Nuclear Reactions During the Onset of Type I X-ray Bursts

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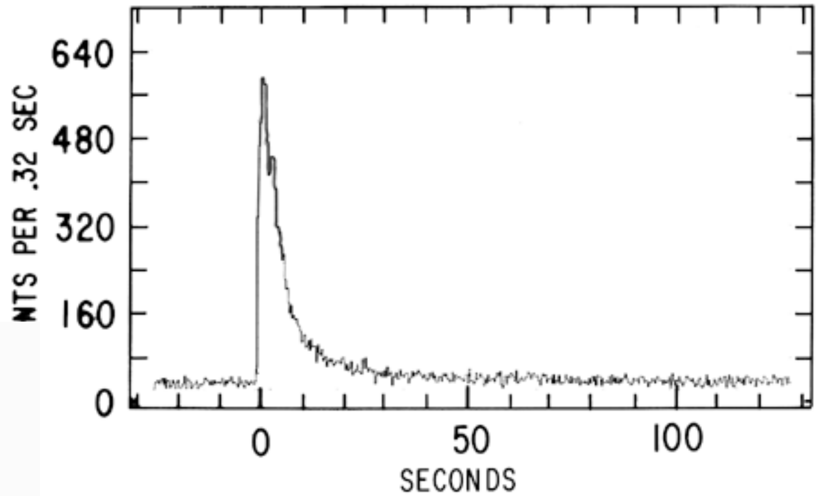

