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Article

X-ray bursts from neutron stars: A brief review of the current state of research

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Abstract: X-ray thermonuclear bursts (Type I X-ray bursts) are among the most informative and intense transient phenomena associated with accreting neutron stars in low-mass X-ray binaries (LMXBs). These bursts occur due to unstable thermonuclear burning of accreted hydrogen and helium on the neutron star surface, and occasionally heavier fuels, producing bright, short-lived X-ray outbursts. The observed burst properties carry crucial information about nuclear synthesis processes under extreme conditions, the physics of neutron star envelopes and crusts, and the accretion environment. Over the past five decades, the field of burst research has undergone significant advancements thanks to the evolution of observational facilities—from the first detectors aboard SAS-3 and ANS satellites to extensive RXTE catalogs and modern high-precision instruments such as NICER, NuSTAR, Swift, and INTEGRAL. Simultaneously, theoretical models describing ignition, flame propagation, and nuclear reaction chains, including the rp-process and carbon ignition responsible for superbursts, have progressed substantially. Despite these achievements, key open questions remain regarding detailed nuclear reaction pathways, the influence of burst oscillations on surface modes and neutron star rotation, mechanisms of rare phenomena such as type II bursts and superbursts, and systematic uncertainties in using Photospheric Radius Expansion (PRE) bursts to constrain neutron star mass and radius. This review integrates the historical development, current observational data, theoretical modeling, and future prospects of X-ray burst studies. It summarizes major milestones, including the compilation of burst catalogs and statistical population studies, discovery and interpretation of oscillations and PRE bursts, development of multi-zone numerical models of thermonuclear ignition and flame spreading, as well as identification and investigation of superbursts. Particular attention is given to how bursts enable constraints on nuclear physics and the equation of state of ultra-dense matter, and experimental and observational approaches are proposed to address outstanding issues. The goal of this review is to provide a comprehensive reference for researchers entering the field and to outline a roadmap for future interdisciplinary projects connecting high-energy astrophysics, nuclear experiments, advanced computational techniques, and multi-messenger observations.

Keywords: X-ray thermonuclear bursts, stars, neutron, accretion disks, nuclear reactions, equation of state

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1. Introduction

Skin X-ray bursts represent some of the most powerful and rapidly evolving phenomena observed from compact objects, providing a unique window into the physics of matter under extreme densities, temperatures, and gravitational fields. They manifest as short (seconds to minutes) increases in X-ray luminosity, often exceeding the persistent emission by factors of 10 to 100. The majority of these events—Type I bursts—are interpreted as unstable thermonuclear ignition of accumulated hydrogen and helium layers on the neutron star surface [1-5]. Now we know of over 100 Type I X-ray bursters in the Galaxy and several in the nearby galaxies [6].

The significance of X-ray bursts extends beyond astrophysics. Their light curves and spectra encode information on nuclear reaction pathways far beyond stability, thermal and compositional structure of neutron star envelopes, and potentially allow constraints

on the equation of state of ultra-dense matter. The interplay of accretion physics, nuclear astrophysics, and general relativity renders bursts a key topic for interdisciplinary research.

Beyond their purely physical implications, X-ray bursts also highlight humankind's growing ability to explore the most extreme manifestations of matter and energy in the Universe. By probing these distant flashes of nuclear fire, we gain not only quantitative insight into stellar evolution but also a deeper appreciation of our place in a cosmos governed by the same laws that operate within ourselves.

In a broader astrophysical context, X-ray thermonuclear bursts serve as important observational links between the evolution of compact binaries, accretion processes, and high-energy transient phenomena. Unlike supernovae or gamma-ray bursts, bursts repeat at the same source, allowing detailed population and statistical studies dependent on accretion states.

From a nuclear physics perspective, bursts provide natural laboratories to study rapid proton capture (rp) and αp reaction chains at temperatures exceeding 10^9 K. Reaction rates involved often lie beyond the reach of terrestrial accelerators, making burst observations unique tools for indirect nuclear constraints [7,8]. Furthermore, detection of superbursts—events lasting several hours caused likely by carbon ignition at depths thousands of times greater than typical bursts—links burst studies to the thermal structure and long-term evolution of neutron star crusts [9,10].

2. Historical Overview and Early Observations

Until the mid-1970s, the concept of short thermonuclear bursts on neutron star surfaces remained speculative. Early prophetic theoretical works (e.g. [11]) considered the possibility of nuclear avalanches in accreted matter on compact objects, drawing analogies to novae, but lacked direct observational confirmation. The launch of early X-ray astronomy satellites—Uhuru (1970), Ariel V (1974), and ANS (1974) —enabled variability studies on timescales of minutes, critical for detecting bursts.

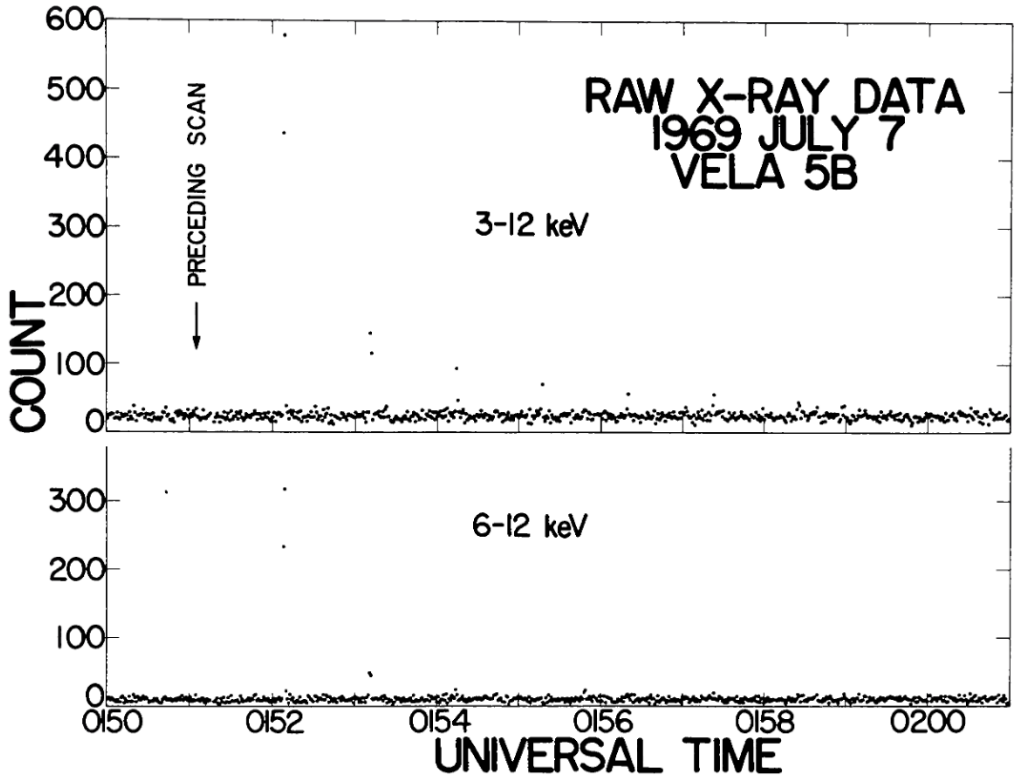

Figure 1. First ever detected Type I X-ray bursts: they were observed by the Vela 5B satellite on July 7, 1969 [12]; the x-axis shows time (UT), and the y-axis shows Vela 5B counts in two energy bands.

The first highly interrupted observation of a Type I X-ray burst was performed in July 1969 (Fig. 1), while the first unambiguous detection of an X-ray burst occurred aboard the Dutch-American ANS satellite from source

4U 1820–30 in the globular cluster NGC 6624 [1]. The burst exhibited a rapid rise (~1 s) and exponential decay (~10 s) with a peak flux near the Eddington limit for a neutron star. Nearly simultaneously, the SAS-3 satellite detected similar bursts from multiple sources, including 4U 1728–34 and GX 3+1 [13,14]. These discoveries quickly established the phenomenological picture: bursts are recurrent, thermally emitting events well modeled by blackbody spectra with temperatures around 2–3 keV, frequently reaching Eddington luminosity.

By 1977–1978, observational programs with SAS-3, Hakucho, and HEAO-1 amassed numerous bursts allowing classification into two primary types: Type I bursts with characteristic spectral cooling during decay, interpreted as cooling of the neutron star surface after thermonuclear flash, and Type II bursts without significant spectral evolution and rapid recurrence (seconds to minutes), associated with accretion instabilities, exemplified by the Rapid Burster (MXB 1730–335). The type I burst thermonuclear model was independently proposed by Woosley and Taam [2], Maraschi & Cavaliere [3], and Joss [15], successfully explaining burst energetics, recurrence times, and spectral evolution. The key insight was that hydrogen/helium-rich material from a low-mass companion accumulates on the neutron star surface until critical conditions trigger explosive ignition [4,5,16].

The detection of recurrent Type I bursts provided one of the earliest and most direct pieces of evidence that the compact objects in low-mass X-ray binaries possess solid surfaces rather than event horizons. Since such bursts require the accumulation and thermonuclear ignition of material on a physical surface, their observation effectively rules out black holes as the central accretors in these systems [1,4].

During the 1980s, with EXOSAT and Tenma satellites, the number of known bursting sources exceeded twenty, and intervals between bursts ranged from minutes to days, enabling comparative studies correlating burst properties with accretion rates [17]. Notably, detection of PRE bursts allowed distance estimates based on the assumption of Eddington-limited luminosity [18,19].

Early burst observations provided some of the strongest direct evidence for neutron stars possessing solid surfaces, as opposed to black holes. Repeated thermonuclear bursts implied a physical surface on which fuel accumulates and ignites. This era also marked the beginning of using bursts as probes of neutron star parameters, although uncertainties in composition, anisotropy, and distances limited precision.

3. Observational Techniques and Key Missions in the Study of X-ray Bursters

Over the history of X-ray astronomy, progress in the study of bursters has closely followed advances in space instrumentation. In particular, each generation of dedicated observatories expanding our understanding of burst phenomenology, timing properties, spectral characteristics, and population behavior. Below is a brief summary of key space missions and their most essential contributions to the field.

3.1. Early Detection Era (1970–1980)

The initial discovery and characterization of X-ray bursts were made possible by the first generation of X-ray astronomy satellites. The NASA satellite Uhuru (SAS-1, 1970–1973) was the first Earth-orbiting X-ray observatory, providing the earliest X-ray source catalogs and detecting transient phenomena concentrated in the Galactic bulge [20]. The SAS-3 satellite (1975–1979) played a pivotal role by detecting and precisely localizing the first thermonuclear bursts, including those from the archetypal burster 3U 1820–30 [1]. Its high time-resolution detectors were crucial for resolving the rapid burst time profiles. Additionally, HEAO-1 (1977–1979) improved spectral resolution and enabled broad-band spectroscopy, allowing more detailed studies of burst energy distributions [21]. These pioneering missions established the foundation for systematic burst studies and demonstrated the importance of continuous, long-baseline X-ray monitoring, which later became a hallmark of the EXOSAT era.

3.2. The EXOSAT Era (1983–1986)

The European Space Agency's EXOSAT observatory revolutionized burst studies by providing long, uninterrupted observations from its highly eccentric orbit [22]. This capability allowed the discovery and characterization of PRE bursts, measurements of apparent blackbody radii, and detailed investigations into burst recurrence times. EXOSAT's observations confirmed correlations between persistent accretion emission and burst activity, firmly establishing the influence of accretion rate on burst behavior [19,23]. EXOSAT's capability for continuous coverage paved the way for the more comprehensive, population-based surveys conducted by BeppoSAX in the following decade.

3.3. BeppoSAX (1996–2002): The Era of Long Bursts and Superbursts

With the deployment of the BeppoSAX satellite, equipped with its Wide Field Cameras (WFC), burst research entered a new phase marked by the detection of hundreds of bursts, including rare intermediate-duration bursts and the first observed superbursts [24,25]. The wide field of view (~40°) of the WFCs enabled simultaneous monitoring of multiple sources, providing the first statistically significant samples of bursts across the Galactic plane [10].

