AN UNUSUAL PRECURSOR BURST WITH OSCILLATIONS FROM SAX J1808.4–3658

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Received 2006 August 21; accepted 2006 October 20

ABSTRACT

We report the finding of an unusual, weak precursor to a thermonuclear X-ray burst from the accreting millisecond pulsar SAX J1808.4–3658. The burst in question was observed on 2002 October 19 with the Rossi X-Ray Timing Explorer Proportional Counter Array (RXTE PCA). The precursor began ≲1 s prior to the onset of a strong radius expansion burst, lasted for about 0.4 s, and exhibited strong oscillations at the 401 Hz spin frequency. Oscillations are not detected in the ≲0.5 s interval between the precursor and the main burst. The estimated peak photon flux and energy fluence of the precursor are about 1/25 and 1/500 that of the main burst, respectively. From joint spectral and temporal modeling, we find that an expanding burning region with a relatively low temperature on the spinning neutron star surface can explain the oscillations, as well as the faintness of the precursor with respect to the main part of the burst. We discuss some of the implications of our findings for the ignition and spreading of thermonuclear flames on neutron stars.

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1. INTRODUCTION

Four strong thermonuclear (type I) X-ray bursts were observed with the RXTE PCA from the accreting millisecond pulsar SAX J1808.4–3658 when this source was in outburst in 2002 (Chakrabarty et al. 2003). Such bursts are produced by thermonuclear burning of matter accumulated on the surfaces of accreting neutron stars (Woosley & Taam 1976; Lamb & Lamb 1978). All the bursts exhibited strong brightness oscillations near the known stellar spin frequency (∼401 Hz; Wijnands & van der Klis 1998), which confirmed that this timing feature originates near the neutron star surface. During the burst rise, an expanding burning region (hot spot) on the spinning stellar surface may give rise to these oscillations (Strohmayer et al. 1997; Miller & Lamb 1998; Nath et al. 2002), while during the burst decay (when the whole stellar surface may be engulfed by thermonuclear flames), the origin of this timing feature may be temperature variations due to surface waves (Heyl 2005; Lee & Strohmayer 2005; Cumming 2005; Pino & Bildsten 2006). Three of these bursts (October 15, 18, and 19) from SAX J1808.4–3658 exhibited strong oscillations during the intensity rise. Bhattacharyya & Strohmayer (2006c) found evidence for complex variation of the oscillation frequency during the rise of the October 15 and 18 bursts. The October 19 burst did not show evidence for similar variation, although the other properties of this burst were akin to those of the October 15 and 18 bursts.

Analysis of high time resolution light curves just prior to the bursts reveals a weak precursor event to the October 19 burst. To our knowledge this is the first report of such a precursor to a normal, hydrogen-helium powered thermonuclear burst. Several superbursts, which are likely powered by fusion of heavier elements (Strohmayer & Brown 2002; Cumming & Bildsten 2000; Schatz et al. 2001), have shown precursor events that have the characteristics of shorter, normal bursts. The precursor to the October 19 burst looks like a typical thermonuclear burst, except it lasts less than a second and has a peak photon flux only 1/25 of the main burst. Also unique is the fact that strong pulsations are detected during this precursor. The October 15 and 18 bursts do not show a similar precursor. In this paper we describe the properties of the precursor and discuss the implications for its size and oscillation content in the context of ignition and spreading of thermonuclear instabilities on neutron stars.

2. DATA ANALYSIS AND RESULTS

We analyzed the 2002 October 19 archival RXTE PCA data from SAX J1808.4–3658. During this observation the source was in outburst, and the data contain a thermonuclear X-ray burst, some of the properties of which were reported in Chakrabarty et al. (2003). We found an excess of intensity less than a second prior to the rise of this burst, which lasted for ≲0.5 s. Figure 1 shows the light curve of the burst at 1/16 s using a logarithmic intensity scale. The precursor is evident as the spike just prior to the rising edge of the main part of the burst. The precursor has a peak count rate of 2300 s−1 (1/16 s intervals, four PCUs), while the average persistent count rate prior to this feature was ∼640 s−1. This shows that the feature is significant. The rapid rise and slower decay of intensity during the precursor (see Fig. 2) is similar to that seen in most normal bursts, only the peak intensity and time-scale are smaller and shorter, respectively. The spectra of thermonuclear bursts can usually be modeled with a blackbody function (Strohmayer & Bildsten 2006). We therefore fitted the precursor spectrum (using 0.25 s of data) with an absorbed blackbody and found a temperature of 1.26±0.10 keV (reduced χ² ≈ 1.4, 28 degrees of freedom; see Fig. 2). The reduced χ² is acceptable and supports the idea that the precursor is indeed thermonuclear in origin.