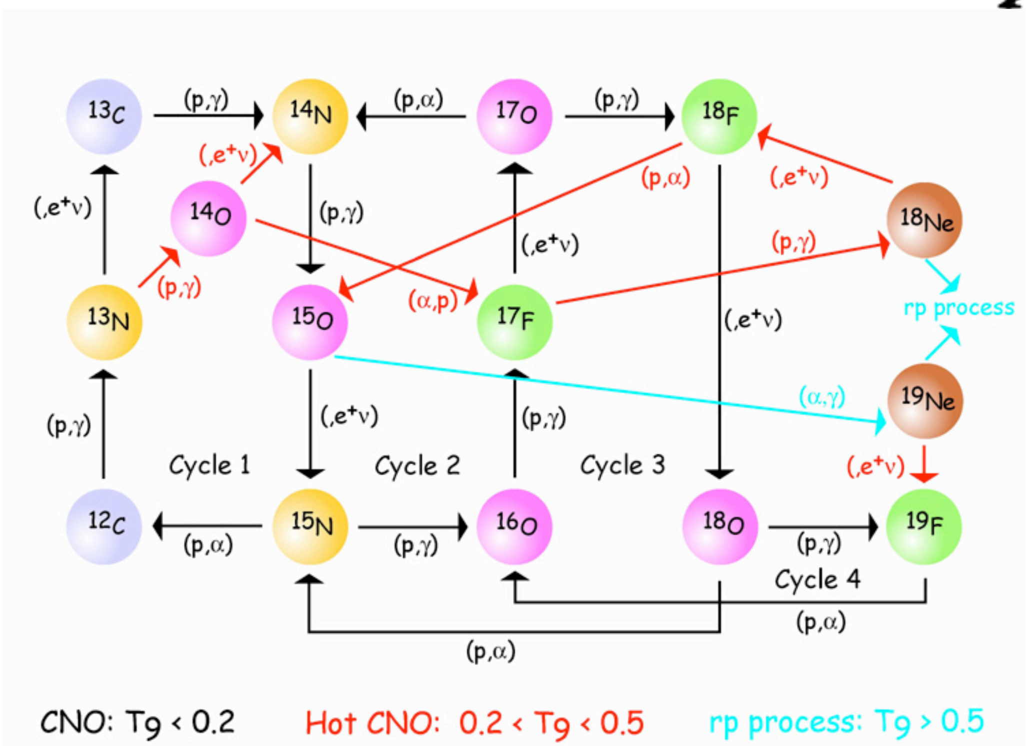

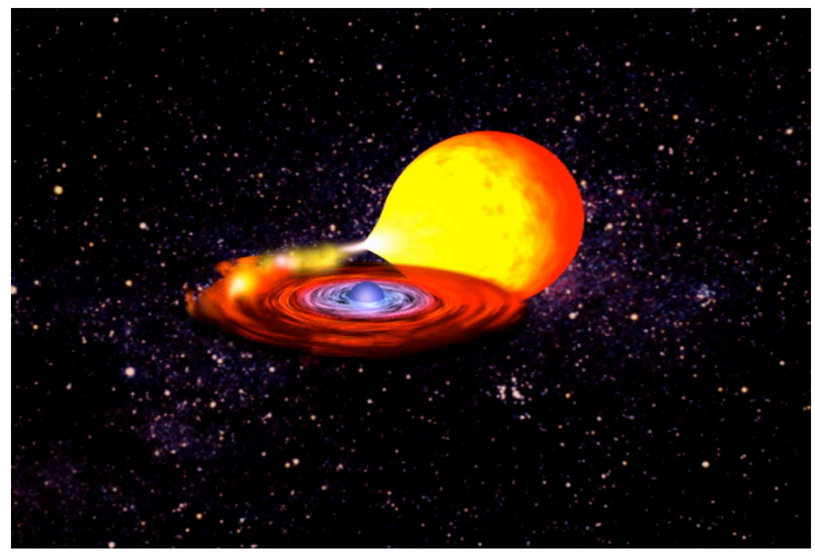

Motivation: *severe* discrepancies between theory and observations at $\dot{M} > 0.1\dot{M}_{\rm Edd}$!

Theoretical Predictions

- Bursts at all $\dot{M} < \dot{M}_{\rm Edd}$
- Bursts have long durations
- Burst rate increases with $\dot{M}$
- Little stable burning
- No ^{12}C for superbursts

Observations

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All of these discrepancies relate to the manner in which the accreted matter burns prior to type I X-ray bursts!

Need to understand the nuclear physics of the burst onset…

Outline

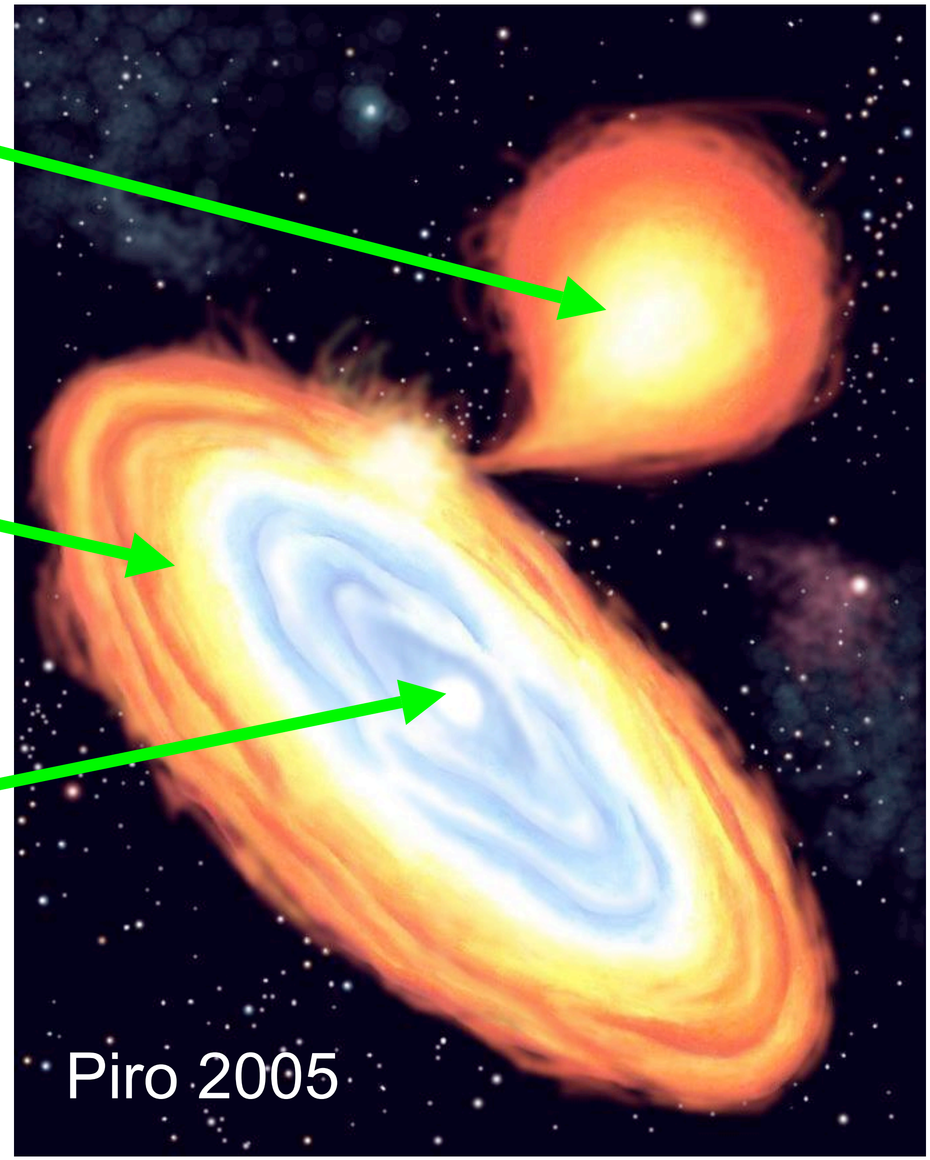
1. Introduction to bursts
2. Thermal instability that triggers bursts
3. Nuclear reactions of burst onset
    - 3α reaction
    - Hot CNO cycle breakout reactions
4. Possible ways forward?

