Consistent Modeling of GS 1826-24 X-Ray Bursts for Multiple Accretion Rates Demonstrates the Possibility of Constraining rp-process Reaction Rates

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Abstract

Type-I X-ray burst light curves encode unique information about the structure of accreting neutron stars and the nuclear reaction rates of the rp-process that powers bursts. Using the first model calculations of hydrogen/helium-burning bursts for a large range of astrophysical conditions performed with the code MESA, this work shows that simultaneous model–observation comparisons for bursts from several accretion rates  are required to remove degeneracies in astrophysical conditions that otherwise reproduce bursts for a single  and that such consistent multi-epoch modeling could possibly limit the reaction rate. Comparisons to the 1998, 2000, and 2007 bursting epochs of the neutron star GS 1826-24 show that  must be larger than previously inferred and that the shallow heating in this source must be below 0.5 MeV/u, providing a new method to constrain the shallow heating mechanism in the outer layers of accreting neutron stars. Features of the light curve rise are used to demonstrate that a lower limit could likely be placed on the reaction rate, demonstrating the possibility of constraining nuclear reaction rates with X-ray burst light curves.

Key words: nuclear reactions, nucleosynthesis, abundances -- stars: neutron -- X-rays: bursts

1. Introduction

Type-I X-ray bursts, periodic thermonuclear explosions driven and fueled by hydrogen- and/or helium-rich mixtures siphoned from a binary companion, provide unique insight into the structure and dense matter of the neutron stars that host them (Joss 1978; Lamb & Lamb 1978; Schatz et al. 1998; Parikh et al. 2013; Arcones et al. 2017). X-ray burst models require detailed input regarding the compositional and thermal structure of the neutron star envelope, as well as well over 1000 reaction rates involving more than 300 nuclides (Wallace & Woosley 1981; Schatz et al. 2001; Woosley et al. 2004; Fisker et al. 2008; José et al. 2010). Many important calculation inputs, such as the accretion rate  and nuclear reactions rates of the rapid proton-capture (rp)-process powering bursts, have distinctive influences on the calculation results (Woosley et al. 2004; Parikh et al. 2008, 2009; Cyburt et al. 2016; Lampe et al. 2016; Schatz & Ong 2017). This enables model–observation comparisons to determine unique solutions, resulting in astrophysical constraints on an X-ray bursting object (Heger et al. 2007; Galloway et al. 2017; Johnston et al. 2018).

The consistency of the X-ray burster GS 1826-24 (Galloway et al. 2004, 2008) and its “textbook” behavior (Bildsten 2000) have made it the primary target of past model–observation comparisons (Heger et al. 2007; Zamfir et al. 2012; Galloway et al. 2017). To date, all of this pioneering work has been performed using the multizone astrophysical modeling code KEPLER (Weaver et al. 1978; Woosley et al. 2004), aside from initial proof-of-principle calculations performed with the open-source multizone evolution code MESA (Paxton et al. 2015) and a simple ignition model use to predict burst recurrence time (Galloway et al. 2004). These KEPLER model–observation comparisons constrained the astrophysical conditions for GS 1826-24 by reproducing the recurrence time between bursts  for several  and the average burst light curve for a single . However, simultaneous light curve comparisons for a consistently modeled range of  that approximates the observed  variation have not yet been performed. The peril in this approach is that the light curve shape from models is known to vary over the range of  similar to that inferred from observations of hydrogen/helium-burning Type-I X-ray bursts (Lampe et al. 2016).

Furthermore, the sensitivity of models to varied nuclear reaction rates has not yet been accounted for in model–observation comparisons, though some rates are known to substantially impact model calculations. In particular, the reaction rate has been shown to alter beyond observational uncertainties and to modify the light curve shape much more than the natural variations observed for GS 1826-24 over its regular bursting epochs (Fisker et al. 2007; Cyburt et al. 2016).

