Carbon Detonation
in
Superbursts

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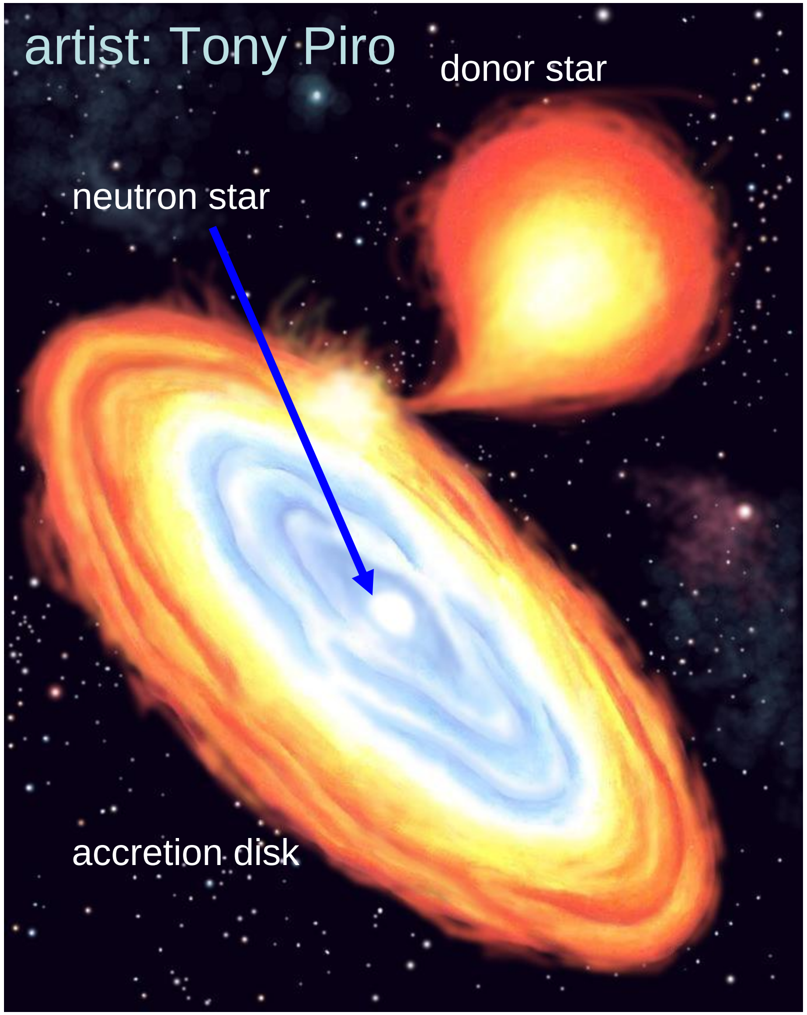
Low-Mass X-ray Binaries (LMXBs)



Neutron star: M ~ 1.3 - 2 M_{sun}

Donor star: two possible types

1. ~0.5 M_{sun} main sequence star…H/He accretion OR
2. He white dwarf…He accretion

