Theory and Observations of Type I X-Ray Bursts from Neutron Stars

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Abstract. I review our understanding of the thermonuclear instabilities on accreting neutron stars that produce Type I X-Ray bursts. I emphasize those observational and theoretical aspects that should interest the broad audience of this meeting. The easily accessible timescales of the bursts (durations of tens of seconds and recurrence times of hours to days) allow for a very stringent comparison to theory. The largest discrepancy (which was found with EXOSAT observations) is the accretion rate dependence of the Type I burst properties. Bursts become less frequent and energetic as the global accretion rate ($\dot{M}$) increases, just the opposite of what the spherical theory predicts. I present a resolution of this issue by taking seriously the observed dependence of the burning area on $\dot{M}$, which implies that as $\dot{M}$ increases, the accretion rate per unit area decreases. This resurrects the unsolved problem of knowing where the freshly accreted material accumulates on the star, equally relevant to the likely signs of rotation during the bursts summarized by Swank at this meeting. I close by highlighting the Type I bursts from GS 1826-238 that were found with BeppoSAX and RXTE. Their energetics, recurrence times and temporal profiles clearly indicate that hydrogen is being burned during these bursts, most likely by the rapid-proton (rp) process.

I INTRODUCTION

The gravitational energy release from matter accreted onto a neutron star (NS) of mass $M$ and radius $R$ is $GMm_p/R \approx 200$ MeV per nucleon, much larger than that released from thermonuclear fusion ($E_{\text{nuc}} \approx 5$ MeV per nucleon when a solar mix goes to iron group elements). Hansen and Van Horn (1975) showed that the burning of the accumulated material in the NS atmosphere occurred in radially thin shells and so was susceptible to a thermal instability. Evidence of the instability came soon after with the discovery of recurrent Type I X-ray bursts from low accretion rate ($\dot{M} < 10^{-9} M_\odot \text{yr}^{-1}$) NSs. The successful association of the thermal instabilities found by Hansen & Van Horn (1975) with the X-ray bursts made a nice picture of a recurrent...
cycle that consists of fuel accumulation for several hours followed by a thermonuclear runaway that burns the fuel in $\sim 10 - 100$ seconds (see Lewin, van Paradijs and Taam 1995 for an overview and references). The observational quantity $\alpha$ (defined as the ratio of the time-averaged accretion luminosity to the time-averaged burst luminosity) is close to the value expected (i.e. $\alpha = (GM/R)/E_{\text{nuc}} \approx 40$) for a thermonuclear burst origin.

Though our basic understanding from 25 years ago is unchanged, we now know much more about how the thermal instability depends on $\dot{M}$, both theoretically and observationally. It is this comparison that I emphasize, as it provides many important lessons that are likely applicable to thin shell flashes on accreting white dwarfs (classical novae); where 100-1000 yr recurrence times prohibit such detailed comparisons. I focus solely on NSs accreting at $\dot{M} > 10^{-10} M_\odot$ yr$^{-1}$, which is appropriate for most persistently bright Low Mass X-ray Binaries (in particular the “Z” and “Atoll” sources of Hasinger & van der Klis 1989). These NSs are weakly magnetic, with $B < 10^{10}$G.

I start by reviewing the simplest aspects of the physics of the accumulation and ignition of the fresh fuel on the NS (leaning heavily on results from my Bildsten 1998 review article, to which I refer the reader for the complete set of original references). I then discuss the EXOSAT observations of the $\dot{M}$ dependence of the Type I X-Ray burst properties and speculate that a solution to these puzzles is possible if freshly accreted matter accumulates near the equator. This problem, as well as the observations of nearly coherent oscillations during the burst (summarized by Swank at this meeting) are the first good indicators of the breaking of spherical symmetry. I close with a detailed discussion of the Type I bursts from the binary GS 1826-234, which is a beautiful example of limit-cycle mixed hydrogen/helium burning.

## II ACCUMULATION, IGNITION, EXPLOSION

Once the freshly accreted hydrogen and helium has thermalized and become part of the “star”, it undergoes hydrostatic compression from the new material that is continuously piled on. The extreme gravity on the NS surface compresses the fresh fuel to ignition densities and temperatures within a few hours to days.\footnote{The physics of the compression and burning depends on the accretion rate per unit area, $\dot{m} \equiv \dot{M}/A_{\text{acc}}$, where $A_{\text{acc}}$ is the covered area of fresh material. I sometimes quote numbers for both $\dot{m}$ and $\dot{M}$. When I give $\dot{M}$, I have assumed $A_{\text{acc}} = 4\pi R^2 \approx 1.2 \times 10^{13}$ cm$^2$.} The short thermal time in the atmosphere (only $\sim 10$ s at the ignition location, $P \approx 10^{22} - 10^{23}$ erg cm$^{-3}$) compared to the time to accumulate the material (hours to days) makes the compression far from adiabatic. Indeed, the temperature contrast from the photosphere to the burning layer is a factor of ten; whereas the density contrast exceeds $10^4$.

