

Research Progress on Multi-peak Structure of Type I X-ray Bursts (Postprint)

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Abstract

Type I X-ray bursts (thermonuclear bursts) are a high-energy phenomenon occurring in low-mass X-ray binary neutron star systems, characterized by a sudden and substantial increase in X-ray flux. Under the thermonuclear flash model, this phenomenon is believed to be primarily caused by thermonuclear unstable burning on the neutron star surface. The light curve of a typical X-ray burst exhibits a single-peaked structure with a rapid rise (1–5 s) and an exponential decay (10–100 s). With the increasing sample of X-ray bursts, a class of thermonuclear bursts with multi-peaked structures has been observed. Among the existing 115 burst sources, at least 6 sources exhibit such multi-peaked bursts. Through studying the observational properties of multi-peaked bursts, it is found that multi-peaked bursts only appear in a very small number of burst sources of different types and accretion states, wherein the peak flux of most multi-peaked bursts is less than the Eddington limit. Except for a few multi-peaked bursts that show a triple-peaked structure, most multi-peaked bursts are double-peaked, and the relative strength of the two peaks in double-peaked bursts shows no fixed pattern. The occurrence of burst oscillations in multi-peaked bursts also shows no obvious regularity. In response to these observational phenomena, multiple theoretical explanations for multi-peaked bursts have been summarized.

Full Text

Preamble

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Research Progress on Multi-Peaked Structures in Type-I X-Ray Bursts

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Abstract

Type-I X-ray bursts (thermonuclear bursts) are high-energy phenomena characterized by sudden, large-amplitude increases in X-ray flux in low-mass X-ray binary systems containing neutron stars. Within the thermonuclear flash model, this phenomenon is believed to be primarily caused by unstable thermonuclear burning on the neutron star surface. Typical X-ray burst light curves exhibit a single-peaked structure with a rapid rise (1–5 s) and exponential decay (10–100 s). With the increasing sample of X-ray bursts, a class of multi-peaked thermonuclear bursts has been observed in the data. Among the current 115 burster sources, at least six have exhibited such multi-peaked structures. By studying the observational properties of multi-peaked bursts, we find that they appear only in a very small number of different types of bursters with different accretion states. Most multi-peaked bursts have peak fluxes below the Eddington limit. Except for a few triple-peaked bursts, the majority are double-peaked, and there is no fixed pattern in the relative strengths of the two peaks. The occurrence of burst oscillations in multi-peaked bursts also shows no obvious regularity. In response to these observational phenomena, we summarize several theoretical models for multi-peaked bursts.

Keywords: low-mass X-ray binary; accreting neutron star; X-ray bursts; Type-I X-ray bursts

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1 Introduction

Type-I X-ray bursts (thermonuclear bursts) are high-energy phenomena in which the X-ray flux suddenly increases with short durations (10–100 s), reaching peak fluxes 10–100 times higher than the persistent pre-burst emission. These explosive phenomena typically occur in low-mass X-ray binary systems (LMXBs) [1, 2]. LMXBs are a subclass of X-ray binary systems generally

composed of a compact object and a companion star with mass less than M_{\odot} [3]. LMXBs can be divided into many subcategories: based on the type of compact object, they are classified as black-hole LMXBs (BH-LMXBs) and neutron-star LMXBs (NS-LMXBs). Neutron-star LMXBs are further divided into Z sources and Atoll sources based on their different tracks in color-color diagrams and timing properties [4].

As shown in [Figure 1: see original paper], Z sources display a “Z”-shaped track in the color-color diagram with variability timescales ranging from hours to days and generally high luminosities. They sequentially traverse the horizontal branch (HB), normal branch (NB), and flaring branch (FB), with corresponding mass accretion rates gradually increasing and spectra evolving from low/hard to high/soft states. Atoll sources show annular evolutionary tracks in the color-color diagram with variability timescales from days to tens of days and lower luminosities [5]. Atoll sources can be divided from upper right to lower right into the island state (IS) and banana state, with the banana state further subdivided into the lower banana (LB) and upper banana (UB) states, where the accretion rate increases along the evolutionary track.

For most NS-LMXBs, the primary star is typically a neutron star with a weak magnetic field (10^8 – 10^{10} G) that accretes matter from the companion through an accretion disk. The companion’s material first fills its Roche lobe, then passes through the Lagrangian point into the neutron star’s accretion disk, eventually reaching the neutron star surface.

Grindlay [7] discovered the first Type-I X-ray burst in 1976 using the Astronomische Nederlandse Satelliet (ANS) satellite in the globular cluster NGC 6624’s 3A 1820–30 binary system, observing clear spectral softening during the burst decay. As observational data increased, so did the number of X-ray bursts. Galloway et al. [8] combined data from multiple satellites to detect and analyze 7,083 Type-I X-ray bursts from 85 burster sources. As of July 2020, the number of burster sources had increased to 115, with burst source data and Type-I burst information available in the Multi-Instrument Burst Archive (MINBAR) database. MINBAR contains the most complete sample of Type-I bursts, including observations from Rossi X-ray Timing Explorer (RXTE), BeppoSAX, and INTEGRAL satellites. The database provides uniform analysis of each burst’s light curve, offering information such as rise times, peak intensities, power-law decay timescales, and other photometric data, as well as information from time-resolved spectroscopy [8], which is helpful for statistical studies of specific Type-I burst properties.

