MODELS OF TYPE I X-RAY BURSTS FROM 4U 1820–30

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ABSTRACT

I present ignition models for type I X-ray bursts and superbursts from the ultracompact binary 4U 1820–30. A pure helium secondary is usually assumed for this system (which has an orbital period \( \approx 11 \) minutes); however, some evolutionary models predict a small amount of hydrogen in the accreted material (mass fraction \( X \approx 0.1 \)). I show that the presence of hydrogen significantly affects the type I burst recurrence time if \( X \approx 0.03 \) and the CNO mass fraction \( \gtrsim 3 \times 10^{-2} \). When regularly bursting, the predicted burst properties agree well with observations. The observed 2–4 hr recurrence times are reproduced for a pure He companion if the time-averaged accretion rate is \( \langle M \rangle \approx (7–10) \times 10^{-9} M_\odot \text{ yr}^{-1} \) or a hydrogen-poor companion if \( \langle M \rangle \approx (4–6) \times 10^{-9} M_\odot \text{ yr}^{-1} \). This result provides a new constraint on evolutionary models. The burst energetics are consistent with complete burning and spreading of the accreted fuel over the whole stellar surface. Models with hydrogen predict \( \sim 10\% \) variations in burst fluence with recurrence time, which could perhaps distinguish the different evolutionary scenarios. I use the accretion rates determined by matching the type I burst recurrence times to predict superburst properties. The expected recurrence times are \( \approx 1–2 \) yr for pure He accretion (much less than that found by Strohmayer & Brown) and \( \approx 5–10 \) yr if hydrogen is present. Determination of the superburst recurrence time would strongly constrain the local accretion rate and thermal structure of the neutron star.

Subject headings: accretion, accretion disks — stars: individual (4U 1820–30) — stars: neutron — X-rays: bursts

1. INTRODUCTION

Type I X-ray bursts are well understood as thermonuclear flashes on the surface of an accreting neutron star (for reviews, see Lewin, van Paradijs, & Taam 1995; Strohmayer & Bildsten 2003). The basic theory was outlined more than 20 yr ago (for an overview, see Fujimoto, Hanawa, & Miyaji 1981; Bildsten 1998), successfully explaining the typical burst energetics \( (10^{39}–10^{40} \text{ ergs}) \), durations \( (\sim 10–100 \text{ s}) \), and recurrence times \( (\text{hours to days}) \). However, detailed comparisons of theory and observations have had mixed success (Fujimoto et al. 1987; van Paradijs, Penninx, & Lewin 1988; Bildsten 2000; Galloway et al. 2003).

The ultracompact binary 4U 1820–30 \( (P_{\text{orb}} = 11.4 \text{ minutes}; \text{Stella, Priedhorsky, & White 1987}) \) is a promising system for such a comparison. It has a known distance, being located in the metal-rich globular cluster NGC 6624 \((\text{[Fe/H]} \approx -0.4, \text{distance} \ 7.6 \pm 0.4 \text{ kpc}; \text{Rich, Minniti, & Liebert 1993}; \text{Kuulkers et al. 2003}) \). It undergoes a regular \( \approx 176 \text{ day} \) accretion cycle (Priedhorsky & Terrell 1984), switching between high and low states differing by a factor \( \approx 3 \) in accretion rate (e.g., see the Rossi X-Ray Timing Explorer/All Sky Monitor [RXTE/ASM] light curve in Fig. 1 of Strohmayer & Brown 2002, hereafter SB02). In the low state, regular type I bursts are seen \((\pm 23 \text{ days} \) around the minimum luminosity; Chou & Grindlay 2001), with recurrence times \( \approx 2–4 \text{ hr} \) (Clark et al. 1976, 1977; Haberl, Stella, & White 1987; Cornelisse et al. 2003). No bursts are seen during the rest of the cycle, implying a “nonbursting” mode of burning (e.g., Bildsten 1995). In the low state, 4U 1820–30 has also shown an extremely energetic \((\sim 10^{42} \text{ ergs}) \) “superburst,” likely due to deep ignition of a carbon layer (SB02; see Kuulkers et al. 2002 and Strohmayer & Bildsten 2003 for a summary of superburst properties).

Different evolutionary scenarios for 4U 1820–30 have been proposed. Those involving direct collision of a red giant and a neutron star (Verbunt 1987), or formation of a neutron star–main-sequence binary by tidal capture (Bailyn & Grindlay 1987) or an exchange interaction (Rasio, Pfahl, & Rappaport 2000) followed by a common envelope phase, lead to accretion of pure helium from the helium core of the red giant. A different picture is that the mass transfer starts just after central hydrogen exhaustion (Tutukov et al. 1987; Fedorova & Ergma 1989; Podsiadlowski, Rappaport, & Pfahl 2002), in which case the accreted material is again mostly helium but contains some hydrogen \((\approx 5\%–35\% \text{ by mass}; \text{Fedorova & Ergma 1989}; \text{Podsiadlowski et al. 2002}) \).

The observed energetics and recurrence times of the type I bursts from 4U 1820–30 fit well with a picture of accumulation and burning of helium-rich material. The ratio of persistent fluence (persistent flux integrated over the burst recurrence time) to burst fluence is \( \alpha \approx 120 \) (Haberl et al. 1987). For a gravitational energy \( GM/R \approx 200 \text{ MeV nucleon}^{-1} \), this implies a nuclear energy release \( \approx 1.6 \text{ MeV nucleon}^{-1} \), as expected for helium burning to iron group elements. The mass of helium required to power the observed energetics is roughly the mass accreted in the burst recurrence time at the inferred accretion rate. The burst fluence \( \approx 3.5 \times 10^{-7} \text{ ergs cm}^{-2} \) (Haberl et al. 1987) implies a total burst energy \( 2.5 \times 10^{39} \text{ ergs}(d/7.6 \text{ kpc})^{2} \) or a mass of helium \( \Delta M \approx 1.6 \times 10^{21} \text{ g} \). The persistent luminosity when bursts are seen is \( L_{\text{X}} \approx 2.8 \times 10^{37} \text{ ergs s}^{-1}(d/7.6 \text{ kpc})^{2} \). The accretion rate \( \dot{M} \approx 1.5 \times 10^{17} \text{ g s}^{-1} \approx 2.4 \times 10^{-9} M_\odot \text{ yr}^{-1} \) for a 1.4 \( M_\odot \) neutron star with radius \( R = 10 \text{ km} \). At this rate, a mass \( \Delta M \) is accreted in 3 hr, in excellent agreement with the observed recurrence times.