Here, the first consistent comparison to X-ray burst light curves for a bursting source over a range of  is used to demonstrate that multi-epoch reproduction is required to remove degeneracies in astrophysics model parameters and achieve tighter astrophysical constraints than previously possible. These calculations, the first to model hydrogen/helium-burning bursts for a large range of input conditions with MESA, demonstrate that model–observation comparisons can place tight constraints on the strength of shallow heating in the accreted neutron star outer layers and that GS 1826-24 has a higher  than previously inferred from models. Additionally, the possibility of constraining nuclear reaction rates in the rp-process with X-ray burst light curves is demonstrated by showing that a lower limit could likely be placed on the reaction rate. A follow-up paper will compare results from the full grid of model calculations used for this work to results from a similar grid of calculations performed with KEPLER (Lampe et al. 2016). A previous paper featured MESA X-ray burst ash abundances (Meisel & Deibel 2017).

2. Model Calculations

Type-I X-ray burst model calculations were performed with the one-dimensional stellar evolution code MESA version 9793.
The numerical approach and physics models adopted in MESA are detailed in the associated instrumentation papers (Paxton et al. 2011, 2013, 2015, 2018). Here, the most pertinent details for this work are summarized. The neutron star envelope is 0.01 km thick, with an inner boundary of neutron star mass $M_{NS} = 1.4 \ M_\odot$ and radius $R_{NS} = 11.2 \ km$, comprised initially of 70% hydrogen, 28% helium, and 2% metals, by mass, using the solar metallicity $Z$ of Grevesse & Sauval (1998). The envelope is discretized into $\sim 1000$ zones, which adapts during the calculation, where the local gravity in a zone is corrected for general relativity effects using a post-Newtonian correction. Convection is approximated using the mixing length theory of Henyey et al. (1965) and is time dependent (Paxton et al. 2011). Accretion is achieved by adding a small amount of mass to the model’s outer layers and readjusting the stellar structure (Paxton et al. 2011). The spatial and time resolution are adaptive, where the MESA settings varcontrol_target=1d-3 and mesh_delta_coeff=1.0 (Paxton et al. 2013) were chosen after tests for convergence of the light curve shape and $\Delta t_{rec}$ in which varcontrol_target from $10^{-4}$ to $10^{-2}$ and mesh_delta_coeff from 0.5 to 2.0 were investigated. Here, convergence means that the mean light curve and recurrence time changed $\ll 1\sigma$ for finer spatial and/or time resolution settings. The nuclear reaction network includes the 304 isotopes of Fisker et al. (2008) using reaction rates from the REACLIB V2.2 library (Cyburt et al. 2010).

Sequences of X-ray bursts were simulated for 84 different sets of initial conditions, where models differed in $M$, $Q$, $Z$, hydrogen mass fraction $X$, and a reduction factor for the $^{15}\text{O}(\alpha,\gamma)$ reaction rate $R$. The number of bursts $N$ belonging to a sequence varies, mostly due to numerical and practical challenges. Example burst sequences are shown in Figure 1. Simulations were performed in sets of three for $M$, with a low, medium, and high multiple of the Eddington accretion rate $M_{\text{Edd}} = 1.75 \times 10^{-8} \ M_\odot \ yr^{-1}$ (Schatz et al. 1999). A low set, $M = 0.05$, 0.07, 0.08$M_\odot$, matched observed $M$ for the 1998, 2000, and 2007 bursting epochs of GS 1826-24 (Galloway et al. 2008). A high set, $M = 0.11$, 0.15, 0.17$M_\odot$, employed $M$ used in the proof-of-principle X-ray burst calculations of Paxton et al. (2015) for the highest $M$ and then reduced this by the ratio of $M$ for the observation epochs. For example, $0.17 \ M_{\text{Edd}} \times (0.05)/(0.08) \approx 0.11 \ M_{\text{Edd}}$. $Q_b = 0.1$, 0.5, 1.0 MeV/u were used to mimic the shallow heating of unknown origin that is thought to operate in the outer layers of accreting neutron stars (Brown & Cumming 2009; Keek & Heger 2017), where the lower limit on the order expected from accretion-induced reactions in the accreted neutron star crust (Gupta et al. 2007; Meisel et al. 2016) and the upper limit is on the order of typical shallow heating inferred from observations of neutron star cooling after accretion turn-off (Brown & Cumming 2009; Turlione et al. 2015). In MESA this is achieved by fixing the luminosity of the base of the envelope, so that the base luminosity depended on $Q_b$ and $M$ of the model. $Z = 0.01$, 0.02 were used to investigate the solar $Z$ favored by previous investigations of GS 1826-24 (Galloway et al. 2004; Heger et al. 2007) and a slight reduction from that value. $X = 0.7$ and helium mass fraction $Y = 0.28$ were used for most simulations, while $X = 0.75$ and $Y = 0.23$ were employed for a set of simulations with $Q_b = 0.1$ and 1.0 MeV/u for each $M$, $R = 1$, 5, 10 were used, as $R = 10$ is roughly the inferred lower limit for the $^{15}\text{O}(\alpha,\gamma)\gamma$ rate uncertainty (Tan et al. 2007; Davids et al. 2011) and rate increases have not been found to impact the burst light curve (Cyburt et al. 2016). Strictly speaking, using a rate scaling factor is a simplification as compared to using upper and lower rate limits based on experimental uncertainties. However, the present rate uncertainty is generally a factor of 10 or larger in the temperature range of interest (Davids et al. 2011), namely, from the onset of hot CNO cycle burning to breakout, $\sim 0.1$–0.5 GK (Wiescher et al. 1999). Furthermore, a rate scaling factor enables a more direct comparison to similar calculations performed in the past with the codes KEPLER and AGILE (Fisker et al. 2007; Cyburt et al. 2016).

