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Experimental measurements of the 15O(alpha,gamma)19Ne reaction rate and the stability of thermonuclear burning on accreting neutron stars

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The ^{15}O(α,γ)^{19}Ne reaction rate and the stability of thermonuclear burning on accreting neutron stars

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ABSTRACT

Neutron stars in close binary star systems often accrete matter from their companion stars. Thermonuclear ignition of the accreted material in the atmosphere of the neutron star leads to a thermonuclear explosion which is observed as an X-ray burst occurring periodically between hours and days depending on the accretion rate. The ignition conditions are characterized by a sensitive interplay between the accretion rate of the fuel supply and its depletion rate by nuclear burning in the hot CNO cycle and the *rp*-process. For accretion rates close to stable burning the burst ignition therefore depends critically on the hot CNO breakout reaction $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ that regulates the flow between the hot CNO cycle and the rapid proton capture process. Until recently, the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ reaction rate was not known experimentally and the theoretical estimates carried significant uncertainties. In this paper we perform a parameter study of the uncertainty of this reaction rate and determine the astrophysical consequences of the first measurement of this reaction rate. Our results corroborate earlier predictions and show that theoretically burning remains unstable up to accretion rates near the Eddington limit, in contrast to astronomical observations.

Subject headings: X-rays: bursts — nuclear reactions — stars: neutron

1. Introduction

Recently, many groups (Woosley et al. 2004; Amthor et al. 2006; Cooper & Narayan 2006a; Fisker et al. 2006, 2007; Roberts et al. 2006) have considered the nuclear reactions of the explosive thermonuclear runaway that lead to a type I X-ray burst on the surface of an accreting neutron star (for reviews, see Bildsten 1998; Strohmayer & Bildsten 2006). The $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$-reaction is particularly interesting because it is the gateway between the hot CNO cycles, which are associated with stable burning during the quiescent phase, and the *rp*-process, which is associated with the thermonuclear runaway (Wallace & Woosley 1981).

When hydrogen and helium accrete onto the neutron star and advect into the atmosphere, hydrogen burns via the hot CNO cycle $^{12}\mathrm{C}(p,\gamma)$ $^{13}\mathrm{N}(p,\gamma)$ $^{14}\mathrm{O}(\beta^+\nu_e)$ $^{14}\mathrm{N}(p,\gamma)$ $^{15}\mathrm{O}(\beta^+\nu_e)$ $^{14}\mathrm{N}(p,\alpha)$ $^{12}\mathrm{C}$. The hot CNO cycle is temperature independent (β-limited) and therefore its rate depends only on the abundance of $^{14}\mathrm{O}$ and $^{15}\mathrm{O}$. Us-

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ing a time-dependent X-ray burst model, Fisker et al. (2006) investigated the importance of the $^{15}O(\alpha,\gamma)$ ^{19}Ne breakout reaction rate and showed that a lower breakout rate restricts the outflow from the hot CNO cycle so that the hot CNO cycle processes hydrogen to helium at a faster rate. This increases the energy output and thereby raises the temperature of the entire envelope so that ^{4}He burns to ^{12}C further out in the atmosphere, which in turn increases the efficacy of the hot CNO cycle. This moves the hydrogen burning front (defined by $X_H = 0$) further out where ^{4}He burns slower. The energy generation rate therefore decreases until the hydrogen burning front advects down to a sufficient depth and restarts this cycle. For a global accreting rate of $\dot{M} = 1 \times 10^{17}\,\mathrm{g\,s^{-1}}$, this results in the non-bursting oscillatory luminosity found in time-dependent model simulations by Fisker et al. (2006) and later in the two-zone model of (Cooper & Narayan 2006b). The result of this burning behavior is a copious production of ^{12}C (Fisker et al. 2006) which theoretically would provide the required fuel concentration to explain superbursts (Cumming & Bildsten 2001). Unfortunately for this theory, astronomers frequently observe X-ray bursts at this accretion rate (e.g., Cornelisse et al. 2003; Galloway et al. 2006), which suggests that the aforementioned burning cycle does not occur. This leads to the astrophysically based conclusion that the true $^{15}O(\alpha,\gamma)^{19}$Ne reaction rate must be higher than the lower limit calculated by Fisker et al. (2006).