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A previous comparison of theory with observations of 4U 1820–30 was carried out by Bildsten (1995, hereafter B95), who conducted time-dependent simulations of pure helium burning on accreting neutron stars. He found good agreement with observed energetics and recurrence times but for a somewhat hotter base temperature than expected. In this paper, I calculate ignition models for type I bursts from 4U 1820–30 and survey the conditions necessary to ignite helium at the inferred mass $\Delta M$. I allow for a small amount of hydrogen in the accreted material and show that this has a large effect on the burst recurrence time because of extra heating from hot CNO hydrogen burning as the layer accumulates. Finally, I discuss what we might learn from simultaneous modeling of type I bursts and superbursts. The plan of the paper is as follows. The main results are presented in § 2. I calculate the critical mass needed for ignition and show the effect of hydrogen on recurrence times and energetics. I compare these results with observations of type I bursts and to evolutionary models. Finally, I use the constraints from type I bursts to construct ignition models for superbursts from 4U 1820–30 and compare them with the model of SB02. I summarize in § 3 and discuss the remaining open issues.

2. IGNITION MODELS AND COMPARISON WITH OBSERVATIONS

2.1. Calculation of Ignition Conditions

The physics and different regimes of nuclear burning on accreting neutron stars have been described by several authors (for reviews, see Lewin et al. 1995; Bildsten 1998). Here, I follow the X-ray burst ignition calculations of Cumming & Bildsten (2000, hereafter CB00). I adopt plane-parallel coordinates in the thin accreted layer and work in terms of the column depth $y = P/g$, where $dy = -pdz$. $P$ is the hydrostatic pressure, $\rho$ is the density, and $g$ is the surface gravity. I assume a 1.4 $M_\odot$ neutron star with radius $R = 10$ km, giving $g = (1 + z)GM/R = 2.45 \times 10^{14}$ cm s$^{-2}$, where the gravitational redshift is $z = (1 - 2GM/Rc^2)^{-1/2} - 1 = 0.31$ (similar to the value $\approx 0.35$ recently inferred from absorption lines in XMM-Newton burst spectra of EXO 0748–676; Cottam, Paerels, & Mendez 2002). I include general relativistic effects when calculating observable quantities. Cumming et al. (2002) showed that the Newtonian equations of CB00 have the same form under general relativity, as long as $\nu$ and $\eta$ refer to rest mass rather than to gravitational mass.

The thermal profile of the accumulating layer is described by the heat equation $F = (4acT^3/3k_\nu)(dT/dy)$, where the opacity $\kappa$ is calculated as described by Schatz et al. (1999), and the entropy equation $dF/dy = -\epsilon$, where $F$ is the heat flux and $\epsilon$ contains contributions from hot CNO hydrogen burning and compressional heating. Compressional heating always plays a minor role at these accretion rates, giving $\sim c_p T \approx 5k_B T/2 \mu m_p \approx 0.02 T_b$ MeV nucleon$^{-1}$. The hot CNO energy production rate is $\epsilon_{\nu\text{c}} = 5.8 \times 10^{33}$ ergs g$^{-1}$ s$^{-1}(Z/0.01)$ (Hoyle & Fowler 1965), where $Z$ is the CNO mass fraction. I follow the changing hydrogen abundance with depth as described in CB00 (see eq. [3] of that paper). Unless otherwise stated, I set $Z = 0.01$. When alpha burning during accumulation is not included; this has only a small effect on the ignition conditions. I assume the individual CNO abundances are those of the equilibrium hot CNO cycle ($^{14}$O and $^{15}$O). In the pure He case, the accreted $^{14}$N survives to a density $\approx 10^6$ g cm$^{-3}$, when it converts to $^{14}$C by electron capture (Hashimoto et al. 1986). For the conditions here, no further processing occurs until helium ignites via triple alpha.

To find the thermal profile, I repeatedly integrate downward through the accreted layer, iterating until $F = F_{\text{crust}}$ at the base, where $F_{\text{crust}} = Q_{\text{crust}}(\eta)$ is the heat flux from deeper layers. Here, $Q_{\text{crust}}$ is the energy per nucleon released in the crust from pycnonuclear and electron capture reactions that escapes from the surface. Brown (2000) showed that $Q_{\text{crust}} \approx 0.1$ MeV nucleon$^{-1} \approx 10^{17}$ ergs g$^{-1}$ for $\eta \gtrsim 10^4$ g cm$^{-2}$ s$^{-1}$. I assume $F_{\text{crust}}$ is set by the time-averaged local accretion rate $\langle \dot{\eta} \rangle$, rather than the instantaneous rate $\dot{\eta}$, because the thermal time in the crust is much longer than the $\sim 6$ month luminosity cycle. Throughout this paper, I assume the instantaneous rate when bursts are seen is half the time-averaged rate, $\dot{\eta} = \langle \dot{\eta} \rangle/2$ (as inferred from the RXTE/ASM light curve; e.g., Fig. 1 of SB02).

The ignition column depth $y_{\text{ign}}$ is found by increasing the depth of the layer until the condition for ignition,

\[ \frac{d\epsilon_{\text{cool}}}{dT} = \frac{d\epsilon_{\text{crust}}}{dT} \]

(Fujimoto et al. 1981; Fushiki & Lamb 1987b; Bildsten 1998), is met at the base. Here $\epsilon_{\text{crust}}$ is the triple alpha energy production rate (Fushiki & Lamb 1987a) and $\epsilon_{\text{cool}} = acT^4/3\kappa \nu y$ is a local approximation to the radiative cooling. The ignition criterion (1) says that ignition occurs when the heating from triple alpha is more temperature-sensitive than the cooling and is large enough to change the temperature of the layer. Following CB00, we include a multiplicative factor of 1.9 in $\epsilon_{\text{crust}}$ to account for two proton captures on $^{14}$C when hydrogen is present.