3.4. RXTE (1995–2012): Precision Timing

The Rossi X-ray Timing Explorer (RXTE), with its Proportional Counter Array (PCA), introduced microsecond-level timing precision that was critical for detecting burst oscillations—nearly coherent modulations in burst light curves linked to neutron star spin frequencies. RXTE enabled detailed studies of frequency drifts during bursts and their connection to surface nuclear burning physics. Furthermore, simultaneous spectral and timing analyses with RXTE established links between accretion states and burst properties [26]. The unprecedented timing precision and long operational lifetime of RXTE made it the cornerstone for quantitative burst population analyses, a legacy still vital today.

3.5. INTEGRAL (2002–2025): Wide-Field Hard X-ray Monitoring

The European Space Agency's INTEGRAL mission, featuring the IBIS and JEM-X instruments, expanded burst detection capabilities into the hard X-ray energy band [27,28]. This allowed the observation of rare bursts visible in harder X-rays (over 20 keV) and contributed to the long-term monitoring of bursters in crowded Galactic bulge fields, providing complementary insights into burst energetics and spectral evolution at higher energies. The wide field of view of the IBIS telescope allowed the detection of burst-only sources and identification of new bursters (e.g. [29,30]). The large number of bursts detected by INTEGRAL has widened the pathway for studying their properties as a family of phenomena (Fig. 2). INTEGRAL's extensive burst catalog continues to provide a bridge between classical soft X-ray observations and modern broadband population studies.

3.6. Swift (2004–Present): Rapid Localization and Follow-up

While primarily designed for gamma-ray burst studies, Swift's Burst Alert Telescope (BAT) and X-ray Telescope (XRT) have proved highly valuable for detecting and rapidly localizing X-ray bursts. Swift's capability for quick multi-wavelength follow-up observations has enhanced the characterization of burst sources and their environments [32]. These capabilities established Swift as an important link between high-energy and soft X-ray observatories, enabling rapid multiwavelength follow-up of bursting sources.

3.7. NICER (2017–Present): Soft X-ray Precision

Mounted on the International Space Station, the Neutron Star Interior Composition Explorer(NICER) provides high-throughput, low-background observations in the soft X-ray range (0.2–12 keV) with sub-microsecond timing accuracy. NICER's data have enabled unprecedented constraints on neutron star radii and atmospheric properties, significantly advancing equation-of-state studies [33].

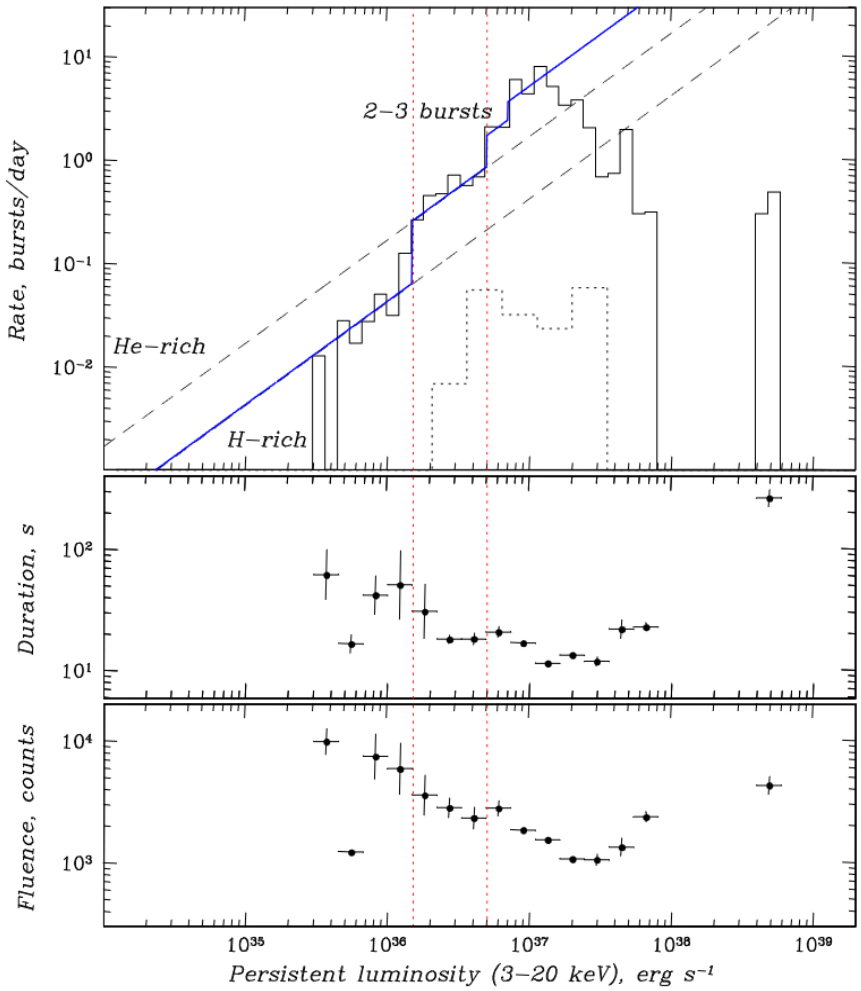

Figure 2. (a) Rate of X-ray bursts from bursters constructed based on the INTEGRAL data versus system luminosity. The dashed lines indicate the predictions of the model of complete burning in a burst of the matter fallen to the neutron star surface since the previous burst. The upper and lower lines correspond to the different presumed helium abundances. The thick solid line indicates the prediction with allowance made for the spreading layer. At higher luminosities bursts disappear due to the onset of stable burning of the accreted material; (b) Mean burst duration versus luminosity. (c) Mean fluence in a burst (in counts) versus luminosity [31].

3.8. Key Observational Challenges

Despite remarkable progress, several challenges remain for burst observations. The unpredictable nature of bursts necessitates long-term monitoring to accumulate sufficient events. Energy coverage gaps persist, as soft X-ray instruments may miss hard X-ray burst tails, while hard X-ray detectors often lack sensitivity for soft bursts. Additionally, source confusion in dense Galactic bulge regions complicates burst identification and localization. In summary, the study of X-ray bursters has progressed through successive generations of space-based observatories, each contributing unique capabilities to probe burst timing, spectra, and population properties. Early missions such as Uhuru, SAS-3, and HEAO-1 enabled the first burst detections and time-resolved profiles. EXOSAT's long uninterrupted observations revealed PRE events and accretion–burst correlations. BeppoSAX introduced wide-field, long-term monitoring, leading to the discovery of intermediate-duration bursts and superbursts. RXTE's microsecond timing precision uncovered burst oscillations linked to neutron star spins. INTEGRAL expanded burst studies into the hard X-ray regime, while Swift brought rapid localization and follow-up capabilities. NICER now provides unprecedented soft X-ray timing and high-throughput, moderate-resolution spectroscopy, enabling improved constraints on neutron-star radii and atmospheres. Despite these advances, challenges such as unpredictable burst occurrence, incomplete energy coverage, and source confusion in dense fields remain central obstacles for future observational progress [10,19,26]. The cumulative progress of these missions reflects

the broader trajectory of high-energy astrophysics—from initial discovery to precise, predictive understanding of matter under extreme conditions.

4. Burst Catalogs

Building upon the observational progress summarized above, systematic burst catalogs have become a cornerstone of population-level studies of thermonuclear bursts. Systematic compilations of Type I X-ray bursts have played a central role in shaping our understanding of neutron star accretion physics, burst phenomenology, and nuclear burning regimes. By aggregating large samples of events across many sources, such catalogs enable statistical studies of recurrence times, energetics, spectral evolution, and correlations with accretion properties.

The earliest burst compilations emerged from the EXOSAT mission (1983–1986), which, thanks to its long uninterrupted observations, produced detailed recurrence time statistics for dozens of sources [34]. Subsequent missions expanded these datasets considerably. The BeppoSAX Wide Field Cameras (1996–2002) provided all-sky coverage of the Galactic center region, leading to the discovery of numerous new bursters and the first population-level analyses of burst rates and fuel compositions [35].

Significant contributions to burst detection and cataloging have been made by the INTEGRAL mission, where long-term monitoring of the Galactic bulge yielded extensive samples of bursts, including rare events detectable at higher ($\gtrsim$20 keV) energies [27,28,36]. These works systematically documented burst occurrence rates, energetics, and correlations with persistent emission, as well as identified new bursting sources [30,37]. Dedicated INTEGRAL-based catalogs remain important for cross-mission statistical studies and for tracking long-term burst activity patterns.

A major advance came with the MINBAR project (Multi-INstrument Burst ARchive), which unified burst detections from RXTE, BeppoSAX, and INTEGRAL into a single homogenized database [6]. MINBAR includes over 7,000 bursts from more than 80 sources, with standardized spectral and temporal measurements, enabling robust cross-mission comparisons. Analyses of this dataset have refined our understanding of ignition conditions, accretion rate dependencies, and the occurrence of rare burst types such as intermediate-duration bursts and superbursts [10]. MINBAR has also served as the foundation for machine-readable public databases, facilitating reproducible research and cross-validation between missions.

In addition to large mission-driven archives, specialized catalogs focus on particular phenomena. For example, the PRE burst catalogs [19] provide curated samples of radius-expansion events, which are used as distance indicators and to constrain neutron star radii. Similarly, targeted burst oscillation catalogs [38,39] compile measurements of nearly coherent modulations to study neutron star spin and surface burning patterns.

Recent efforts also integrate data from NICER (2017–present) and Insight-HXMT, allowing improved soft X-ray coverage and extended monitoring. The future of burst catalogs lies in real-time, multi-mission pipelines combining MAXI, AstroSat, potentially eROSITA, and next-generation observatories, enabling prompt identification and follow-up of unusual events.

In summary, type I X-ray burst catalogs are essential tools for both population studies and the detailed investigation of individual burster properties. From early mission-specific lists to modern unified archives like MINBAR, these datasets allow the identification of systematic trends, the discovery of rare burst classes, and the calibration of neutron star parameters. As new instruments expand spectral coverage and temporal precision, future catalogs will provide increasingly complete views of thermonuclear bursting behavior across the Galactic population. Looking ahead, next generation of burst archives will increasingly rely on automated, cross-mission data fusion and community-driven infrastructure. Such developments will transform catalogs from static repositories into dynamic platforms for real-time discovery, model testing, and rapid coordination between observatories.

The observed diversity of X-ray bursts led to a classification scheme based on spectral evolution, temporal profiles, and recurrence properties [4,5]. The main division is between Type I and Type II bursts, with additional categories for rare, long-duration events. A concise summary table (Tab. 1) has been introduced below to assist readers in navigating the main burst categories and their characteristic properties.

Table 1. Summary of X-ray burst types

Type	**Duration**	**Energy (erg)**	**Physical mechanism**	**Representative sources**
I	10–100 s	10^{39}–10^{40}	Unstable thermonuclear ignition (H/He)	4U 1820–30, GX 3+1
II	1–100 s	10^{37}–10^{38}	Accretion flow instabilities	MXB 1730–335
Intermediate	few–tens of minutes	10^{41}	Helium layer ignition at low accretion rates	SLX 1737−282, SLX 1735−269
Superburst	hours	10^{42}	Carbon ignition in deep crust	4U 1820–30

Type I bursts are characterized by a rapid rise (0.5–2 seconds) and longer decay (10–100 seconds), accompanied by significant spectral softening [14]. Their spectra are well fit by blackbody models with temperatures of ~1.5–3 keV and emitting areas consistent with neutron star radii (~10 km). Recurrence times vary from minutes to days, depending on accretion rate and fuel composition [40]. The underlying mechanism is unstable thermonuclear ignition of a thin accreted fuel layer, with ignition conditions sensitive to accretion rate and chemical makeup [4,5,23]. These bursts serve as direct probes of nuclear burning regimes and neutron star envelope conditions, linking observational and theoretical efforts across multiple disciplines.

Within Type I, subtypes include helium-rich bursts with short durations (~10 seconds) occurring at high accretion rates, mixed hydrogen/helium bursts with longer durations (up to 100 seconds), and PRE bursts reaching the Eddington limit, where the neutron star atmosphere temporarily expands and then contracts [41]. PRE bursts serve as distance indicators [19,42,43].

Type II bursts have a different origin: they are linked not to thermonuclear burning but to accretion flow instabilities [16]. They feature short recurrence intervals (seconds to minutes), lower energies compared to Type I, and lack significant spectral evolution. The Rapid Burster (MXB 1730–335) is a prominent example, where matter accumulation in the inner disk leads to cyclic release onto the surface [16,44]. While less energetic, Type II bursts provide valuable insight into disk–magnetosphere interactions and accretion feedback processes.