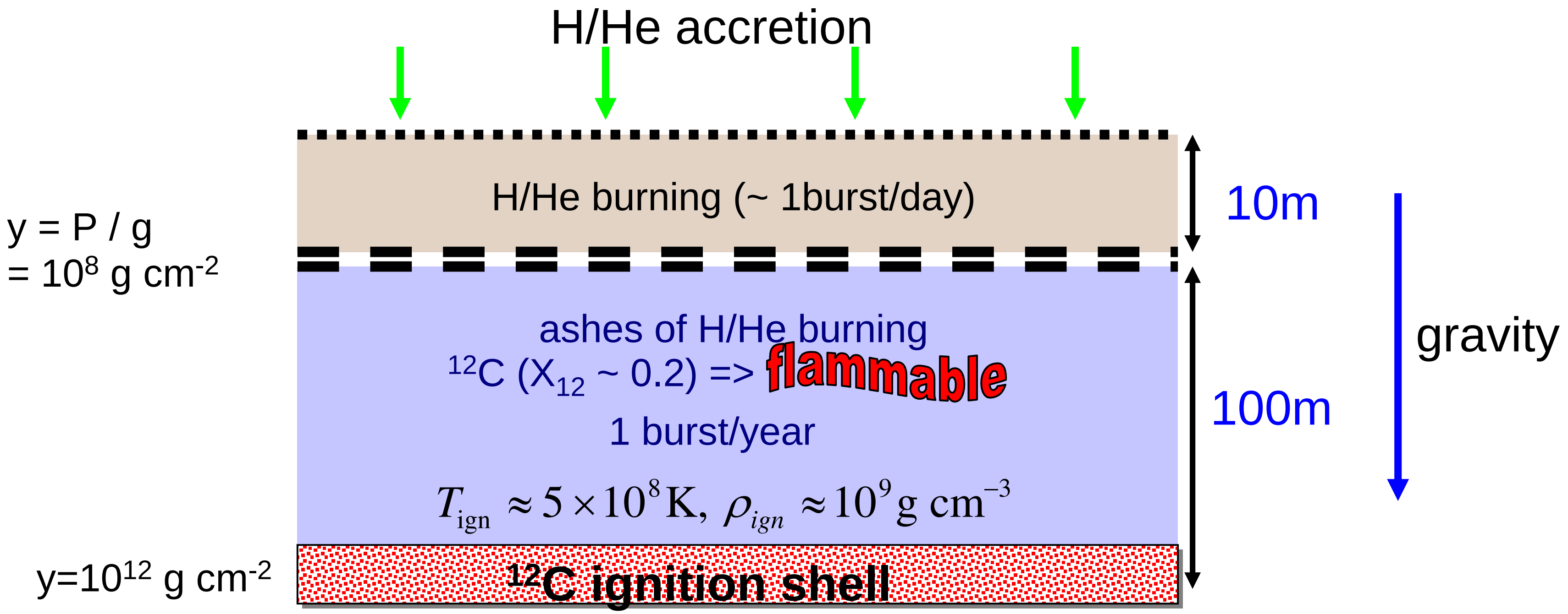
$$\begin{aligned}\dot{M} &\sim 10^{-10} - 10^{-8} M_\odot \text{ yr}^{-1}\\ &= 0.01 - 1 \dot{M}_{\rm Edd}\end{aligned}$$

$$\begin{aligned}L_{\rm acc} &= \frac{G M_{\rm NS} \dot{M}}{R_{\rm NS}}\\ &\sim 10^{36} - 10^{38} \text{ ergs s}^{-1}\end{aligned}$$

B << 10^9 G

What are superbursts?

- Superbursts are X-ray bursts that last for several hours.
- So far, superbursts seen in 8 LMXB systems.
- Likely due to unstable burning of a deep layer of ^{12}C in neutron star ocean.
- ^{12}C produced during H/He burning at much shallower depths (i.e., in normal X-ray bursts and/or stable H/He burning).
- After building up ^{12}C layer for ~1 year (~1000 Type I bursts), T and ρ high enough at base that the ^{12}C ignites.



H/He accretion

H/He burning (~ 1burst/day)

10m

$y = P / g$
$= 10^8$ g cm^{-2}

ashes of H/He burning
^{12}C (X_{12} ~ 0.2) => flammable

1 burst/year

$$T_{ign} \approx 5\times10^{8}\,\mathrm{K},\ \rho_{ign} \approx 10^{9}\,\mathrm{g\ cm^{-3}}$$