The advantage of this “semianalytic” approach is that it allows a survey of parameter space, while still giving a good estimate of the ignition depth. CB00 compared the ignition conditions predicted by equation (1) with time-dependent models in the literature. For mixed H/He ignition, the agreement was to 10%–30% and better than a factor of 2 for pure He ignitions. In addition, I have compared results for pure helium with those of B95. For a given $\dot{\eta}$, I adjust the flux from the base to match the base temperature specified by B95. For the accretion rates relevant to this paper, I find that the ignition column depth from equation (1) underpredicts the ignition column by 10%–30%.

I estimate the burst energy by assuming complete burning of the accreted layer and taking a nuclear energy release $Q_{\text{nuc}} = 1.6 + 4.0(X)\text{ MeV nucleon}^{-1}$, where $\langle X \rangle$ is the mass-weighted mean $X$ in the layer at ignition. This expression for $Q_{\text{nuc}}$ includes 35% energy loss in neutrinos during hydrogen burning (Fujimoto et al. 1987). This is appropriate for rp-process hydrogen burning up to the iron group and may be an overestimate for small $X_0$ in which case we underestimate the burst energy by up to $\approx 10\%$ for $\langle X \rangle \sim 0.1$. Assuming the layer of fuel covers the whole star, the total burst energy is $E_{\text{burst}} = 4\pi R^2 \langle \nu \text{V}_{\text{ign}}Q_{\text{nuc}}/(1 + z) \rangle$, where the $(1 + z)$ factor accounts for gravitational redshift.

2.2. Effect of Hydrogen

Hydrogen burning gives $\approx 7$ MeV nucleon$^{-1}$, so that even a small amount of hydrogen burning during accumulation dominates the $\approx 0.1$ MeV nucleon$^{-1}$ coming from the crust.
For pure helium accretion, $F_{\text{crust}} = \langle m \rangle Q_{\text{crust}} \approx 10^{31}$ ergs cm$^{-2}$ s$^{-1}$. This sets the temperature of the accumulating layer. If hydrogen is present, the flux from the hot CNO cycle is

$$F_{\text{H}} = \epsilon_{\text{H}} y_{\text{H}} = 5.8 \times 10^{31} \text{ergs cm}^{-2} \text{s}^{-1} y_{\text{H}} Z (Z/0.01).$$

Here, $y_{\text{H}}$ is the column density of the layer that is burning hydrogen; this is either the column depth at which hydrogen runs out or the depth at which helium ignites, whichever occurs first. Whether $F_{\text{H}} > F_{\text{crust}}$ depends on $y_{\text{H}}$, since this measures the amount of hydrogen burning. The time to burn all the hydrogen is

$$t_{\text{H}} = E_{\text{H}} X_{0}/\epsilon_{\text{H}},$$

where $E_{\text{H}} = 6.0 \times 10^{18}$ ergs g$^{-1}$ is the energy release per gram from hydrogen burning (unlike CB00, we include the energy release from neutrons here as given by Wallace & Woosley 1981) and $X_0$ is the initial hydrogen abundance. If the burst recurrence time $t_{\text{recur}} < t_{\text{H}}$, then helium ignition occurs before hydrogen exhaustion, giving

$$y_{\text{H}} = \langle m \rangle t_{\text{recur}}.$$  

Then requiring $F_{\text{H}} > F_{\text{crust}}$ gives

$$Z > 3.5 \times 10^{-3} Q_{\text{17}} \left( \frac{t_{\text{recur}}}{3 \text{ hr}} \right).$$

If $t_{\text{recur}} > t_{\text{H}}$, all of the hydrogen is burned before helium ignites, giving

$$y_{\text{H}} = \frac{m_{\text{H}}}{m} = 1.2 \times 10^8 \text{ g cm}^{-2} (X_0/0.1)(\langle m \rangle/1.2)(0.01/Z),$$

then

$$X_0 > 0.034 Q_{\text{17}} \left( \frac{\langle m \rangle}{2 m} \right).$$

is required for $F_{\text{H}} > F_{\text{crust}}$.

Equations (3) and (4) show that if hydrogen burning is to affect the temperature profile in the layer, both the amount of hydrogen and the metallicity must be large enough. Evolutionary models for 4U 1820–30 with hydrogen give $X \gtrsim 0.1$ (e.g., Podsiadlowski et al. 2002), satisfying equation (4). In addition, NGC 6624 is metal-rich ($\langle \text{Fe}/\text{H} \rangle \approx -0.4$; Rich et al. 1993) so that the accreted metallicity satisfies equation (3) (although spallation in the accretion shock could reduce the metallicity in the accreted layer; Bildsten, Salpeter, & Wasserman 1992).

### 2.3. Comparison with Observations

Several authors have presented observations of regular bursting from 4U 1820–30 (the first source to exhibit X-ray bursts; Grindlay et al. 1976). Clark et al. (1976) saw 10 bursts with $\text{SAS-3}$ with a recurrence time of 4.4 ± 0.17 hr (a 4% variation) and mean fluence $\approx 2.9 \times 10^{-7}$ ergs cm$^{-2}$ (1–10 keV). The persistent flux was $\approx 1/5$ of the peak flux seen in the high state. Further $\text{SAS-3}$ observations of the transition from low to high state found 22 bursts (Clark et al. 1977). The recurrence time decreased from 3.4–2.2 hr as the flux increased by a factor of $\approx 5$. The mean burst fluence was $\approx 4 \times 10^{-7}$ ergs cm$^{-2}$. The decay time of the bursts decreased slightly as flux increased. Haberl et al. (1987) saw seven bursts in a 20 hr $\text{EXOSAT}$ observation with a recurrence time of $3.2 \pm 0.05$ hr, mean fluence $3.48 \pm 0.16 \times 10^{-7}$ ergs cm$^{-2}$, and $\alpha = 142 \pm 10$. The persistent flux was $\approx 4.3 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$. Most recently, $\text{BeppoSAX}$/WFC accumulated $\approx 7$ Ms of exposure of the Galactic center region, observing 49 bursts from 4U 1820–30 (Cornelisse et al. 2003; Kuulkers et al. 2003). These bursts show a transition from regular to irregular bursting as persistent flux increases (Cornelisse et al. 2003).