Intermediate-duration bursts (several minutes to tens of minutes) with energies up to 10^{41} erg are believed to arise from ignition of thick helium layers at low accretion rates [45]. The longest events—superbursts—last for hours with energies up to 10^{42} erg and are most likely caused by unstable carbon burning deep in the neutron star crust. These events are extremely rare, with expected recurrence times of years [10]. Because of their extreme energetics and long recurrence, these events provide constraints on crustal heating and deep nuclear processes within neutron stars.

Additional categories include double and multiple bursts (Fig. 3) with short inter-burst intervals [32,46,47], as well as nearly coherent oscillations observed during some Type I X-ray bursts, interpreted as rotational modulation of hot spots on the neutron star surface, thus enabling measurement of neutron star spin frequencies [26].

In summary, X-ray bursts are broadly classified into Type I (thermonuclear origin) and Type II (accretion instability origin), with additional rare categories within Type I like intermediate-duration bursts and superbursts. Type I bursts show characteristic fast-rise/slow-decay profiles, blackbody-like spectra, and recurrence times dependent on accretion rate and fuel composition. PRE bursts within Type I reach the Eddington limit and can serve as distance indicators. Type II bursts, observed in sources like the Rapid Burster, are driven by episodic accretion events rather than nuclear burning. Longer events—intermediate bursts and superbursts—result from ignition of thick helium layers or deep carbon burning, respectively. Observed variations such as burst oscillations and multiple-burst sequences further enrich the phenomenology and provide valuable probes of neutron star properties [4,5,10,16,19,26].

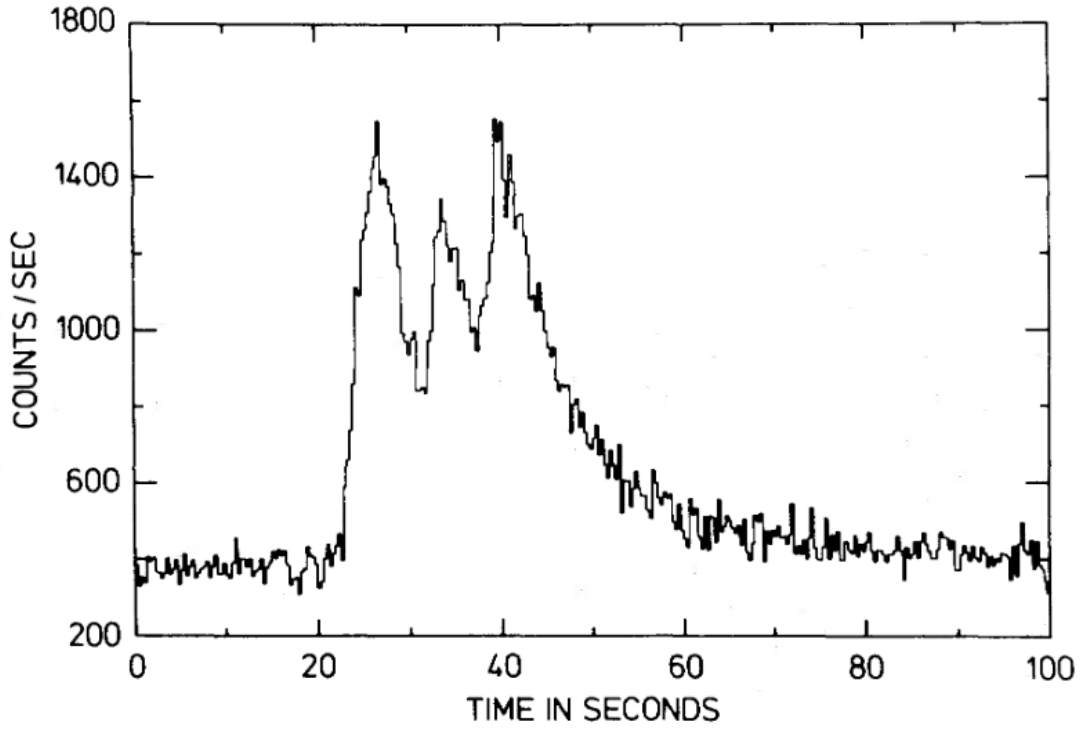

Figure 3. Raw countrate profile (1-20 keV) of the unique triple-peaked burst observed from 4U/MXB 1636-53 by the EXOSAT mission [48].

5. Physics of Thermonuclear X-ray Bursts

Low- Low-mass X-ray binaries consist of a neutron star accreting matter from a companion star, typically via Roche-lobe overflow or stellar wind [4,23]. The accreted material, predominantly hydrogen and helium, accumulates on the neutron star's surface, forming a thin layer subjected to an immense gravitational field on the order of 10^{14} cm s^{-2}. The accretion rates in these systems generally range between $\sim 10^{-10}$–10^{-8} $M_{\odot}$ yr^{-1} [5]. Given a neutron star mass M and radius R, the surface gravity g is given approximately by:

$$g = \frac{GM}{R^2} \approx 1.9 \times 10^{14} \left(\frac{M}{1.4M_{\odot}}\right)\left(\frac{10km}{R}\right)^2 cm\ s^{-2} \quad (1)$$

This extreme gravity compresses the accreted material into a dense, thin shell, where nuclear burning can occur.

The pressure at a given column depth y in the fuel layer is given by P=gy, with typical ignition column depths on the order of 10^8–10^9 g cm^{-2} [40]. Thermonuclear ignition arises when the nuclear energy generation rate, ϵ_{nuc} surpasses local cooling processes, triggering an unstable runaway. The temperature sensitivity of nuclear reactions plays a crucial role in determining whether burning proceeds stably or explosively [49].

The primary nuclear processes governing X-ray bursts include hydrogen burning via the CNO cycle, which steadily converts hydrogen to helium [50], and helium burning through the highly temperature-dependent triple-alpha process:

$$3\,He^4 \rightarrow C^{12} + \gamma + 7.275\ MeV \quad (2)$$

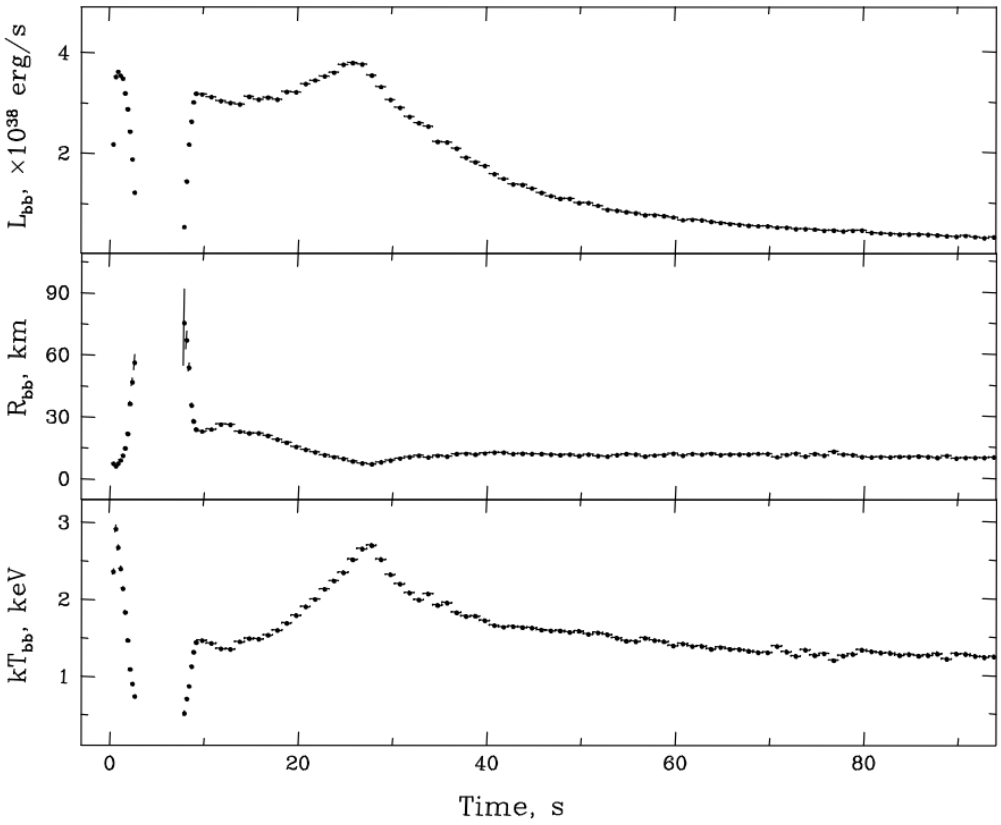

Figure 4. Evolution of the bolometric luminosity, radius and effective temperature of the neutron star photosphere during the burst in 4U1724−307 [51].

which can ignite explosively due to its strong dependence on temperature (approximately proportional to T^{40} at relevant conditions) [52]. In mixed hydrogen/helium environments, the rapid proton capture process (rp-process) can synthesize heavier nuclei up to mass number $A \sim 100$ [53,54]. Once the temperature reaches approximately $(1–2)\times10^8$ K helium ignition triggers a thermonuclear runaway described by the energy balance [50]:

$$\frac{dT}{dt} = \frac{\epsilon_{nuc} - \epsilon_{cool}}{C_p} \quad (3)$$

where C_p is the heat capacity and ϵ_{cool} represents radiative cooling [23]. If heating dominates, the temperature rises rapidly, releasing energies in the range of 10^{39}–10^{40} erg.

The recurrence time between bursts, t_r, is governed by the ignition column depth and local accretion rate per unit area, following

$$t_r = \frac{y_{ign}}{\dot{m}} \quad (4)$$

where $\dot{m}$ is the local accretion rate per unit area.

Following ignition, the neutron star's atmosphere cools predominantly via radiative diffusion, producing burst light curves well-modeled by blackbody emission with evolving temperature and radius [5]. Typical cooling timescales range from tens of seconds.

At luminosities approaching the Eddington limit,

$$L_{Edd} = \frac{4\pi GMc}{\kappa} \tag{5}$$

where κ is the opacity dominated by electron scattering, radiation pressure can lift the atmosphere, causing PRE. This phenomenon manifests as an increase in the apparent photospheric radius accompanied by a temporary cooling of the emission spectrum (Fig. 4), followed by contraction as the burst energy subsides [4].

Although PRE bursts serve as powerful probes for estimating neutron star masses and radii, these measurements are subject to significant systematic uncertainties. The inferred Eddington luminosity depends on the chemical composition of the photosphere (particularly the hydrogen fraction), the degree of emission anisotropy, and the assumed source distance. In addition, atmospheric effects such as spectral hardening and deviations from a pure blackbody spectrum can bias radius determinations by 10–30%. Accounting for these factors is essential when using PRE bursts to constrain the equation of state of dense matter [55,56]. Together, these processes link the microphysics of nuclear burning to the macroscopic observables of burst behavior and neutron star structure.

In summary, thermonuclear X-ray bursts occur when accreted hydrogen and helium on a neutron star's surface ignite unstably under extreme gravity. The interplay of the CNO cycle, triple-alpha process, and rp-process governs the burning behavior. Burst properties—energy, duration, recurrence time—are determined by ignition depth, accretion rate, and nuclear reaction sensitivities. Observations of phenomena such as PRE events provide direct probes of neutron star surface conditions, while theoretical models link burst physics to neutron star structure and accretion processes [50].

6. Superbursts and Advanced Thermonuclear Burning Models

Superbursts represent a rare class of X-ray bursts distinguished by their extraordinary energy release (~10^{42} erg), long durations (several hours) (Fig. 5), and recurrence intervals spanning years to decades [24]. Unlike typical Type I bursts fueled by hydrogen and helium burning, superbursts most likely originate from unstable carbon ignition deep within the neutron star's ocean of nuclear ashes, at column depths around 10^{12} g cm^{-2} [4,5,9,10].

These events thus represent the deepest and most energetic manifestation of thermonuclear burning on accreting neutron stars, bridging the regime between surface bursts and deep crustal heating phenomena.

The carbon layer accumulates over time from residual ashes left by prior bursts and stable burning, undergoing compressional heating within the neutron star envelope [57]. Ignition temperatures for carbon burning reach approximately 5×10^{8} K, with thermonuclear runaway conditions governed by the balance between nuclear heating ϵ_C and thermal diffusion. This balance can be roughly expressed as

$$\epsilon_C \approx \frac{KT}{y^2} \tag{6}$$

where K is the thermal conductivity [58]. Carbon fusion proceeds primarily via

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow \text{products} + \mathrm{Q}\ (\approx 13\ \mathrm{MeV}) \tag{7}$$

with the reaction rates exhibiting extreme temperature sensitivity, thereby triggering the superburst ignition [10,59].