The temperature exceeds $10^7$ K in most of the accumulating atmosphere, so that hydrogen burns via the CNO cycle and we can neglect the pp cycles.
At high temperatures \((T > 8 \times 10^7 \text{ K})\), the timescale for proton captures becomes shorter than the subsequent \(\beta\) decay lifetimes, even for the slowest \(^{14}\text{N}(p,\gamma)^{15}\text{O}\) reaction. The hydrogen then burns in the “hot” CNO cycle and is limited to \(5.8 \times 10^{15} Z_{\text{CNO}}\) ergs s\(^{-1}\), where \(Z_{\text{CNO}}\) is the mass fraction of CNO and is independent of temperature. The hydrogen burns this way in the accumulating phase when \(\dot{m} > 900\) g cm\(^{-2}\) s\(^{-1}\)(\(Z_{\text{CNO}}/0.01\))\(^{1/2}\) and is thermally stable. The amount of time it takes to burn the hydrogen is \(\approx (10^3/Z_{\text{CNO}})\) s, or about one day for solar metallicities. For lower \(\dot{m}\)’s, the hydrogen burning is thermally unstable and is the trigger for the Type I burst.

The slow hydrogen burning during the accumulation allows for a unique burning regime at high \(\dot{m}\)’s. This simultaneous H/He burning occurs when \(\dot{m} > (2 - 5) \times 10^3\) g cm\(^{-2}\) s\(^{-1}\)(\(Z_{\text{CNO}}/0.01\))\(^{13/18}\), as at these high rates the fluid element is compressed to helium ignition conditions long before the hydrogen is completely burned (Lamb and Lamb 1978, Taam and Picklum 1978). The strong temperature dependence of the helium burning rate (and lack of any weak interactions) leads to a strong thin-shell instability for temperatures \(T < 5 \times 10^8 \text{ K}\) and causes the Type I X-Ray burst for these \(\dot{m}\)’s. The critical condition of thin burning shells \((h \ll R)\) is true before burning and remains so even during the flash (when temperatures reach \(10^9\) K) as the large gravitational well on the neutron star requires temperatures of order \(10^{12}\) K for \(h \sim R\). Stable burning sets in at higher \(\dot{M}\)’s (comparable to the Eddington limit) when the helium burning temperature sensitivity finally becomes weaker than the cooling rate’s sensitivity (Ayasli & Joss 1982 and Taam, Woosley & Lamb 1996).

For solar metallicities, there is a narrow window of \(\dot{m}\)’s where the hydrogen is completely burned before the helium ignites. In this case, a pure helium shell accumulates underneath the hydrogen-burning shell until densities and pressures are reached for ignition of the pure helium layer. The recurrence times of these bursts must be longer than the time to burn all of the hydrogen, so pure helium flashes should have recurrence times in excess of a day and \(\alpha \approx 200\). To summarize, in order of increasing \(\dot{m}\), the regimes of unstable burning we expect to witness from NSs accreting at sub-Eddington rates \((\dot{m} < 10^5\) g cm\(^{-2}\) s\(^{-1}\)) are (Fujimoto, Hanawa & Miyaji 1981, Fushiki and Lamb 1987):

1. Mixed hydrogen and helium burning triggered by thermally unstable hydrogen ignition for \(\dot{m} < 900\) g cm\(^{-2}\) s\(^{-1}\) \((\dot{M} < 2 \times 10^{-10} M_\odot\) yr\(^{-1}\))
2. Pure helium shell ignition for \(900\) g cm\(^{-2}\) s\(^{-1}\) < \(\dot{m} < (2 - 5) \times 10^3\) g cm\(^{-2}\) s\(^{-1}\) following completion of hydrogen burning.
3. Mixed hydrogen and helium burning triggered by thermally unstable helium ignition for \(\dot{m} > (2 - 5) \times 10^3\) g cm\(^{-2}\) s\(^{-1}\) \((\dot{M} > 4.4 - 11.1 \times 10^{-10} M_\odot\) yr\(^{-1}\)).
The transition \( \dot{m} \)'s are for \( Z_{CNO} \approx 0.01 \). Reducing \( Z_{CNO} \) lowers the transition accretion rates and, more importantly, makes the \( \dot{m} \) range for pure helium ignition quite narrow. We now discuss what happens as the thermal instability develops into a burst and what observational differences are to be expected between a pure helium ignition and a mixed hydrogen/helium ignition.