In the first part of this paper, we therefore perform a parameter study of the $^{15}O(\alpha,\gamma)^{19}$Ne reaction rate as a function of the accretion rate to investigate the impact of uncertainty of the reaction rate. The results of this study corroborate earlier estimates of the critical accretion rate by Fushiki & Lamb (1987); Bildsten (1998); Fisker et al. (2003); Woosley et al. (2004); Heger et al. (2005); Cooper & Narayan (2006a). It also strengthens the astrophysically based conclusion of Fisker et al. (2006) that set a lower limit on the $^{15}O(\alpha,\gamma)$ ^{19}Ne breakout reaction rate

In the second part, we use the recently measured rate of Tan et al. (2007), which includes an experimentally determined lower limit and repeat and improve the calculations of Fisker et al. (2006). We also take advantage of the significantly reduced uncertainty to determine the uncertainty range in the transition accretion rate between stable and unstable burning.

We discuss the computational model in §2. The parameter study is described in §3 which is followed by a discussion of the implication of Tan et al. (2007)'s new rate in §4 and the conclusion in §5.

2. Computational Model

The impact of the $^{15}O(\alpha,\gamma)^{19}$Ne rate has been investigated in the framework of a dynamical and self-consistent spherically symmetric X-ray burst model that has been used also in Fisker et al. (2005a,b, 2006, 2007). This model couples a modified version of a general relativistic hydrodynamics code (Liebendörfer et al. 2002) with a generic nuclear reaction network (Hix & Thielemann 1999) using the operator-split method (Henyey et al. 1959). The nuclear reaction flow and the conductive, radiative, and convective heat transport are computed in a general relativistic spherically symmetric geometry.

The reaction network comprises the same 298 isotope network between the valley of stability and the proton drip line as Fisker et al. (2006). Except for the $^{15}O(\alpha,\gamma)^{19}$Ne-rate, all the proton-, neutron-, and alpha-induced reactions are adopted from the latest version of the REACLIB library (Sakharuk et al. 2006) which was also used in Weinberg et al. (2006).

The radiative, conductive, and convective heat transport is treated in the formalism of Thorne (1977). The radiative opacities due to Thompson scattering and free-free absorption are calculated according to Schatz et al. (1999) and the conductivities for electron scattering on electrons, ions, phonons, and impurities are based on the work of Brown (2000). The accreted matter is assumed to be fully ionized on impact. We use an arbitrarily relativistic and arbitrarily degenerate equation of state to describe the electron gas. Due to the shorter quantum wavelength of the nucleons, the nucleon gas behaves as an ideal gas.

The model code tracks energy transport with high precision and takes into account the heat transport between the atmosphere and the neutron star core (Brown 2004). The thermal energy released from the core is $0.11\mathrm{MeV\,nuc^{-1}}$ for $\dot{M} = 1.12 \times 10^{17}\mathrm{g\,s^{-1}}$, but it generally depends on the accretion rate, the composition of the X-ray burst ashes, the temperature of the envelope, and the mass and radius of the core. The neutron star core boundary corresponds to a pressure of $P = 7 \times 10^{23}\,\mathrm{dyn\,cm^{-2}}$ and the core itself is characterized by a mass of $1.4M_\odot$ and a radius of 11.06 km leading to a redshift of $1+z = (1-2GM/Rc^2)^{-1/2} = 1.27$ and a gravitational acceleration of $g = (1+z)GM/R^2 = 1.8 \times 10^{14}\mathrm{cm\,s^{-2}}$. Similarly, the upper atmosphere is described by a relativistically corrected grey atmosphere (Thorne 1977; Weiss et al. 2004) using a 4th order Runge-Kutta method to numerically integrate the hydrostatic heat and pressure equations from the model boundary out to $P = 10^{18}\,\mathrm{dyn\,cm^{-2}}$.

The computation followed a sequence of accretion and burst phases until a limit cycle equilibrium was reached. This was performed for different $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ rates for a range of accretion rates as described in the next section.