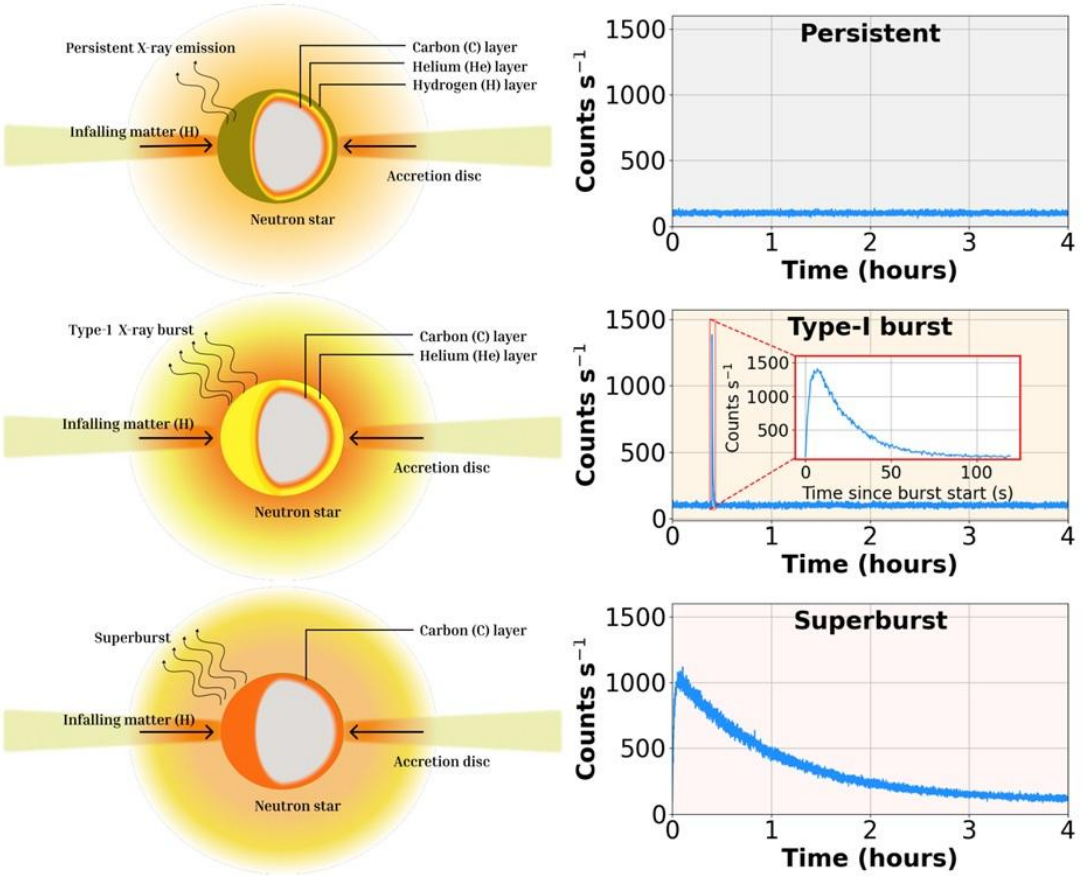

Figure 5. (Left) Schematic representation of a neutron star low-mass X-ray binary system during persistent emission from steady accretion (top); type-I X-ray burst triggered by unstable helium burning (middle); a superburst driven by carbon ignition (bottom). (Right) Corresponding X-ray light curves over time (Credit: URSC website).

Numerical models incorporating thermal conduction, nuclear burning networks, and hydrodynamics successfully reproduce the observed superburst light curves, characterized by a rapid rise phase over seconds followed by prolonged decay lasting several hours, reflecting heat diffusion from deep layers [10,60].

Recent theoretical developments have extended our understanding of thermonuclear burning by implementing multi-zone simulations capturing detailed nuclear reaction networks [61], considering effects of neutron star rotation and magnetic fields on burning front propagation [62], and investigating stable burning regimes at elevated accretion rates [63]. Additionally, the roles of sedimentation and mixing of accreted material have been explored to explain diverse burst phenomenology, such as intermediate-duration bursts, ignition latitude dependence, burst oscillations, and quenching by stable burning [26,64,65]. These theoretical developments have provided a framework for interpreting observed superburst light curves and recurrence patterns in specific sources. Observationally, superbursts have been detected in a limited number of systems, including GX 17+2 [66] and well-studied sources like 4U 1820–30 and 4U 1636–53, with data primarily obtained by RXTE, BeppoSAX, and INTEGRAL. The lengthy recurrence times of superbursts imply deep fuel accumulation and slow cooling processes [10,67].

In summary, superbursts are exceptionally powerful thermonuclear events on neutron stars, fueled by unstable carbon ignition at great depths. Their rare occurrence, multi-hour durations, and multi-year recurrence times distinguish them from standard Type I bursts. Modern models that couple thermal conduction, nuclear reaction networks, and hydrodynamics have reproduced key observational features, while recent advances explore the roles of magnetic fields, rotation, and material mixing. Observations of sources like 4U 1820–30 and 4U 1636–53 provide critical constraints on ignition conditions, deep crustal heating, and accretion physics, making superbursts a unique probe of neutron star interiors and nuclear processes under extreme conditions [4,5,10]. Future progress in superburst studies is expected to rely on continuous all-sky monitoring and high-sensitivity soft X-ray missions capable of capturing full light curves and recurrence cycles. Coupling such observations with next-

generation multi-zone simulations and improved nuclear reaction networks will enable deeper insights into the thermal and compositional structure of accreting neutron stars.

7. Type II Bursts and Accretion Instabilities

Type II X-ray bursts represent a distinct class of transient phenomena observed in a small subset of neutron star LMXBs. Unlike thermonuclear (Type I) bursts, which are powered by unstable nuclear burning on the neutron star surface, Type II bursts are widely believed to originate from episodic accretion instabilities in the inner disk or magnetospheric region [68,69]. These bursts exhibit highly variable recurrence times, ranging from seconds to minutes, and are characterized by rapid rises, sharp decays, and complex light-curve morphologies. Their energetics are limited by the small mass reservoir available in the inner accretion flow, resulting in fluences orders of magnitude lower than the total energy released by persistent accretion over comparable timescales. However, their peak luminosities—typically reaching 10^{37}–10^{39} erg s^{-1}—are comparable to the instantaneous accretion luminosity, consistent with a gravitational, rather than thermonuclear, origin.

The occurrence of Type II bursts is strongly correlated with peculiar states of the accretion flow, in which the mass transfer rate from the companion star remains relatively steady, yet the inflow onto the neutron star becomes intermittent [70]. In this regime, the accretion disk acts as a dynamic reservoir that alternately stores and releases material, producing the observed burst sequences. This suggests the action of a regulatory mechanism, or "accretion gating," whereby matter is cyclically stored and released on short timescales. The unique phenomenology of the so-called "Rapid Burster", demonstrating both Type I and Type II bursts (Fig. 6), provides an unparalleled laboratory for studying such processes [16,68].

7.1. Rapid Burster (MXB 1730−335) phenomenology

MXB 1730−335, located in the globular cluster Liller 1, is the archetypal and, for decades, the only confirmed source of Type II bursts [16]. Since its discovery in 1976, it has demonstrated a remarkable diversity of burst profiles, ranging from short (~1 s) symmetric pulses to longer (~100 s) events with extended, structured decays. Recurrence times vary from a few seconds to several minutes, with observed sequences occasionally displaying a quasi-periodic character [69].

In addition to its bursting activity, the Rapid Burster exhibits complex persistent emission that can coexist with, or be interrupted by, bursting episodes. The transition between bursting and non-bursting intervals can occur on timescales of hours to days, often in correlation with changes in the inferred accretion state [71]. Observations with missions such as RXTE and NICER have revealed that the source's X-ray spectrum during bursts is dominated by thermal Comptonization components, often with evidence of cooling during the decay phase, consistent with the release of gravitational potential energy from infalling matter [16,69,72].

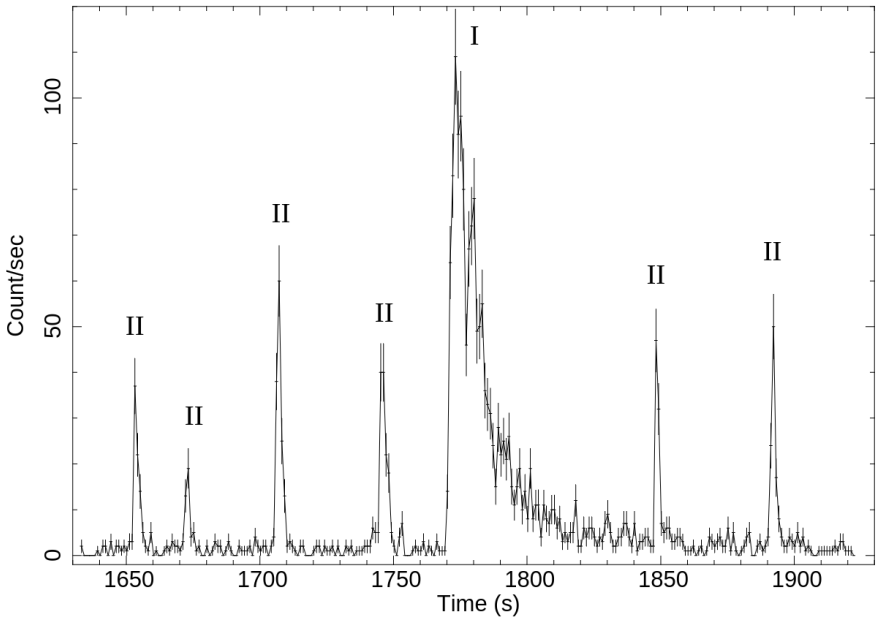

Figure 6. Swift/XRT lightcurve (0.2-10 keV) of the Rapid Burster on 2009 March 5 [73]. Six type II bursts are visible, along with a photospheric-radius-expansion (PRE) Type I burst.

Importantly, MXB 1730−335 also exhibits Type I bursts, indicating that nuclear burning on the surface of the neutron star can occur alongside—or independently of—the accretion-driven bursting behavior. This duality makes it a critical testbed for disentangling accretion and nuclear processes in LMXBs [4,5].

7.2. Proposed mechanisms: accretion gating, disk instabilities and magnetospheric interaction

7.2.1. Accretion gating

In this scenario, matter is intermittently halted near the neutron star due to magnetospheric pressure exceeding the ram pressure of the inflowing gas [74,75]. When the inner disk is truncated outside the corotation radius, a centrifugal "propeller" effect can inhibit accretion, causing matter to accumulate. Once the ram pressure of the accumulated gas exceeds the magnetic barrier, a rapid inflow ensues, releasing the stored gravitational energy in the form of a burst [76]. The cycle then repeats, leading to quasi-periodic bursts whose recurrence times are set by the accumulation rate and magnetospheric size.

7.2.2. Disk instabilities

Alternatively, the bursts may arise from viscous or thermal instabilities in the inner accretion disk [77-79]. In this picture, a limit-cycle behavior develops due to a steep dependence of viscosity on surface density, or due to ionization transitions in the disk plasma [80]. Such instabilities can lead to rapid depletion and refilling of the inner disk, producing bursts without requiring strong magnetic fields. The observed scaling of burst fluence with recurrence time in MXB 1730−335 is consistent with the release of a finite mass reservoir during each cycle [69].

7.2.3. Magnetospheric interaction

A hybrid class of models considers the interaction between the inner disk and the neutron star's magnetic field as a source of burst regulation [81,82]. Even for relatively weak magnetic fields ($B \sim 10^8$–10^9 G), the coupling between disk plasma and field lines can introduce quasi-periodic reconnection or slippage events [83]. These processes may modulate the effective inner disk radius, leading to episodic accretion bursts that combine features of both gating and disk-instability mechanisms.

While none of these models fully accounts for the full phenomenology of the Rapid Burster, current evidence suggests that the interplay between magnetospheric truncation and inner-disk instabilities is a promising framework [69,84]. Continued multiwavelength and high-time-resolution observations will be crucial for discriminating between competing scenarios, and for constraining the physical parameters—such as magnetic field strength, spin period, and disk viscosity—that govern the unique and intriguing behavior of Type II bursters [16].