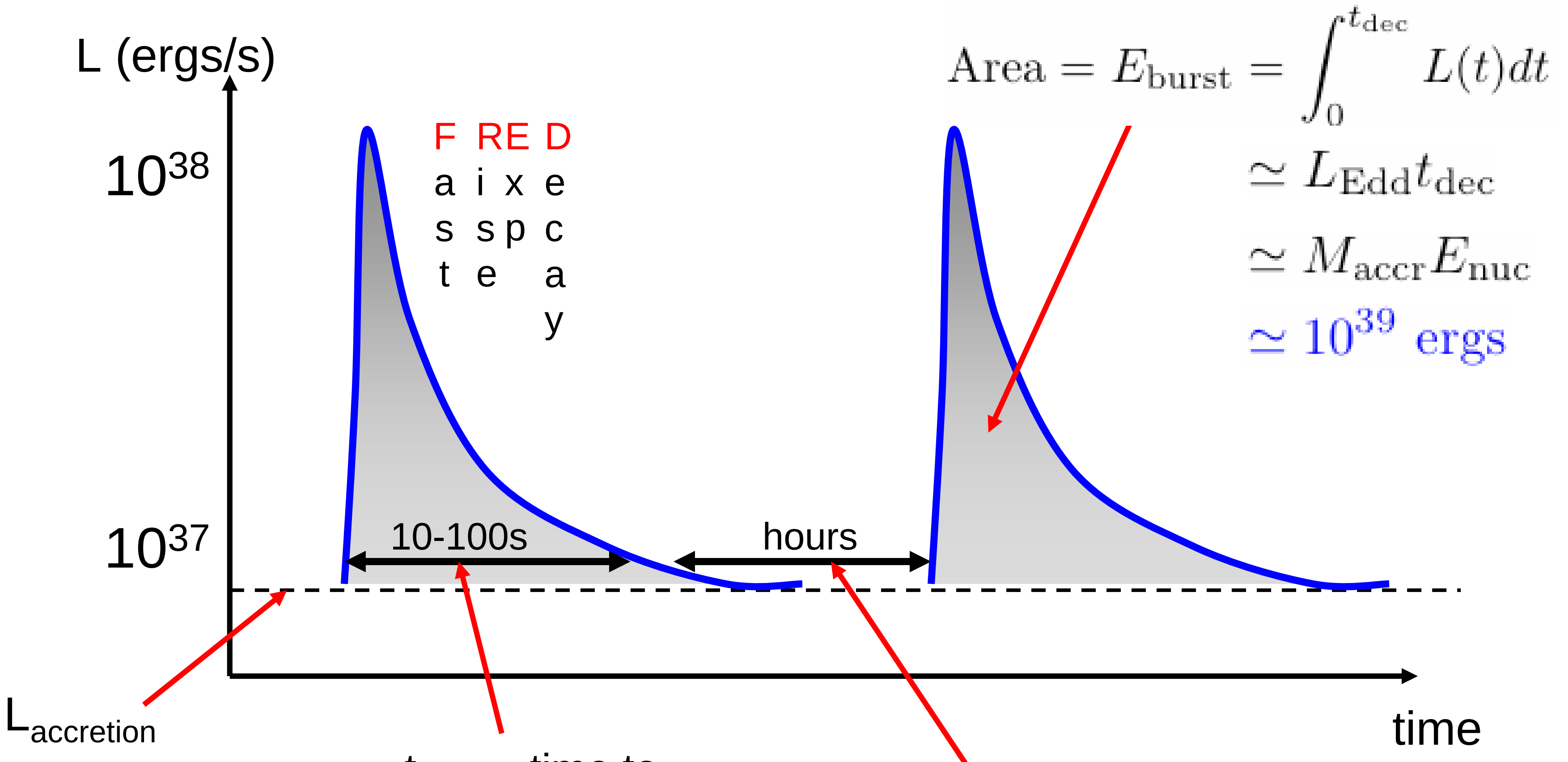
100m

gravity

$y = 10^{12}$ g cm^{-2}

^{12}C ignition shell

Type I X-Ray Bursts



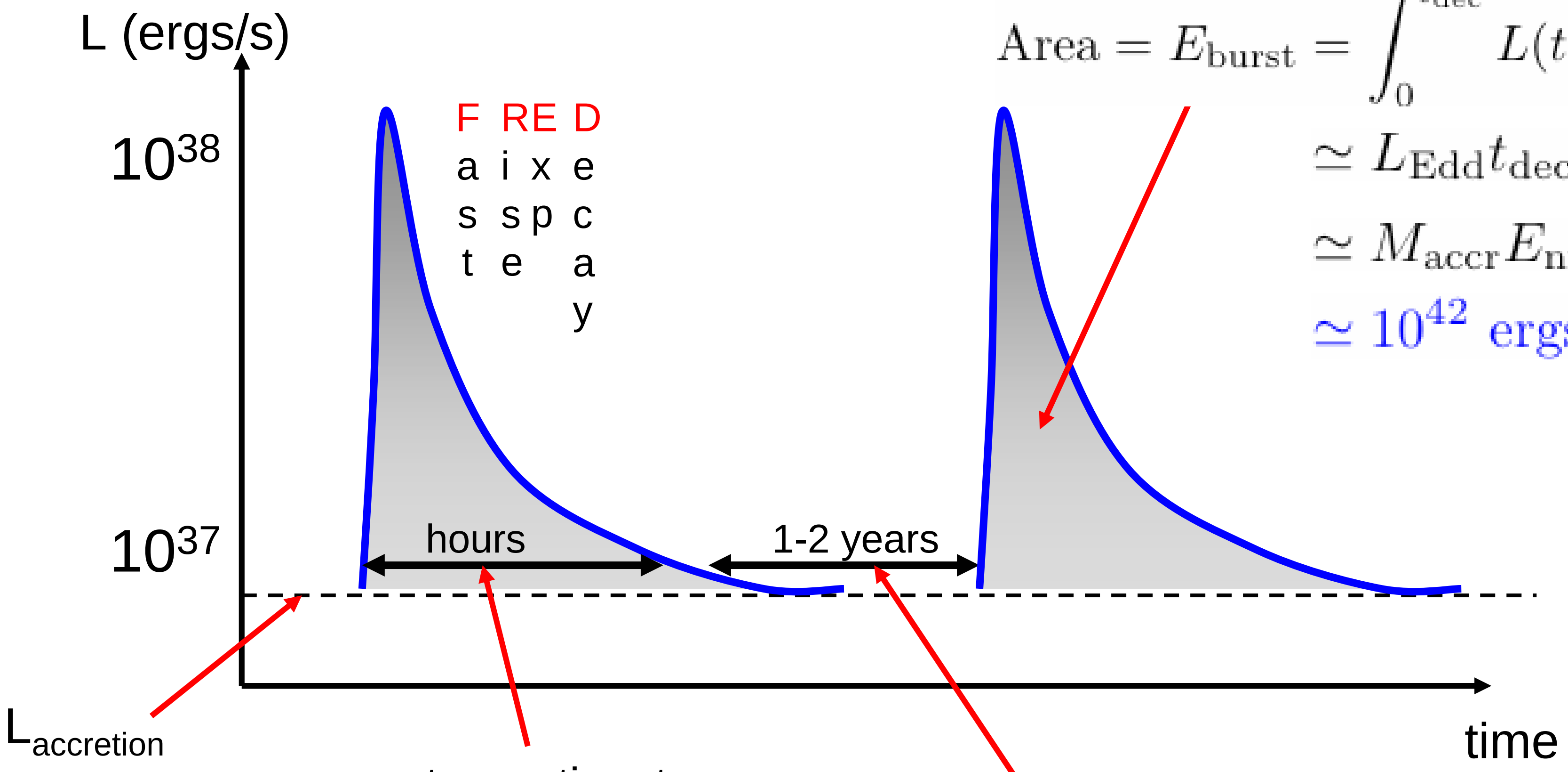
$$\mathrm{Area} = E_{\mathrm{burst}} = \int_0^{t_{\mathrm{dec}}} L(t)dt$$
$$\simeq L_{\mathrm{Edd}} t_{\mathrm{dec}}$$
$$\simeq M_{\mathrm{accr}} E_{\mathrm{nuc}}$$
$$\simeq 10^{39}\ \mathrm{ergs}$$

t_{decay}= time to burn fuel & cool

$t_{recurrence}$= time to accumulate fuel for next burst

S-bursts

$$\text{Area} = E_{\text{burst}} = \int_0^{t_{\text{dec}}} L(t)dt$$
$$\simeq L_{\text{Edd}} t_{\text{dec}}$$
$$\simeq M_{\text{accr}} E_{\text{nuc}}$$
$$\simeq 10^{42} \text{ ergs}$$