The flash occurs at fixed pressure, and the increasing temperature eventually allows the radiation pressure to dominate. For an ignition column of \( 10^8 \text{ g cm}^{-2} \), the pressure is \( P = gy \approx 10^{22} \text{ ergs cm}^{-3} \), so \( aT_{\text{max}}^4/3 \approx P \) gives a maximum temperature \( T_{\text{max}} \approx 1.5 \times 10^9 \text{ K} \). For pure helium flashes, the fuel rapidly burns (since there are no limiting weak interactions) and the local Eddington limit is often exceeded, leading to a radius expansion burst and a duration set mostly by the time it takes the heat to escape, \( \sim 5 - 10 \) seconds.

When hydrogen and helium are both present, the high temperatures reached during the thermal instability easily produces elements far beyond the iron group (Hanawa et al. 1983; Wallace & Woosley 1984; Hanawa and Fujimoto 1984) via the rapid-proton (rp) process of Wallace and Woosley (1981). This burning starts a few seconds after the initial helium flash (see Hanawa and Fujimoto 1984 for an illuminating example) that makes new seed nuclei and increases the temperature. The rp process burns hydrogen by successive proton captures and \( \beta \) decays. The seed nuclei move up the proton-rich side of the valley of stability (much like the r-process which occurs by neutron captures on the neutron rich side) more or less limited by the \( \beta \)-decay rates. Theoretical work shows that the end-point of this time-dependent burning is at elements far heavier than iron (Hanawa and Fujimoto 1984, Schatz et al. 1997, Koike et al. 1999). The long series of \( \beta \) decays allows for energy release 10-100 seconds after the burst has started. We thus expect a mixed hydrogen/helium burst to last much longer than a pure helium burst.

### III OBSERVATIONS OF \( \dot{M} \) DEPENDENCIES

The 3.8 day orbit of EXOSAT was an excellent match for the long-term monitoring of the Type I bursters needed to reveal the dependence of their nuclear burning behavior on \( \dot{M} \). While in a particular burning regime, we expect that the time between bursts should decrease as \( \dot{M} \) increases since it takes less time to accumulate the critical amount of fuel at a higher \( \dot{M} \). Exactly the opposite behavior was observed from many low accretion rate (\( \dot{M} < 10^{-9} \dot{M}_\odot \text{ yr}^{-1} \)) NSs. A particularly good example is 4U 1705-44, where the recurrence time increased by a factor of \( \approx 4 \) when \( \dot{M} \) increased by a factor of \( \approx 3 \).

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2) In steady-state burning at \( \dot{M} > 10^{-8} \dot{M}_\odot \text{ yr}^{-1} \) Schatz et al. (1999) showed that the rp-process burns all of the hydrogen and ends at nuclei with \( A \) near 100.

3) I hope that the equally well-matched Chandra and XMM satellites will devote as much time to Type I bursters. As I will make clear from this discussion, detailed spectroscopy during the bursts would be very informative.
of \( \approx 2 \) (Langmeier et al. 1987, Gottwald et al. 1989). If the star is accreting matter with \( Z_{CNO} = 10^{-2} \) then these accretion rates are at the boundary between unstable helium ignition in a hydrogen-rich environment at high \( \dot{M} \) and unstable pure helium ignition at lower \( \dot{M} \). The expected change in burst behavior as \( \dot{M} \) increases would then be to more energetic and more frequent bursts. This was not observed.

Other NSs showed similar behavior. van Paradijs, Penninx & Lewin (1988) tabulated this effect for many bursters and concluded that increasing amounts of fuel are consumed in a less visible way than Type I X-ray bursts as \( \dot{M} \) increases. The following trends were always found as \( \dot{M} \) increases:

- The recurrence time increases from 2-4 hours to > day.
- The bursts burn less of the accumulated fuel, with \( \alpha \) increasing from \( \approx 40 \) to \( > 100 \) (see top panel of Figure 1).
- The duration of the bursts decrease from \( \approx 30 \) s to \( \sim 5 \) s.