![Figure 1](image_url)

**Figure 1.** Bolometric luminosity over time (not redshifted), for example, MESA calculations. The legends indicate, in order, $M$, $Q_b$, $Z$, and $R$, $X = 0.7$ for each of these models. The bottom panel shows the average light curve, excluding the first burst, for all bursts in a sequence for a set of conditions, where the color of the band matches the color of the corresponding burst sequence above.

### 3. Light Curve Construction

In order to compare to observational data, bursts in a simulated sequence needed to be stacked (as is done with observed light curves) so that an average light curve and uncertainty band could be calculated. The first burst in a sequence was excluded, as the first simulated burst is typically far more energetic than subsequent
bursts (Woosley et al. 2004). The burst start time \( t = 0 \) was defined as the point when the luminosity crossed a threshold indicating thermonuclear runaway. Individual bursts were mapped onto the same time grid with a linear spline and, to mitigate numerical noise, each burst light curve was smoothed by averaging over the luminosity for a \( \pm 1 \) s time window. This smoothing is frequently done for multizone numerical calculations of X-ray burst light curves, e.g., as described for the KEPLEER models of Cyburt et al. (2016). Using luminosity data from all bursts (after the first) in a sequence, an average luminosity and upper and lower \( 1\sigma \) uncertainties were computed for each time point. An example of this process is shown in Figure 2.

4. Observational Data

The observed light curve data for GS 1826-24 are courtesy of the Multi-Instrument Burst Archive.2 The data analysis is described in Galloway et al. (2017) and is briefly rehashed here. Observational data from the Rossi X-ray Timing Explorer (Galloway et al. 2004, 2008) were stacked and averaged in a similar manner as described above for the simulated light curves of this work. Since uninterrupted observation was not possible due to periodic occultation by the Earth, observed recurrence times were determined using an iterative approach. Each burst was assigned a trial integer indicating which burst it was in the sequence and a fit was performed to quantify how well the set of assignments matched the data if one assumes a regular recurrence time. The observed \( M \) were determined using a distance of 6.1 kpc, a bolometric correction \( c_{\text{bol}} \) between \( \approx 1.75-1.8 \), and the average persistent flux \( F_p \) over the burst sequence, where \( M = 4\pi d^2 F_p c_{\text{bol}} / M_E \).