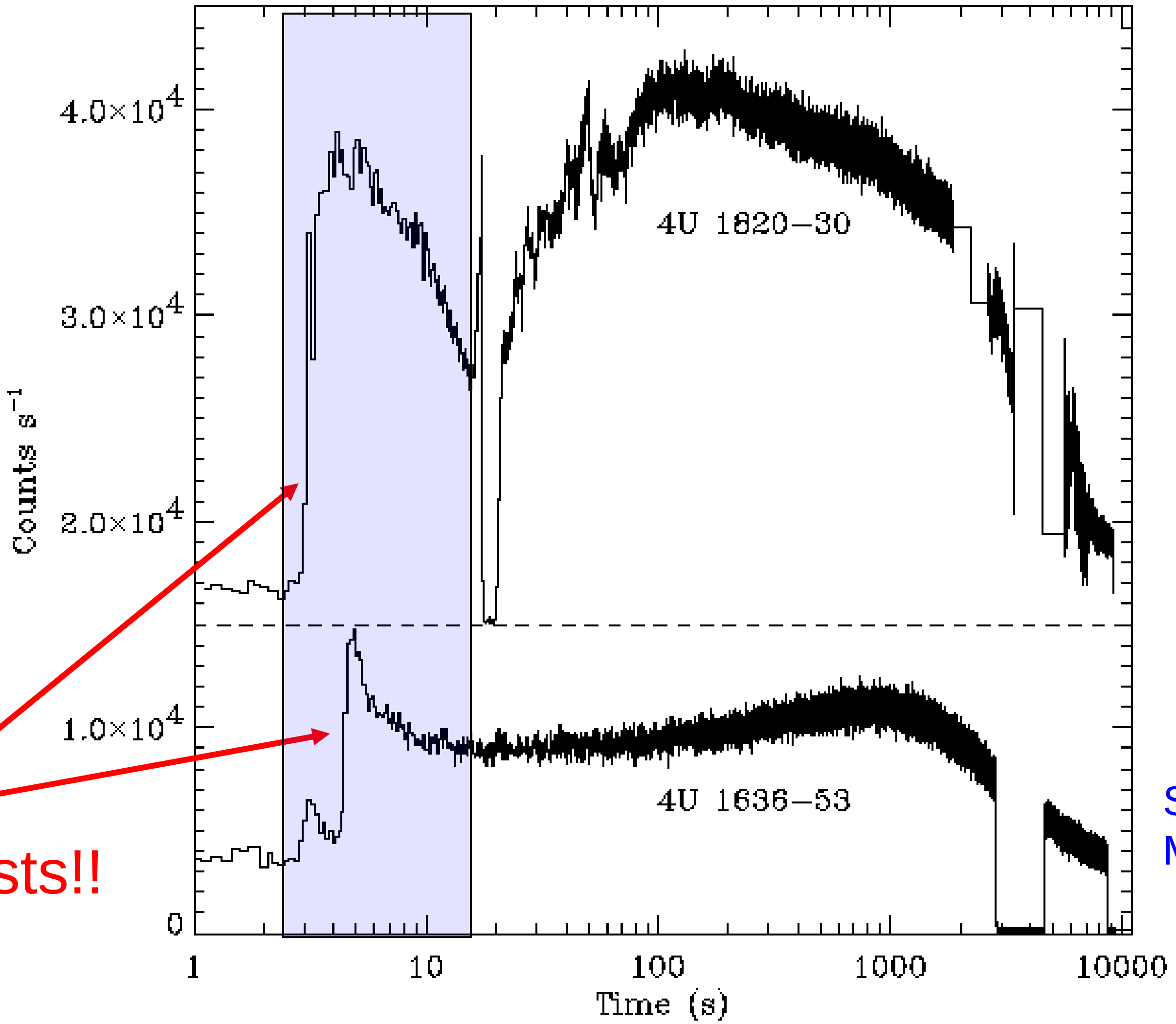


F RE D
Fast Rise Exp Decay

t_{decay}= time to burn fuel & cool

$t_{\text{recurrence}}$= time to accumulate fuel for next burst

S-bursts



4U 1820-30

Strohmayer & Brown 2002

4U 1636-53

Strohmayer & Markwardt 2002

precursor
Type I bursts!!

Late-time light curves (>1000 s):

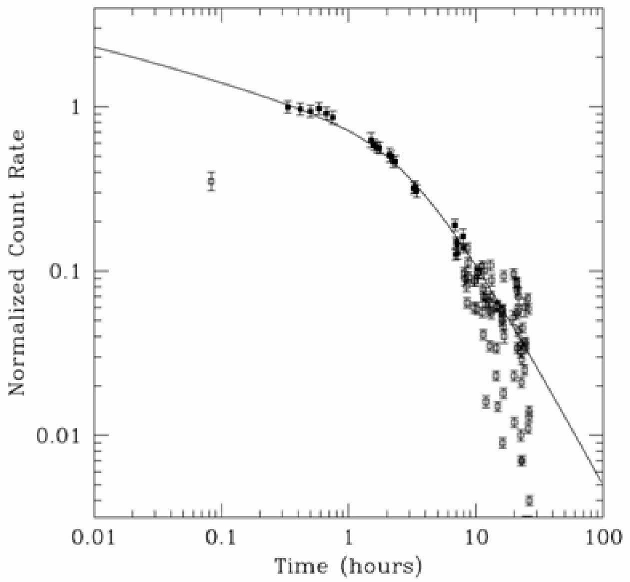


FIG. 5.—Fitted light curve for KS 1731−260, assuming the distance given in Table 1. Solid data points are included in the fit, open data points (with fluxes less than 0.1 of the peak flux) are not included.

