MODELS OF TYPE I X-RAY BURSTS FROM GS 1826–24: A PROBE OF rp-PROCESS HYDROGEN BURNING

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ABSTRACT

The X-ray burster GS 1826–24 shows extremely regular Type I X-ray bursts whose energetics and recurrence times agree well with thermonuclear ignition models. We present calculations of sequences of burst light curves using multizone models that follow the nucleosynthesis (αp and rp-processes) with an extensive nuclear reaction network. The theoretical and observed burst light curves show remarkable agreement. The models naturally explain the slow rise (duration ≈5 s) and long tails (≈100 s) of these bursts, as well as their dependence on mass accretion rate. This comparison provides further evidence for solar metallicity in the accreted material in this source and gives a distance to the source of 6.07 ± 0.18 kpc, where ξ, is the burst emission anisotropy factor. The main difference is that the observed light curves do not show the distinct two-stage rise of the models. This may reflect the time for burning to spread over the stellar surface or may indicate that our treatment of heat transport or nuclear physics needs to be revised. The trends in burst properties with accretion rate are well reproduced by our spherically symmetric models that include chemical and thermal inertia from the ashes of previous bursts. Changes in the covering fraction of the accreted fuel are not required.

Subject headings: accretion, accretion disks — stars: individual (Ginga 1826–238, GS 1826–24) — stars: neutron — X-rays: bursts

1. INTRODUCTION

The basic physics of Type I X-ray bursts as thin shell flashes on the surfaces of accreting neutron stars was understood many years ago (e.g., Fujimoto et al. 1981; Lewin et al. 1995). Nonetheless, detailed comparisons of observations and theory are often less than successful (Fujimoto et al. 1987; van Paradijs et al. 1988). The burster GS 1826–24 (aka Ginga 1826–24) is an important exception. Ubertini et al. (1999) dubbed it the “clocked burster” because of its extremely regular bursting behavior. They found a burst recurrence time close to 6 hr with a dispersion of approximately 6 minutes. Bildsten (2000) dubbed it the “textbook burster” because of the good agreement with theory. He noted that the burst energetics and recurrence times were as expected for the inferred accretion rate $\dot{M} \approx 10^{-9} M_{\odot} \, yr^{-1}$ and proposed that the long burst tails, lasting ≈100 s, were powered by rp-process hydrogen burning (Wallace & Woosley 1981; Hanawa & Fujimoto 1984). The rp-process involves a series of proton captures and beta-decays on heavy nuclei close to the proton drip line, for which there are considerable uncertainties in beta decay rates, reaction rates, and nuclear masses. Type I X-ray bursts offer an important test of our understanding of this process.

Galloway et al. (2004, hereafter G04) studied 24 bursts observed from GS 1826–24 by the Rossi X-Ray Timing Explorer (RXTE) between 1997 November and 2002 July and carried out a detailed comparison of the observed recurrence times and energetics with theory. During this period, the accretion rate (assumed to be proportional to the persistent X-ray luminosity) increased by ≈50%, while the burst recurrence time decreased from $\Delta t \approx 6$ hr to $\approx 4$ hr. At the observed accretion rate $\dot{M} \approx 10^{-9} M_{\odot} \, yr^{-1}$, hydrogen burns stably between bursts by the beta-limited hot CNO cycle (Hoyle & Fowler 1965), heating the accumulating layer of hydrogen and helium at a rate that depends only on the mass fraction of CNO elements. The resulting ignition column depth of $\approx 2 \times 10^{19} g \, cm^{-2}$ is nearly independent of $\dot{M}$ (e.g., Cumming & Bildsten 2000), in agreement with the observed scaling, which is close to $\Delta t \propto 1/\dot{M}$.

G04 used the variation of burst energetics with accretion rate to constrain the composition of the accreted material. The energetics are measured by the ratio $\alpha$ of integrated persistent flux between bursts to the burst fluence, equivalent to the ratio of the gravitational energy release from accretion to the nuclear energy release in bursts. The observed value $\alpha \approx 40$ is close to the value expected for the 4–5 MeV per nucleon energy release in hydrogen burning (Bildsten 2000). G04 found that $\alpha$ decreased from $\approx 44$ in 1997 to $\approx 40$ in 2002. This is consistent with the change in composition of the fuel layer expected from hot CNO burning between bursts, if the accreted material has solar metallicity. For a shorter recurrence time, less hydrogen burns between bursts, resulting in a larger burst energy and smaller $\alpha$. In addition, G04 found that whereas the ignition models predicted that the ignition column depth should increase slightly with $\dot{M}$, the observed trend was the opposite.