Next, we searched for oscillations in the 0.3 s of event mode data (shown with dotted lines in Fig. 2) for which the precursor intensity was significantly above the persistent level. We computed a power spectrum with a Nyquist frequency of 2048 Hz and a frequency resolution of 3.3 Hz, and found a peak (power level ∼43.9) near the known stellar spin frequency ∼401 Hz (Fig. 3). As burst oscillation frequencies are not known to evolve by more than ∼6 Hz (Giles et al. 2002; Munro et al. 2002a; Bhattacharyya & Strohmayer 2005), considering the number of trials Ntrial = 2, we have a significance of 6.01 × 10−10, which implies a >6 σ
detection of oscillations during the precursor. The fractional rms amplitude for this 0.3 s interval is $A_1 = 0.375 \pm 0.068$ (reduced $\chi^2 = 7.0/13$ from fitting a constant+sinusoid model to the persistent emission-subtracted, phase-folded light curve), and no significant harmonic component was detected. This high amplitude and the comparatively broad peak in the power spectrum show that these oscillations originate from the precursor and are not accretion-powered pulsations. We also calculated dynamic $Z^2$ power spectra (Strohmayer & Markwardt 1999) and the corresponding power contours. Figure 2 shows that there are two sets of disconnected power contours: one during the precursor and another during the rise of the main burst. This shows that the oscillations during the precursor are unique to it and are not connected to the main burst.

Now two important questions are: (1) Why did the precursor occur about a second prior to the main burst, and (2) why was it so much fainter than the main burst? Note that this burst may not be considered as a single double-peaked nonphotospheric radius expansion (non-PRE) burst, because such bursts are always weak (i.e., sub-Eddington; Sztajno et al. 1985), while the main burst was a strong PRE burst. Therefore, sequential emissions from two different portions of the neutron star surface (Bhattacharyya & Strohmayer 2006a, 2006b) or a two-step energy generation due to convective mixing of the nuclear fuel (Fujimoto et al. 1988) probably cannot explain the precursor event. A two-step energy release might answer the first question. The second question may be addressed in the following way. Near the peak of the main burst, most of the neutron star surface is expected to emit near the Eddington temperature. Therefore, a smaller emission region and/or a lower temperature during the precursor would explain its faintness compared to the main burst. This might happen in three ways: (1) if the fuel for the precursor is confined to a small portion of the stellar surface (possibly by the magnetic field), and the burning region has a high temperature (the small hot spot can produce high-amplitude, spin-modulated pulsations); (2) if the thermonuclear flame spreads all over the stellar surface in $<0.1$ s at the onset of the precursor, and the whole surface emits at a low temperature (in such a case, surface modes might account for the oscillations; see 1); and (3) if the thermonuclear flame with an intermediate average temperature takes $\sim$0.2–0.3 s to spread (in this case, the expanding hot spot may give rise to the oscillations). Joint timing and spectral modeling can help us discriminate between these alternatives.

To be more specific about the joint analysis, let us first assume that the observed photon flux (after the subtraction of the persistent emission) in any time bin during a burst is $F$. Then we note that the ratio of $F$ near the peak of the main burst (the last time bin of the bottom panel of Fig. 2, hereafter bin 1) to $F$ during the precursor (the first bin of the bottom panel of Fig. 2, hereafter bin 2) is $25.1 \pm 1.5$ (the energy flux ratio is about 45 : 1). The corresponding observed blackbody temperatures during these bins are $T_{\text{obs,1}} = 2.94 \pm 0.13$ and $T_{\text{obs,2}} = 1.26^{+0.16}_{-0.14}$ keV (mentioned in the paper).
before), respectively. We also note that the fractional rms amplitude of oscillations during bin 2 is $A_2 = 0.403 \pm 0.071$. From our spectral modeling we also find that the precursor contained only $\approx 1/400$ of the energy in the main burst. Now for the joint modeling, assuming the stellar and other source parameter values, one needs to reproduce the oscillation amplitude $A_2$, and then, with the same parameter values (including the average burning region size), one needs to reproduce ratio from $T_{\text{obs,1}}$ and $T_{\text{obs,2}}$. We do this in § 3.2.