Low-Mass X-ray Binaries

Mass donor star
loses matter via
tidal stripping

Accretion disk
forms around
neutron star

Neutron star
accretes matter
lost from disk

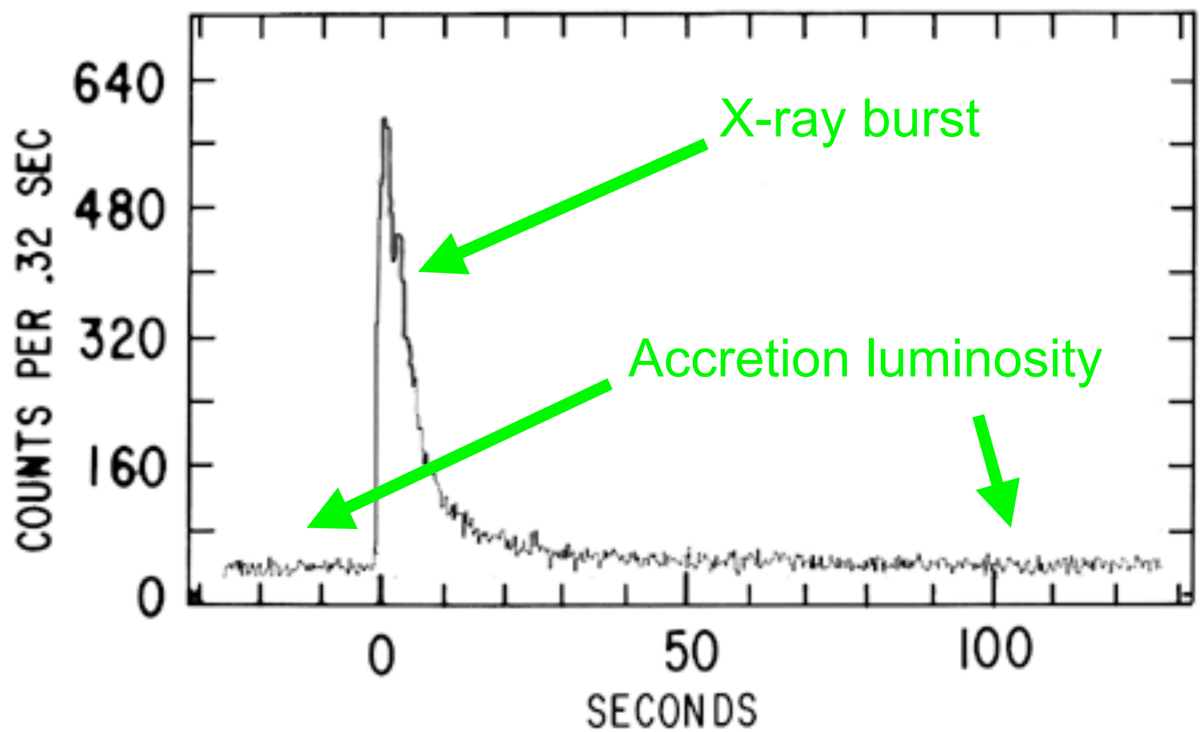


Type I X-ray Bursts

Thermonuclear explosions on accreting neutron stars

Burst properties

- t_{recur} ~ hours - days
- t_{rise} ~ 1 s
- t_{decay} ~ 10 - 100 s



Why does it burst?

