), had almost the same duration, always much longer than 13 min characteristic for Aql X-1. This suggests
Fig. 3: JEM-X/INTEGRAL photon count rates (the 3–20 keV energy band) in the observing sessions on August 8, 2004 (top), and August 26, 2005 (bottom), during which double thermonuclear X-ray bursts were detected from the X-ray burster 4U 1636-53 6. In the inserts the burst profiles are shown with a better time resolution.
Fig. 4: JEM-X/INTEGRAL photon count rates (the 3–20 keV energy band) in the observing sessions on October 10–11, 2005 (top), and March 21, 2006 (bottom), during which double thermonuclear X-ray bursts were detected from the X-ray burster XTE J1739-285. In the inserts the burst profiles are shown with a better time resolution.
Fig. 5: JEM-X/INTEGRAL photon count rates (the 3–20 keV energy band) from the source GX 3+1 in the observing sessions on April 2 (top) and 13 (bottom), 2010, during which double and triple thermonuclear X-ray bursts were detected by this telescope. The time interval between the bursts is shorter than the sample-averaged interval between the bursts from this source only by a few times. In the inserts the burst profiles are shown with a better time resolution.
that the series duration reflects the neutron star properties, the accretion rate characteristic for a given source, and/or the composition of the accreting matter. On the other hand, both anomalously long (\(\sim 42\) min, Fig. 4a) and anomalously short (\(\sim 5\) min, Fig. 4b) series of two bursts were detected for the source XTE 1739-285.

For one more source, the known burster GX 3+1, all the detected series of bursts were anomalously long, \(\gtrsim 40\) min (Fig. 5). The recurrence time of ordinary bursts from this source averaged over the entire sample of events recorded by the JEM-X telescope, \(t_a\), was longer only by a factor of \(\sim 4\) (see the table). Therefore, as has already been noted above, we cannot unambiguously assert that series of bursts similar to those discussed above rather than pairs of close single bursts were actually detected. Besides, this source is characterized by a very high persistent flux \((65 - 80) \times 10^{-10}\) erg s\(^{-1}\) cm\(^{-2}\). It exceeds the fluxes from other bursters by several times and clearly suggests a high accretion rate onto this source.

On the other hand, it is interesting that apart from the double bursts, a triple burst was also detected from this source (Fig. 5, bottom panel), whose properties, except for the time scale on which it developed, are very close to those of the triple bursts from other bursters (Fig. 1). In particular, the middle event in this burst also occurred with a delay by \(\sim 15\%\) relative to the middle of the interval between the first and last events.

**DISCUSSION**

Our analysis of a sample of multiple X-ray bursts detected by the JEM-X telescope onboard the INTEGRAL observatory has revealed several trends that can give a key to understanding this interesting phenomenon.

1. The profiles of such bursts and especially triple bursts with powerful first and last events and a much fainter middle event are unique and uniform for different sources; these are very difficult to explain in the model of successively resuming thermonuclear burning of stratified (consisting of the layers of different elements) fuel.

2. The double bursts can be failed triple bursts in which the middle burst was too faint to be detected.

3. The duration of the series of bursts is, on average, unique for each specific source, probably reflecting the parameters of the neutron star in it, the characteristic accretion rate, and the composition of the accreting matter.
4. The intermediate (second) burst of the triple events is delayed relative to the middle of the interval between the first and last events by 10–15%.

5. In addition to the previously discussed series of bursts with a total duration \( \sim 10 \) min, there can exist series of bursts with a duration \( \gtrsim 40 \) min from some sources.

The unique profiles of multiple bursts are naturally explained in the model of a spreading layer of accreting matter over the neutron star surface (Inogamov and Sunyaev 1999, 2010). In this model, reaching the surface of the neutron star in the equatorial region, the accretion disk matter is displaced in a spiral toward its poles and only there does it lose its angular momentum in two ring zones, radiate the energy being released, and settle to the surface. The probability of reaching the critical conditions for thermonuclear ignition of the matter accumulated during accretion is high precisely in these regions. Since it is obvious that the flash begins initially only in one of the ring zones, it will be responsible for the first most powerful burst in the series. Once the matter accumulated in this zone has burnt out, the thermonuclear flame propagates with a deflagration wave speed \( v_{\text{def}} \approx 0.01 \text{ km s}^{-1} \) over the stellar surface toward the equator and then toward the opposite stellar pole and the second ring zone. On reaching it, the last burst in the series begins. Note that although the bulk of the matter during accretion falls in these ring zones, some moderate amount of matter must also settle from the spreading layer on its way to these zones; otherwise there would be no radiative energy for its maintenance (recall that the layer must be a radiation-dominated and levitating one). It is through this settled matter that the deflagration wave propagates after the first explosion. The matter from the ring zones that slowly spreads over the neutron star surface can also contribute to the layer of fuel accumulated here.