3. COMPARISON WITH MODELS

The primary aim of our modeling is to understand both the faintness of the precursor (relative to the peak of the burst) and the presence of high-amplitude brightness oscillations. In our simple model, we assume emission from a circular burning region (hot spot) on the rotating stellar surface (Bhattacharyya et al. 2005; see also some other works, e.g., Munu et al. 2002b; Miller & Lamb 1998; Cadeau et al. 2007; Braje et al. 2000; Poutanen & Gierliński 2004). Brightness oscillations occur as the image of the hot spot in the observer’s sky periodically changes with the stellar spin. The corresponding fractional rms amplitude ($A$) can be determined by fitting the phase-folded light curve (normalized to have the observed count rate). The total observed photon flux can also be computed from the blackbody spectrum for an assumed temperature. For these calculations, we combine the model with the appropriate instrument response matrix. Our model includes the following physical effects: (1) Doppler effect due to rapid stellar spin, (2) special relativistic beaming, and (3) gravitational redshift and light bending (assuming Schwarzschild spacetime). In our numerical calculations, we track the paths of photons in order to incorporate the light-bending effect in the calculated photon flux (Bhattacharyya et al. 2001). We use the following parameters in our model: (1) neutron star mass $M$ (in solar masses), (2) dimensionless stellar radius $R_c$—to mass ratio $R_c^2/GM$, (3) stellar spin frequency $\nu$ ($\approx 401$ Hz; § 1), (4) observer’s inclination angle $i$ measured from the upper rotational pole, (5) polar angle of the hot spot center $\theta_c$, (6) angular radius of the hot spot $\Delta \theta_c$, and (7) the blackbody temperature $T_{\text{BB}}$. For SAX J1808.4–3658, Li et al. (1999) and Bhattacharyya (2001) calculated constraints on $M$ and $R_c^2/GM$ (although they assumed that the stellar magnetic field is entirely dipolar). For example, if the lower limit of $R_c^2/GM$ is 4.0, the upper limit of $M$ is $\approx 1.4$ (eq. [6] of Bhattacharyya 2001). Here, for our illustrative model, we assume $M = 1.4$ and $R_c^2/GM = 4.0$ (i.e., radius $R \approx 8.3$ km). However, other values of $M$ and $R_c^2/GM$ in reasonable ranges do not alter our conclusions significantly. In our calculations, we mostly use $i = 60^\circ$, as this is the average value for a randomly oriented stellar spin axis. We use $i \approx 80^\circ$ as the upper limit, because of the absence of a deep eclipse indicates $i < 82^\circ$ (Chakrabarty & Morgan 1998). For a source distance $d = 3$ kpc, Wang et al. (2001) suggested $i \approx 20^\circ$–$65^\circ$ (with 90% confidence) based on the modeling of the X-ray and optical emission from SAX J1808.4–3658. A higher value of $d$ (3.4–3.6 kpc; Galloway & Cumming 2006) would shift this range of $i$ toward slightly smaller values. We therefore consider the case $i = 40^\circ$ in our joint spectral and timing modeling in § 3.2. We vary the other parameter values for our model calculations.