The simplest model is to consider pure helium accretion at the rate inferred from the X-ray luminosity in § 1 and to take $Q_{\text{crust}} = 0.1$ MeV nucleon$^{-1}$, as found by Brown (2000). As a useful reference point, I refer to this accretion rate as $m_{\text{X}} = 1.2 \times 10^4$ g cm$^{-2}$ s$^{-1}$. Figure 1 shows the temperature profile at ignition for this case (bottom curve). The recurrence time and burst energy are $\approx 5$ times larger than the observed values. Ignition occurs at a column depth $\approx 7 \times 10^8$ g cm$^{-2}$, giving a recurrence time of 16.5 hr and burst energy $1.1 \times 10^{40}$ ergs. A model with hydrogen gives much better agreement. The top curve in Figure 1 shows the same model, but with $X_0 = 0.1$. The extra heating from hot CNO burning leads to earlier ignition, $y \approx 2 \times 10^8$ g cm$^{-2}$, giving $t_{\text{recur}} = 4.4$ hr and $E_{\text{burst}} = 3.1 \times 10^{39}$ ergs.

Unfortunately, this result cannot be taken as evidence for the presence of hydrogen. A larger flux from below will also heat the layer and lead to earlier ignition. For pure helium accretion at $m = m_{\text{X}}$, I find that $Q_{\text{crust}} = 0.4$ MeV nucleon$^{-1}$ is required to bring the recurrence time down to $\approx 3$ hr. This is larger than expected from heating in the crust (Brown 2000). However, additional heating might be provided by a previous X-ray burst. Most of the energy released in a burst is radiated from the surface of the star; however, some energy is conducted inward and emerges on a longer timescale. This effect has been emphasized by Taam and coworkers (Taam 1980; Taam et al. 1993), who refer to it as “thermal inertia.” To estimate the size of this effect, I assume a fraction $f$ of the nuclear energy flows inward and is released at a constant rate between bursts. The extra flux is then $f E_{\text{burst}}/4\pi R^2 t_{\text{recur}}$, giving a contribution to $Q_{\text{crust}}$ of $\approx 0.1$ MeV nucleon$^{-1}$ ($f/0.1)(3/h_{\text{recur}})(E_{\text{burst}}/3)(m_{\text{X}}/m)$. This is likely an overestimate, since the energy release decreases over time. A better estimate requires time-
Dependent simulations of a sequence of bursts. For now, I incorporate this uncertainty into $Q_{\text{crust}}$.

An additional uncertainty is the $L_X-m$ relation, which allows some freedom in setting $m$. Pure helium models nicely agree with observations if $m \approx (1.5-2)m_X$ (for $Q_{\text{crust}} = 0.1-0.2$ MeV nucleon$^{-1}$). This is shown in Figure 2, in which $t_{\text{recur}}$ and $E_{\text{burst}}$ are plotted against $m$. For each choice of $m$, the time-averaged rate is assumed to be $(m) = 2m$. The vertical bars at $m = m_X$ show the observed range of recurrence time and energy. As we found above, hydrogen models require $m = m_X$ to give agreement.

Table 1 shows the same result for some specific models. Here, I choose $X_0$, $Z$, and $Q_{\text{crust}}$ and then vary $m$ to match the recurrence time seen by Haberl et al. (1987), $t_{\text{recur}} = 3.2$ hr. There are a few points worth noting. First, the ignition depth in the helium models is sensitive to $Q_{\text{crust}}$, since this sets the temperature of the accumulating layer. As $Q_{\text{crust}}$ increases, $Y_{\text{ign}}$ decreases. Second, hydrogen models show two regimes of behavior. If $t_{\text{recur}} < t_t$ (see eq. [2]), hydrogen burning occurs throughout the accumulating layer. Then $Y_{\text{ign}}$ depends on the metallicity $Z$, which determines the amount of hot CNO burning, but not on $Q_{\text{crust}}$ or $m$. As $Z$ decreases, $Y_{\text{ign}}$ increases. An extreme case is model 7 in Table 1 ($Z = 10^{-5}$), in which case little heating occurs and the ignition conditions are similar to pure helium. If $t_{\text{recur}} > 1$ hydrogen runs out and ignition occurs in a pure helium layer. Then $Y_{\text{ign}}$ is sensitive to $m$, explaining the steep increases in $t_{\text{recur}}$ and $E_{\text{burst}}$ for the H models in Figure 2 (see CB00 for more discussion of these different regimes).

In general, the burst energy is overpredicted in these models, by factors of up to $\approx 70\%$. This discrepancy is easily accounted for by anisotropic burst emission (e.g., Lapidus & Sunyaev 1985; Fujimoto 1988) (although there may be other explanations; see discussion in §3.1). For the remainder of this section, I renormalize the predicted fluence to agree with the EXOSAT mean value (Haberl et al. 1987).

Figure 3 shows the expected variations in burst fluence and recurrence time as a function of persistent flux. I show hydrogen models with metallicity $Z = 0.01$ ($X = 0.1$ and 0.2), a low-metallicity model $Z = 10^{-3}$ ($X = 0.1$), and a helium model with $Q_{\text{crust}} = 0.1$. I assume $Q_{\text{crust}}$ is independent of accretion rate, not including any variations with $m$ because of thermal inertia. In each case, I normalize the $F_X-m$ relation to give $t_{\text{recur}} = 3.2$ hr for $F_X = 4.3 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ (Haberl et al. 1987). To do this, I write $F_X = L_X/4\pi d^2 = mQ_{\text{grav}}(R/d)^2c_{\text{sp}}^{-1}$, where $Q_{\text{grav}} = c^2 z/(1 + z)$ is the gravitational energy release (221 MeV nucleon$^{-1}$ for $z = 0.31$) and the factor $c_{\text{sp}}$ accounts for the anisotropy of the X-ray emission, as well as additional uncertainties such as luminosity emerging at other wavelengths. Given the $m$