Observationally, most thermonuclear bursts show a single-peaked FRED (fast rise and exponential decay) profile. Based on duration, X-ray bursts can be divided into three categories [8]. The first category consists of “typical” Type-I bursts with durations of about 1 minute [7, 9] and recurrence timescales of hours; these bursts have pre-burst accretion rates of approximately 1%–30% [2]. The second category comprises “intermediate-duration” bursts lasting about 0.5 hours, accompanied by strong radiation pressure effects [10]; these events are

generally thought to originate from ignition of pure He layers at accretion rates one to two orders of magnitude lower than typical bursts [11, 12]. The third category, “superbursts” [13], lasts longer than 1 hour and is currently believed to result not from unstable burning of H or He but from carbon burning.

Another class of X-ray bursts observed to be short-duration with hard spectra may originate from accretion disk instabilities and are called Type-II X-ray bursts [9]. Bagnoli et al. [14] noted that Type-II bursts have a wider duration range than Type-I bursts, from less than 1 second to over 500 seconds, with most distributed below 20 seconds.

The generally accepted view is that in NS-LMXB systems, the fuel for Type-I X-ray bursts comes from H and He material in the companion star’s envelope that accumulates on the neutron star surface through the accretion disk, forming a layer several meters thick. As accreted material is continuously compressed and heated, when the temperature and density become sufficiently high, unstable burning is triggered, rapidly consuming all available fuel on the neutron star surface and forming the observed thermonuclear burst [1, 2, 15]. Two observational evidences support the thermonuclear origin of Type-I X-ray bursts: (1) The ratio (α parameter) of the time-integrated persistent flux between bursts to the burst fluence is 40–100, consistent with the ratio calculated from gravitational potential energy and nuclear fusion model efficiencies; (2) The blackbody temperature decreases during the burst decay phase. Time-resolved spectral fitting shows that the blackbody temperature initially rises, then approaches a power-law decay during the flux decline until it returns to the pre-burst persistent level.

Thermonuclear X-ray burst luminosities can reach the Eddington limit, where radiation pressure balances gravitational pressure. When burning continues and radiation pressure exceeds gravitational pressure, material is blown outward, and the burning shell’s radius expands beyond the neutron star radius. Such bright thermonuclear X-ray bursts are called photospheric radius expansion (PRE) bursts. PRE bursts have luminosities in the Eddington range, with temperature squared inversely correlated with radius. For objects of known mass, PRE bursts can serve as standard candles for distance measurement.

Pre-burst spectra are generally described by a thermal component for the accretion disk and neutron star hot surface, plus a non-thermal component for the high-energy corona. During bursts, time-resolved X-ray spectra include both burst and non-burst components. The “standard” method for analyzing Type-I burst spectral evolution assumes that the non-burst component during the burst has the same magnitude and spectral shape as the pre-burst emission. The net burst spectrum, obtained by subtracting the non-burst component (pre-burst emission) from the burst spectrum, is typically described by a blackbody with a color temperature of 2–3 keV [1]. With known source distances, we can use the blackbody model to estimate the bolometric flux, calculate the peak flux $F_{\text{bb,max}}$, and the total burst fluence E_b (integral of net burst flux). These quantities can be used to define burst parameters: the ratio of average persistent

flux to burst fluence ($\alpha = F_{\text{pers}} \times \Delta t$, where Δt is the time interval between bursts), and the average burst duration ($\tau = E_b / F_{\text{bb,max}}$). Worpel et al. [16, 17] introduced the f_a factor in their spectral fitting of Type-I bursts observed by RXTE, assuming that the non-burst component during the burst has the same spectral shape as the pre-burst emission but possibly different intensity, with f_a characterizing intensity variations. They found that the f_a method provided significantly better fits than the standard method, with f_a generally greater than 1 during bursts, possibly caused by increased mass accretion rates on the neutron star surface.

Other studies have also shown that the burst component spectrum may be modified during bursts, meaning the non-burst component changes [18–21]. These modifications may result from disk reflection [22], changes in the accretion flow due to Poynting-Robertson drag [23], or coronal cooling [24].

Burst oscillation phenomena have been detected in some Type-I bursts, possibly arising from highly asymmetric radiation from the accreting neutron star surface [25]. The oscillation frequency is closely related to the neutron star spin frequency and provides a method for measuring it. Oscillation models typically involve thermonuclear flame propagation, nuclear burning processes, rapid neutron star rotation, and magnetic field dynamics, but their production mechanism remains mysterious [25–27].