3.1. Inferences from Timing Data

Before conducting the joint spectral and timing modeling, we explore whether or not a hot spot model can reproduce the observed amplitude $A_1 = 0.375 \pm 0.068$ (§ 2) during the precursor. A burning region with $i = 60^\circ$, $\theta_c = 60^\circ$, $\Delta \theta = 60^\circ$, and the observed $T_{\text{BB}} = 1.26$ keV gives the amplitude $A = 0.364 \pm 0.048$, which is consistent with $A_1$. Here we note that the harmonic content of this model light curve cannot be significantly detected because of the small number of observed counts, consistent with the observations. Next, we change $T_{\text{BB}}$ to 1.0 keV, which does not alter $A = (0.372 \pm 0.048)$ much, and $i = 80^\circ$ can also reproduce $A_1$ for similar values of $\theta_c$, $\Delta \theta$, and $T_{\text{BB}}$. We note that $A$ increases with the increase of $i$ and $\theta_c$ (up to $\theta_c = 90^\circ$), and with the decrease of $\Delta \theta$. For example, keeping $i = 60^\circ$ and $T_{\text{BB}} = 1.26$ keV, if we change $\theta_c$ to 45$^\circ$, then to reproduce an $A = (0.354 \pm 0.048)$, which is consistent with $A_1$, $\Delta \theta$ has to be 5$^\circ$. This demonstrates two points: (1) for fixed values of other parameters and a lower limit on $\Delta \theta$ (such a lower limit should exist, as the burning region has to have a finite size; Spitkovsky et al. 2002), there is a lower limit on $\theta_c$; and (2) the size of the burning region cannot be meaningfully constrained from the lower side using the observed oscillation amplitude alone. However, this size can be constrained from the upper side, as $i = 80^\circ$ and $\theta_c = 90^\circ$ (which allows the near-maximum value of $\Delta \theta$ for a given oscillation amplitude $A_1$) give $\Delta \theta_{\text{max}} \approx 90^\circ$. Therefore, our modeling of the timing data shows that a hot spot that does not encompass most of the stellar surface can give rise to the observed oscillation amplitude.

3.2. Joint Spectral and Timing Inferences: An Illustration

For our joint modeling (last paragraph of § 2), we assume emission from the whole stellar surface during bin 1 (a time bin during the peak of the main burst; see § 2). This is because a smaller burning region would give rise to significant oscillations (which are not observed at this time) and would probably imply a super-Eddington luminosity. For this analysis, we consider the same values of $M$, $R_c^2/GM$, $\nu$, and $i$ (as mentioned earlier in this section), and vary the values of $\theta_c$ and $\Delta \theta$ for the precursor. However, for $T_{\text{BB}}$, we use the surface color temperature $T_{\text{eff}}$, which is related to the observed temperature $T_{\text{obs}}$ by $T_{\text{eff}} = T_{\text{obs}}(1 + z)$ [where the surface gravitational redshift $1 + z = (1 - 2GM/R_c^2)^{-1/2}$]. Moreover, due to spectral hardening in the neutron star atmosphere, the effective surface temperature ($T_{\text{eff}}$) is related to $T_{\text{eff}}$ by $T_{\text{eff}} = T_{\text{eff}}/f$, where the color factor $f$ is greater than 1 (London et al. 1984). Therefore, in order to calculate the observed photon flux, we use $(1/f^2)E_{\text{em}}(T_{\text{eff}})$ as the emitted specific intensity ([F & Taim 1990; Bhattacharyya et al. 2001]). Here, $B$ is the Planck function and $E_{\text{em}}$ is the energy of a photon in the emitter’s frame. Özel (2006) has recently suggested the following expression for $f$ (based on the model atmosphere calculations of Madej et al. 2004):

$$f = 1.34 + 0.25 \left(\frac{1 + X}{1.7}\right)^{2.2} \left[\frac{T_{\text{eff}}/10^7 \text{ K}}{g/10^{13} \text{ cm s}^{-2}}\right]^{2.2}.$$  

Here, the surface gravitational acceleration $g$ is given by $(GM/R^2)(1 - 2GM/Rc^2)^{-1/2}$, and $X$ is the hydrogen mass fraction. For our illustrative model, initially we assume the cosmic abundance $X = 0.7$ for both bin 1 and bin 2 (time bins from Fig. 2; see the last paragraph of § 2). However, we note that the change in the value of $X$ does not alter our timing results, as the oscillation amplitude does not depend on $f$, and hence on $X$. For our assumed values of the parameters, $f = 1.805$ ($T_{\text{eff},1} = 2.30$ keV; bin 1) and $1.344$ ($T_{\text{eff},2} = 1.33$ keV; bin 2). Here we note that, although $T_{\text{eff},1}$ is high, the corresponding luminosity is less than (but close to) the Eddington luminosity, which shows the consistency among our assumed parameter values.