Consider quiescent nuclear burning of accreting matter…

$\varepsilon_{nuc} \equiv$ heating rate due to nuclear burning

$\varepsilon_{cool} \equiv$ cooling rate due to radiative diffusion & emission

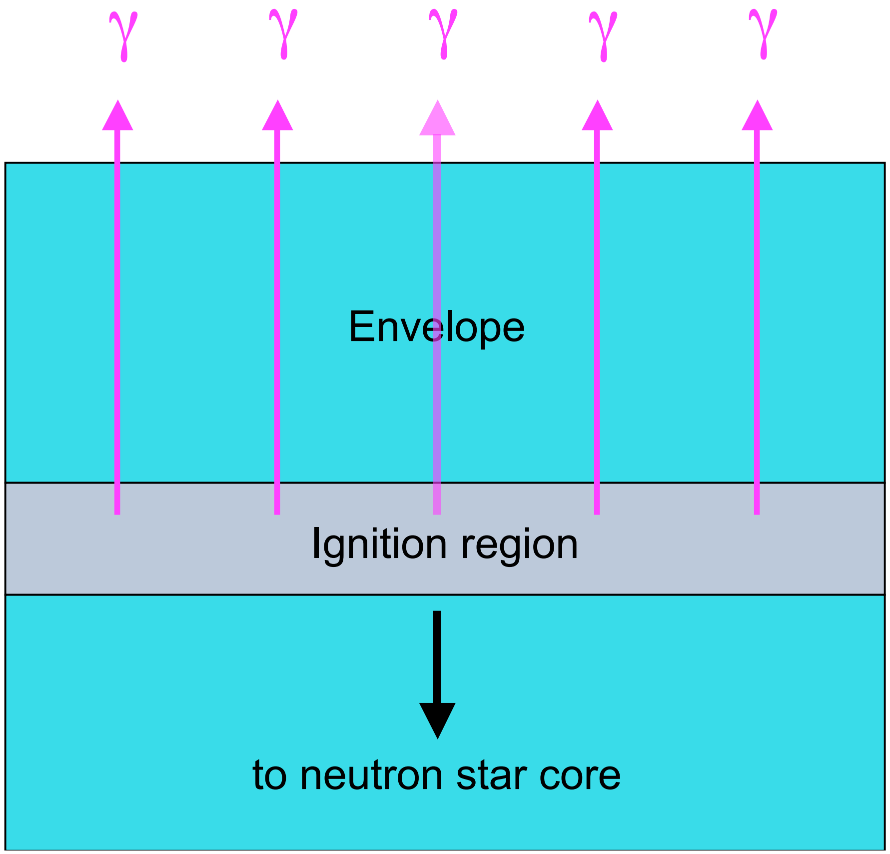
In steady state: $\varepsilon_{nuc} = \varepsilon_{cool}$

Stability analysis: if

$$\frac{\partial \varepsilon_{nuc}}{\partial T} > \frac{\partial \varepsilon_{cool}}{\partial T}$$

burning is thermally unstable!

Which reactions trigger bursts?



Burst Trigger

First guess: hydrogen burning

For $T < 8 \times 10^7$ K, H burns via cold CNO cycle

$$^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(\beta^+\nu)^{15}N(p,\alpha)^{12}C$$

but for $T > 8 \times 10^7$ K, H burns via hot CNO cycle

$$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^+\nu)^{14}N(p,\gamma)^{15}O(\beta^+\nu)^{15}N(p,\alpha)^{12}C$$