The study of G04 did not include models of the burst light curves. In this Letter, we compare observations of GS 1826–24 with multizone models (Woosley et al. 2004) that include a large nuclear reaction network to follow the rp-process in detail. We show that these models naturally explain the slow rise (duration $\approx 5$ s) and long tails (≈100 s) of these bursts. We show that our time-dependent models reproduce the scalings of the recurrence time with accretion rate for a metallicity near solar.

2. COMPARISON OF OBSERVATIONS WITH TIME-DEPENDENT BURST MODELS

We calculate sequences of bursts as described by Woosley et al. (2004, hereafter W04). The KEPLER code (Weaver et al. 1978) is used to follow the evolution of the outer layers of the neutron star through a sequence of successive bursts. A
A summary of the results is given in Table 1. For each sequence of bursts, we list the rest mass accretion rate $\dot{M}$, recurrence time $\Delta t$, burst energy $E_{\text{burst}}$, gravitational mass accumulated between bursts $\Delta M = M\Delta t/(1 + z)$, and $\alpha = F_p \Delta t/E_{\text{burst}} = \Delta M c^2/2E_{\text{burst}}$, all as seen by an observer at infinity. The quantities given are averaged over all bursts except the first burst in each sequence, which is typically more energetic than the subsequent bursts (W04). We give the standard deviation of each quantity in parentheses, to show the burst-to-burst variations. Models A4 and B3, which have $\dot{M} \approx 3\%$ between the burst properties in models A4 and B3. These models are chosen because they have similar recurrence times to the observed recurrence time of 4.1 hr. We calculate the mean light curves by aligning bursts in each sequence by their peak luminosities. The error bars in Figure 1 show the $1\sigma$ burst-to-burst variation about the mean observed light curve. The shaded region shows the same variation for the theoretical light curves.

For this comparison, we choose the distance to the source (within the allowed range $4 < d < 8$ kpc; G04) so that the peak luminosity of the observed bursts agrees with the peak luminosity of bursts from model A3. The relation between the peak burst luminosity $L_{\text{peak}}$ and the observed peak flux is $4\pi d^2 \xi_s F_{\text{peak}} = L_{\text{peak}}$, where $\xi_s$ is a factor that accounts for possible anisotropy in the burst emission (e.g., Fujimoto 1988). The average observed peak flux in the 2000 epoch is $(2.93 \pm 0.15) \times 10^{30} \text{ ergs cm}^{-2} \text{ s}^{-1}$, and the average peak luminosity of bursts in model A3 is $L_{\text{peak}} = (1.29 \pm 0.04) \times 10^{30} \text{ ergs s}^{-1}$, giving a distance $d = 6.07 \pm 0.18$ kpc $\xi_s^{1/2}$.

Once the bursts have been normalized in this way, the agreement between the observed and theoretical light curves for $Z = 0.02$ (model A3) is remarkable. Model A3 fits the observed decay exceedingly well out to about 40 s, falling a little below the observed flux between 40 and 120 s. The burst-to-burst variations in the models are also of comparable magnitude to the burst-to-burst variations in the data. The most significant difference is that the theoretical model shows a distinct two-stage rise that is not apparent in the observed light curve (see Fig. 1 inset).

Model B3, which has a low metallicity, does not reproduce the observed light curve. Given the uncertainty in the distance to the source, the normalization may be adjusted to bring the observed and predicted peak luminosities into agreement, but the shape of the decay provides an additional constraint. In model B3, the lower metallicity leads to very little hydrogen.
burning between bursts, giving less helium and more hydrogen at ignition than in the solar-metallicity model. The result is a burst with a much longer tail, inconsistent with the observed profile for any distance.

In Figure 2, we compare the burst recurrence times, energies, $\alpha$-values, and ignition masses as a function of accretion rate for the observed bursts and the solar-metallicity models A1–A4. The observed burst fluence $F_b$ is related to the burst energy $E_b$ by $F_b = 4\pi d^2 \xi_s E_b$, and we adopt the same value of $\xi_s d^2$ that we determined earlier by comparing the burst peak luminosity with the observed peak flux. We convert the bolometric flux $F_X$ to accretion rate $\dot{M}$ using the relation $4\pi d^2 \frac{\dot{M}}{c^2} F_X = Mc^2\nu/(1+z)$, where $\xi_p$ is a factor that accounts for possible anisotropy in the persistent emission (e.g., Fujimoto 1988). For the same value of distance, we find that $\xi_p/\xi_s = 1.55$ is required for the recurrence times to match in Figure 2. The theoretical $\alpha$-values have been divided by this same factor to give the correct prediction for $\alpha$ including anisotropic emission.