3. Parameter study of $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$

Increased availability of computing power has significantly expanded our ability to perform parameter studies of full one-dimensional X-ray burst simulations. Fig. 1 shows the results of a parameter study of 72 simulations where the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ rate of Caughlan & Fowler (1988), which is based on the work of Langanke et al. (1986), has been scaled linearly with a parameter, f. Similarly the accretion rate has been scaled linearly with a parameter, I, where $I = 1$ corresponds to the Eddington limit $\dot{M}_{\mathrm{Edd.}} = 1.12 \times 10^{18}\mathrm{g\,s^{-1}}$. The local Eddington limit is $\dot{m}_{\mathrm{Edd.}} = \dot{M}_{\mathrm{Edd.}}/(4\pi R^2) = 6.62 \times 10^4\mathrm{g\,cm^{-2}\,s^{-1}}$ assuming that accretion is spherically symmetric. The simulations were computed on an 8×9 grid corresponding to the u (bursting behavior) and s (non-bursting behavior) letters in Fig. 1. The grid covers the range between H/He ignited bursts and stable burning. In the following subsections we describe the different outcomes of this study.

3.1. High values of f

For $\log(f) \gtrsim -1.5$ burning is unstable for accretion rates up to $\log(I)$ =0.2–0.4 (see Fig. 1) and a H/He triggered burst occurs after the $^{15}\mathrm{O}(\alpha,\gamma)\,^{19}\mathrm{Ne}(\beta^+,\nu)\,^{19}\mathrm{F}(p,\alpha)\,^{16}\mathrm{O}(p,\gamma)\,^{17}\mathrm{F}(p,\gamma)\,^{18}\mathrm{Ne}(\beta^+,\nu)\,\,^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ cycle (for details, see

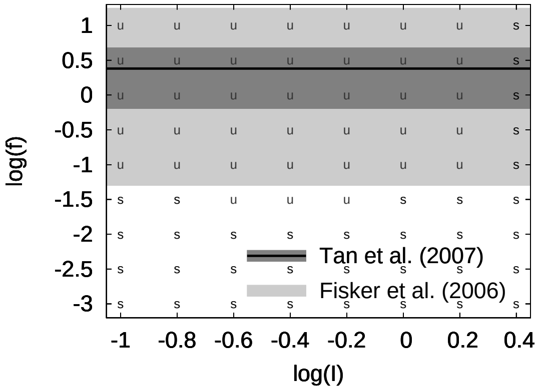

Fig. 1.— The figure shows a log-log plot of the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ rate of Caughlan & Fowler (1988) scaled with a parameter, f, and the accretion rate scaled linearly with a parameter, I, so $\dot{M} = I \times 1.12 \times 10^{18}\mathrm{g\,s^{-1}}$. Each letter represents a simulation with u showing bursting behavior and s showing non-bursting behavior. For reference, the solid line shows the rate of the new measurement for $T = 4 \times 10^8$K. The light and dark shaded areas show the uncertainty at $T = 4 \times 10^8$K of the estimate of Fisker et al. (2006) and Tan et al. (2007) respectively.

Cooper & Narayan 2006a; Fisker et al. 2007) has been active for several hundreds of seconds before the runaway. Once the 3α reaction triggers, the ^{19}Ne(p,γ) ^{20}Na breakout reaction starts the *rp*-process. This activates the ^{14}O(α,p) ^{17}F-reaction and creates a direct reaction flow from helium into the *rp*-process viz. from 3α to ^{12}C(p,γ) ^{13}N(p,γ) ^{14}O(α,p) ^{17}F(p,γ) ^{18}Ne(α,p) ^{21}Na. This reaction circumvents the $T_{1/2} = 76.4\,\mathrm{s}$ β^{+}-decay of ^{14}O and allows a flow directly into the *rp*-process.

For $\log(f) \geq -1.0$ burning becomes stable for $\log(I)$ =0.2–0.4 independent of the exact value of the ^{15}O(α,γ) ^{19}Ne reaction. This means that previous theoretical and computational estimates of the critical accretion rate (Fushiki & Lamb 1987; Bildsten 1998; Fisker et al. 2003; Woosley et al. 2004; Heger et al. 2005) which were based on the rate of Caughlan & Fowler (1988), i.e. $\log(f) \equiv 0$, are independent of the exact value of the reaction rate. For $\log f \sim -1.5$, small uncertainties the ^{15}O(α,γ) ^{19}Ne reaction rate would be sufficient to change the critical accretion rate by almost an order of magnitude (Cooper & Narayan 2006a; Fisker et al. 2006).

3.2. Low values of f at low accretion rates

For $\log(f) \lesssim -2$ and $\log(I) \lesssim -0.5$, the ^{15}O(α,γ) ^{19}Ne-reaction is too weak, so the above mentioned cycle never activates the ^{14}O(α,p) ^{17}F-reaction; the small amount of unstable helium fizzles, and the thermonuclear runaway never happens. This results in an oscillating behavior (Fisker et al. 2006).