The low \( \dot{M} \) bursts look like mixed hydrogen/helium burning (namely, energetic and of long duration from the rp-process) whereas the high \( \dot{M} \) bursts look like pure helium burning (not so energetic, recurrence times typically long enough to have burned the hydrogen to helium before the burst and short duration due to the lack of any weak interactions). The simplest explanation would be to say that the NS has transitioned from the low \( \dot{M} \) mixed burning regime (noted as 1 in §II) to the higher \( \dot{M} \) pure helium burning (noted as 2 in §II). For this to be true, these NSs should be accreting at \( \dot{M} \approx (3 - 30) \times 10^{-10} \, M_\odot \, yr^{-1} \), at least a factor of three (and typically more) higher than the calculated rate where such a transition should occur. Moreover, if the accretion rates were as low as needed, the recurrence times for the mixed hydrogen/helium burning would be about 30 hours, rather than the observed 2-4 hours. Fujimoto et al. (1987) discussed in some detail the challenges these observations present to a spherically symmetric model, while Bildsten (1995) attempted to resolve this by having much of the thermally unstable burning occur via slow deflagration fronts that do not lead to Type I bursts, but rather slow hour-long flares.

Another comparably embarrassing conundrum is the lack of regular bursting from the six “Z” sources (Sco X-1, Cyg X-2, GX 5-1, GX 17+2, GX 340+0, GX 349+2) which are accreting at \( 3 \times 10^{-9} - 2 \times 10^{-8} \, M_\odot \, yr^{-1} \). These NSs very rarely show Type I bursts, and when they do, they are so infrequent that the resulting \( \alpha \) values are usually \( > 10^3 \) (see Kuulkers et al. 1997 and Smale.
FIGURE 1. Properties of the Type I X-ray bursts from EXO 0748-676 from Gottwald et al. (1986). The value of $\alpha$ (top panel) and the apparent black-body radius ($R_{\text{app}}$ for $d = 10$ kpc) in the tail of the burst, are shown as a function of the persistent X-ray flux, $F_x = L_x / 4\pi d^2$. The solid squares denote those that are well measured (for some of these, the $\alpha$ parameters and $R_{\text{app}}$ are lower limits; see Gottwald et al. 1986). The hatched region is where burst properties cluster at low $F_x$. The lower (upper) solid line on the bottom panel denotes where the accretion rate per unit area is constant at $\dot{m} = 8.3 \times 10^3 \text{ g cm}^{-2} \text{ s}^{-1}$ ($\dot{m} = 3.7 \times 10^3 \text{ g cm}^{-2} \text{ s}^{-1}$). The arrow points in the direction of increasing $\dot{m}$.

1998 for examples and discussions). In other words, these bursts are clearly not responsible for burning all of the accreted fuel, whereas theory clearly says that these objects should be burning nearly all of their fuel unstably in the mixed hydrogen/helium regime (noted as 3 above). The same mystery holds for the Atoll sources with $\dot{M} \sim 10^{-9}M_\odot \text{ yr}^{-1}$ (GX 3+1, GX 13+1, GX 9+1 and GX 9+9), which at best are infrequent bursters.

IV ACCUMULATION IN THE EQUATOR?

Many of these puzzles are resolved by relaxing our spherical symmetry presumption and allowing the fresh material to only cover a fraction of the star prior to igniting. There are observational hints that this is happening, as the other clear trend (in addition to those noted in the previous section) found by EXOSAT was an increase in the apparent black-body radius ($R_{\text{app}}$) as $\dot{M}$ increased (see bottom panel in Figure 1). This parameter is found by spectral fitting in the decaying tail of the Type I bursts and is susceptible to absolute spectral corrections (see discussion in Lewin, van Paradijs and Taam 1995) that will hopefully be resolved with XMM observations. In a similar vein, van der Klis et al. (1990) found that the temperature of the burst at the moment
when the flux was one-tenth the Eddington limit decreased as $\dot{M}$ increased (hence a larger area) for the Atoll source 4U 1636-53. In total, these observations raise the distinct possibility that the covered area increases enough with increasing $\dot{M}$ so that the accretion rate per unit area actually decreases.

By interpreting the measured $R_{\text{app}}$ as an indication of the fraction of the star that is covered by freshly accreted fuel, we can measure directly $\dot{m} = \dot{M}/4\pi R_{\text{app}}^2$, which is independent of the distance to the source, as $F_x = GM\dot{M}/4\pi d^2 R$ gives $\dot{m} \approx (F_x R/GM)(d/R_{\text{app}})^2$. The bottom panel of Figure 1 shows data for the burster EXO 0748-676. The lower (upper) solid lines are curves where the local accretion rate is constant at $\dot{m} = 8.3 \times 10^3$ g cm$^{-2}$ s$^{-1}$ ($\dot{m} = 3.7 \times 10^3$ g cm$^{-2}$ s$^{-1}$). The arrow points in the direction of increasing $\dot{m}$. The points at higher $\dot{M}$ (as inferred from $F_x$) tend to lie at comparable or slightly lower $\dot{m}$. The radius increase appears adequate to offset the $\dot{M}$ increase. In addition, for this source, the inferred values of $\dot{m}$ are in the range where the NS is transitioning from the mixed H/He burning at high $\dot{m}$ to the pure helium case at lower $\dot{m}$. More physically stated, the data point to the possibility that, as $\dot{M}$ increases, the area increases fast enough to allow the hydrogen to complete its burning before high enough pressures are reached for helium ignition. If such small covering areas persist to the higher $\dot{M}$’s of the Z sources, then their apparently stable nuclear burning is easily explained.