The agreement between the models and observations in Figure 2 is excellent. The main difference is that the burst energy is overpredicted by approximately 5% and the $\alpha$-value underpredicted by the same factor. The low-metallicity models B1–B3 are not consistent with the observed trends. For example, the burst energies show a factor of 2 variation in these models over the observed accretion rate range (Table 1), much larger than the $\approx 10\%$ variations seen in the data.

Figure 3 shows how the burst light curves change with accretion rate (models A1–A3). G04 pointed out that the burst light curves changed with recurrence time. They fitted the decay of the bursts to an exponential profile with a break in the exponential decay time. The theoretical curves show a similar two-timescale decay (this is particularly apparent in the lower panel of Fig. 1). G04 noted a significant increase in the first exponential decay timescale as $\Delta t$ decreased, from $14.7 \pm 0.7$ s when $\Delta t \approx 6$ hr to $17.5 \pm 1.1$ s when $\Delta t \approx 4$ hr. The second exponential decay timescale $43 \pm 1$ s showed no significant change. G04 speculated that this change was a result of the composition of the fuel, since more hydrogen is depleted between bursts for larger $\Delta t$.

Figure 3 shows that the model light curves show a similar change with accretion rate to the observed light curves, presumably relating to the changing hydrogen/helium ratio at ignition. This is quantified in Figure 4, which shows fitted exponential decay times for the observed and model bursts. Overall, the agreement is good, although the decay times of the model bursts are generally slightly shorter than observed (consistent with the difference in the burst tails in Fig. 1), and they show much larger burst-to-burst variations than observed. Also, whereas the observed bursts are well fitted by a two-timescale decay, some of the model bursts show a more complex decay profile, which we have fitted with three timescales.

3. DISCUSSION

We have presented a first comparison between multizone burst models and the observed bursts from GS 1826–24. The good agreement further confirms GS 1826–24 as a “textbook” burster. For a distance of $6.07 \pm 0.18$ kpc $\xi_s^{-1/2}$ (where $\xi_s$ is the burst emission anisotropy factor), our solar-metallicity models closely match the observed light curves. Both the long rise and decay times arise naturally from rp-process hydrogen burning. From the very regular nature of the bursting, G04 argued that the accreted material covers the entire surface of the neutron star; this is supported by the excellent agreement of our spherically symmetric models. Solar-metallicity models agree best with the observed light curves. Low-metallicity models
produce too little helium by hot CNO burning prior to ignition, leading to a lower peak luminosity and a longer rp-process tail. This agrees with the conclusions of G04, who argued for solar metallicity on the basis of the burst energetics. The estimate of the distance is based on a comparison of mean burst light curve at a single epoch, with the light curve predicted by the model for parameters giving the same recurrence time. It is possible that light-curve comparisons at different epochs (i.e., values of the recurrence time) may result in different values of the distance and/or anisotropy parameters. Such comparisons will provide an additional consistency check for the distance estimation, which we will undertake in a future paper.

Our models reproduce the observed variation in burst recurrence times, energies, and $\alpha$-values with accretion rate for a ratio of anisotropy factors for the persistent and burst emission as well as a slightly shorter burst tail. Another difference in burst shape is that, unlike the observations, some of the model light curves show a three-stage rather than two-stage decay. These differences may relate to our treatment of heat transport (especially convection) or nuclear physics. W04 confirmed previous findings that burst tails are sensitive to nuclear flows above the iron group (Schatz et al. 2001; Koike et al. 1999) and also pointed out that the rise times are sensitive to nuclear decays below the iron group. An alternative for the rise is that a finite propagation time for the burning around the star of $\sim 1$ s (e.g., Fryxell & Woosley 1982; Spitkovsky et al. 2002) might act to “wash out” the kink.

The neutron star mass and radius also change the predicted burst properties. In this Letter, we have considered a neutron star with redshift factor $z = 0.26$, corresponding to $M = 1.4 M_\odot$ and $R = 11.2$ km. A smaller radius of 10.6 km would reduce the predicted burst energies by 5% and would increase the redshift factor and therefore $\alpha$, bringing both of these quantities into better agreement with observations (Fig. 2). We will investigate the constraints on the neutron star mass and radius in detail in future work.

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