Among the large sample of thermonuclear bursts, a class showing multi-peaked structures in X-ray bands has emerged. Since Sztajno et al. [28] first observed a double-peaked burst in 4U 1636–53 using EXOSAT, the sample of double-peaked bursts has grown with more observational facilities and discoveries of new bursters and Type-I bursts. In 2019, NICER satellite detected very bright double-peaked bursts in different sources, renewing interest in double-peaked thermonuclear bursts. Therefore, it is necessary to review the development of double-peaked thermonuclear bursts. Section 2 introduces the common characteristics of multi-peaked thermonuclear bursts and observational phenomena in different sources. Section 3 reviews existing theoretical models for multi-peaked bursts based on Type-I burst models. Section 4 discusses how current observational results constrain existing models and prospects for multi-peaked burst research.

2 Observations of Multi-Peaked Type-I X-Ray Bursts

The double-peaked X-ray bursts initially observed may have been artifacts caused by instrumental energy band limitations rather than physical origins of the burst sources. Hoffman et al. [29] first discovered double-peaked thermonuclear bursts from three sources: MXB 1743–29, MXB 1728–34, and MXB 1850–08. These very bright PRE double-peaked bursts showed clear double-peaked structures only in high-energy bands (8–19 keV), while the structures were unclear or disappeared in low-energy or broad-band light curves. Haberl et al. [30] also observed such high-energy-only double-peaked bursts in 4U 1820–30

using EXOSAT, as shown in [Figure 2: see original paper]. Paczynski [31] argued that this double-peaked structure observed only in high-energy X-ray light curves and disappearing in broad-band PRE bursts is an instrumental effect: when the burst begins, outward radiation pressure increases, the material envelope moves away from the neutron star, temperature decreases, and radiated photon energies drop below the X-ray band, causing a dip in the observed light curve; as the gas shell contracts under gravity and temperature rises again, a second peak forms.

Another class of double-peaked bursts shows double-peaked structures in both X-ray band and broad-band flux [32]. Such light curves may reflect real changes in thermonuclear energy generation or release processes [9]. To date, these double-peaked bursts have been observed in several NS-LMXB systems: 4U 1636–53, 4U 1608–52, XTE J1709–267, GX 17+2, MXB 1730–335, and SAX J1808.4–3658. In addition to double-peaked bursts, triple-peaked thermonuclear bursts have also been observed in 4U 1636–53 [33, 34].

For all double-peaked burst samples across different sources, the burst durations are basically on the order of 1 minute. There is no clear pattern in the relative strengths of the two peaks: some have a stronger first peak, some a stronger second peak, and some have comparable peaks. Spectral evolution of double-peaked bursts shows that blackbody temperature and radius also exhibit clear double-peaked structures with flux variations. Most double-peaked bursts have relatively low peak fluxes [32, 35], though some reach Eddington luminosity PRE bursts [36, 37]. Analysis of pre-burst spectra shows that most double-peaked bursts occur in systems with relatively high accretion rates [34, 35, 37–40]. Some double-peaked bursts show burst oscillation phenomena, with frequencies matching the neutron star spin frequencies in their host LMXBs. We now describe in detail the diverse observational characteristics of these double-peaked X-ray bursts in different sources.

2.1.1 Source 4U 1636–53

NS-LMXB 4U 1636–53 is a very active Atoll source for X-ray bursts [4], with a binary orbital period of 3.8 h [41], primary spin frequency of 581 Hz [42, 43], and an 18 mag blue companion star [1]. All multi-peaked bursts observed in 4U 1636–53 are low-luminosity, non-PRE bursts. Sztajno et al. [28] observed four double-peaked thermonuclear bursts in 4U 1636–53 using EXOSAT, marking the first detection of double-peaked X-ray bursts showing this structure simultaneously in X-ray band light curves and broad-band flux evolution. As shown in bursts a), b), c), and e) of [Figure 3: see original paper], the light curves [9] always show the first peak count rate higher than the second, with inter-peak intervals of 4–7 s. The second peak’s rise time (1.9–3.5 s) is similar to the first peak’s rise time (2.0–4.0 s). The waiting times between each multi-peaked burst and its predecessor (1.3–2.3 h) fall in the intermediate range of recurrence times for single-peaked bursts. The four double-peaked bursts have relatively low peak fluxes, not reaching Eddington luminosity. Spectral analysis revealed similar

double-peaked structures in blackbody temperature during the bursts. Sztajno et al. [28] did not perform timing analysis on these four multi-peaked bursts.

Galloway et al. [1] summarized XTE observations of four other double-peaked thermonuclear bursts in this source (shown in [Figure 4: see original paper]), finding inter-peak intervals of 4–5 s. Unlike earlier observations, three of these four double-peaked bursts had second peaks larger than the first. All four were low-luminosity, non-PRE double-peaked bursts. Timing analysis of burst (d) in [Figure 4: see original paper] detected 581 Hz burst oscillations in its first peak [44]. Watts and Maurer [32] performed statistical analysis of accretion rates from pre-burst spectra of these four bursts, finding that multi-peaked bursts did not appear at the highest accretion rates. Compared to single-peaked bursts, double-peaked bursts were more likely to occur at higher accretion states; when at similar accretion rates, single-peaked bursts had lower burst fluences than double-peaked bursts.