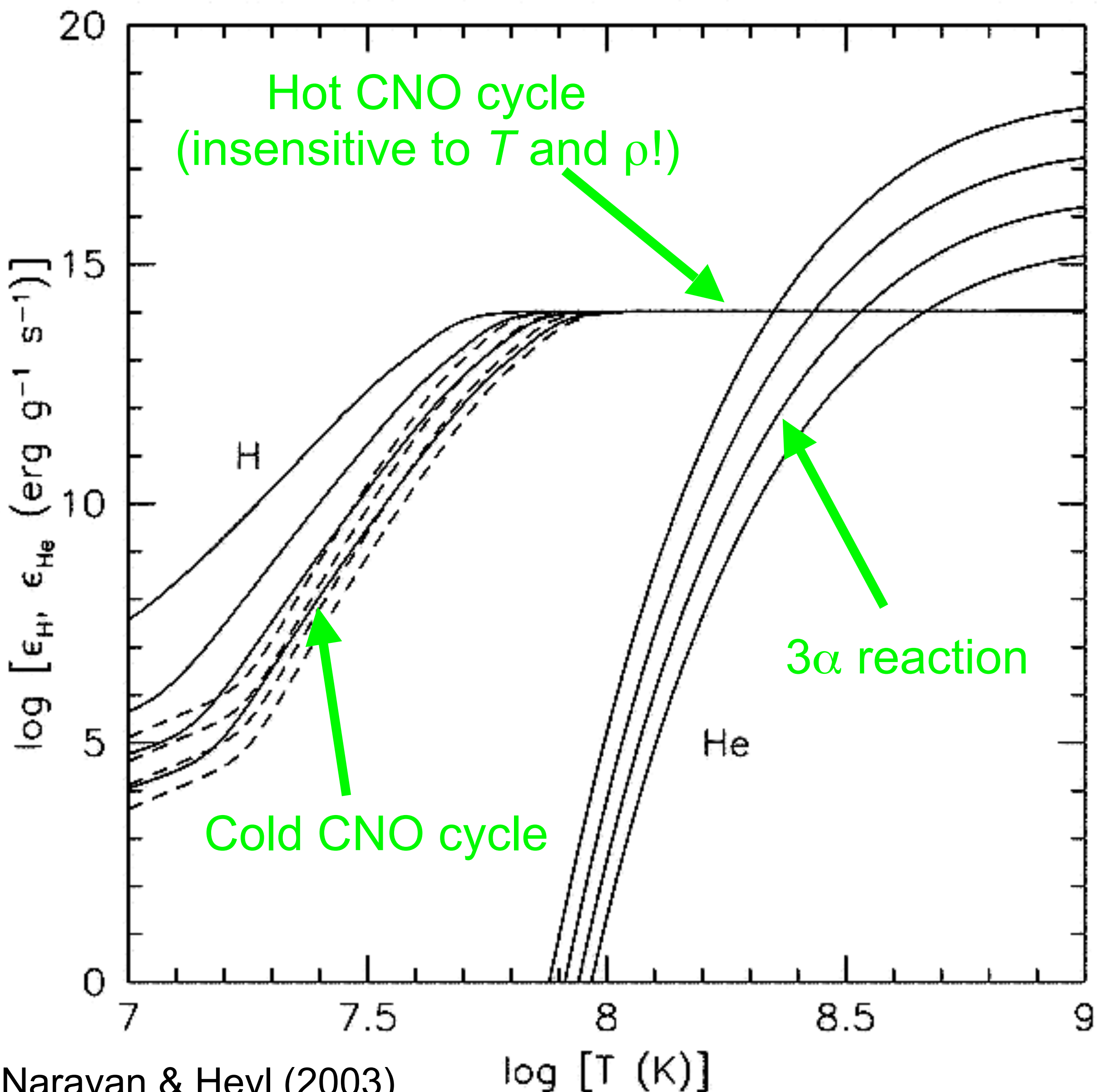
Slow ^{14}O and ^{15}O decay rates ($\tau_{1/2} \approx 70$ s and 120 s, respectively) make hot CNO cycle T-independent!

Second guess: helium burning

Helium burns via the 3α reaction

$$\alpha + \alpha + \alpha \rightarrow {}^{12}C$$

Burst Trigger



Narayan & Heyl (2003)

3α reaction is very *T*-sensitive and therefore triggers type I X-ray bursts…

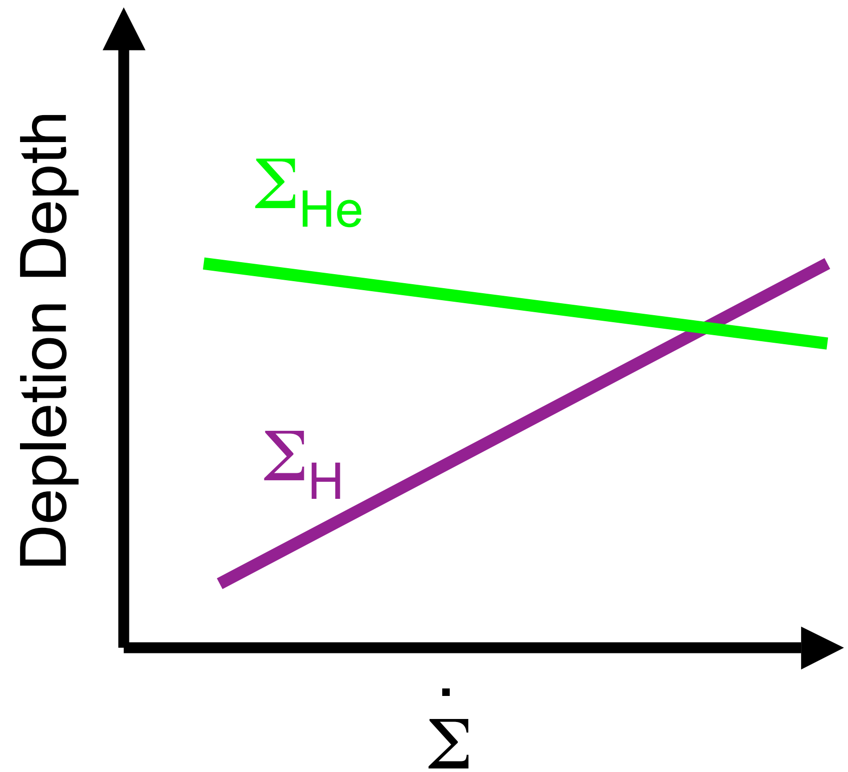
e.g. Fujimoto et al. (1981)

… but this simple picture doesn't work for $M > 0.1\ M_{\mathrm{Edd}}$!