In summary, Type II bursts in neutron star LMXBs, exemplified by MXB 1730−335, are now understood to arise from rapid, recurrent changes in accretion flow of matter from the companion star rather than from nuclear burning of this matter on the surface of the neutron star. Their short recurrence times and energetics point toward mechanisms involving magnetospheric gating, disk instabilities, or a hybrid of both. The Rapid Burster's unique coexistence of Type I and Type II bursts makes it a key source for probing the coupled physics of accretion dynamics and neutron star surface processes. The coexistence of accretion-driven and nuclear-powered bursting in the same system highlights the complex coupling between disk dynamics and surface thermonuclear processes—a challenge that remains only partially understood. Future progress will require coordinated observational campaigns, refined magnetohydrodynamic modeling, and comparisons with laboratory plasma physics, to constrain the relevant parameters driving these extreme astrophysical events.

8. Links Between Burst Behavior and Accretion Environment

The occurrence and properties of X-ray bursts are intimately connected to the physical state of the accretion flow onto the neutron star. Changes in the accretion rate, disk geometry, and magnetospheric coupling can alter the conditions for thermonuclear ignition, modulate fuel composition, and in some cases suppress bursting altogether. Understanding these connections is essential for interpreting burst phenomenology and for using bursts as probes of nuclear physics and neutron star structure — an intriguing goal for modern astrophysics [5,17]. These interactions between accretion flow and nuclear ignition link microphysical processes on a neutron-star surface to the macroscopic evolution of compact binaries and the chemical enrichment of the Galaxy. Understanding them is therefore not only a question of nuclear physics, but also of how energy and matter behave under the most extreme conditions accessible to observation.

8.1. State dependence of burst properties

Observations across multiple sources reveal that burst properties—such as recurrence time, duration, and peak luminosity—often vary systematically with the persistent X-ray emission state [35,85]. At low accretion rates, the fuel layer accumulates over longer intervals, leading to less frequent but more energetic bursts. Conversely, at higher accretion rates, ignition occurs sooner, resulting in shorter recurrence times and generally weaker bursts. State transitions, often identified in color–color or hardness–intensity diagrams, can be accompanied by marked changes in burst morphology, suggesting that the thermal structure of the accreted layer is influenced by the accretion flow configuration (e.g., banana versus island states in atoll sources [86]).

8.2. Burst–persistent emission interactions

The interplay between burst emission and the surrounding accretion environment has been detected in a range of phenomena, from temporary changes in persistent flux to alterations in disk reflection signatures [72,87]. During some bursts, irradiation of the accretion disk by the burst's X-ray flash produces observable changes in Fe Kα line strength and continuum reflection components, providing insights into disk ionization and geometry [88,89]. In a subset of sources, "burst-induced accretion enhancement" has been inferred, where the burst appears to drive additional material inward, temporarily increasing the persistent emission after the burst peak [90].

8.3. Effects of accretion rate variability on ignition conditions

Variations in the accretion rate on timescales shorter than the burst recurrence time can have cumulative effects on ignition conditions [67]. A gradual increase in accretion rate between bursts may raise the base temperature of the fuel layer, lowering the critical column depth for ignition and producing shorter, less energetic bursts. Conversely, intermittent dips in accretion rate may allow additional fuel accumulation, leading to stronger events [46]. In transiently accreting systems, burst properties often evolve systematically over an outburst, reflecting the changing accretion rate and disk–magnetosphere configuration [4,91].

8.4. Burst suppression and quenching by stable burning

At sufficiently high accretion rates, hydrogen burning via the hot CNO cycle may become stable, preventing the accumulation of thick, unstable fuel layers [23,40]. This "quenching" of bursts by stable burning (Fig. 2) is well documented in several systems that cease bursting when the persistent luminosity exceeds a threshold of order 0.1–0.3 L_{Edd} [5,35]. In some cases, bursts reappear only after the accretion rate has declined for weeks to months, consistent with a cooling timescale for the neutron star envelope [92]. This transition between unstable and stable burning regimes provides one of the few observational handles on the thermal regulation of accreting neutron star envelopes. Such behavior highlights the role of steady-state nuclear burning in regulating burst activity and sets important constraints on both ignition models and nuclear reaction rates.

In summary, the strong coupling between burst properties and the accretion environment underscores the necessity of considering both thermonuclear and accretion physics when interpreting observations. Such studies serve as a bridge between high-energy astrophysics and nuclear physics, allowing us to probe matter at supranuclear densities through macroscopic observables. By mapping burst characteristics across different accretion states and luminosity regimes, it is possible to disentangle the effects of fuel composition, ignition depth, and envelope temperature, paving the way for more robust constraints on both nuclear processes and neutron star structure.

9. Connections to Nuclear Physics and Dense Matter

Thermonuclear X-ray bursts on accreting neutron stars provide a unique laboratory for studying nuclear physics under extreme conditions inaccessible on Earth. Thermonuclear runaways in Type I bursts probe nuclear reaction networks at temperatures above 10^9 K and densities around 10^5–10^6 g cm^{-3}. Rp-process, αp-processes, and β-decay chains drive fuel burning, powering burst lightcurves and shaping burst ashes. The interplay between nuclear reaction rates, decay lifetimes, and mass models with macroscopic neutron star properties (e.g., surface gravity, thermal transport) is crucial for interpreting observations. PRE bursts and spectral diagnostics offer direct ways to constrain the neutron star's mass, radius, and thus the dense-matter equation of state (EOS) [4,5,19,50]. Ultimately, the study of X-ray bursts connects the microscopic world of nuclear reactions to the macroscopic behavior of matter under supranuclear densities. These systems thus serve as natural laboratories for testing how the laws of physics operate when both quantum and relativistic effects are equally essential.

9.1. Sensitivity of burst lightcurves to nuclear reaction rates

Burst lightcurves and spectra encode the underlying nuclear energy release: the rise phase is dominated by runaway H/He burning, while the decay traces envelope cooling and ash composition. Studies have shown that varying key reaction rates—such as breakout reactions from the hot CNO cycle and rp-process proton captures—can significantly affect burst rise time, peak luminosity, and decay shape. For instance, [93] demonstrated that altering certain (p, γ) reaction rates by orders of magnitude can change peak luminosity by ~10%. Later sensitivity surveys (e.g., [94,95]) mapped which reactions most strongly influence model predictions and ash compositions. In some cases, modified breakout rates delayed the rp-process onset, producing longer rise times, while faster rates yielded more abrupt and luminous rises. Direct experimental measurements of key reactions have recently refined these nuclear inputs, leading to improved predictions for burst observables [50,96].

9.2 Laboratory constraints (rare-isotope experiments) and model inputs

Rare-isotope beam facilities such as FRIB, RIKEN, and FAIR have enabled measurements of resonance energies, lifetimes, and branching ratios for nuclei along the rp-process path—critical data for reliable astrophysical reaction rates. These constraints reduce uncertainties in network inputs, enhancing the predictive power of burst models [7,97]. Where experimental data are absent, theoretical calculations—such as Hauser–Feshbach statistical models or large-scale shell-model studies—are used. Combining these theoretical results with targeted experiments has proven essential for building accurate nuclear data sets for burst modeling [98,99]. The resulting improved inputs are incorporated into hydrodynamic simulations, linking laboratory nuclear physics to macroscopic observables such as burst duration, recurrence time, and ash composition [50].

9.3. Using bursts (PRE, spectral features) to constrain NS mass/radius and EOS

PRE bursts are powerful diagnostics: when luminosity reaches the Eddington limit, the photosphere expands, and from the observed touchdown flux and cooling-tail evolution one can infer the neutron star's Eddington luminosity and apparent angular size. Bayesian analyses using PRE bursts have yielded constraints in the mass–radius plane [73,100]. However, such inferences remain sensitive to uncertainties in distance, atmospheric composition, and anisotropy of emission, which can systematically shift the derived parameters by up to 20–30% [55,56]. For example, PRE bursts from MXB 1730−335 have been used to derive $M \approx 1.1 \pm 0.3\ M_\odot$ and $R \approx 9.6 \pm 1.5$ km, ruling out the stiffest EOS models [73]. High-resolution X-ray spectroscopy can reveal absorption lines from heavy elements in the photosphere; if identified, their gravitational redshift gives a direct measure of compactness (GM/Rc^2) [101]. Cooling-tail spectral fitting techniques [56,102] have placed lower limits on the neutron star radius, often favoring stiffer EOS scenarios. Recently, combined electromagnetic and gravitational-wave analyses have provided consistent EOS constraints across independent observational channels [19,103,104].

In summary, precise knowledge of nuclear reaction rates, constrained by both experiments and theory, is essential for accurate burst modeling. PRE bursts and spectral diagnostics provide robust methods to infer neutron star mass and radius, offering direct EOS constraints. By integrating rare-isotope experimental results with astrophysical modeling, researchers bridge scales from femtometer nuclear structure to kilometer-scale neutron star observables, uniting laboratory and cosmic frontiers of nuclear physics.

10. X-ray Bursts as Probes of Neutron Star Structure

Thermonuclear X-ray bursts, particularly those exhibiting PRE and other distinctive spectral features, can serve as powerful diagnostics of neutron star mass, radius, and the underlying equation of state (EOS) of dense matter. By combining burst observations with physical models of neutron star atmospheres and accretion environments, it is possible to derive constraints that complement those obtained from other astrophysical methods such as pulsar timing, gravitational wave detections, and quiescent NS spectroscopy [4,100].

10.1. PRE bursts and Eddington-limited luminosities

By measuring the peak flux during PRE events (Sec. 6) and applying models for the Eddington luminosity, one can infer the source distance or, if the distance is known, place constraints on NS mass and radius [105,106]. The method requires corrections for atmospheric composition, anisotropy of emission, and gravitational redshift, as well as careful consideration of systematic uncertainties [5,19,102].

10.2. Cooling-tail spectroscopy

Following the PRE phase, the photosphere settles back to the NS surface, and the burst enters a cooling phase. The decay of the bolometric flux and color temperature—the "cooling tail"—can be modeled with neutron star atmosphere spectra to constrain surface gravity and redshift, providing an independent, model-based path to infer neutron star compactness (Fig. 7) [107,108]. This method benefits from using data from multiple bursts in similar spectral states, thereby reducing statistical noise and mitigating variability due to changing accretion conditions [109].

10.3. Gravitational redshifts from spectral features

High-resolution spectroscopy of bursts has occasionally revealed discrete absorption features that, if of photospheric origin, could yield direct measurements of gravitational redshift and hence the mass-to-radius ratio [101,110]. However, the rarity and potential transient nature of such features, as well as the possibility of origin in the accretion disk or wind, complicate their interpretation [111]. Future missions with larger collecting areas and high spectral resolution, such as *Athena* and *XRISM*, may enable more robust detections.

10.4. Constraints on mass, radius, and the dense-matter EOS

By jointly analyzing PRE bursts, cooling-tail spectra, and potential gravitational redshift measurements, one can delineate allowed regions in the neutron star mass–radius plane [55,112]. These constraints can then be compared with theoretical EOS models, providing valuable information on the composition and microphysics of cold, catalyzed matter at supranuclear densities [113]. Although systematic uncertainties remain significant, especially regarding atmospheric composition and accretion geometry, burst-based constraints are increasingly seen as complementary to those from gravitational wave observations (e.g., GW170817 [114]) and NICER pulse-profile modeling [19,103,115].

In summary, X-ray bursts, and especially PRE events, remain among the most powerful astrophysical tools for probing neutron star parameters and the EOS of dense matter. While uncertainties in model assumptions and accretion environment effects remain a challenge, the combination of multi- epoch burst analysis, improved atmosphere models, and next-generation X-ray instrumentation promises significant advances in our ability to measure neutron star masses and radii with high precision [6,116]. Ultimately, integrating burst-based constraints with those from gravitational waves and pulse-profile modeling will enable a coherent, multi-messenger framework for determining the properties of matter at supranuclear densities.