Zhang et al. [38] reported 12 double-peaked bursts in 4U 1636–53 from RXTE observations in 2011, finding these double-peaked bursts occurred at high accretion rate positions in the color-color diagram, while single-peaked bursts appeared throughout the diagram.

In addition to double-peaked bursts, even rarer triple-peaked bursts have been observed in this source. van Paradijs et al. [33] first observed a triple-peaked thermonuclear burst in 4U 1636–53 using EXOSAT, as shown in [Figure 5a: see original paper]. Within 10% precision, the three peaks had identical rise rates, with intervals between peaks 1-2 and 2-3 both about 4 s. Time-resolved spectral analysis showed no significant radius changes during the triple-peaked burst, suggesting it was not caused by photospheric expansion of the neutron star surface. The triple-peaked structure appeared in X-ray band light curves, broad-band flux, and temperature evolution. Zhang et al. [34] observed another triple-peaked burst in 4U 1636–53 using RXTE, shown in [Figure 5b: see original paper]. This triple-peaked burst also showed the three-peak structure in X-ray light curves, broad-band luminosity, and temperature evolution. Timing analysis revealed no significant burst oscillations during the outburst. Comparing the two reported triple-peaked bursts: (1) The interval between the first and last peaks in [Figure 5a: see original paper] (about 17 s) is roughly twice that in [Figure 5b: see original paper]; (2) In color-color diagrams, accretion rate increases along the track from upper right to lower right. Therefore, the triple-peaked burst observed by van Paradijs et al. [33] (triangles in [Figure 6: see original paper]) occurred at higher accretion rates than that observed by Zhang et al. [34] (open circles in [Figure 6: see original paper]). Currently, 4U 1636–53 has the largest sample of multi-peaked thermonuclear bursts from RXTE observations.

2.1.2 Source 4U 1608–52

Burst source 4U 1608–52 is a transient source in LMXBs and an Atoll source [45, 46], with a binary orbital period of 0.537 d and a companion star that is an H/He-rich late-F or early-G type star QX Nor [47, 48]. All bursts observed in 4U 1608–52 are very bright PRE double-peaked bursts. Penninx et al. [49] confirmed a double-peaked burst with duration of about 20 s in 4U 1608–52 using EXOSAT. This burst showed double-peaked structures in three energy bands: 1.4–3.4 keV, 3.4–11.0 keV, and 11.0–20.0 keV. Spectral fitting showed the peak flux reached Eddington flux, with a 25% dip near peak flux, as shown in [Figure 7: see original paper], where the first peak was higher than the second. Poutanen et al. [39] observed two double-peaked X-ray bursts among 21 PRE bursts using XTE data. The fluences of these two double-peaked bursts were $(3.28 \pm 0.01) \times 10^{-13} \text{ J cm}^{-2}$ and $(3.28 \pm 0.01) \times 10^{-13} \text{ J cm}^{-2}$, slightly higher than all other PRE bursts in the same sample.

Jaisawal et al. [37] observed a PRE double-peaked burst in 4U 1608–52 using NICER in 2019 (see [Figure 8: see original paper]), marking the first detection of a double-peaked structure in an Eddington-limited thermonuclear burst below 1.5 keV. In NICER’s 0.3–12 keV light curve, the first peak had a rise time of about 3.5 s, with the second peak appearing 5 s after the first. No Fe line features were detected in the pre-burst spectrum.

After accounting for instrumental effects, the PRE bursts found by Poutanen et al. [39] and Jaisawal et al. [37] still showed double-peaked structures in flux, temperature, and radius. However, the two double-peaked bursts from Poutanen et al. [39] occurred when the source was in a low/hard state, while Jaisawal et al. [37]’s double-peaked burst occurred in a soft state. Timing analysis by Jaisawal et al. [37] found no burst oscillations near the peaks of their double-peaked X-ray burst.

2.1.3 Source XTE J1709–267

The neutron star soft X-ray source XTE J1709–267 is an intermittent transient source with X-ray outburst periods of 2–3 years [50, 51]. Jonker et al. [52] observed a Type-I X-ray burst in XTE J1709–267 using RXTE, whose flux evolution consisted of a “precursor” and “main burst” (see [Figure 9: see original paper]), with a light curve morphology similar to [Figure 4d: see original paper] where the second peak is very strong. Spectral analysis revealed double-peaked structures in both temperature and radius. They found the precursor was not related to photospheric expansion, and the burst itself was not a PRE burst. Its broad-band peak flux was $(1.40 \pm 0.06) \times 10^{-15} \text{ J cm}^{-2} \text{ s}^{-1}$. Timing analysis revealed no burst oscillations.