Cooper & Narayan (2006a) speculated that a low value of f could stabilize bursts at lower accretion rates. Using the time-dependent model at low values of f, we find the same stable/unstable transition accretion rate for the helium trigger at $\log(I) \sim -0.5$ thus complimenting the calculations of Cooper & Narayan (2006a). However, It should be noted that for $\log(f) \lesssim -2$ the instability of the helium trigger never results in a burst as explained in the preceding paragraph and the next subsection. Therefore this behavior is marked with an *s* in Fig. 1.

3.3. Low values of f at high accretion rates

For $\log(f) \lesssim -2$ and $\log(I) \gtrsim -0.5$, the higher accretion rate increases compressional heating which heats the atmosphere to several hundred million degrees. Despite the low value of f the natural temperature dependence of the ^{15}O(α,γ) ^{19}Ne-reaction means that helium burning triggers the *rp*-process. However, since the value of f is small, the *rp*-process is fed very slowly resulting in increasingly longer luminosity rise times on the order tens of seconds as f decreases with burning becoming stable at very low values of f as shown in Fig. 2. For these values of f, the accretion rate at which unstable burning transitions to stable burning is still uncertain.

Fig. 2 shows luminosity peaks with an almost symmetrical decay suggesting that the atmosphere is driven by an oscillating burning front rather than a thermonuclear burst followed by a thermal decay. Such long rise times have never been observed at any accretion rate, so this result strengthens the argument for a lower limit on the ^{15}O(α,γ)^{19}Ne rate but does not change the bounds on the astrophysically based lower limit set by Fisker et al. (2006). This means that the oscillatory burning behavior found in Fisker et al. (2006) is most likely not the generator of the ^{12}C that fuels superbursts (Cumming & Bildsten 2001), although such a generator has not yet been found in other multi-zone simulations either (Woosley et al. 2004; Fisker 2004; Fisker et al.

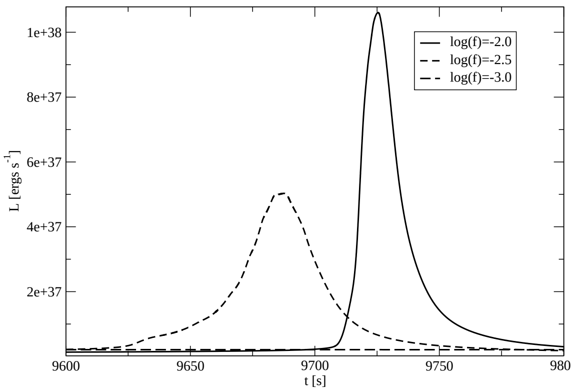

Fig. 2.— This figure shows the luminosity for three different values of f as a function of time for simulations with an accretion rate of $\log(I) = -0.4$. Notice the very long rise times and the symmetrical decays.

3.4. Comparison to observations

Observations indicate that type I X-ray bursts occur for $\log(I) \lesssim -0.5$ and cease for $\log(I) \gtrsim -0.5$ (van Paradijs et al. 1979, 1988; Cornelisse et al. 2003; Remillard et al. 2006; Galloway et al. 2006). In contrast with the global linear stability analysis of Cooper & Narayan (2006a), our full network time-dependent simulations show no single trial value of f that is consistent with observations over the entire range of accretion rates we consider. This suggests that more complex physics must be included in the simulation. The most important parameters of the bursting behavior as a function of accretion rate are the accreted composition – here assumed to be solar – and the mass and radius of the neutron star. Other possible factors include the sedimentation of CNO ions (Peng et al. 2007) as well as the geometry of the flow from the accretion disk through the boundary layer and onto the neutron star (Inogamov & Sunyeav 1999). Here the flow of the accreted matter may change as the thermonuclear burning transitions from unstable bursts to stable burning.