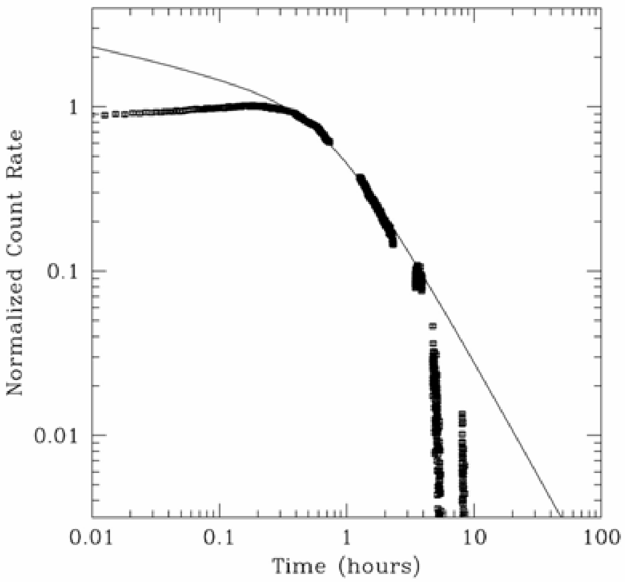


FIG. 6.—Fitted light curve for 4U 1636−54.

Cumming et al. 2006

- late-time light curve set by thermal cooling wave propagating through the hot ashes into the star
- assuming all the ^{12}C fuel burns instantly and hydrostatically provides a good fit to late time light curve
- but…
  - not a good fit to early time light curve.
  - what triggers the precursor Type I burst?

Burning Questions

Given that:

1. The ^{12}C ignites at such high densities ($\rho \sim 10^9$ g cm^{-3} => strong degeneracy)…
2. And ^{12}C burning is so temperature sensitive ($\varepsilon \sim T^{26}$)…

Q: Will the burning become hydrodynamic?

Specifically, will the nuclear heating timescale

$$t_{heat} \sim (d\ln T/dt)^{-1} \sim C_p T/\ \varepsilon_{nuc}$$

during the burn become shorter than the dynamical time

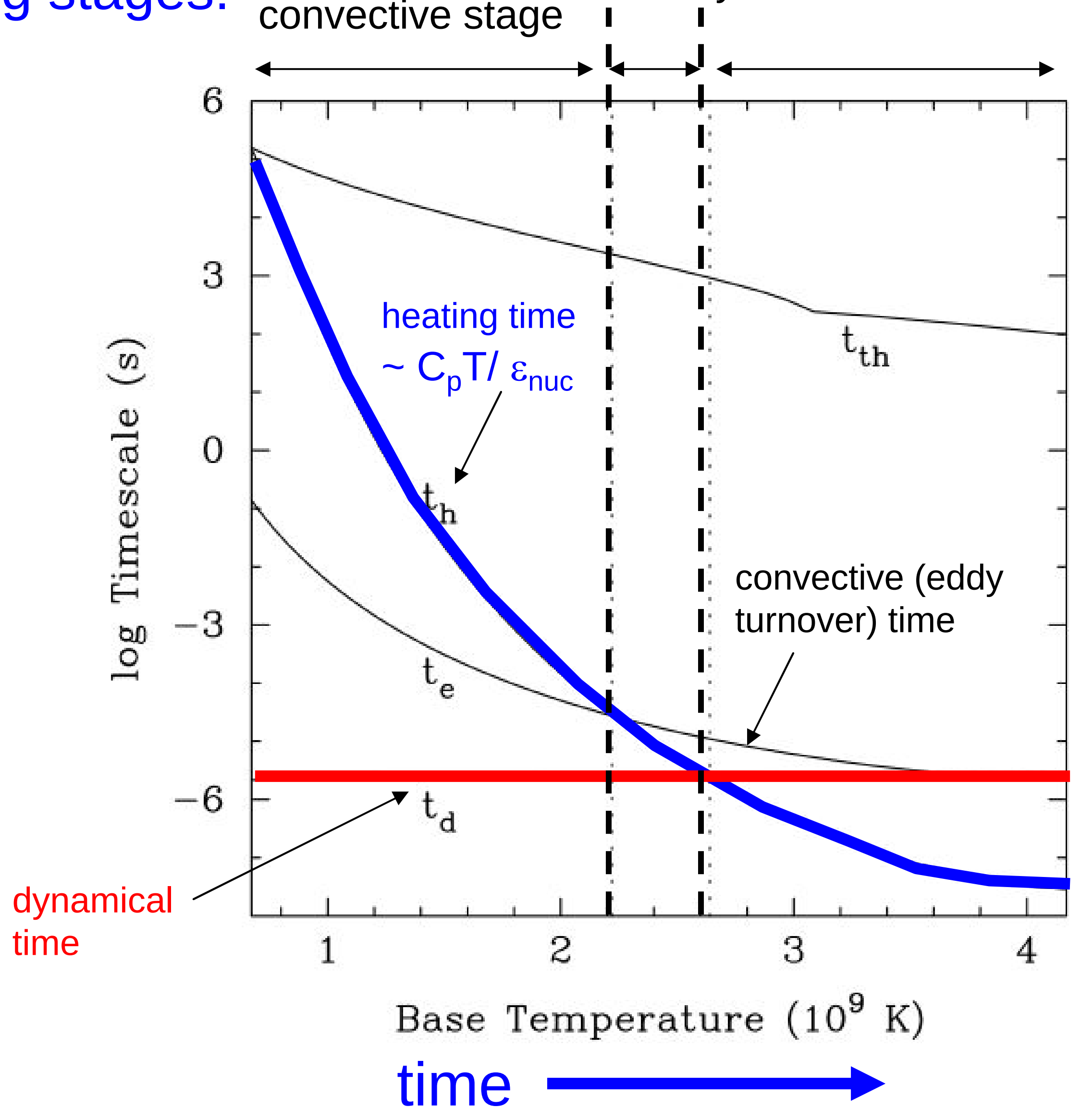
$$t_{dyn} \sim h/c_s \sim 10^{-6}\mathrm{s}\ ?$$