2.1.4 Source GX 17+2

GX 17+2 is one of the few Z sources that exhibit thermonuclear bursts [4]. Kuulkers et al. [40] found a double-peaked burst with duration of about 10 s

among three short bursts in GX 17+2 using RXTE data. This double-peaked burst was weaker than other short bursts, with peak intensity about half that of other bursts, and occurred at the low normal branch (LNB) position in the Z source color-color diagram. Spectral fitting of this double-peaked burst and pre-burst spectrum yielded a broad-band blackbody net peak flux of $(0.79 \pm 0.05) \times 10^{-15} \text{ J cm}^{-2} \text{ s}^{-1}$, burst fluence of $(5.54 \pm 0.09) \times 10^{-15} \text{ J cm}^{-2}$, and average burst duration $\tau = (7.0 \pm 0.5) \text{ s}$. No burst oscillations were detected during the outburst.

2.1.5 Source MXB 1730–335

MXB 1730–335 is an Atoll source [35] located in the globular cluster Liller 1 [53] that can exhibit both Type-II and Type-I bursts during active periods [14]. Bagnoli et al. [35] discovered six double-peaked non-PRE thermonuclear bursts using RXTE observations. The double-peaked structure in these six bursts appeared only during the decay phase, with the first peak generally stronger than the second. In the X-ray light curves, the dip between peaks lasted relatively long, generally 25–72 s. In bursts a) and b) of [Figure 10: see original paper], the dip was about 10 s below the pre-burst persistent flux level, with non-burst component spectral shapes differing from pre-burst spectra and absorbing column densities increasing by 4 times. After the bursts ended, the non-burst component recovered its pre-burst spectral shape. These six bursts in [Figure 10: see original paper] occurred in the transient state from high/soft to low/hard states in the color-color diagram, suggesting such double-peaked X-ray bursts are restricted to specific accretion rate ranges. Their fluences ranged from $(1.72\text{--}28.80) \times 10^{-15} \text{ J cm}^{-2}$, significantly higher than other observed single-peaked Type-I X-ray bursts. Timing analysis detected low-frequency quasi-periodic oscillations (QPOs) at 0.25 Hz during the decay phases.

2.1.6 Source SAX J1808.4–3658

SAX J1808.4–3658 is the first accreting millisecond pulsar discovered by BeppoSAX [54], with neutron star spin (or persistent-state millisecond pulsations) of 401 Hz [55, 56] and binary orbital period of 2.1 h [57]. SAX J1808.4–3658 is an Atoll source whose Type-I bursts are basically high-luminosity PRE bursts [1].

Bult et al. [36] discovered a very bright PRE burst in SAX J1808.4–3658 using NICER [58] observations (caused by unstable He burning, see [Figure 11: see original paper]). This burst’s light curve showed a first peak higher than the second in count rate, with an obvious “stall” portion during the first peak’s rise. Spectral analysis revealed a weak double-peaked structure in broad-band flux, with maximum broad-band peak flux of $(2.3 \pm 0.1) \times 10^{-14} \text{ J s}^{-1} \text{ cm}^{-2}$, the brightest X-ray burst observed by NICER to date. Although this was a PRE burst, photospheric radius expansion cannot explain the double-peaked structure’s origin. The “stall” and dip in the light curve corresponded temporally to the first and second peaks in the temperature curve. Both the stall portion

and dip region had the same broad-band flux of $(1.43 \pm 0.09) \times 10^{-14} \text{ J s}^{-1} \text{ cm}^{-2}$. They found this flux ratio to the peak flux exactly matches the ratio of Eddington fluxes for H and He atmospheres for the same neutron star mass. Timing analysis detected clear 401 Hz burst oscillations during the burst cooling phase.

2.2 Summary of Multi-Peaked Thermonuclear Burst Observations

We summarize some observational properties of double-peaked thermonuclear bursts from different sources. Statistical results show that relative to the currently observed X-ray burster sources (115), only a few sources (6) have been reported to exhibit these rare double-peaked bursts. shows that double-peaked bursts appear in different source types without being limited to specific categories. The table summarizes observational phenomena of double-peaked bursts from different sources, including light curve or flux evolution (peak separation, duration), pre-burst source state, and burst oscillations.

We find that light curves vary among double-peaked burst samples, with no clear pattern in relative peak strengths: some have stronger first peaks, some stronger second peaks, and some comparable peaks, demonstrating complex light curve structures in the double-peaked burst sample. Source 4U 1636–53 has the richest variety of double-peaked burst light curve morphologies and the largest sample of non-PRE double-peaked bursts. Except for MXB 1730–335, double-peaked bursts in other sources have durations less than 1 minute and peak separations of about 10 s. The six double-peaked bursts in MXB 1730–335 have more regular light curves, with the second peak always in the decay phase. These six bursts have long durations (about 200 s) and peak separations (25–72 s) that are 2–7 times longer than other sources.