These observed \( M \) are potentially systematically shifted by some factor from the true \( M \) based on the fact that no burst anisotropy \( \xi \) (Fujimoto 1988; He & Keek 2016) is assumed. Anisotropy accounts for the fact that X-ray flux can be beamed toward or away from the observer, where the effect depends on the accretion disk geometry and source inclination angle and can be different for the burst flux and the persistent flux. This is described in more detail in the discussion.

5. Model–Observation Comparisons

Comparison to observations required adjusting the simulated light curve for the distance and surface gravitational redshift \( (1+z) \). The burst anisotropy \( \xi_b \) is included in the distance, so that distance is \( d_{b}^{1/2} \). The luminosity \( L \) to flux \( F \) conversion is \( F = L/(4\pi c_{\text{bol}} (1+z) d_{b}^{2}) \) (Galloway et al. 2017). Time is redshifted by multiplying the simulation time by \( (1+z) \). In principle, the neutron star mass and radius adopted for the simulations correspond to \( (1+z) = 1.26 \), so choosing other redshifts is inconsistent. However, in practice, burst properties are insensitive to modest changes in \( M_{\text{NS}} \) and \( R_{\text{NS}} \) (Ayisli & Joss 1982; Zamfir et al. 2012).

Model–observation comparisons were performed by calculating \( F(t) \) for the averaged light curve for the highest \( M \) in a set of three and comparing to the 2007 burst epoch of GS 1826-24. For each point in a grid of \( d_{b}^{1/2} \), \( (1+z) \), and a time shift \( \delta t \), \( x_{\text{red}}^2 \) was calculated using data from \( t = 0-50 \) s. \( \delta t \) is necessary, so that neither the burst rise nor tail dominates \( x_{\text{red}}^2 \). \( d_{b}^{1/2} \) varied in steps of 0.2 kpc from 4 to 8 kpc, based on observational limits (Galloway et al. 2004). \( (1+z) \) varied in steps of 0.02 from 1.18 to 1.44, in order to roughly stay within the range \( R_{\text{NS}} \sim 8-15 \) km determined by Steiner et al. (2010) for \( M_{\text{NS}} = 1.4 M_{\odot} \). \( \delta t \) varied from 0.5 to 1.5 s in steps of 0.1 s, as the best fit was located in this range for each of the 84 models. The results for the best fit out of all models (which also roughly reproduced the observed \( \Delta t_{\text{obs}} \); see Figure 5) is shown in Figure 3. The tight constraints on \( d_{b}^{1/2} \) are due to its strong

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1 An example of when this has not been done are the light curves of Josè et al. (2010), where (inconsequential) sharp, unphysical features are seen in some calculation results.
2 https://burst.science.monash.edu/minbar/
impact on the peak $F$, where as $(1+z)$ is poorly constrained due to the competition between fitting the burst rise and burst tail (and is sensitive to the range over which time is fit; Zamfir et al. 2012).

To move beyond previous studies, a consistent comparison to the 1998, 2000, and 2007 burst epochs was performed by calculating $F(t)$ for each model using $d_{b}^{1/2}$, $(1+z)$, and $\delta t$ obtained for the best fit to the 2007 outburst for the highest $M$ model in a set of three, i.e., $F(t)$ for $M = 0.05$ and $0.07 M_{\odot}$ models were calculated using the best-fit $d_{b}^{1/2}$, $(1+z)$, and $\delta t$ found for $M = 0.08 M_{\odot}$ models, whereas $M = 0.11$ and $0.15 M_{\odot}$ $F(t)$ were calculated based on $M = 0.17 M_{\odot}$ models, for the same $Q_{b}$, $Z$, $X$, and $R$. The justification for comparing simulations with $M$ higher than the observed values to observed light curves is that $\xi_{b}$ can differ from the persistent anisotropy $\xi_{b}$ in between bursts, so that the true $M$ could be different than inferred from observations (Fujimoto 1988; Galloway et al. 2017). Example model–observation comparisons are shown in Figure 4, including a comparison to the best fit found with KEPLER, as reported by Galloway et al. (2017), using light curves calculated by Lampe et al. (2016). The lowest $M$ KEPLER model shown is not as low as would be required to match the observed $M$ ratio, but is the closest available. $\mathcal{A}_{\text{rec}}$ is the average time between thermonuclear runaways using the best-fit $(1+z)$ for the highest $M$ in the set of three. Comparisons to the observed $\mathcal{A}_{\text{rec}}$, normalizing $M$ so that the highest $M$ of a set of three (i.e., 0.08 or 0.17 $M_{\odot}$) matches $M$ for the 2007 epoch of GS 1826-24, are shown in Figure 5.