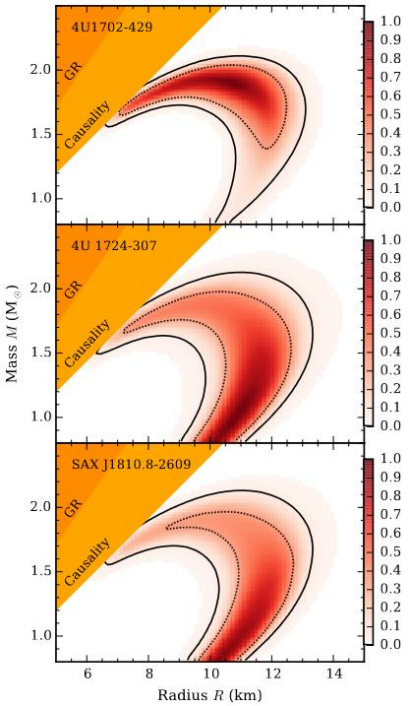

Figure 7. Mass-radius constraints for the sources from the hard state PRE bursts. Constraints are shown by 68% (dotted line) and 95% (solid line) confidence level contours. The upper-left region is excluded by constraints from the causality and general relativistic requirements [108].

11. Open Questions and Future Directions

As the diagnostic potential of X-ray bursts continues to expand, several fundamental problems remain unsolved despite decades of observational and theoretical progress. These open questions span nuclear astrophysics, accretion physics, and neutron star structure, and their resolution will require coordinated advances in observations, modeling, and laboratory measurements.

11.1. Ignition physics and multi-dimensional effects

Most burst models assume one-dimensional ignition and flame propagation, yet recent multi-dimensional hydrodynamic simulations indicate that ignition latitude, magnetic topology, and Coriolis forces may significantly modify flame spreading [62,117]. Observed burst oscillations indicate complex patterns of surface burning, but the transition from localized ignition to global flame coverage is still not fully understood. Progress will depend on coupling nuclear burning models to realistic surface flow dynamics in multidimensional simulations [26,118,119].

11.2. Burst–accretion flow coupling

The mechanisms by which bursts influence the accretion disk and magnetosphere—producing persistent flux variations, reflection signatures, and possible disk winds—remain poorly constrained [72,87]. The timescales and amplitudes of these effects vary widely between sources and even between bursts from the same source. Coordinated broadband monitoring, including simultaneous X-ray and optical/IR coverage, could clarify the interplay between thermonuclear burning and the surrounding plasma.

11.3. Stable burning and burst cessation

The transition between unstable and stable burning regimes is critical for understanding burst rate evolution, yet observational thresholds often differ from theoretical predictions [5,17]. Factors such as rotationally induced mixing, localized accretion, and compositional gradients in the fuel layer may shift the stability boundary [89,120]. Addressing this discrepancy will require more detailed models incorporating time-dependent accretion flows and multi-zone nuclear burning.

11.4. Nuclear physics uncertainties

The sensitivity of burst lightcurves to key nuclear reaction rates—particularly those in the rp-process—remains a major source of modeling uncertainty [7,94]. Even with new data from rare-isotope beam facilities, large portions of the relevant reaction network remain experimentally inaccessible. Statistical model calculations will need to be benchmarked against laboratory measurements wherever possible to reduce uncertainties in predicted burst properties [50,95]. Ongoing experiments at next-generation rare-isotope facilities (FRIB, FAIR, RIKEN) will be crucial for anchoring burst models to experimentally verified reaction pathways.

11.5. Constraints on neutron star mass, radius, and EOS

Although PRE bursts and cooling-tail spectroscopy have yielded promising constraints on neutron star parameters, systematic uncertainties—such as unknown atmosphere composition and anisotropic emission—still limit precision [55,107]. Combining burst analyses with independent methods, including pulse-profile modeling from NICER and gravitational wave constraints, offers the best route to robust EOS determination [19,103,114,115].

11.6. Next-generation observational opportunities

Forthcoming and proposed X-ray missions—such as *Athena*, *eXTP*, and *STROBE-X*—promise transformational improvements in sensitivity, spectral resolution, and timing capabilities [121,122]. These will enable detailed time-resolved spectroscopy of bursts, detection of weak spectral features, and mapping of burst oscillation patterns with unprecedented precision. Combining these data with advances in multi-dimensional modeling and laboratory nuclear physics will allow a new generation of high-fidelity comparisons between theory and observation.

In summary, X-ray bursts remain a fertile ground for discovery, linking extreme astrophysical environments to fundamental questions in nuclear physics and dense matter theory. Progress will rely on bridging disciplinary

boundaries—uniting observational astrophysics, high-energy instrumentation, computational modeling, and experimental nuclear physics—to build a comprehensive framework linking microphysical processes in nuclear burning to the macroscopic behavior of accreting neutron stars.

12. Philosophical and Cosmological Significance

Beyond their physical properties, X-ray bursts from neutron stars invite reflection on deeper cosmological and existential questions. The study of such extreme phenomena exemplifies humanity's capacity to explore the ultimate limits of matter, energy, and physical law, expanding our comprehension of the Universe's structure and origins.

Neutron stars—transitional states between stability and collapse—embody the tension between creation and destruction, between existence and the boundary of the possible. They compel us to ask whether these compact remnants are not merely astrophysical objects, but natural laboratories where the fundamental symmetries of the cosmos are tested to their extremes. The use of X-rays as our observational window underscores a profound truth: the most energetic and transformative processes in the Universe are often invisible to the human eye. Through X-ray astronomy, we illuminate the hidden architecture of reality, revealing the mechanisms by which matter reorganizes itself under the most extreme conditions.

In this sense, the exploration of X-ray bursts is not only a scientific pursuit but also a philosophical act — a dialogue between the human intellect and the cosmos itself. By studying these brief yet powerful flashes of nuclear fire, humankind participates in uncovering the unity of physical processes that link the subatomic and the cosmic, the transient and the eternal. Ultimately, this endeavor reflects our enduring search for meaning within a vast and dynamic Universe.

13. Summary and Outlook

Thermonuclear (Type I) X-ray bursts provide an exceptional natural laboratory for studying the intertwined physics of accretion, nuclear burning, and neutron star structure. Over the past five decades, space-based X-ray observatories have revealed an extraordinary diversity in burst phenomenology—from short, regular bursts to irregular, multi-peaked events and rare superbursts [4,5]. These observations have been matched by advances in theoretical modeling, which now incorporate detailed nuclear reaction networks, time-dependent accretion physics, and increasingly realistic neutron star atmosphere models [10,49,107]. The Key achievements over the past decades include:

1. Probing accretion physics through burst–disk interactions and recurrence statistics [72,87].
2. Constraining nuclear physics by mapping rp-process pathways and identifying key reaction-rate uncertainties [7,50,123].
3. Inferring dense-matter properties by deriving neutron star mass–radius limits from PRE bursts, cooling tails, and potential spectral features [19,55,112].

A brief, prioritized list of the most pressing open questions includes:

1. How do multi-dimensional effects—such as flame spreading, magnetic confinement, and rotation —govern the ignition and propagation of thermonuclear burning?
2. What are the dominant nuclear reaction rate uncertainties along the rp- and αp-process paths, and how do they shape burst light curves and ashes?
3. To what precision can PRE bursts, cooling-tail spectroscopy, and burst oscillations constrain the neutron star equation of state (EOS)?
4. What mechanisms drive the transition between unstable and stable burning regimes, and how do they depend on accretion geometry and composition?
5. How do bursts interact with and modify the surrounding accretion flow and magnetosphere across different luminosity states?

Despite these open problems, the field stands at the threshold of a data-rich era. Next-generation X-ray observatories such as *Athena*, *eXTP*, *STROBE-X* will deliver unprecedented spectral and temporal resolution, enabling detailed mapping of burst ignition and propagation, and the detection of faint spectral signatures from the neutron star surface and surrounding plasma [121,122]. In parallel, facilities such as FRIB and RIKEN will provide critical nuclear data to reduce uncertainties in burst modeling [95,124].

In summary, X-ray burst research is poised for major advances through the integration of high-quality multi-wavelength observations, sophisticated multi-dimensional simulations, and precise laboratory nuclear physics. This synergy will allow the community not only to resolve long-standing questions about burst mechanisms but also to transform these cosmic thermonuclear explosions into precision tools for probing the fundamental properties of matter under the most extreme conditions known in the Universe.

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References

1. Grindlay, J. E. et al. Discovery of intense X-ray bursts from the globular cluster NGC 6624. *ApJ 205*, 127-130 (1976). DOI: 10.1086/182105
2. Woosley, S. E. and Taam, R. E. γ-ray bursts from thermonuclear explosions on neutron stars. *Nature 263*(5573), 101-103 (1976). DOI: 10.1038/263101a0
3. Maraschi, L. and Cavaliere, A. X-Ray Bursts of Nuclear Origin? In *Highlights of Astronomy Vol. 4 Issue 1* (Reidel, 1977). https://doi.org/10.1017/S1539299600002483
4. Lewin, W. H. G. et al. X-Ray Bursts. *Space Sci. Rev. 62*(3-4), 223-389 (1993). DOI: 10.1007/bf00196124
5. Galloway, D. K. et al. Thermonuclear (Type 1) X-Ray Bursts Observed by the Rossi X-Ray Timing Explorer. *ApJS 179*(2), 360-422 (2008). DOI: 10.1086/592044
6. Galloway, D.K. et al. The Multi-Instrument Burst Archive. *ApJS 249*(2), 1-105 (2020). DOI: 10.3847/1538-4365/ab9f2e
7. Schatz, H. et al. End Point of the rp Process on Accreting Neutron Stars. *PRL 86*(16), 3471-3474 (2001). DOI: 10.1103/PhysRevLett.86.3471
8. Parikh, A. et al. Classical novae and type 1 X-ray bursts: Challenges for the 21st century. *AIP Advances 4*(4), 1-40 (2014). DOI: 10.1063/1.4863946
9. Cumming, A. and Bildsten, L. Carbon Flashes in the Heavy-Element Ocean on Accreting Neutron Stars. *ApJ 559*(2), 127-130 (2001). DOI: 10.1086/323937
10. Strohmayer, T. E. and Brown, E. F. A Remarkable 3 Hour Thermonuclear Burst from 4U. *ApJ 566*(2), 1045-1059 (2002). DOI: 10.1086/338337
11. Shklovskii, I. S. On the Nature of the Source of X-Ray Emission of Sco XR-1. *ApJ 148*(1), 1-4 (1967). DOI: 10.1086/180001
12. Belian, R.D., Conner, J. P. and Evans, W. D. A Probable Precursor to the X-Ray Nova Centaurus XR-4. *ApJ 171*, 87-90 (1972). DOI: 10.1086/180874
13. Belian, R. D., Conner, J. P. and Evans, W. D. The discovery of X-ray bursts from a region in the constellation Norma. *ApJ 206*, 135-138 (1976).
14. Hoffman, J. A. et al. SAS 3 observations of two X-ray transient events with precursors. *ApJ 221*, 57-62 (1978). DOI: 10.1086/182664
15. Joss, P. C. X-ray bursts and neutron-star thermonuclear flashes. *Nature 270*(5635), 310-314 (1977). DOI: 10.1038/270310a0
16. Lewin, W. H. G. et al. The discovery of rapidly repetitive X-ray bursts from a new source in Scorpius. *ApJ 207*, 95-99 (1976). DOI: 10.1086/182188
17. Van Paradijs, J. and Verbunt, F. A comparison of soft X-ray transients and dwarf novae. *AIP Conference Proceedings 115*, 149-162 (1984).
18. Lewin, W. H. G., Vacca, W. D. and Basinska, E. M. Precursors to X-ray burst: the result of expansion and subsequent contraction of the neutron star's photosphere. *ApJ 277*, 57-60 (1984). DOI: 10.1086/184202
19. Kuulkers, E. et al. Photospheric radius expansion X-ray bursts as standard candles. *A&A 399*, 663-680 (2003). DOI: 10.1051/0004-6361:20021781
20. Giacconi, R., Gursky, H., Kellogg, E., Schreier, E. and Tanabaum, H. Discovery of Periodic X-Ray Pulsations in Centaurus X-3 from UHURU. *ApJ 167*, 67-73 (1971). DOI: 10.1086/180762
21. Pravdo, S. H. et al. HEAO 1 observations of the X-ray pulsar 4U 1626-67. *ApJ 231*, 912-918 (1979). DOI: 10.1086/157254
22. Parmar, A. N., White, N. E., Gilmmi, P. and Gottwald, M. The Discovery of 3.8 Hour Periodic Intensity Dips and Eclipses from the Transient Low-Mass X-Ray Binary EXO 0748-676. *ApJ 308*, 199-212 (1986). DOI: 10.1086/164490
23. Bildsten, L. Thermonuclear Burning on Rapidly Accreting Neutron Stars. In *The Many Faces of Neutron Stars Vol. 515* (Kluwer Academic, 1998). DOI: 10.48550/arXiv.astro-ph/9709094
24. Cornelisse, R., Heise, J., Kuulkers, E., Verbunt, F. and in'tZand, J. J. M. The longest thermonuclear X-ray burst ever observed? A BeppoSAX Wide Field Camera observation. *A&A 357*, 21-24 (2000). DOI: 10.48550/arXiv.astro-ph/0003454
25. In 't Zand, J. J. M. et al. The first outburst of SAX J1818.4-3658 revisited. A*&A 372*, 916-921 (2001). DOI: 10.1051/0004-6361:20010546