Most double-peaked bursts have relatively low peak fluxes, though some are double-peaked PRE bursts, indicating that peak flux is not a limiting factor for double-peaked structure appearance. In nearly all sources, the double-peaked structure appears simultaneously in flux, temperature, and radius evolution. All currently observed double-peaked bursts in 4U 1636–53 are non-PRE. Source 4U 1608–52 shows active PRE bursts, and its double-peaked thermonuclear bursts are all PRE. Double-peaked bursts in MXB 1730–335 are all non-PRE.

Double-peaked bursts appear in Atoll sources, Z sources, and transient sources. In Atoll sources, double-peaked burst samples in 4U 1636–53 and MXB 1730–335 appear at relatively high accretion rates [35, 38], while pre-burst states in 4U 1608–52 are not fixed, occurring in both soft states (higher accretion rates) and low/hard states (lower accretion rates). The double-peaked burst in Z source GX 17+2 occurred in the low normal branch (moderate accretion rate). Not all double-peaked bursts show oscillations, and some studies did not perform timing analysis. Among double-peaked bursts where burst oscillations were observed, their locations vary: some appear in the first peak [60], others in the second

peak (decay phase) [36].

Among the relatively large sample of non-PRE double-peaked thermonuclear bursts, the six multi-peaked bursts observed in MXB 1730–335 are special, with longer dips in their light curves and low-frequency QPOs detected in the second peak (decay phase). The double-peaked Type-I bursts in this source may result from brief obscuration of the neutron star surface during the decay phase rather than nuclear physics processes.

3 Theory and Simulations of Multi-Peaked Type-I X-Ray Bursts

The most successful theoretical model for Type-I X-ray bursts is the thermonuclear flash model—unstable thermonuclear burning of accreted material on neutron star surfaces. In this model, Type-I burst observational characteristics are closely related to burning material composition, residuals from previous bursts, burning region, thermonuclear burning processes, and accretion rate. Therefore, Type-I bursts can be used to study accreted material composition, density, temperature, accretion rate, and internal thermal state of neutron stars, providing important insights into surface radiation characteristics and accretion environments.

Stable and unstable burning in the accreted layer depends on whether nuclear energy generation and cooling rates reach equilibrium, which in turn depends on the layer's temperature and column density. For several important thermonuclear processes, at a given column density, the nuclear energy generation rate grows rapidly with temperature, so heating from nuclear burning further increases the burning rate. When the burning rate increases rapidly enough to locally consume most fuel within 1 second, it leads to thermonuclear unstable burning. Assuming a density of 10^5 g cm^{-3} , when temperature $\gtrsim 0.7 \times 10^8 \text{ K}$, H fusion (CNO cycle) energy generation rate becomes essentially temperature-independent; when temperature $> 3 \times 10^8 \text{ K}$, He fusion (3α process) energy generation rate also becomes temperature-independent. Therefore, for CNO and 3α processes, nuclear energy generation rates increase rapidly with temperature at lower temperatures but become stable at higher temperatures. Carbon's energy generation rate remains temperature-sensitive, allowing unstable burning at higher temperatures. Considering both column density and temperature can delineate stable and unstable burning regimes for these three nuclear processes [2, 61].

The temperature and column density of the accreted layer increase primarily through compression from accreted material, so compressional heating is proportional to the mass accretion rate. For H/He accreted on neutron star surfaces, thermonuclear burning stability depends strongly on accretion rate \dot{M} [62]. Therefore, burning of H/He materials and changes in ignition states can predict certain burning environments, some of which have been observationally confirmed. Galloway and Keek [2] recently summarized typical physical scenar-

ios for different burning environments predicted by models.

The standard thermonuclear flash model can reproduce basic observed features of Type-I X-ray bursts: short rise times (about 1 s), recurrence timescales (about 1 hour), burst energies (about 10^{32} – 10^{33} J), α parameter values (40–100), and spectral softening during decay. The standard model, considering continuous energy release, predicts single-peaked FRED-shaped light curves. Multi-peaked Type-I burst observations cannot be explained by the standard thermonuclear flash model or instrumental effects in PRE bursts. Theoretical models for multi-peaked Type-I bursts generally consider stepwise energy release from thermonuclear reactions [63–65], stepwise burning during accretion, or ignition at different latitudes [60, 66]. Multi-peaked Type-I bursts provide more observational information and are important for studying ignition methods and material composition on neutron star surfaces.

3.1 “Pauses” in Thermonuclear Reaction Processes

Fisker et al. [63] proposed that double-peaked structures are caused by “pauses” between He flashes and rapid proton (rp) process burning in upper layers. For double-peaked bursts, at a given accretion rate, He accumulated at the base burns completely within 10 s, creating a large enough temperature gradient for efficient convective heat transport to the surface, causing the first peak (observationally, this results in surface luminosity rise times < 1 s). The He burning region radiates and convects outward, leaving insufficient time for H to transform into He, so it ignites and burns via the rp process, which is temperature-dependent only. If reaction rates are blocked by isotopes causing a “pause,” the nuclear energy release rate decreases, creating a dip in surface luminosity. After the “pause,” when the nuclear energy release rate rises again, surface luminosity increases again, forming the second peak. In short, they attribute the first peak to He burning and the second peak to renewed nuclear energy release. Simulation results are shown in [Figure 12: see original paper]a.