Yes

➡ Explosive burning… a detonation!

Timescales during burn

3 burning stages: hour-long convective stage, runaway, detonation



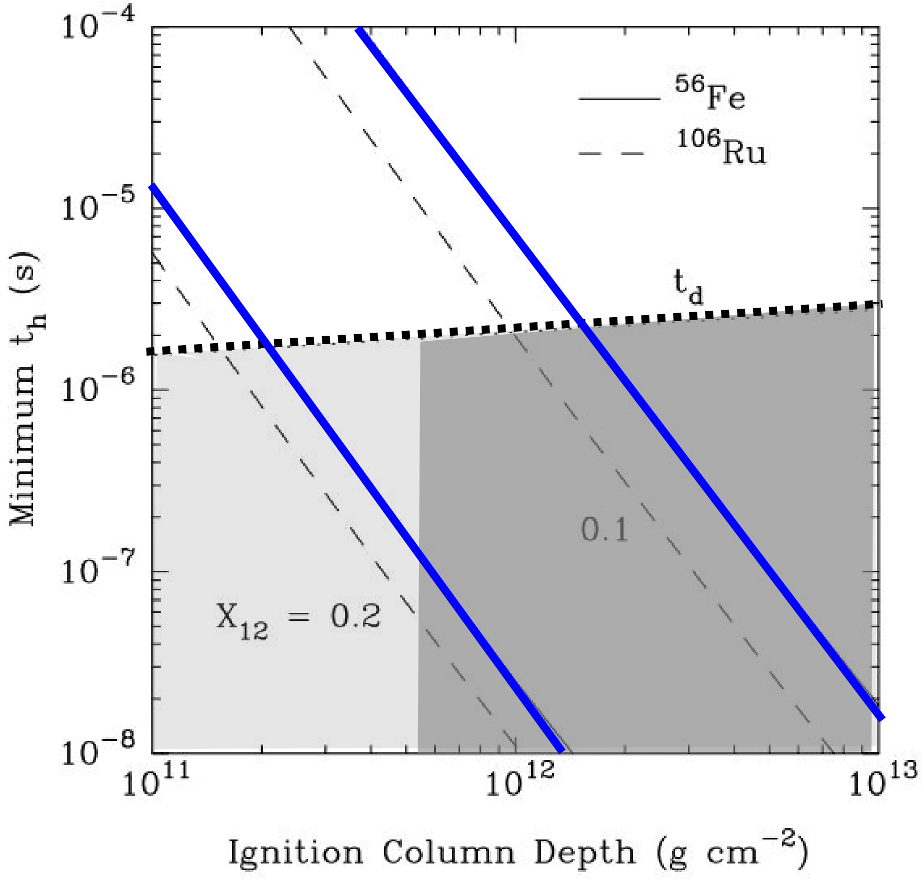
heating time ~ C_pT/ε_{nuc}

convective (eddy turnover) time

dynamical time

time

Timescales during burn



Minimum ignition depth needed to get hydrodynamic burn $t_{heat} < t_{dyn}$:

$$\boxed{y_{ign} > (2.4\times10^{11}\,\mathrm{g\ cm^{-2}})\left(\frac{0.2}{X_{12}}\right)^{3.2}\left(\frac{Y_e}{0.5}\right)^{3.0}\left(\frac{2}{g_{14}}\right)^{0.7}}$$

Equivalently, minimum energy release needed to get $t_{heat} < t_{dyn}$:

$$\boxed{E > (3.4\times10^{41}\,\mathrm{ergs})\left(\frac{0.2}{X_{12}}\right)^{2.2}\left(\frac{Y_e}{0.5}\right)^{3.0}\left(\frac{2}{g_{14}}\right)^{0.7}}$$