6. Discussion

6.1. Model Parameter Impacts

Prior to discussing the results from model–observation comparisons, the impact of model parameters on the X-ray burst light curve and recurrence time are briefly discussed.

Increased $M$ decreases $\mathcal{A}_{\text{rec}}$. This is because the shallow heating scales with the accretion rate, increased heating speeds up the CNO cycle, which results in an earlier arrival at the temperature and He abundance required to trigger the $3\alpha$ reaction for burst ignition. Lower $M$ requires more H to be burned prior to burst ignition, resulting in a smaller H/He ratio at burst ignition, and therefore a relatively He-rich burst. He-rich bursts burn fuel more rapidly, with higher peak luminosities and shorter tail decay times as compared to less He-rich conditions (Weinberg et al. 2006).

Increased $Q_{b}$ decreases $\mathcal{A}_{\text{rec}}$ for a given $M$ due to the influence of shallow heating on burst recurrence discussed above for $M$. Similarly, for a given $M$, increased $Q_{b}$ preserves H prior to burst ignition, extending the burst tail, which is powered by H-burning. When considering a range of $M$, increased $Q_{b}$ increases the curvature in the trend for the $M - \mathcal{A}_{\text{rec}}$ relationship. This is because the shallow heating in the model results from the product of $M$ and $Q_{b}$, and therefore increasing both has a nonlinear influence on $\mathcal{A}_{\text{rec}}$.

Increased $Z$ corresponds to increased CNO abundances, increasing the amount of H-burning prior to burst ignition and leaving less H to burn during the burst. $Z$ was varied over a relatively small range here, so the only obvious impact is a slightly extended burst tail for $Z = 0.01$ relative to $Z = 0.02$. Increased $X$, at the expense of $Y$, naturally results in a reduced He abundance at burst ignition, and therefore a decreased peak luminosity, and more H left to burn during the burst, and therefore an extended burst tail.

The influence of $R$ on the burst properties derives from the nature of $^{15}\text{O}(\alpha,\gamma)$ as a “valve” controlling the flow of material out of the hot CNO cycle during interburst burning (Fisker et al. 2006; Cyburt et al. 2016). Decreasing the $^{15}\text{O}(\alpha,\gamma)$ reaction rate (increasing $R$) reduces the amount of material escaping the hot CNO cycle during quiescent burning, enabling more He to be produced prior to burst ignition, shortening $\mathcal{A}_{\text{rec}}$ and resulting in a more He-rich burst.

6.2. $M$ and $Q_{b}$ Constraints

Figure 4 demonstrates that the light curve shape for the 2007 burst epoch of GS 1826-24 can be accommodated for by several $M$ and $Q_{b}$, meaning reproduction of a light curve for a single observed $M$ is insufficient to constrain an X-ray bursting source’s conditions with model–observation comparisons. While $M = 0.08 M_{\odot}$ reproduces the 2007 epoch, lower $M$ in the set results in a larger peak flux and shorter burst tail decay than seen in observations, particularly for the lowest $M$. The figure shows that this result is not only seen with MESA, but also for KEPLER models. Therefore, the GS 1826-24 $M$ for observed bursting epochs must be larger than previously inferred.

Figure 5 demonstrates that $\mathcal{A}_{\text{rec}}$ provides an additional necessary discriminant, as models reproducing the light curve shape for all three observed epochs do not necessarily reproduce the observed $\mathcal{A}_{\text{rec}}$. Though $Q_{b} = 0.5 \text{MeV/u}$ can accommodate the light curve shape for all bursting epochs, $\mathcal{A}_{\text{rec}}$ is significantly shorter than for observations. Therefore, shallow heating in GS 1826-24 is limited to $\leq 0.5 \text{MeV/u}$, providing an example of how multi-epoch X-ray burst modeling can be used to constrain the shallow heating mechanism in accreting neutron star outer layers.