4. The new ^{15}O$(\alpha,\gamma)^{19}$Ne reaction rate

The ^{15}O$(\alpha,\gamma)^{19}$Ne reaction rate is dominated by the resonance contributions at temperatures above 0.1 GK (Langanke et al. 1986). However, the partial widths Γ_α and Γ_γ of the relevant states with excitation energies of 4-5 MeV are not sufficiently well known for calculating the reaction rate reliably. Of particular interest is the resonance at an excitation energy of 4.03 MeV in ^{19}Ne, just above the ^{15}O$+\alpha$ threshold. This resonance dominates the reaction rate at temperatures below 0.6 GK (Langanke et al. 1986) and therefore determines the temperature conditions for the breakout from the hot CNO cycles. Its γ width was first measured by Tan et al. (2005) and later confirmed by Kanungo et al. (2006). However, its small α-decay branching ratio of the order 10^{-4} (see Davids et al. 2003; Rehm et al. 2003, for previous upper limits) prevented a reliable estimate of the reaction rate until the recent work by Tan et al. (2007).

A new ^{15}O$(\alpha,\gamma)^{19}$Ne rate was proposed by Tan et al. (2007) based on the measured α-decay branching ratios and lifetimes of the relevant states in ^{19}Ne (for details, see Tan et al. 2007). This rate is shown in Fig. 3 with one sigma uncertainty indicated by the darker area, and it is significantly improved as compared to the previous model-dependent estimate by Fisker et al. (2006). In addition, dominant contributions at higher temperatures from the states at 4.14 and 4.60 MeV were unexpected. This new rate not only allows a better identification of the ignition conditions of X-ray bursts but also permits the improved analysis of the dynamics and mechanism of X-ray bursts as demonstrated below.

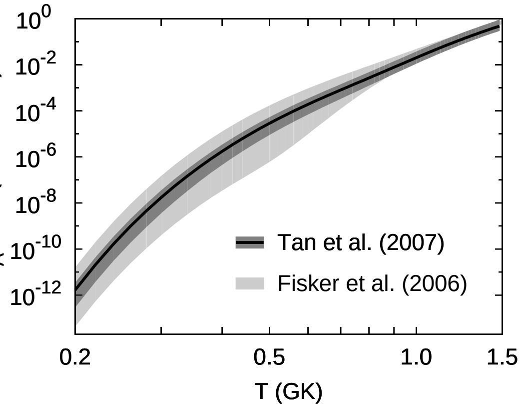

Fig. 3.— Figure shows the newly measured reaction rate along with 1σ upper and lower experimental uncertainties. The uncertainty range discussed by Fisker et al. (2006) is also shown.

4.1. Astrophysical consequences

Repeating the calculations of Fisker et al. (2006) for the lower limit of the ^{15}O$(\alpha,\gamma)^{19}$Ne reaction rate, Fig. 4 shows a comparison between the luminosity as a function of time for the previous lower limit and the present experimental lower limit for a constant accretion rate. The results show that the new rate within its experimental uncertainties is sufficient to trigger the observed sequences of bursts for a constant accretion rate.

By doing a parameter study covering the previous experimental uncertainty range for the ^{15}O$(\alpha,\gamma)^{19}$Ne reaction it was shown in section 3 and in Fisker et al. (2006) that past X-ray burst models have been subject to a very large uncertainty due to the uncertainty of the ^{15}O$(\alpha,\gamma)^{19}$Ne reaction rate. Fortunately, the widely used rate of Caughlan & Fowler (1988) (viz. $\log(f) \equiv 0$) is

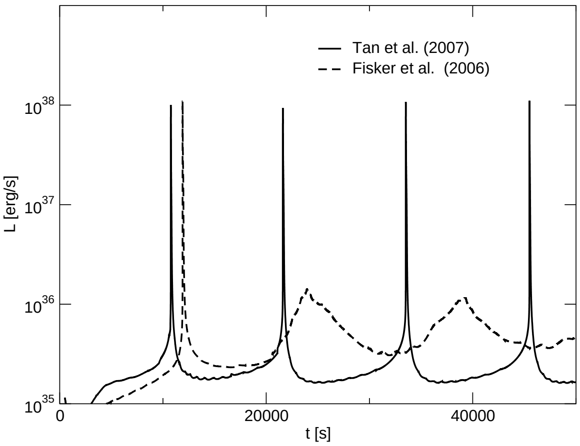

Fig. 4.— This figure shows the luminosity as a function of time for a simulation with an accretion rate of $\dot{M} = 10^{17}\mathrm{g\,s^{-1}}$ comparing the lower limit of the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ for this work vs. the lower limit of the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ rate used by Fisker et al. (2006). We note that the reduced uncertainty of the rate presented in this work corroborates observations and thus constitutes a major improvement of the rate.

very close to the newly measured rate of Tan et al. (2007). This means that the conclusions of earlier calculations (Fushiki & Lamb 1987; Bildsten 1998; Fisker et al. 2003; Woosley et al. 2004; Heger et al. 2005; Cooper & Narayan 2006a) hold.