H and He Burning Depths

ε_{He} is very *T*-sensitive, so Σ_{He} (column depth at which He depletes via nuclear burning) *decreases* with $\dot{\Sigma}$ (local accretion rate).

ε_H depends only on CNO abundance, so $\Sigma_H = \dot{\Sigma} t_H$ *increases* with $\dot{\Sigma}$.



$\Rightarrow$ at high $\dot{M}$, He ignites in a H-rich environment!

How does H affect thermal instability?

Nuclear Reactions

Hot CNO cycle hydrogen burning (*T*-independent!):

$$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^{+}\nu)^{14}N(p,\gamma)^{15}O(\beta^{+}\nu)^{15}N(p,\alpha)^{12}C$$

3α reaction:

$$\alpha + \alpha + \alpha \rightarrow {}^{12}C$$

Interplay between reactions:

H burning generates He for 3α reaction

He burning generates seed nuclei for hot CNO cycle

Hot CNO cycle stabilizes nuclear burning, so to initiate a thermal instability and hence a bursts, H burning must “break out” of the hot CNO cycle!

Hot CNO Cycle Breakout

H must break out of hot CNO cycle to trigger at burst!

$(\alpha,\gamma)^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}\ldots$

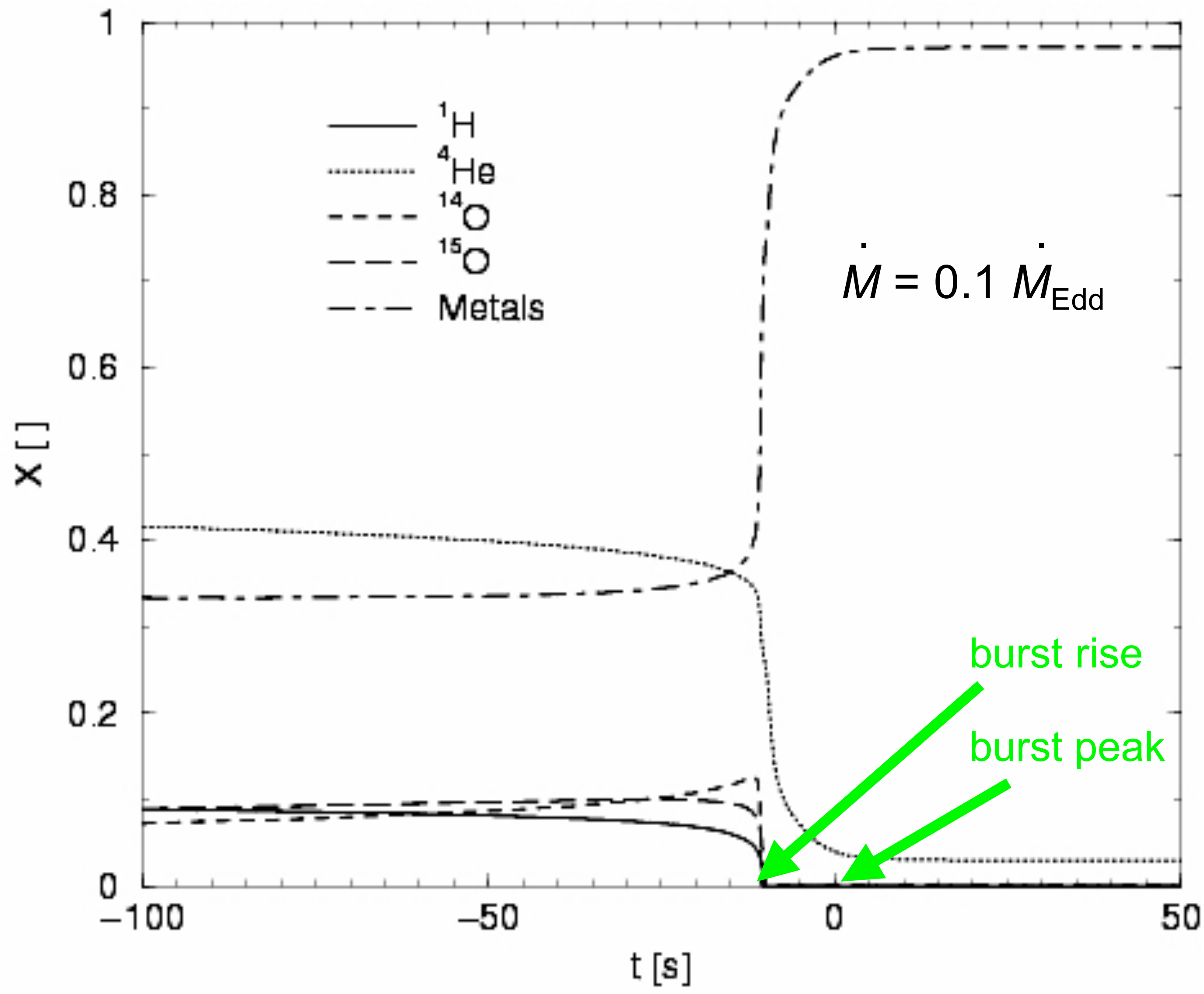
$3\alpha \rightarrow {}^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}(\beta^{+}\nu)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta^{+}\nu)^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$