26. Strohmayer, T. E. et al. Millisecond X-Ray Variability from an Accreting Neutron Star System. *ApJ 469*, 9-12 (1996). DOI: 10.1086/310261
27. Chelovekov, I. V., Grebenev, S. A. and Sunyaev, R. A. Hard X-ray bursts detected by the IBIS-telescope onboard the INTEGRAL observatory in 2003-2004. *Astron. Lett. 32*, 456-477 (2006). DOI: 10.1134/S1063773706070025
28. Chelovekov, I. V., Grebenev, S. A., Mereminskiy, I. A. and Prosvetov, A. V. Type 1 X-ray Bursts Detected by the JEM-X Telescope Onboard the INTEGRAL observatory in 2003-2015. *Astron. Lett. 43*, 781-795 (2017). DOI: 10.1134/S1063773717120076
29. Chelovekov, I. V. and Grebenev, S. A. Detection of the first thermonuclear X-ray burst from AXJ1754.2 -2754. *Astron. Lett. 33*, 807-813 (2007). DOI: 10.1134/S1063773707120043
30. Chelovekov, I. V. and Grebenev, S. A. Investigation of the transient X-ray burster IGR J17380-3749 discovered by the INTEGRAL observatory. *Astron. Lett. 36*, 895-903 (2010). DOI: 10.1134/S1063773710120030
31. Krimm, H. A. et al. THE *SWIFT*/BAT HARD X-RAY TRANSIENT MONITOR. *ApJS 209*(14), 1-33 (2013). DOI: 10.1088/0067-0049/209/1/14
32. Grebenev, S.A. and Chelovekov, I.V. Single X-ray Bursts and the Model of a Spreading Layer of Accreting Matter over the Neutron Star Surface. *Astron. Lett. 44*, 777-781 (2018). DOI: 10.1134/S1063773718120083
33. Riley, T. E. et al. A NICER View of the Massive Pulsar PSR J0740+6620 Informed by Radio Timing and XMM-Newton Spectroscopy. *ApJL 918*(2), 27-57 (2021). DOI: 10.3847/2041-8213/ac0a81
34. Gottwald, N., Haberi, F., Parmar, A. N. and White, N. E. THE BURSTING BEHAVIOR OF THE TRANSIENT X-RAY BURST SOURCE EXO 0748-676: A DEPENDENCE BETWEEN THE X-RAY BURST PROPERTIES AND THE STRENGTH OF THE PERSISTENT EMISSION. *ApJ 308*, 213-224 (1986). DOI: 10.1086/164491
35. Cornelisse, R. et al. Six years of BeppoSAX Wide Field Cameras observations of nine galactic type I X-ray bursters. *A&A 405*(3), 1033-1042 (2003). DOI: 10.1051/0004-6361:20030629
36. Chelovekov, I. V. and Grebenev, S. A. Hard X-ray bursts recorded by the IBIS telescope of the INTEGRAL observatory in 2003-2009. *Astron. Lett. 37*, 597-620 (2011). DOI: 10.1134/S0320010811090026
37. Chelovekov, I. V., Lutovinov, A. A., Grebenev, S. A. and Sunyaev, R. A. Observations of the X-ray Burster MX 0836-42 by the INTEGRAL and RXTE Orbiting Observatories. *Astron. Lett. 31*, 681-694 (1998). DOI: 10.1134/1.2075311
38. Watts, A. L. Thermonuclear Burst Oscillations. *ARA&A 50*, 609-640 (2012). DOI: 10.1146/annurev-astro-040312-132617
39. Bilous, A. V. and Watts, A. L. A Uniform Search for Thermonuclear Burst Oscillations in the RXTE Legacy Data Set. *ApJSS 245*(1), 19-60 (2019). DOI: 10.3847/1538-4365/ab2fe1
40. Fujimoto, M. Y., Hanawa, T. and Miyaji, S. Shell flashes on accreting neutron stars and X-ray bursts. *ApJ 247*, 267-278 (1981). DOI: 10.1086/159034
41. Ebisuzaki, T., Hanawa, T. and Sugimoto, D. Mass Loss from the Neutron Stars Associated with X-Ray Bursts. *PASJ 35*(1), 17-32 (1983).
42. Van Paradijs, J. Possible observational constraints on the mass-radius relation of neutron stars. *ApJ 234*, 609-611 (1979). DOI: 10.1086/157535
43. Damen, E. et al. X-ray bursts with photospheric radius expansion and the gravitational redshift of neutron stars. *A&A 237*, 103-109 (1990).
44. Taam, R. E. and Lin, D. N. C. The evolution of the inner regions of viscous accretion disks surrounding neutron stars. *ApJ 287*, 761-768 (1984). DOI: 10.1086/162734
45. In 't Zand, J. J. M., Cumming, A., Van der Sluys, M. V., Verbunt, F. and Pols, O. R. On the possibility of a helium white dwarf donor in the presumed ultracompact binary 2S 0918-549. *A&A 441*, 675-684 (2005). DOI: 10.1051/0004-6361:20053002
46. Keek, L., Galloway, D. K., In'tZand, J. J. M. and Heger, A. MULTI-INSTRUMENT X-RAY OBSERVATIONS OF THERMONUCLEAR BURSTS WITH SHORT RECURRENCE TIMES. *ApJ 718*, 292-305 (2010). DOI: 10.1088/0004-637x/718/1/292
47. Grebenev, S.A. and Chelovekov, I.V. Multiple X-ray bursts and the model of a spreading layer of accreting matter over the neutron star surface. *Astron. Lett. 43*, 583-594 (2017). DOI: 10.1134/S106377371709002X
48. Van Paradijs, J. et al. A unique triple-peaked type-1 X-ray burst from 4U/MXB 1636–53. *MNRAS 221*(3), 617-623 (1986). DOI: 10.1093/mnras/221.3.617
49. Schatz, H. and Rehm, K. E. X-ray binaries. *Nucl. Phys. A 777*, 601-622 (2006). DOI: 10.1016/j.nuclphysa.2005.05.200
50. Wallace, R. K. and Woosley, S. E. Explosive hydrogen burning. *ApJS 45*, 389-420 (1981). DOI: 10.1086/190717
51. Molkov, S. V., grebenev, S. A. and Lutovinov, A. A. An X-ray burst with strong photospheric radius expansion observed from the source 4U1724−307 in Terzan2. *A&A 357*, 1-4 (2000). DOI: 10.48550/arXiv.astro-ph/0005082
52. Kippenhahn, R. and Weigert, A. *Stellar Structure and Evolution* (Springer-Verlag, 1990). DOI: 10.1007/978-3-642-61523-8
53. Schatz, H. et al. rp-process nucleosynthesis at extreme temperature and density conditions. *Phys. Rep. 294*(4), 167-263 (1998). DOI: 10.1016/S0370-1573(97)00048-3
54. Fisker, J., Schatz, H. and Thielemann, F. EXPLOSIVE HYDROGEN BURNING DURING TYPE I X-RAY BURSTS. *ApJS 174*(1), 261-276 (2008). DOI: 10.1086/521104
55. Özel, F. and Psaltis, D. STATISTICS OF MEASURING NEUTRON STAR RADII: ASSESSING A FREQUENTIST AND A BAYESIAN APPROACH. *ApJ 810*(1), 135-142 (2015). DOI: 10.1088/0004-637x/810/2/135
56. Suleimanov, V. F., Klochkov, D., Poutanen, J., and Werner, K. Probing the possibility of hotspots on the central neutron star in HESS J1731−347. *A&A 600*, 43-50 (2017). DOI: 10.1051/0004-6361/201630028

57. Schatz, H., Bildsten, L. and Cumming, A. PHOTODISINTEGRATION-TRIGGERED NUCLEAR ENERGY RELEASE IN SUPERBURSTS. *ApJ 583*, 87-90 (2003). DOI: 10.1086/368107
58. Cumming, A. and Macbeth, J. The Thermal Evolution following a Superburst on an Accreting Neutron Star. *ApJ 603*(1), 37-40 (2004). DOI: 10.1086/382873
59. Gasques, L.R. et al. Nuclear fusion in dense matter: Reaction rate and carbon burning. *PhysRevC 72*(2): 025806 (2005). DOI: 10.1103/PhysRevC.72.025806
60. Keek, L. and Heger, A. MULTI-ZONE MODELS OF SUPERBURSTS FROM ACCRETING NEUTRON STARS. *ApJ 743*(2), 189-203 (2011). DOI: 10.1088/0004-637x/743/2/189
61. Woosley, S. E. et al. MODELS FOR TYPE I X-RAY BURSTS WITH IMPROVED NUCLEAR PHYSICS. *ApJS 151*(1), 75-102 (2004). DOI: 10.1086/381533
62. Spitkovsky, A., Levin, Y. and Ushomirsky, G. PROPAGATION OF THERMONUCLEAR FLAMES ON RAPIDLY ROTATING NEUTRON STARS: EXTREME WEATHER DURING TYPE I X-RAY BURSTS. *ApJ 566*(2), 1018-1038 (2002). DOI: 10.1086/338040
63. Heger, A., Cumming, A. and Woolsey, S. E. MILLIHERTZ QUASI-PERIODIC OSCILLATIONS FROM MARGINALLY STABLE NUCLEAR BURNING ON AN ACCRETING NEUTRON STAR. *ApJ 665*(2), 1311-1320 (2007). DOI: 10.1086/517491
64. Peng, F., Brown, E. and Truran, J. SEDIMENTATION AND TYPE I X-RAY BURSTS AT LOW ACCRETION RATES. *ApJ 654*(2), 1022-1035 (2007). DOI: 10.1086/509628
65. Cooper, R. L. and Narayan, R. HYDROGEN-TRIGGERED TYPE I X-RAY BURSTS IN A TWO-ZONE MODEL. *ApJ 661*(1), 468-476 (2007). DOI: 10.1086/513461
66. In 't Zand, J. J. M., Cornelisse, R. and Cumming, A. Superbursts at near-Eddington mass accretion rates. *A&A 426*, 257-265 (2004). DOI: 10.1051/0004-6361:20040522
67. Cumming, A., Macbeth, J., in'tZand, J. J. M. and Page, D. LONG TYPE I X-RAY BURSTS AND NEUTRON STAR INTERIOR PHYSICS. *ApJ 646*(1), 429-451 (2006). DOI: 10.1086/504698
68. Lewin, W. H. G., van Paradijs, J. and van den Heuvel, E. P. J. *X-ray binaries* (Cambridge Univ. press, 1995).
69. Bagnoli, T., in'tZand, J. J. M., D'Angelo, C. R. and Galloway, D. K. A population study of type II bursts in the Rapid Burster. *MNRAS 449*(1), 268-287 (2015). DOI: 10.1093/mnras/stv330
70. Lubin, L. M. et al. A new kind of oscillation in the persistent emission of the Rapid Burster. *MNRAS 258*(4), 759-772 (1992). DOI: 10.1093/mnras/258.4.759
71. Masetti, N. et al. Hard X-rays from Type II bursts of the Rapid Burster and its transition toward quiescence. *A&A 363*, 188-198 (2000). DOI: 10.48550/arXiv.astro-ph/0009044
72. Worpel, H., Galloway, D. K. and Price, D. J. EVIDENCE FOR ACCRETION RATE CHANGE DURING TYPE I X-RAY BURSTS. *ApJ 772*, 94-107 (2013). DOI: 10.1088/0004-637X/772/2/94
73. Sala, G. et al. CONSTRAINTS ON THE MASS AND RADIUS OF THE ACCRETING NEUTRON STAR IN THE RAPID BURSTER. *ApJ 752*(2), 158-164 (2012). DOI: 10.1088/0004-637X/752/2/158
74. Spruit, H. C. and Taam, R. E. An Instability Associated with a Magnetosphere-Disk Interaction. *ApJ 402*, 593-604 (1993). DOI: 10.1086/172162
75. D'Angelo, C. R. and Spruit, H. C. Episodic Accretion on to Strongly Magnetic Stars. *MNRAS 406*, 1208-1220 (2010). DOI: 10.1111/j.1365-2966.2010.16749.x
76. Illarionov, A. F. and Sunyaev, R. A. Why the Number of Galactic X-ray Stars Is so Small? *A&A 39*, 185-195 (1975).
77. Lightman, A. P. and Eardley, D. M. Black Holes in Binary Systems: Instability of Disk Accretion. *ApJ 187*, 1-3 (1974). DOI: 10.1086/181377
78. Eardley, D. M. and Lightman, A. P. Magnetic viscosity in relativistic accretion disks. *ApJ 200*(1), 187-203 (1975). DOI: 10.1086/153777
79. Lasota, J.-P. The disc instability model of dwarf novae and low-mass X-ray binary transients. *New Astron. Rev. 45*(7), 449-508 (2001). DOI: 10.1016/s1387-6473(01)00112-9
80. Hameury, J.-M. et al. Accretion disc outbursts: a new version of an old model. *MNRAS 298*, 1048-1060 (1998). DOI: 10.1046/j.1365-8711.1998.01773.x
81. Romanova, M. M., Ustyugova G. V., Koldoba, A. V. and Lovelace, R. V. E. THREE-DIMENSIONAL SIMULATIONS OF DISK ACCRETION TO AN INCLINED DIPOLE. II. HOT SPOTS AND VARIABILITY. *ApJ 610*(2), 920-932 (2014). DOI: 10.1086/421867.
82. Kulkarni, A. K. and Romanova, M. M. Accretion to Magnetized Stars through the Rayleigh-Taylor Instability: Global Three-Dimensional Simulations. *MNRAS 386*, 673-688 (2008). DOI: 10.1111/j.1365-2966.2008.13094.x
83. Uzdensky, D. A. PARTIAL FIELD OPENING AND CURRENT SHEET FORMATION IN THE DISK MAGNETOSPHERE. *ApJ 52*(1), 432-444 (2002). DOI: 10.1086/340308
84. D'Angelo, C. R. and Spruit, H. C. Accretion discs trapped near corotation. *MNRAS 420*(1), 416-429 (2011). DOI: 10.1111/j.1365-2966.2011.20046.x
85. Muno, M. P., Fox, D. W., Morgan, E. H. and Bildsten, L. NEARLY COHERENT OSCILLATIONS IN TYPE I X-RAY BURSTS FROM KS 1731-260. *ApJ 542*(2), 1016-1033 (2000). DOI: 10.1086/317031
86. Lewin, M. and Van Der Klis, M. eds. *Compact Stellar X-ray Sources* (Cambridge Univ. press, 2006). DOI: 10.1017/CBO9780511536281