It is evident that $X = 0.75$ cannot be accommodated either, since there is a significant curvature in $\mathcal{A}_{\text{rec}}$ for decreasing $M$ that is not seen in the observed data. One sees a similar behavior in KEPLER models, which can be seen by comparing models a003 and a020 of Lampe et al. (2016). $X$ less than 0.7...
were not explored here as this would move toward the conditions for helium bursts, as most or all of the hydrogen would be burned stably before burst ignition.

The best-fit MESA model for light curve shape and $\Delta t_{\text{rec}}$ has $M = 0.17 M_E$ (for the 2007 epoch), $Q_h = 0.1 \, \text{MeV/u}$, $R = 1$, $X = 0.70$, and $Z = 0.02$, though the same conditions with $Z = 0.01$ perform nearly as well.

**Figure 4.** Comparison of light curves calculated with MESA (red bands) to GS 1826-24 light curves observed for 1998 (brown), 2000 (green), and 2007 (purple). Legends indicate the same information as the legend in Figure 1, where the additional number in parentheses is $N$. The red bands in the bottom right panel are light curves calculated with KEPLER from Lampe et al. (2016) using the optimum distance and redshift determined in Galloway et al. (2017).

6.3. Comparison to KEPLER

Figure 5 also highlights a discrepancy between MESA and KEPLER models. While KEPLER reproduces the 2007 epoch $\Delta t_{\text{rec}}$ with $M = 0.09 M_E$, MESA models require $M = 0.17 M_E$, as noted by Paxton et al. (2015). This cannot be explained by the slightly higher $Q_h$ employed in the best fit for KEPLER (Galloway et al. 2017), as the MESA model with $M = 0.08 M_E$
and \( Q_b \) 0.5 MeV/u results in \( \Delta t_{rec} \) roughly 2/3 larger than observed for the 2007 epoch. Systematic comparisons between MESA and KEPLER, which are beyond the scope of this work, are necessary to resolve this discrepancy.

Nonetheless, the constraints on \( \Delta t_{rec}^{1/2} \) for past KEPLER fits and for this work are in agreement, where the best fit here (see Figure 3) favors 6 kpc and the most recent KEPLER results (Galloway et al. 2017) favor 6.1 kpc. This work favors a much larger redshift than Galloway et al. (2017), \( (1+z) = 1.42 \) as compared to 1.23; however, Figure 3 demonstrates that \( (1+z) \) down to \( \sim 1.28 \) performs nearly as well. As in Galloway et al. (2017), uncertainties are not quoted here due to the large number of systematics that will require several further studies to quantify. It should be noted that \( (1+z) = 1.42 \) corresponds to \( R_{NS} = 8.2 \) km for the canonical \( M_{NS} = 1.4 \, M_\odot \), which is smaller than expected (Steiner et al. 2013), though \( R_{NS} = 11.7 \) km for \( M_{NS} = 2.0 \, M_\odot \) (Lampe et al. 2016).

6.4. Anisotropies

The burst anisotropy \( \xi_b \) and persistent anisotropy \( \xi_p \) between bursts can differ substantially due to the burst influence on accretion disk geometry. This ratio can be inferred from simulation results via \( \xi_p/\xi_b = M c^2 (z/(1 + z))/ (4 \pi d^2 F_c c_{bol}) \), where \( c \) is the speed of light (Heger et al. 2007). Using this work’s best-fit \( M, z, \) and \( d \) and \( F_c \) and \( c_{bol} \) from Galloway et al. (2017), \( \xi_p/\xi_b = 3.5 \). This could be explained (see Figure 12 of He & Keek 2016) by a flat accretion disk for a system with a relatively high inclination angle \( \theta \approx 80^\circ \). For the same conditions, the KEPLER best fit requires \( \theta \approx 65^\circ \), whereas roughly the same \( \theta \) explains the best fit from both codes if a curved accretion disk is assumed.