Now we follow the procedure that is described in the last paragraph of § 2. First, we calculate the photon flux (for $f = 1.805$) for the emission from the whole stellar surface at the color temperature $T_c = 4.16$ keV (corresponding to $T_{\text{obs},1}$; bin 1).
Then we compute the oscillation amplitude $A$ and the photon flux for bin 2 using $T_{BB} = 1.78$ keV (i.e., $T_e$ corresponding to $T_{BB}$), $f = 1.344$, and various values of $i$, $\theta_e$, and $\Delta \theta$. For $i = 60^\circ$, $\theta_e = 65^\circ$, and $\Delta \theta = 55^\circ$, we find $A = 0.398 \pm 0.050$ and ratio $= 25.3$, which are consistent with $A_2$ and the observed value of ratio, respectively. These two observed parameter values can also be reproduced for $i = 80^\circ$ for slightly different values of $\theta_e$ and $\Delta \theta$. Moreover, for $i = 40^\circ$, $\theta_e = 110^\circ$, and $\Delta \theta = 67^\circ$, we get $A = 0.391 \pm 0.050$ and ratio $= 25.7$. These show that our simple hot spot model is consistent with the timing and the spectral data simultaneously, and the inferred size of the hot spot (i.e., burning region) is similar to that inferred in § 3.1. For $i = 60^\circ$, $\theta_e = 50^\circ$, and $\Delta \theta = 5^\circ$, $A = 0.378 \pm 0.050$ is consistent with $A_2$, but ratio $= 2504.3$ is widely different from the observed value. This shows that the spectral data do not allow a small hot spot for the precursor burst. In fact, for a variable $\theta_e$ and for $i = 60^\circ$ (and other assumed parameter values), $\Delta \theta$ cannot be much less than $55^\circ$. As in § 3.1, we next try to determine $\Delta \theta_{\text{max}}$ for $i = 80^\circ$ and $\theta_e = 90^\circ$. We can reproduce $A_2$ well for $\Delta \theta = 85^\circ$, but the corresponding ratio $= 13.8$ is much less than the observed value. Therefore, spectral data indicate that $\Delta \theta < 85^\circ$ and support the inference from the timing data (§ 3.1) that the average angular radius of the burning region of the precursor cannot be much larger than $90^\circ$. In Figure 4 we summarize these results.

In the previous paragraph, we assumed $X = 0.7$ for both the time bins. But if the precursor (bin 2) and the main burst (bin 1) were ignited at different layers of accreted matter (§ 2), $X_{\text{prec}}$ might be greater than $X_{\text{main}}$. Here we assume the extreme values ($X_{\text{prec}} = 0.7$, i.e., hydrogen-rich, and $X_{\text{main}} = 0.0$, i.e., helium-rich) and check if the inferences of the previous paragraph still hold. Clearly, the new value of $X_{\text{main}}$ alters (increases) only the photon flux for bin 1 (as $f$ becomes 1.654), and hence the value of ratio changes. For $i = 60^\circ$, $\theta_e = 75^\circ$, and $\Delta \theta = 70^\circ$ (for bin 2), we find $A = 0.389 \pm 0.050$ and ratio $= 25.3$, which are consistent with the observed values. Therefore, our simple hot spot model can simultaneously explain both the timing and the spectral data, even when the chemical composition of the burning matter of the two bursts is very different. For $X_{\text{main}} = 0.0$, as the value of $f$ (for bin 1) decreases, and hence the corresponding model photon flux increases, the model photon flux (and hence the hot spot size) of the precursor has to increase in order to reproduce the observed ratio. Therefore, a small hot spot is even more disfavored for $X_{\text{prec}} = 0.7$ and $X_{\text{main}} = 0.0$. But do these extreme values of $X$ allow a precursor burning region that is much larger than $90^\circ$? For $i = 80^\circ$ and $\theta_e = 90^\circ$ (for bin 2), we can reproduce $A_2$ for $\Delta \theta = 85^\circ$, but the corresponding ratio $= 19.7$ is significantly less than the observed value. Therefore, even when the chemical composition of the bursts are considerably different, the modeling of the spectral data indicates $\Delta \theta \approx 90^\circ$ for the precursor.