87. In 't Zand, J. J. M., Galloway, D. K. and Ballantyne, D. R. Achromatic late-time variability in thermonuclear X-ray bursts An accretion disk disrupted by a nova-like shell? *A&A 525*, 111-117 (2011). DOI: 10.1051/0004-6361/201015556
88. Ballantyne, D. R. and Strohmayer, T. E. THE EVOLUTION OF THE ACCRETION DISK AROUND 4U 1820 30 DURING A SUPERBURST. *ApJ 602*(2), 105-108 (2004). DOI: 10.1086/382703
89. Keek, L., Ballantyne, D. R., Kuulkers, E. and Strohmayer, T. E. X-RAYING AN ACCRETION DISK IN REALTIME: THE EVOLUTION OF IONIZED REFLECTION DURING A SUPERBURST FROM 4U 1636–536. *ApJ 797*(2), 23-27 (2014). DOI: 10.1088/2041-8205/797/2/L23
90. Worpel, H., Galloway, D. K. and Price, D. J. EVIDENCE FOR ENHANCED PERSISTENT EMISSION DURING SUB-EDDINGTON THERMONUCLEAR BURSTS. *ApJ 801*(1), 60-73 (2015). DOI: 10.1088/0004-637x/801/1/60
91. Chenevez, J. et al. A SOFT X-RAY SPECTRAL EPISODE FOR THE CLOCKED BURSTER, GS 1826–24 AS MEASURED BY SWIFT AND NuSTAR. *ApJ 818*(2), 135-146 (2016). DOI: 10.3847/0004-637x/818/2/135
92. Keek, L., Heger, A. and in'tZand, J. J. M. SUPERBURST MODELS FOR NEUTRON STARS WITH HYDROGEN-AND HELIUM-RICH ATMOSPHERES. *ApJ 752*(2), 150-162 (2012). DOI: 10.1088/0004-637X/752/2/150
93. Amthor, A. M. et al. Sensitivity of Type I X-Ray Bursts to rp-Process Reaction Rates. In *International Symposium on Nuclear Astrophysics- Nuclei in the Cosmos- IX*, Geneva, Switzerland (25-30 June 2006).
94. Cyburt, R. H. et al. DEPENDENCE OF X-RAY BURST MODELS ON NUCLEAR REACTION RATES. *ApJ 830*(2), 55-74 (2016). DOI: 10.3847/0004-637x/830/2/55
95. Meisel, Z., Merz, G. and Medvid, S. Influence of Nuclear Reaction Rate Uncertainties on Neutron Star Properties Extracted from X-Ray Burst Model–Observation Comparisons. *ApJ 872*(1), 84-101 (2019). DOI: 10.3847/1538-4357/aafede
96. Tan, W. P. et al. New Measurement of $^{12}C + ^{12}C$ Fusion Reaction at Astrophysical Energies. *PhRv 124*(19): 192702, (2020). DOI: 10.1103/PhysRevLett.124.192702
97. Parikh, A., Jose, J., Sala, G. and Iliadis, C. Nucleosynthesis in type I X-ray bursts. *Progress in Particle and Nuclear Physics 69*, 225-253 (2013). DOI: 10.1016/j.ppnp.2012.11.002
98. Iliadis, C., Longland, R., Champagne, A. E., Coc, A. and Fitzgerald, R. Charged-particle thermonuclear reaction rates: II. Tables and graphs of reaction rates and probability density functions. *Nucl. Phys. A 841*, 31-250 (2010). DOI: 10.1016/j.nuclphysa.2010.04.009
99. Meisel, Z. et al. Nuclear mass measurements map the structure of atomic nuclei and accreting neutron stars. *PhRvC 101*: 2801, (2020). DOI: 10.1103/PhysRevC.101.052801
100. Özel, F. and Freire, P. Masses, Radii, and Equation of State of Neutron Stars. *ARA&A 54*, 401-439 (2016). DOI: 10.1146/annurev-astro-081915-023322
101. Cottam, J., Paerels, F. and Mendez, M. Gravitationally redshifted absorption lines in the X-ray burst spectra of a neutron star. *Nature 420*, 51-54 (2002). DOI: 10.1038/nature01159
102. Suleimanov, V. Poutanen, J. and Werner, K. X-ray bursting neutron star atmosphere models: spectra and color corrections. *A&A 527*, 139-157 (2011). DOI: 10.1051/0004-6361/201015845
103. Miller, M. C. et al. PSR J0030+0451 Mass and Radius from NICER Data and Implications for the Properties of Neutron Star Matter. *ApJ 887*, 24-51 (2019). DOI: 10.3847/2041-8213/ab50c5
104. Raaijmakers, G. et al. Constraints on the Dense Matter Equation of State and Neutron Star Properties from NICER's Mass–Radius Estimate of PSR J0740+6620 and Multimessenger Observations. *ApJ 918*(2), 29-41 (2021). DOI: 10.3847/2041-8213/ac089a
105. Paczynski, B. Models of X-ray bursters with radius expansion. *ApJ 267*, 315-321 (1983). DOI: 10.1086/160870
106. Özel, F. Soft equations of state for neutron-star matter ruled out by EXO 0748 − 676. *Nature 441*, 1115-1117 (2006). DOI: 10.1038/nature04858
107. Suleimanov, V., Poutanen, J., Revnivtsev, M. and Werner, K. A NEUTRON STAR STIFF EQUATION OF STATE DERIVED FROM COOLING PHASES OF THE X-RAYBURSTER4 U1724−307. *ApJ 742*(2), 122-133 (2011). DOI: 10.1088/0004-637X/742/2/122
108. Nättilä, J. et al. Neutron star mass and radius measurements from atmospheric model fits to X-ray burst cooling tail spectra. *A&A 608*, 31-45 (2017). DOI: 10.1051/0004-6361/201731082
109. Poutanen, J. et al. The effect of accretion on the measurement of neutron star mass and radius in the low-mass X-ray binary 4U 1608−52. *MNRAS 442*(4), 3777-3790 (2014). DOI: 10.1093/mnras/stu1139
110. Rauch, T., Suleimanov, V. and Werner, K. Absorption features in the spectra of X-ray bursting neutron stars. *A&A 490*(3), 1127-1134 (2008). DOI: 10.1051/0004-6361:200810129
111. Lattimer, J. M. and Steiner, A. W. NEUTRON STAR MASSES AND RADII FROM QUIESCENT LOW-MASS X-RAY BINARIES. *ApJ 784*(2), 123-137 (2014). DOI: 10.1088/0004-637x/784/2/123
112. Steiner, A. W. et al. Constraining the mass and radius of neutron stars in globular clusters. *MNRAS 476*(1), 421-435 (2018). DOI: 10.1093/mnras/sty215
113. Lattimer, J. M. and Prakash, M. The equation of state of hot, dense matter and neutron stars. *Phys. Rep. 621*, 127-164 (2016). DOI: 10.1016/j.physrep.2015.12.005
114. Abbott, B. P. et al. GW170817: Measurements of Neutron Star Radii and Equation of State. *Phys. Rev. Lett. 121*, 161101-161110 (2018). DOI: 10.1103/physrevlett.121.161101
115. Riley, T. E. et al. A NICER View of PSR J0030+0451: Millisecond Pulsar Parameter Estimation. *ApJ 887(*1), 21-80 (2019). DOI: 10.3847/2041-8213/ab481c

116. Watts, A. L. et al. Colloquium: Measuring the neutron star equation of state using x-ray timing. *Rev. Mod. Phys. 88*(2): 021001, (2016). DOI: 10.1103/revmodphys.88.021001
117. Cavecchi, Y., Watts, A. I., Braithwaite, J. and Levin, Y. Flame propagation on the surfaces of rapidly rotating neutron stars during Type I X-ray bursts. *MNRAS 434*(4), 3526-3541 (2013). DOI: 10.1093/mnras/stt1273
118. Zingale, M. et al. HELIUM DETONATIONS ON NEUTRON STARS. *ApJS 133*(4), 195-220 (2001). DOI: 10.1086/319182
119. Cavecchi, Y., Levin, Y., Watts, A. L. and Braithwaite, J. Fast and slow magnetic deflagration fronts in type I X-ray bursts. *MNRAS 459*(2), 1259-1275 (2016). DOI: 10.1093/mnras/stw728
120. Johnston, Z, Heger, A. and Galloway, D. K. Simulating X-ray bursts during a transient accretion event. *MNRAS 477*(2), 2112-2118 (2018). DOI: 10.1093/mnras/sty757
121. In 't Zand, J. J. M. et al. Observatory science with eXTP. *Sci. China Phys. Mech. Astron*. 62(2): 29506, (2019). DOI: 10.1007/s11433-017-9186-1
122. Watts, A. L. et al. Dense matter with eXTP. *Sci. China Phys. Mech. Astron. 62*(2): 29503, (2019). DOI: 10.1007/s11433-017-9188-4
123. Meisel, Z. et al. Consistent Modeling of GS 1826-24 X-Ray Bursts for Multiple Accretion Rates Demonstrates the Possibility of Constraining rp-process Reaction Rates. *ApJ 860*(2), 147-154 (2018). DOI: 10.3847/1538-4357/aac3d3
124. Schatz, H. et al. Strong neutrino cooling by cycles of electron capture and β^- decay in neutron star crusts. *Nature 505*, 62-65 (2014). DOI: 10.1038/nature12757