| Model | $X_0$ | $Z$ | $Q_{\text{crust}}$ | $m$ | $Y_{\text{ign}}$ | $T_8$ | $X_0$ | $X$ | $Q_{\text{mc}}$ | $E_{39}$ |
|-------|-------|-----|--------------------|-----|-----------------|------|-------|----|----------------|--------|
| 1     | 0.0   | 0.01| 0.1                | 2.3 | 2.7             | 1.7  | 0.00  | 0.0| 1.6            | 3.9 |
| 2     | 0.0   | 0.01| 0.1                | 1.7 | 1.9             | 1.8  | 0.00  | 0.0| 1.6            | 2.8 |
| 3     | 0.0   | 0.01| 0.1                | 1.4 | 1.6             | 1.8  | 0.00  | 0.0| 1.8            | 2.6 |
| 4     | 0.2   | 0.01| 0.1                | 1.4 | 1.6             | 1.9  | 0.09  | 0.1| 2.2            | 3.2 |
| 5     | 0.3   | 0.01| 0.1                | 1.4 | 1.6             | 1.9  | 0.19  | 0.2| 2.4            | 3.9 |
| 6     | 0.1   | 0.01| 0.2                | 1.2 | 1.4             | 1.9  | 0.00  | 0.5| 1.8            | 2.3 |
| 7     | 0.1   | 0.001| 0.1               | 2.0  | 2.3             | 1.7  | 0.09  | 0.09| 2.0            | 4.2 |

Note.—Col. (1): Model. Col. (2): Accreted hydrogen fraction $X_0$. Col. (3): CNO mass fraction $Z$. Col. (4): $Q_{\text{crust}}$. Col. (5): Local accretion rate $m_c = m/10^4$ g cm$^{-2}$ s$^{-1}$. Col. (6): Ignition column depth $y_{\text{ign}} = y/10^6$ g cm$^{-2}$. Col. (7): Ignition temperature $T_8 = T/10^8$ K. Col. (8): Hydrogen mass fraction at the base $X$. Col. (9): Mean hydrogen mass fraction $X = \int dy X(y)/y$. Col. (10): Nuclear energy release, $Q_{\text{mc}} = 1.6 + 4.0(X)$ MeV nucleon$^{-1}$. Col. (11): Predicted burst energy $E_{39} = E_{\text{burst}}/10^{39}$ ergs.
X = 0.1 model shows a significant deviation from a 1/m law, but in the opposite direction. For \( t_{\text{recur}} < t_{\text{H}} = 3 \) hr, \( t_{\text{recur}} \) falls off more steeply than 1/m, rather than less steeply as observed.

In Figure 4, I plot fluence against \( t_{\text{recur}} \) directly. The fluence is renormalized to agree with the mean EXOSAT value, highlighting the variation in fluence with \( t_{\text{recur}} \). Hydrogen models show a change in fluence of \( \approx 10\% \) as the recurrence time varies over the observed range, whereas the helium and low-metallicity models have roughly constant fluence. When hydrogen is present, the variation arises because the composition of the layer at ignition changes according to the amount of hydrogen burning that occurs during accumulation. I also plot the observed values in Figure 4, showing the range of recurrence times for the Clark et al. (1977) observations, measurements for individual bursts from Haberl et al. (1987), and the mean fluence reported by Clark et al. (1976). There is a \( \approx 30\% \) variation in the reported fluences. However, the error in the SAS-3 fluence measurements is likely larger than this. For example, a reanalysis by Clark (reported by Vacca, Lewin, & van Paradijs 1986) gave a \( \approx 40\% \) reduction in the peak luminosities of individual bursts. Therefore, any conclusions drawn from Figure 4 are probably unwarranted. The comparison is complicated by intrinsic scatter in the burst fluences. The scatter in the Haberl et al. (1987) points in Figure 4 is 4%, comparable to the predicted variation with recurrence time if hydrogen is present. Nonetheless, looking for variations in fluence with recurrence time or persistent flux is a promising way to distinguish between models with and without hydrogen. It perhaps could be addressed with the BeppoSAX data (Cornelisse et al. 2003).
2.4. Comparison with Evolutionary Models

The requirement that \( \dot{m} \approx \dot{m}_X \) if hydrogen is present, or \( \dot{m} \approx (1.5–2)\dot{m}_X \) for pure helium, is a new constraint on evolutionary models. Evolutionary models for 4U 1820–30 predict values of \( \dot{M} \) and \( X_0 \) (Fedorova & Ergma 1989; Podsiadlowski et al. 2002). Table 2 gives the resulting ignition conditions for type I bursts. There is a remarkable agreement between the accretion rates required to match type I burst properties and those predicted by evolutionary models (although it should be noted that these predicted accretion rates are rather uncertain; e.g., see Podsiadlowski et al. 2002). For example, if the companion is a cold helium white dwarf, then gravitational radiation angular momentum losses give \( \dot{M}_{\text{GR}} \approx 8.8 \times 10^{-9} \dot{M}_\odot \text{ yr}^{-1} \) (for a companion mass of 0.068 \( M_\odot \); Podsiadlowski et al. 2002) or \( \dot{m} \approx \dot{m}_X / 2 \approx 2.2 \times 10^{-6} \text{ g cm}^{-2} \text{ s}^{-1} \) \((R/10 \text{ km})^{-2}\), consistent with the values we find in Table 1 for \( X = 0 \). In addition, evolutionary models with hydrogen tend to have lower accretion rates than pure helium models, by about a factor of 2, so that in general both are consistent with the data. There are particular models, however, that do not give good agreement. For example, Podsiadlowski et al. (2002) give a hydrogen model with \( \dot{M} = 1.1 \times 10^{-8} \dot{M}_\odot \text{ yr}^{-1} \), which has a recurrence time of 1.4 hr, outside the observed range.