$(\alpha,p)^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}\ldots$

Burning must flow through ${}^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$ for a thermal instability, but it won’t activate without a “push” from ${}^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}\ldots$

3α and ${}^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ TOGETHER govern stability!!!

Nuclear Reactions at Burst Onset



Pre-burst reactions:

- Hot CNO cycle
- 3α
- *rp*-process via $^{15}O(\alpha,\gamma)^{19}Ne$

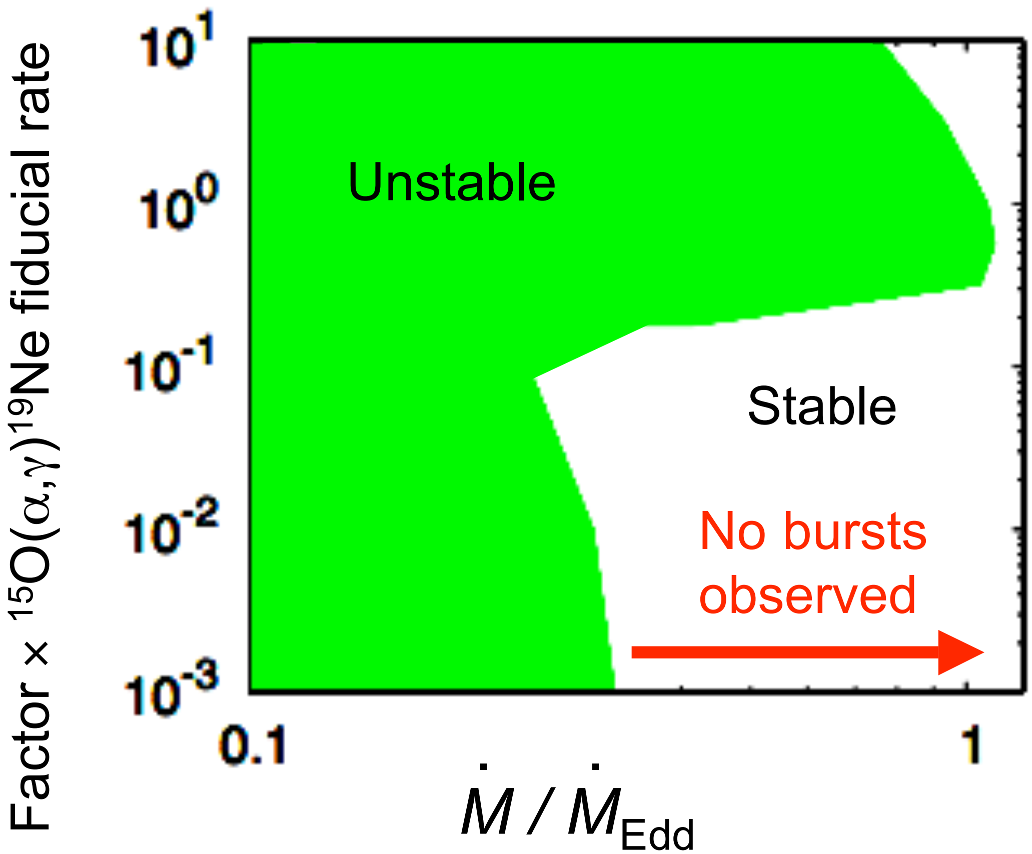
Burst rise reactions:

- 3α
- *rp*-process
- αp-process via $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$

Fisker, Schatz, & Thielemann (2007)

$^{15}O(\alpha,\gamma)^{19}Ne$ and Thermal Stability

The stability of nuclear burning is very sensitive to the strength of the uncertain $^{15}O(\alpha,\gamma)^{19}Ne$ rate!