We know that these NSs accrete from a disk formed in the Roche lobe overflow of the stellar companion. However, there are still debates about the “final plunge” onto the NS surface. Some advocate that a magnetic field controls the final infall, while others prefer an accretion disk boundary layer. This is now an important issue to resolve, both for the reasons I have noted here as well as for the oscillations seen during the bursts. If material is placed in the equatorial belt, it is not clear that it will stay there very long. If angular momentum was not an issue, the lighter accreted fuel (relative to the ashes) would cover the whole star quickly. However, on these rapidly rotating neutron stars, the fresh matter added at the equator must lose angular momentum to get to the pole. This competition (namely understanding the spreading of a lighter fluid on a rotating star) has just been recently investigated by Inogamov and Sunyaev (1999), to which I refer the interested reader.

V AN EXAMPLE OF MIXED H/HE BURSTS

Despite the complications I discussed in the previous sections, there are times when Type I bursters behave in a near limit cycle manner, with bursts occurring nearly periodically as $\dot{m}$ apparently stays at a fixed value for a long time. The most recent (and beautiful!) example of such a Type I burster is GS 1826-238. Ubertini et al. (1999) show that during 2.5 years of monitoring with the BeppoSAX Wide Field Camera, 70 bursts were detected from this ob-
The type I bursts from this source are a “textbook” case for the mixed hydrogen/helium burning expected at these accretion rates. The estimated $\dot{m}$ gives an accumulated column on the NS prior to the burst of $1.6 \times 10^8 \text{ g cm}^{-2}$, just what is expected from theory. These quasi-periodic bursts allow for a very secure measurement of $\alpha \approx 50$, which implies a nuclear energy release of 4 MeV per accreted nucleon for a $1.4M_\odot$, 10 km NS. Energy releases this large can only come about via hydrogen burning and the long (> 100s) duration of the bursts are consistent with the expected long-time energy release from the rp-process. Figure 2 shows the time profile of such a burst seen with RXTE (Kong et al. 2000) in a few different energy bands. Though these data were taken to study the optical reprocessing (top panel is the simultaneous optical burst), they provide an important confirmation of the delayed energy release expected when hydrogen is burning via an rp-process. The resemblance of these profiles to Hanawa and Fujimoto’s (1984) theoretical results are striking.

The upcoming launch of the High Energy Transient Explorer should provide comparable long-term coverage as the Wide Field Camera on BeppoSAX and gather more information on such nice bursts from many more LMXB’s.
VI CONCLUSIONS

I hope I have made the case that Type I bursts from neutron stars are still very interesting to study in their own right and provide important lessons to those studying thin shell flashes in other astrophysical contexts. The detailed comparison provided by the neutron star systems is likely telling us to seriously consider the possibility and repercussions of fuel preferentially accumulating in the equatorial region. Another place where this might prove immediately applicable are the recurrent novae, where currently one infers high accretion rates and white dwarf masses in order to get the short recurrence times of 20-50 years (Livio 1994). These constraints are relaxed if we allow for a smaller covering fraction. I am not the first to say this, but hopefully the Type I burst observations make such a warning harder to ignore!

Jean Swank reviewed the observations of nearly coherent oscillations in the 300-600 Hertz range during many Type I bursts and so I will not summarize those results here. Though I am convinced that these modulations are intimately connected to rapid stellar rotation, there are still important unresolved questions. The ones that bother me most are:

1. What causes the asymmetry at late times in the burst, long after the peak?
2. Why does the modulation appear sometimes at twice the spin frequency?
3. How does the burning front really spread on a rapidly rotating star? Ignition at one spot is plausible, but we do not understand how the ignited/hot fuel spreads around a rapidly rotating star.

It is even an open question as to why, from a particular NS, only some bursts show these oscillations. Before any meaningful theoretical work can be carried out, what is needed is the phenomenology of the oscillations in the context of the well established burst phenomenology I have discussed here. My current mental tabulations point to a complete absence of oscillations during the long bursts (even during the long rise) indicative of mixed H/He burning. All reported detections of oscillations during bursts that I am aware of are from short duration, high $\alpha$ bursts.

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