José et al. [65] found in subsequent simulations that a small fraction of double-peaked bursts are related to changes in burst material composition. Lampe et al. [64] used the KEPLER model [67] to simulate the thermonuclear origin model for double-peaked bursts proposed by Fisker et al. [63]. They found double-peaked bursts occur more easily at high metallicity and low accretion rates (as shown in [Figure 12: see original paper]b), and as accretion rate increases, the first peak becomes increasingly suppressed while the second peak becomes relatively larger. When metallicity is increased to solar values, the first peak becomes less prominent with increasing accretion rate, making the overall flux variation appear more like continuous burst growth. Lampe et al. [64] showed that double-peaked bursts can be of thermonuclear origin but require higher metallicity, and the magnitude of the He peak depends strongly on accretion rate. Although this model can physically simulate double-peaked structures (as in [Figure 12: see original paper]b), it struggles to reproduce the deep, long-duration dips observed in some double-peaked bursts [66].

3.2 High-Latitude Ignition Model/Geometric Effects

Based on studies of thermonuclear flame propagation [68, 69], Bhattacharyya and Strohmayer [66] proposed a high-latitude ignition model. They argue that accreted fuel is distributed across the neutron star surface, and when a burst ignites at a specific location, it propagates across the surface to ignite all fuel. After ignition at high latitudes, a latitude-symmetric burning band forms. As this band propagates toward the equator, it is hindered by accreted material moving from equator to poles, causing stagnation at low latitudes that produces the dip after the first peak. After crossing the equator, the burning band accelerates again toward the opposite pole, forming the second peak. Ignition at the poles quickly forms a latitude-symmetric burning cap, and neutron star rotation would not produce burst oscillations in the first peak. Non-polar high-latitude ignition would produce burst oscillations during the first peak's rise as the burning band forms.

The high-latitude ignition model for thermonuclear propagation quantitatively explains the basic features of light curves in [Figure 4: see original paper]c) and d), reproduces the spectral evolution of these two double-peaked bursts (as shown in [Figure 13: see original paper]), and explains the absence of oscillations in [Figure 4: see original paper]c) and the detection of burst oscillations in the first peak of [Figure 4: see original paper]d). The high-latitude ignition model requires more complex stagnation mechanisms to explain triple-peaked bursts, which would need two stagnation episodes before all surface fuel is consumed [34].

3.3 Accretion-Burning Layer Thermal Exchange Instability Model

Regev and Livio [70] proposed an “accretion-burning layer thermal exchange instability model” to explain double-peaked structures in thermonuclear bursts. They assume two zones on the neutron star surface: a very thin burning layer at the bottom of accreted material (zone 1), and an overlying accretion layer without thermonuclear reactions (zone 2). As burning proceeds, zone 1's temperature rises rapidly, but heat transfer is too slow to completely release energy from the burning layer, so some energy heats zone 2. As zone 1's temperature begins to decline, the temperature gradient between zones decreases. Under specific conditions, the heat transfer rate from the burning layer to the accretion layer falls below its generation rate, producing the second peak. Thus, the second peak results from thermal exchange instability between accretion and burning layers. This model can simulate double-peaked bursts lasting tens of seconds with sharp first-peak rises and shallow dips. However, Fisker et al. [63] later increased the number of zones in subsequent work and found the effect disappeared when zones increased to about 25, making the two-zone model physically too simplistic.

3.4 Shear Instability Model

Fujimoto et al. [71] proposed a model where shear instability in the material layer leads to stepwise energy release. They argue that material carrying angular momentum from the accretion disk flows onto the neutron star surface with differential rotation relative to the burning layer. Thermonuclear burning drives convection, causing angular momentum redistribution. The interaction between differential rotation of the accreted layer and convection driven by the thermonuclear flash produces shear instability. This shear instability mixes unburned fuel from upper layers with the burning layer, causing re-ignition and multi-peaked X-ray bursts. They suggest this model applies to low peak flux double-peaked [28] and triple-peaked [33] bursts observed in 4U 1636–53.

Bhattacharyya and Strohmayer [66] note that this model cannot reproduce observed double-peaked bursts, and the conditions for shear instability—maintaining large amounts of unburned material above the burning flame without mixing hot and cold fuel regions—are difficult to satisfy.