Cooper & Narayan (2006)

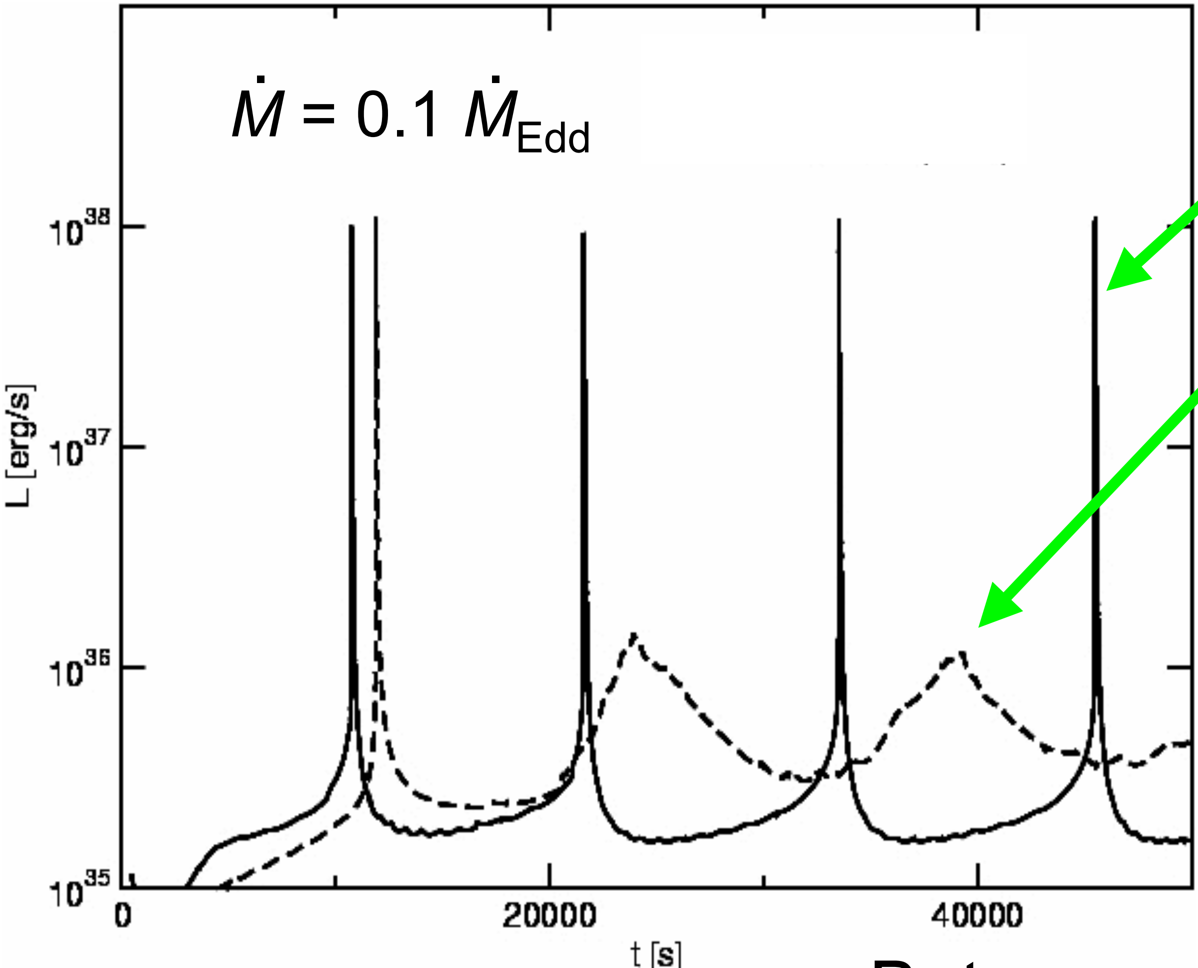
Lowering rate by ~10:

- Reduces critical $\dot{M}$ above which bursts cease
- Shortens burst duration
- Increases stable burning
- Produces more ^{12}C for superbursts

Looks promising! But there is a problem…

$^{15}O(\alpha,\gamma)^{19}Ne$ and Thermal Stability

If rate is too low, burning generates weak oscillations



Fisker et al. (2007)

There seems to be no simple scaling of the $^{15}O(\alpha,\gamma)^{19}Ne$ rate that reproduces observations over entire range of $\dot{M}$

But are we on the right track?

Implications and Speculations

Observations imply that, in quiescence, H burns via the hot CNO to a greater extent than currently predicted.

Is the discrepancy due to

- Uncertainties in nuclear physics (i.e. reactions in hot CNO cycle breakout flows)?
- Sedimentation? (Peng, Brown, & Truran 2007)
- Turbulent mixing? (Piro & Bildsten 2007)

…or should we take the predictions at face value and look elsewhere (e.g. spreading of accreted matter over stellar surface; Heger, Cumming, & Woosley 2007)?