table 2

| (\(\dot{M}\))_{X} | \(X_0\) | \(m_4\) | \(t_{\text{recur}}\) (hr) | \(\dot{m}_X\) | \(E_{\text{rec}}\) |
|----------------|--------|--------|----------------|----------|-----------|
| Podsiadlowski et al. 2002 | | | | | |
| 8.8………………. | 0.00 | 2.2 | 3.5 | 0.00 | 1.6 | 4.1 |
| 4.3………………. | 0.35 | 1.1 | 4.3 | 0.20 | 2.7 | 4.3 |
| 11………………. | 0.18 | 2.8 | 1.4 | 0.13 | 2.2 | 2.9 |
| Fedorova & Ergma 1989 | | | | | |
| 15………………. | 0.00 | 3.6 | 1.4 | 0.00 | 1.6 | 2.6 |
| 4.1………………. | 0.13 | 1.0 | 4.9 | 0.00 | 1.8 | 3.0 |
| 5.8………………. | 0.11 | 1.5 | 2.9 | 0.01 | 1.8 | 2.6 |
| 7.0………………. | 0.09 | 1.8 | 2.3 | 0.01 | 1.8 | 2.4 |
| 9.6………………. | 0.05 | 2.4 | 1.6 | 0.00 | 1.7 | 2.2 |

Note.—Given the time-averaged accretion rate \((\dot{M})_{\text{X}} = \dot{M}_X / 10^{-9} \dot{M}_\odot \text{ yr}^{-1}\) and hydrogen fraction at the surface of the secondary \( X_0 \), I assume \((\dot{m}) = 2\dot{m}_X\), giving \(\dot{m}_X = (\dot{M})_{\text{X}} / 4.0\) for \( R = 10 \text{ km}\).

2.5. Superburst Ignition Conditions

A superburst was seen from 4U 1820–30 on 1999 September 9 (SB02). The source was in the low state, with \( F_X = 3.5 \times 10^{-9} \text{ ergs cm}^{-2} \text{ s}^{-1}\). The total fluence of the superburst was \( 2.7 \times 10^{-4} \text{ ergs cm}^{-2}\), giving a total energy release of \( \approx 2 \times 10^{42} \text{ ergs}\) (almost a factor of 1000 larger than a normal type I burst). SB02 modeled the superburst from 4U 1820–30, proposing that carbon production during stable burning in the high state leads to a thick carbon/iron layer (mass \( \approx 10^{26} \text{ g}\), carbon mass fraction \( X_C \approx 0.3\)), which ignites to give the superburst.

SB02 estimated the accretion rate for their model from the X-ray luminosity, finding \( \dot{m} \approx \dot{m}_X \). I now calculate ignition conditions for the 4U 1820–30 superburst using the accretion rates inferred from type I bursts. I follow the carbon ignition calculations of Cumming & Bildsten (2001, hereafter CB01), except I take the heavy element to be \(^{56}\text{Fe}\) (CB01 considered much heavier elements than iron, made during rp-process burning of hydrogen). I integrate downward through the carbon/iron layer, assuming a constant heat flux from the crust \( F_{\text{crust}} = Q_{\text{crust}}(\dot{m}) \) (I assume that the heat flux is the same as that heating the helium layer between normal type I bursts). I calculate the carbon ignition depth using a similar criterion to equation (1). To estimate the superburst energy, I assume that carbon burning gives 1 MeV nucleon$^{-1}$. The amount of carbon is uncertain and depends on the fraction of stable H/He burning and the carbon yield. To allow a direct comparison with SB02, I assume that the carbon mass fraction \( X_C \) is 30% in these models.

Table 3 gives the resulting ignition conditions. The model numbers correspond to those in Table 1, except for the model labelled “SB02,” which has \( \dot{m} = \dot{m}_X \). This gives \( t_{\text{recur}} = 14 \text{ yr} \) and total energy release \( \approx 4 \times 10^{43} \text{ ergs}\), similar to the values found by SB02. For the helium models, the larger \( \dot{m} \) than assumed by SB02 gives an order-of-magnitude shorter recurrence time, \( \approx 1–2 \text{ yr} \) rather than 14 yr (this sensitivity of recurrence time to \( \dot{m} \) was noted by SB02; see also Fig. 3 of CB01). For the \( X = 0.1 \) models, the recurrence time is longer, 4–10 yr, depending on \( Q_{\text{rec}} \). This shows that the superburst recurrence time, currently not well constrained, is a powerful discriminant between different models.

Note that the total nuclear energy release can be much greater than the observed superburst energy if neutrino emission plays an important role. This was emphasized by


table 3

| Model | \(X_0\) | \((\dot{m})_{X}\) | \(Q_{\text{rec}}\) | \(t_{\text{recur}}\) (yr) | \(\gamma_{12}\) | \(T_8\) | \(E_{\text{43}}\) | \(X_{\text{min}}\) |
|-------|--------|--------|----------------|----------------|----------|-----------|-----------|----------|
| SB02 | 2.4 | 0.1 | 14 | 11 | 3.8 | 3.9 | 0.13 | |
| 1 | 0.0 | 4.6 | 0.1 | 1.9 | 2.8 | 5.0 | 1.0 | 0.08 |
| 2 | 0.0 | 3.4 | 0.2 | 1.1 | 1.2 | 5.6 | 0.43 | 0.16 |
| 3 | 0.0 | 3.4 | 0.2 | 1.1 | 1.2 | 5.6 | 0.43 | 0.16 |
| 4 | 0.0 | 3.4 | 0.2 | 1.1 | 1.2 | 5.6 | 0.43 | 0.16 |
| 5 | 0.0 | 3.4 | 0.2 | 1.1 | 1.2 | 5.6 | 0.43 | 0.16 |

Note.—Values of \((\dot{m})_{X} = (\dot{m}) / 10^4 \text{ g cm}^{-2} \text{ s}^{-1}\); \(\gamma_{12} = \gamma_{12}/10^{12} \text{ g cm}^{-2}\); \(E_{\text{43}} = E_{\text{superburst}} / 10^{46} \text{ ergs}\). We assume a composition of 30% \(^{12}\text{C}\), 70% \(^{56}\text{Fe}\) and calculate the total energy release \(E_{\text{superburst}} = 4\pi R^2 Y_m Q_{\text{rec}}\) assuming \(Q_{\text{rec}} = 1 \text{ MeV nucleon}^{-1}\).