There are several points that do not seem natural in the model of a spreading layer and require an explanation.

**The Origin of the Middle Burst in a Series**

One would think that the intermediate (second) burst in a triple series of bursts cannot be explained in any way in the model of a spreading layer. Proposing it, Inogamov and Sunyaev (1999) assumed that all of the matter from the disk spread in meridional directions. Actually, this cannot be the case, because the matter in the disk has quite a distinct radial velocity \( v_r = \dot{M}/(2\pi R_* \Sigma_d) \), that must not be ignored. This velocity can be slowed down
only through viscosity in a narrow equatorial ring layer like the boundary layer described by Shakura and Sunyaev (1988, 1999) and Kluzhniak (1988). In this case, at least for part of the accreting matter, not only the radial velocity but also the rotation velocity decreases down to the stellar rotation velocity. This matter settles to the stellar surface straight in the equatorial zone. Although the amount of matter settling in this zone and the energy being released in this case are small compared to the matter and the energy settling and being released, respectively, in the polar ring zones of the neutron star, it may turn out to be sufficient to explain the intermediate burst in series of triple burst events. If, alternatively, little matter fell in this zone, then we will be able to see only a double burst. The infall of matter in this zone will be considered in more detail in Grebenev (2017).

Explaining the Asymmetry of the Profile for Triple Bursts

It has been noted above that the intermediate burst in the triple events observed from the bursters Aql X-1 and 4U 1608-622 is delayed by $\sim 50 - 70$ s relative to the middle of the time interval between the first and third bursts. At first glance this delay contradicts the described symmetric picture. Note, however, that the ring zones in which the matter settles and accumulates can be quite extended, depending on the accretion rate (Inogamov and Sunyaev 1999). The first burst begins in the region of maximum surface density that can be near the high-latitude edge of the ring zone. Thereafter, all this zone (or is sufficiently dense part) will be affected by the flame in a time comparable to the duration of the first burst. At the same time, the ignition of the opposite zone begins from its low-latitude edge by the flame front going away from the equator. Thus, the third burst will begin earlier than the first burst relative to the time of passage of the equatorial zone by the flame front and its ignition (i.e., the second burst in the series). In principle, the observation of such triple bursts will allow one to investigate the parameters of the spreading layer and to check the computations performed by Inogamov and Sunyaev (1999).

Series of Bursts of Greater Multiplicity

Keek et al. (2010) reported the detection of a series of X-ray bursts from the source 4U 1636-538 consisting of four events. Such bursts of greater multiplicity can be explained in the proposed model by assuming that shortly before their observation the accretion rate onto the source changed abruptly. In this case, as the burning front passed over the neutron
star surface, the flashes should have occurred in two ring zones associated with the infall of matter at the initial accretion stage and two other ring zones associated with the infall of matter at the final stage. Clearly, this event requires the fulfillment of certain conditions and can occur very rarely, much more rarely than double and triple bursts. This is generally observed.

*Why are Single Bursts observed?*

Or why are double and triple bursts encountered quite rarely? The point is that the model of a spreading layer acts only at sufficiently high accretion rates $\dot{M} \gtrsim 0.01 \dot{M}_{ed}$, where $\dot{M}_{ed}$ is the critical Eddington accretion rate (Inogamov and Sunyaev 1999). As the accretion rate decreases, the ring zones of the main energy release and the infall of accreting matter narrow down and are displaced toward low latitudes. At $\dot{M} \lesssim 0.01 \dot{M}_{ed}$ the entire matter settles in the equatorial zone; accordingly, only one X-ray burst is observed during the thermonuclear explosion in this zone. Moreover, the picture is complicated by the fact that as the accretion rate increases, the thermonuclear burning may not be accompanied by an explosion but be continuous. The exact conditions under which it is possible to observe multiple bursts can be clarified only in future, through detailed numerical simulations of the thermonuclear burning in the physical model being discussed.

**ACKNOWLEDGMENTS**

This work is based on the INTEGRAL data retrieved via its Russian and European science data centers. It was financially supported by the “Transitional and Explosive Processes in Astrophysics” Subprogram of the Basic Research Program P-7 of the Presidium of the Russian Academy of Sciences, the Program of the President of the Russian Federation for support of leading scientific schools (grant NSh-10222.2016.2) and the “Universe” theme of the scientific research program of the Space Research Institute, the Russian Academy of Sciences.
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*Translated by V. Astakhov*