3.5 Accretion Disk Corona Scattering Model

Melia [72] and Melia and Zylstra [73] proposed that multi-peaked Type-I bursts may be caused by changes in accretion disk/corona geometry during outbursts. When thermonuclear unstable burning begins, increased photons thicken the corona or heat the accretion disk, causing surface material to evaporate. Photons are then absorbed or scattered when passing through the corona, decreasing observed photon count rates and creating dips in light curves. As the burst decays, coronal optical depth decreases, scattering capacity declines, and photon counts increase again, forming the observed second peak. Their model can only observe double-peaked bursts within certain inclination ranges ($40^\circ < i < 65^\circ$).

The accretion disk corona scattering model can explain some observational phenomena but has limitations: (1) Why do disk corona shape changes occur only in some bursts, while most single-peaked Type-I bursts in the same source are unaffected? (2) Observed double-peaked bursts in X-ray sources are not affected by viewing inclination. (3) The model struggles to explain observations where the first peak is relatively weak.

3.6 Eddington Limit Model

In the PRE double-peaked burst observed by Bult et al. [36] using NICER, the light curve showed a stall during the rise phase, and burst oscillations were detected during the second peak's decay. They found that the stall, dip between peaks, and onset of burst oscillations all correspond to the Eddington luminosity for H material, leading them to propose an Eddington limit model to explain the dip. The burst ignites in the underlying He layer, and as radiation pressure expands the material outward, H ignites and reaches the Eddington limit for H. The burning material continues expanding outward, He burning reaches the He Eddington limit, undergoes PRE contraction, returns to the neutron star

surface, and again reaches the H Eddington limit, corresponding to the observed dip. Thus, they argue the dip is related to the H layer reaching the Eddington limit. Furthermore, the double-peaked structure in bright bursts may be related to both H and He materials reaching their Eddington limits simultaneously. However, they did not provide explanations for the second peak or observed burst oscillations.

4 Summary and Outlook

For the first time, we have summarized the observational properties and theoretical models of reported multi-peaked bursts. We find that double-peaked burst samples have complex light curve structures with variable relative peak strengths and deep, long-duration dips. Some double-peaked bursts exhibit burst oscillations, and the rare triple-peaked bursts show even more complex light curve structures.

Current theoretical models can only explain some observational phenomena. The thermonuclear reaction “pause” model [63] can explain the double-peaked structure from a nuclear physics origin but has gaps with observations: it cannot explain deep, long-duration dips. The high-latitude ignition model [60, 66] reproduces the light curves and spectral evolution of two observed double-peaked bursts and explains burst oscillations detected in low first peaks, but the stagnation mechanism causing dips remains unclear. Triple-peaked bursts would require more complex stagnation mechanisms. The accretion disk corona scattering model [72, 73] struggles to explain multi-peaked bursts with weak first peaks. The Eddington limit model [36] explains dips in PRE double-peaked bursts in relation to the H Eddington limit but offers no specific reasons for the second peak or observed burst oscillations. Furthermore, existing theoretical models cannot easily explain why double-peaked bursts are so rare compared to single-peaked bursts in the same source, or why only a very few burster sources exhibit double-peaked X-ray bursts.

Since double-peaked thermonuclear bursts were first observed, their numbers have remained very small, and no systematic studies have been conducted. We should select a source with many multi-peaked bursts as a sample to analyze what physical properties have intrinsic connections with double-peaked structures through light curves and spectral evolution. Studying double-peaked burst observations can constrain some models and help screen theoretical models. For example, Cooper and Narayan [74] found that for specific sources, local accretion rates decrease with increasing latitude at a given overall accretion rate. Ignition latitude depends on column density, which depends on accretion rate. Therefore, as overall accretion rate increases, ignition should occur at higher latitudes. The high-latitude ignition model of Bhattacharyya and Strohmayer [66] suggests double-peaked bursts should ignite at higher latitudes. Thus, more double-peaked bursts should be found at high accretion rates than single-peaked bursts in 4U 1636–53. If the work of Cooper and Strohmayer [74] and Bhattacharyya and Strohmayer [66] can be reconciled, it would support the distribu-

tion law of accretion rates on neutron star surfaces and high-latitude ignition for double-peaked bursts. Watts and Maurer [32] analyzed accretion rates for four double-peaked bursts in 4U 1636–53 and found no evidence supporting this conclusion, perhaps due to limited sample size preventing clear statistical constraints on theoretical models.

The double-peaked burst sample from RXTE observations of 4U 1636–53 has rich, varied light curve morphologies and flux variations, is highly representative, and encompasses these outburst patterns, making it worthy of detailed spectroscopic and photometric study as a multi-peaked burst sample. Additionally, 4U 1636–53 has triple-peaked burst samples that can be used to explore differences and connections between multi-peaked and double-peaked bursts. Source 4U 1608–52 is also a noteworthy double-peaked burster, with pre-burst states varying across different satellite observations, promising more multi-peaked burst data for studying pre-burst accretion rates. With more satellite observations of Type-I bursts, multi-peaked burst samples in different energy bands will increase, allowing us to use multi-satellite observations of the same source to search for the physical origin of multi-peaked structures in Type-I bursts.

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