The results of our modeling show that the hot spot during the precursor burst was neither small nor large enough to cover most of the stellar surface. This, along with the faintness of the precursor compared to the main burst, argues against scenarios 1 and 2 (mentioned in § 2). Scenario 2 is further disfavored, because the large observed oscillation amplitude cannot originate from surface modes. Therefore, as the joint analysis suggests, the oscillations were produced by a hot spot (burning region) of moderate size ($\Delta \theta \sim 50^\circ - 75^\circ$). Now, if the burning region expansion does not happen, then the fuel (accreted matter) has to be confined in this hot spot. But it is very difficult to understand what confines the fuel. Magnetic field cannot do it, because (1) the polar cap is unlikely to be as big as the hot spot; (2) the magnetic field of SAX J1808.4–3658 may be of order $10^{-8} - 10^{-9}$ G (Psaltis & Chakrabarty 1999), which cannot confine the fuel; and (3) Bhattacharyya & Strohmayer (2006c) have argued that thermonuclear flame spreading likely occurs in the case of SAX J1808.4–3658 (and hence the fuel does not remain confined). Therefore, it is very likely that before the precursor, there was accreted matter all over the stellar surface, and during the precursor, the burning region (with a relatively low temperature) expanded for $\sim 0.2 - 0.3$ s to engulf the whole stellar surface (scenario 3 of § 2). In such a case, the $\Delta \theta$ of our model represents an average angular radius (during time bin 2), which is consistent with the moderate hot spot size found from the joint analysis. The expanding burning region can naturally account for the observed oscillations, and when the burning covered most of the stellar surface, the oscillations ceased.

4. DISCUSSION AND CONCLUSIONS

In this paper, we have reported the discovery of a unique precursor to a thermonuclear burst that (1) occurred about a second prior to the main burst, (2) existed for a portion of a second, (3) had a peak intensity more than an order of magnitude less than that of the main peak, and (4) showed strong spin modulation pulsations. With relatively simple modeling, we have found that an expanding burning region at a relatively low temperature can explain the oscillations, as well as the faintness of the precursor.

The low temperature and fluence of the precursor (compared to the main peak) suggests that the amount of fuel involved in the precursor is small compared to the total available for the whole burst. It would seem that there are at least three possibilities to account for the precursor. In the first scenario the release of nuclear energy at depth could have such a two-step time dependence. In this case the observed time dependence would be a direct reflection of the time-dependent energy release due to nuclear burning. In the second class of models, the precursor could be produced by a physical separation of fuel layers. This, combined with the finite-energy transport timescale through the surface layers, results in the observed two-step energy release. This scenario, or one very like it, is thought to be responsible for the precursors observed with superbursts (see Strohmayer & Brown 2002; Strohmayer & Markwardt 2003; Weinberg et al. 2006). In superbursts, ignition is
thought to occur via unstable carbon burning, perhaps in a background of heavy rp-process ashes (Cumming & Bildsten 2000; Schatz et al. 2001; Strohmayer & Brown 2002). This occurs at much greater column depths ($\approx 2 \times 10^{12}$ g cm$^{-2}$; Cumming et al. 2006) than the unstable helium burning, which ignites normal bursts ($\approx 2 \times 10^8$ g cm$^{-2}$; Woosley et al. 2004). The energy released at depth by a superburst diffuses upward and, partially, inward. The outward-going flux triggers the hydrogen-helium fuel above it, resulting in the precursor burst. In this case, the combination of radial separation of the fuel layers and finite-energy diffusion timescales results in the observed precursor burst.

A third possibility is that the precursor acts as a “trigger” that initiates the burst. If unstable burning begins somewhere on the star at a column depth above that where simple considerations of the ignition physics would suggest, then it could act as a “spark,” setting off the remaining combustible fuel below. To date, most theoretical investigations have considered ignition conditions based on spherically symmetric perturbations. Recent observations, in the context of burst oscillations, suggest that nonsymmetric processes are likely crucial for a complete understanding of ignition and spreading. Recent theoretical work has also reached this conclusion (see Špicíkovsky et al. 2002). Perhaps temperature, composition, and/or accretion gradients across the stellar surface might bring about such a condition. Once nuclear energy release begins locally, then heat will flow from that layer both in and out. If ignition conditions are relatively finely “balanced,” then it might not take much additional heat flux to set off the rest of the fuel. While the physical quantities that govern ignition are almost certainly not uniform across the star, it remains uncertain whether such conditions vary enough to make this kind of triggering possible.