Since the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$-reaction rate now has experimentally determined upper as well as lower limits, we can determine the accuracy of the theoretical estimate of the critical transition accretion rate between the steady state burning phase and the burst phase in accreting neutron star binary systems.

We already noted from Fig. 1 (see subsection 3.1) that $\log(I)_{crit.} = 0.2$–0.4. This corroborates the majority of previous simulations (Rembges 1999; Fisker et al. 2003; Heger et al. 2005) and calculations (Fujimoto et al. 1981; Bildsten 1998) which have determined the transition point to be around $\dot{M} \sim 2.1 \times 10^{18}\mathrm{g\,s^{-1}}$ for a fiducial neutron star with $R = 10$ km and $M = 1.4 M_\odot$ and adopting a solar composition for the accreted matter.

Using the rate of Tan et al. (2007), several simulations were run for different accretion rates in the $\log(I)_{crit.}$ =0.2–0.4 range while tracking the luminosity resulting from the nuclear burning. The results shown in Fig. 5 show that the burning becomes stable for $\dot{M} \geq 1.9 \times 10^{18}\mathrm{g\,s^{-1}}$. Identical simulations were performed using the one sigma upper and lower limits of the newly measured reaction rate as shown in Fig. 3. While the upper limit yields the same transition accretion rate, the lower limit increases the transition point to $\dot{M} \approx 2.1 \times 10^{18}\mathrm{g\,s^{-1}}$. The astrophysical uncertainty in the determination of the accretion rate at the transition point has thus been reduced to less than 10% compared to previous rate-induced uncertainties of one order of magnitude in the accretion rate c.f. Fig. 1 and Fisker et al. (2006).

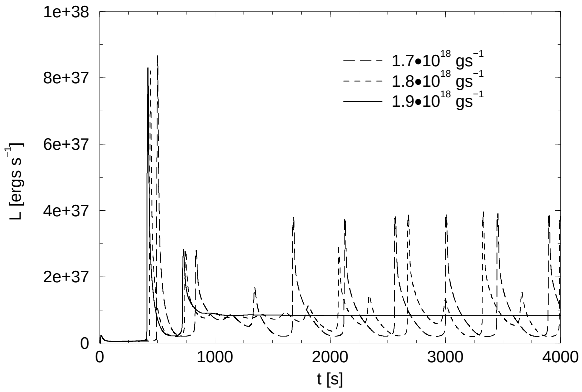

Fig. 5.— We used the newly measured rate to calculate the luminosity originating from the nuclear burning as a function of time for different accretion rates. As is seen from the constant luminosity on the graph, the burning is stable for $\dot{M} \geq 1.9 \times 10^{18}\mathrm{g\,s^{-1}}$.

5. Conclusion

Three important points:

1. We corroborate the stability analysis of Cooper & Narayan (2006a) showing that the atmosphere is stable towards runaways if the $^{15}\mathrm{O}(\alpha,\gamma)$ $^{19}\mathrm{Ne}$ reaction rate is low. However, we also show that this instability does not lead to observable bursts if the $^{15}\mathrm{O}(\alpha,\gamma)$ $^{19}\mathrm{Ne}$ reaction rate is low.

2. The new measurement is close to the previous and widely used rate of Caughlan & Fowler (1988), so the conclusions of previous X-ray burst simulations (e.g. Fushiki &

Lamb 1987; Bildsten 1998; Fisker et al. 2003; Woosley et al. 2004; Heger et al. 2005; Fisker et al. 2007) do not change.

3. The new measurement of the ^{15}O$(\alpha,\gamma)^{19}$Ne reaction rate significantly reduces the model uncertainty but does not result in a value that is in accord with astronomical observations. Therefore further studies of the other determinants (mass, radius, accretion composition, neutron star core, sedimentation, and possibly the accretion geometry) are needed. Such studies are currently underway.

The simulations in this paper demonstrate why it is important to consider the uncertainty associated with the input parameters of an X-ray burst simulation as it can significantly influence the predicted observables. Furthermore, they show how experimental nuclear data can complement observational results for a better understanding of the complex interplay between the fuel supply and burning processes on the surface of accreting neutron stars.

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