* The model number refers to Table 1, except for SB02. Models 1 and 2 are pure He accretion; models 3 and 6 have \( X = 0.1 \).

b The minimum mass fraction of carbon required for unstable ignition. The carbon burns stably during accumulation for lower \( X_C \).
SB02 for their model of the 4U 1820–30 superburst, in which only \(\approx 10^{42}\) ergs (from a total of \(4 \times 10^{45}\) ergs) is radiated from the surface. However, the amount of neutrino emission is strongly dependent on the peak temperature and therefore dependent on carbon fraction and ignition depth (CB01). Time-dependent models are therefore necessary to predict the superburst fluence.

CB01 showed that for small carbon mass fractions, the carbon burns stably as the layer accumulates. Table 3 gives the minimum \(X_C\) required for unstable ignition for each model. The range of values is \(X_{C,\text{min}} = 0.08–0.2\). Less carbon is required for smaller \(Q_{\text{crust}}\), as shown by CB01. The values of \(X_{C,\text{min}}\) given here are a little larger than those shown in Figure 2 of CB01 because the less massive heavy element (\(^{56}\)Fe rather than \(^{104}\)Ru) results in a shallower temperature gradient. The recurrence time for \(X_C = X_{C,\text{min}}\) is \(\approx 10\%\) lower than the recurrence time for \(X_C = 0.3\).

3. SUMMARY AND DISCUSSION

3.1. Type I Bursts

In general, the models of type I X-ray bursts presented in §2 give good agreement with observed recurrence times and energetics. The observed 2–4 hr recurrence times are reproduced for a pure He companion if the time-averaged accretion rate is \(<M> \approx (7–10) \times 10^{-9} \ M_\odot \text{yr}^{-1} (R/10 \text{ km})^2\) or a hydrogen-poor companion if \(<M> \approx (4–6) \times 10^{-9} \ M_\odot \text{yr}^{-1} (R/10 \text{ km})^2\). This difference comes about because of extra heating from hot CNO burning during accumulation when hydrogen is present, leading to earlier ignition and requiring a lower \(m\) to match the observed recurrence times. For hydrogen to affect the temperature profile in the layer requires \(X \approx 0.03\) and \(Z \approx 3 \times 10^{-5}\). If spallation reduces the metallicity in the accreted layer (Bildsten et al. 1992), hydrogen burning will no longer play a role, in which case the accreting layer behaves like pure helium.

These conclusions constrain evolutionary models, although both pure helium evolutionary models and those with hydrogen can be found that are consistent with the data. A promising way to distinguish between different evolutionary scenarios is accurate fluence measurements as a function of \(m\). Models with hydrogen predict \(\approx 10\%\) variations in burst fluence as recurrence times vary, whereas pure helium models show a much smaller variation.

For most models, recurrence time is expected to vary as \(\approx 1/m\), because the ignition depth (determined by hot CNO burning or by the flux from the crust) is insensitive to accretion rate. However, SAS-3 observations showed a much shallower dependence than the expected \(1/m\); Clark et al. (1977) observed the persistent flux to increase by a factor of \(\approx 5\) while \(t_{\text{recur}}\) went from 3.4 to 2.2 hr. Studies of timing and spectral behavior of LMXBs indicate that \(L_X\) is not necessarily well correlated with the underlying accretion rate (e.g., van der Klis et al. 1990). The observed behavior then requires \(m\) to increase less quickly than \(L_X\). It would be interesting to study burst properties as a function of an accretion rate indicator (e.g., position in the color-color diagram) rather than \(L_X\). Variations in heating with \(m\) due to thermal inertia might play some role, something that should be checked with time-dependent simulations. Alternatively, these observations might indicate new physics, for example, that the accreting material covers only part of the star at lower accretion rates, reducing the amount by which the local accretion rate changes (a possibility suggested for hydrogen accretors by Bildsten 2000). An interesting exception to the predicted \(1/m\) behavior is for models with \(X_0 \approx 0.1\), when the time to burn all the hydrogen is \(\approx 3\) hr, in the range of observed recurrence times. For \(X_0 \approx 0.1\) and \(t_{\text{recur}} > 3\) hr, the recurrence time is predicted to increase rapidly with decreasing \(m\), because hydrogen burning no longer occurs throughout the layer. However, this is even less consistent with the observed variations.

The burst energy is overpredicted in these models, in common with some other studies of bursters. For GS 1826–24, Galloway et al. (2003) find a factor of \(\sim 4\) discrepancy depending on metallicity and raise the possibility of partial covering (Bildsten 2000). For 4U 1636–56, Fujimoto et al. (1987) proposed that vertical mixing driven by rotational shear in the incoming material led to early ignition and reduced burst energies. Here, I find discrepancies of less than a factor of 2 for 4U 1820–30. This is easily accommodated, for example, by anisotropic burst emission (Lapidus & Sunyaev 1985; Fujimoto 1988) and does not require incomplete spreading of the fuel or extra mixing. Note, however, that the discrepancy increases if the neutron star radius is larger than the 10 km assumed here (\(E_{\text{burst}} \propto R^2\)).

I have concentrated on the recurrence time and total burst energy and have not discussed other properties, such as the peak luminosity or burst duration. Type I bursts from 4U 1820–30 generally show radius expansion, in which the luminosity reaches the Eddington limit. Kuulkers et al. (2003) recently surveyed the peak luminosity of globular cluster bursters. For 4U 1820–30, the average peak flux is 5.27 \(\pm\) 0.72 \(\times 10^{-2}\) ergs cm\(^{-2}\) s\(^{-1}\), or a luminosity 3.7 \(\times 10^{38}\) ergs s\(^{-1}\) for a distance of 7.6 kpc. The pure helium Eddington limit is \((3.5–5) \times 10^{38}\) ergs s\(^{-1}\) for \(M = 1.4–2 M_\odot\) (not including general relativistic corrections). When hydrogen is present, the Eddington luminosity is reduced by a factor \(1 + X\). However, for small \(X\), this change is much less than the uncertainty in the neutron star mass and so does not allow a determination of hydrogen content.