Can we say whether either of these alternatives is at work (or not) in the 2000 October 19 burst? Based on the recent study of Galloway & Cumming (2006) it seems highly likely that the bursts from SAX J1808.4$-$3658 were ignited in a helium-rich environment. While the exact nuclear composition is not known, and indeed, details of some of the relevant nuclear processes are uncertain, it seems unlikely, although not impossible, that a pure helium ignition would have such a delayed energy release. For example, the calculations of Woosley et al. (2004) indicate a rapid, monotonic rise of the luminosity (without any precursor) from helium-rich ignitions, although we note that these were one-dimensional (radial) calculations. We suggest it is more likely that a situation like the second or third scenario is responsible for the precursor, but it is difficult to be more precise with only one example at present.

An additional clue might be the fact that the October 19 burst was the last observed (of the four bursts detected) and happened at the lowest accretion rate (see Galloway & Cumming 2006). Previous theoretical work has shown that there exists an accretion rate regime in which bursts can be triggered by unstable hydrogen burning (Fujimoto Hanawa & Miyaji 1981; Fushiki & Lamb 1987; Narayan & Heyl 2003). Galloway & Cumming (2006) argued that the bursts observed from SAX J1808.4$-$3658 in 2002 October were in or near the pure helium shell ignition regime, with the accretion rate per unit area of the stellar surface $\dot{m} \sim 1000$ g cm$^{-2}$ s$^{-1}$. This is close to the critical $\dot{m}$ below which stable hydrogen burning switches off (see, for example, Fujimoto et al. 1981). If $\dot{m}$ dropped below this threshold some time after the third burst, then an accumulating hydrogen layer could form above a partially formed helium layer. If unstable burning were then triggered in the hydrogen layer, it would inject enough energy to raise the temperature and stabilize the hydrogen burning, but it might not take much additional energy input to destabilize the helium layer below and set off the remainder of the accreted fuel. This could explain the faintness of the precursor, in that the burning timescale is longer for the temperature-dependent CNO cycle (than for the triple-$\alpha$ process), and/or the fact that it might only take a small amount of energy to destabilize the hydrogen burning once started (Fujimoto et al. 1981). We speculate that such a process might explain the precursor burst.

If this reasoning is correct, then the duration of the precursor, $t_{\text{dur}}$, and the time between its start and the rising edge of the main burst, $\Delta t_{\text{pre}} \approx 1$ s, can provide some rough constraints on several relevant timescales. If energy must flow inward to trigger the main burst, and then flow back out—for us to see the main burst—then $\Delta t_{\text{pre}}$ is approximately twice the radiative diffusion time from the trigger layer to the column depth of helium fuel responsible for the main burst. This gives a diffusion timescale of $\approx 0.5$ s, which is roughly consistent with theoretical calculations (Cumming & Bildsten 2000). While we do not claim to be able to precisely infer this quantity, the fact that it is in qualitative agreement with theoretical expectations provides some support for the idea of radially separated fuel layers.

What about spreading timescales? For this scenario to work, the intensity profile of the precursor would have to be largely controlled by the spreading of the hydrogen-burning layer. In order to account for the overall rise time and duration of the precursor, the spreading time would have to be approximately several tenths of seconds. Indeed, the rise and decay of the precursor would directly represent lateral spreading across the surface. This timescale would also accommodate the observed duration of the oscillations during the precursor. One would likely require that the cooling time for the hydrogen layer be less than or of order the spreading time, or else the decay of the precursor would be difficult to understand. We note that there is evidence for weak emission between the precursor and main burst (see Fig. 1), which provides some support for the idea that the initial (possibly hydrogen) energy release had a longer timescale. Finally, we reported evidence that this burst had a somewhat different frequency evolution of the oscillations observed on the rising edge (of the main burst) compared to the two other bursts (Bhattacharyya & Strohmayer 2006c). It may be possible that the different ignition condition suggested here also contributed to this difference.

While the arguments above seem to provide a reasonable qualitative description, they will remain largely speculative until more detailed calculations are done. It is another indication that high-quality data are forcing us to explore interesting details of nuclear burning on neutron stars. Indeed, it seems clear that these results point toward the necessity of a realistic, three-dimensional model of thermonuclear ignition and flame spreading that considers all the major physical effects including magnetic field, stellar spin, chemical composition, and time-variable accretion.

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