6.5. Possibility to Constrain the \( ^{15}O(\alpha, \gamma) \) \( ^{19}Ne \) Reaction Rate

It is apparent from Figure 5 that \( R \) has a relatively modest impact on \( \Delta t_{rec} \), in agreement with prior observations (Cyburt et al. 2016). However, as shown in Figures 4 and 6, \( R \) significantly increases the departure from linearity in the light curve rise, known as the convexity \( C \) (Maurer & Watts 2008; where \( C = 0 \) is linear). The 1998, 2000, and 2007 epochs of GS 1826-24 exhibit a low \( C \), whereas MESA models with \( R > 1 \) show an increase in \( C \) due to a shoulder introduced in the light curve rise. A similar shoulder is present in KEPLER models for \( R = 10 \) (Cyburt et al. 2016).

It is possible that this signature in the light curve could be erased by convolving the one-dimensional results presented here with a more sophisticated treatment for flame spreading on the neutron star surface, which also impacts the light curve rise. For instance, Maurer & Watts (2008) found using a phenomenological model that the longitudinal dependence of the flame speed can result in \( C > 0 \) or \( <0 \) depending on the ignition latitude. Since \( C \approx 0 \) for the GS 1826-24 1998, 2000, and 2007 burst epochs, the \( R = 5, 10 \) models presented here could potentially describe the observational data if convolved with near-polar burst ignition. Alternatively, relatively slow flame spreading from an equatorial ignition could smear out any intrinsic bump-like artifacts in the light curve rise; however, Zamfir (2010) found that this would require a flame that takes \( \sim 7 \) s to encompass the neutron star surface, which is several times longer than inferred from oscillations in the burst light curve rise (Chakrabarty & Bhattacharyya 2014).

Taking the current results at face value suggests that the \( ^{15}O(\alpha, \gamma) \) \( ^{19}Ne \) reaction rate cannot be more than 5\( \times \) lower than the currently accepted rate of Davids et al. (2011). This limit is more stringent than the constraint derived from nuclear physics experiments, for which the 3\( \sigma \) uncertainty sets a lower limit \( \gtrsim 10 \) (Davids et al. 2011). This limit for the \( ^{15}O(\alpha, \gamma) \) \( ^{19}Ne \) reaction rate, \( >5 \times \) lower than the median rate of Davids et al. (2011), implies that the \( \alpha \)-particle decay branching ratio for the key 4.03 MeV resonance in \( ^{19}Ne \) is likely within reach of a newly developed experimental probe using radioactive ion beams (Wrede et al. 2017). Nonetheless, it should be stressed that more reliable constraints will require systematic investigations, beyond the scope of this work, which employ various treatments of effects impacting the light curve rise that are not included here, especially flame spreading on the neutron star surface. A large number of calculations are underway that will examine the MESA X-ray burst model sensitivity to other nuclear reaction rates, similar to the study of Cyburt et al. (2016).
7. Conclusions

In summary, a large number of X-ray burst model calculations performed with the code MESA have been used to reproduce the 1998, 2000, and 2007 bursting epochs from GS 1826-24. It has been shown that $M$ for these bursting epochs must be larger than previously inferred. This work also shows that model–observation comparisons for X-ray burst light curves and $\Delta t_{\text{rec}}$ performed consistently for several $M$ are necessary to remove model degeneracies. Consistent comparisons can be used to constrain $Q_b$ for a bursting source and can possibly set a lower limit on the $^{16}\text{O}(\alpha,\gamma)$ reaction rate. The $Q_b < 0.5 \text{MeV}/\text{u}$ limit for GS 1826-24 provides a valuable constraint that can be used to investigate the origins of the poorly understood shallow heating mechanism in accreting neutron stars. Furthermore, using the case of $^{16}\text{O}$ poorly understood shallow heating mechanism in accreting nuclear reaction rates will require comparisons to more nuclear masses as well (Schatz & Ong 2017).

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