The durations of bursts from 4U 1820–30 are \(\approx 20–30\) s (with exponential decay times \(\approx 10\) s), consistent with pure helium burning, in which the helium burns rapidly and the burst duration is set by the cooling time of the layer. For solar abundance of hydrogen, slow hydrogen burning via the rp-process (Wallace & Woosley 1981) extends the decay time to \(\sim 100\) s (Hanawa, Sugimoto, & Hashimoto 1983; Wallace & Woosley 1984; Hanawa & Fujimoto 1984; Schatz et al. 1998). However, for \(X_0 \leq 0.1\), most of the protons are able to burn by direct capture on carbon. Therefore, the small amount of hydrogen considered in this paper is not expected to substantially increase the burst duration. This is something that could be addressed by time-dependent simulations with increasing hydrogen fractions.

3.2. Superbursts

In §2.5, I used the accretion rates determined by matching the type I burst recurrence times to calculate superburst ignition conditions. For pure He accretion, the expected superburst recurrence times are \(\approx 1–2\) yr (for \(Q_{\text{crust}} \approx 0.1–0.2\) MeV nucleon\(^{-1}\)), much less than found by SB02 (who took \(m = m\)). If hydrogen is present, the smaller \(m\) gives recurrence times \(\approx 5–10\) yr. This approach of simultaneously modeling type I bursts and superbursts can be usefully
applied to other superburst sources that exhibit regular type I bursts. A promising candidate is KS 1731–260, for which observations of the quiescent flux constrain $Q_{\text{crust}}$ (Rutledge et al. 2002). In addition, these results emphasize that determining the superburst recurrence time would strongly constrain the local accretion rate and thermal structure of the star and thereby constrain the composition of the accreted material.

A direct effect of hydrogen in the accreted material will be to reduce the amount of carbon made during H/He burning. For pure helium accretion, SB02 argued that carbon production occurs during stable burning at high $m$, for which the temperature is low enough to give a high carbon yield (Brown & Bildsten 1998). However, if hydrogen is present, protons will rapidly capture on $^{12}$C, initiating the hot CNO cycle. In that case, breakout reactions $^{15}$O($\alpha$, $\gamma$) and $^{14}$O($\alpha$, $p$) become possible (Wallace & Woosley 1981; Schatz et al. 1998), depleting the CNO abundance and reducing the carbon yield. For $X_{\text{H}} = 0.1$, there are enough protons for one proton capture on each $^{12}$C. The outcome is probably different for $X_{\text{H}}$ above and below this value, which is within the range predicted by models (Podsiadlowski et al. 2002). For solar abundance of hydrogen, Schatz et al. (1999) found stable burning gave $X_{\text{C}} \sim 10\%$ (still enough to ignite a superburst, however, as CB01 showed). Calculations of the carbon production for stable helium burning with a small amount of hydrogen should be carried out.

Finally, it has been noted that the superburst from 4U 1820–30 is different from the superburst seen in other sources (Kuulkers et al. 2002). It was the most energetic and is the only superburst thus far to reach Eddington luminosity. This is probably due to the low hydrogen abundance in the accreted material. A lower hydrogen abundance allows greater carbon production and makes lighter ashes (the heavy nuclei are probably iron group with $A \approx 56$ rather than rp-process ashes with $A \approx 100$), reducing the opacity and giving a deeper ignition. Both these effects give a larger nuclear energy release, which could explain the more energetic and luminous superburst.

3.3. Transition to Stable Burning

The calculations described here apply only to the low state, when regular type I bursts are seen, and do not address the disappearance of bursts in the high state. This is an important question to answer. In spherically symmetric models, burning becomes stable at high accretion rates because the temperature sensitivity of the triple alpha reaction decreases with temperature, and the incoming helium then burns at the rate at which it accretes (Fujimoto et al. 1981; Ayasli & Joss 1982; Taam, Woosley, & Lamb 1996).

However, the transition to stable burning for pure helium accretion occurs at $m_{\text{stab}} \approx 2 \times 10^6$ g cm$^{-2}$ s$^{-1}$ (B95; Bildsten 1998), much higher than the accretion rate of 4U 1820–30. The extra nuclear energy release if hydrogen is present will decrease $m_{\text{stab}}$, but not enough to explain the observed transition. B95 suggested that the missing piece of physics was that the bursts become radiative rather than convective in the high state. The burning then proceeds as a slowly propagating “fire” over the stellar surface rather than dramatic type I bursts. However, the ignition of a local spot on the surface of the star is not understood, requiring stabilization of pressure gradients, perhaps by rapid rotation (Spitkovsky, Levin, & Ushomirsky 2002; Zingale et al. 2003).

4U 1820–30 fits into the pattern of bursting seen in other sources: a transition from frequent, regular bursting to infrequent, irregular bursting as accretion rate increases (van Paradijs et al. 1988). By comparing BeppoSAX/WFC data for nine frequent bursters (including 4U 1820–30), Cornelisse et al. (2003) concluded that this transition occurs at a universal luminosity $L_{\text{X}} \approx 2 \times 10^{36}$ ergs s$^{-1}$. If this behavior is common to all bursters, two explanations that have been put forward for hydrogen accretors may be relevant for 4U 1820–30. First, Narayan & Heyl (2003) recently studied the linear stability of quasi-steady burning shells, finding that some stable burning occurs during accumulation for accretion rates near the transition to stability. Whether this result applies to pure helium accretion should be investigated further. Second, for hydrogen accretors, Bildsten (2000) suggested that the fraction of the star covered with fresh fuel increases with increasing global $M$, so that the local accretion rate $m$ decreases. The observed transition is then from mixed H/He ignition ($t_{\text{recur}} < t_{\text{H}}$) giving frequent, regular bursts to pure He ignition, giving irregular, less frequent bursts ($t_{\text{recur}} > t_{\text{H}}$). The different composition in 4U 1820–30 makes it difficult to apply the same explanation, and the regularity of the bursts perhaps implies complete covering. Increasing area with $M$ would explain the small change in recurrence time seen by Clark et al. (1977). Accurate fluence measurements together with spectral fits to the radius as a function of $t_{\text{recur}}$ are a way to test this picture.

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