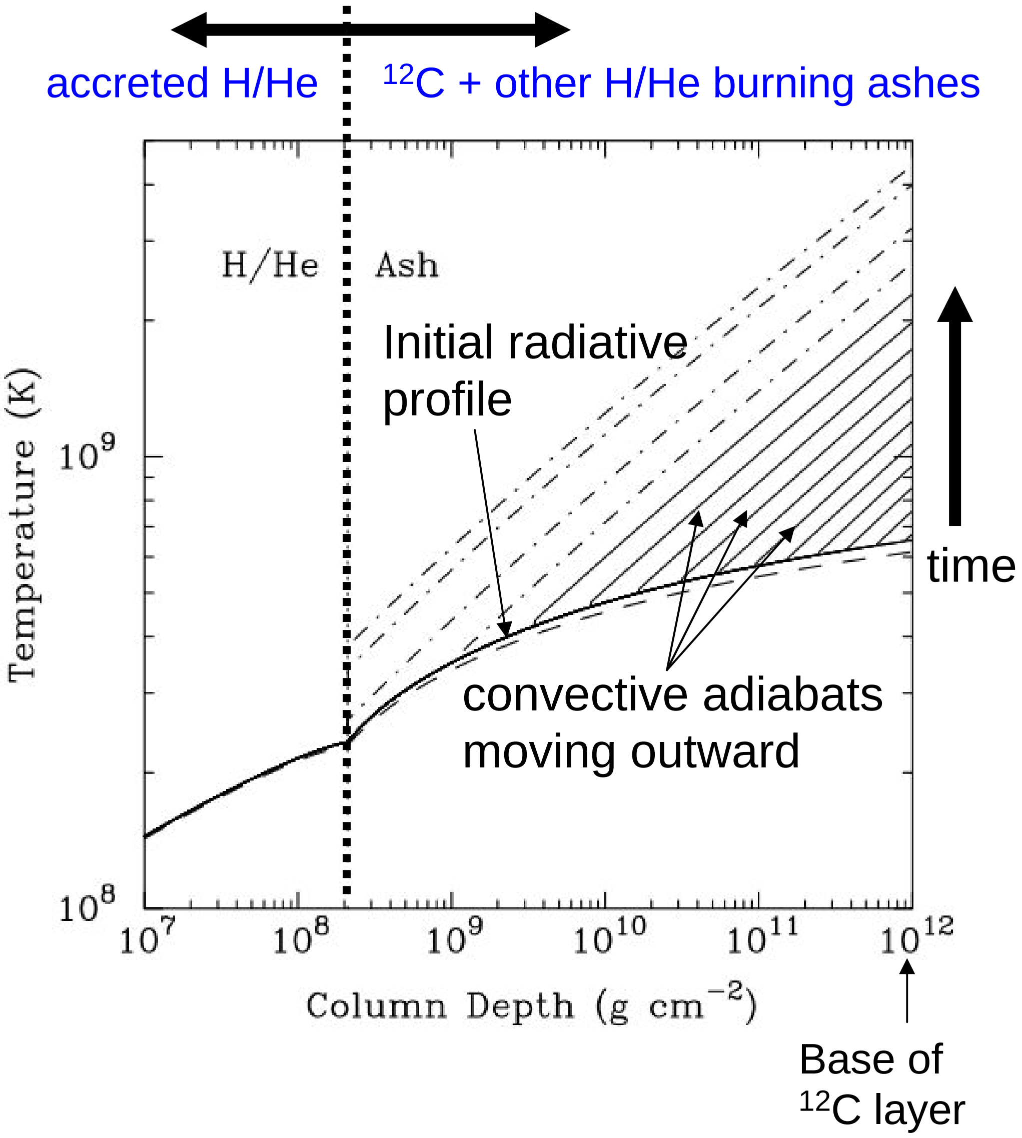
$$E_{\mathrm{observed}} = \int L\,dt \simeq 0.5 - 1.4\times10^{42}\,\mathrm{ergs}$$

Modeling the burn: I. the convective stage

1. Before ignition, entire atmosphere is radiative.
2. After ignition, a convective zone forms; it has an adiabatic temperature structure:

   $T(y) \sim y^n, \; n \sim 0.3$

3. Convective zone grows as ε increases.



accreted H/He

^{12}C + other H/He burning ashes

Initial radiative profile

convective adiabats moving outward

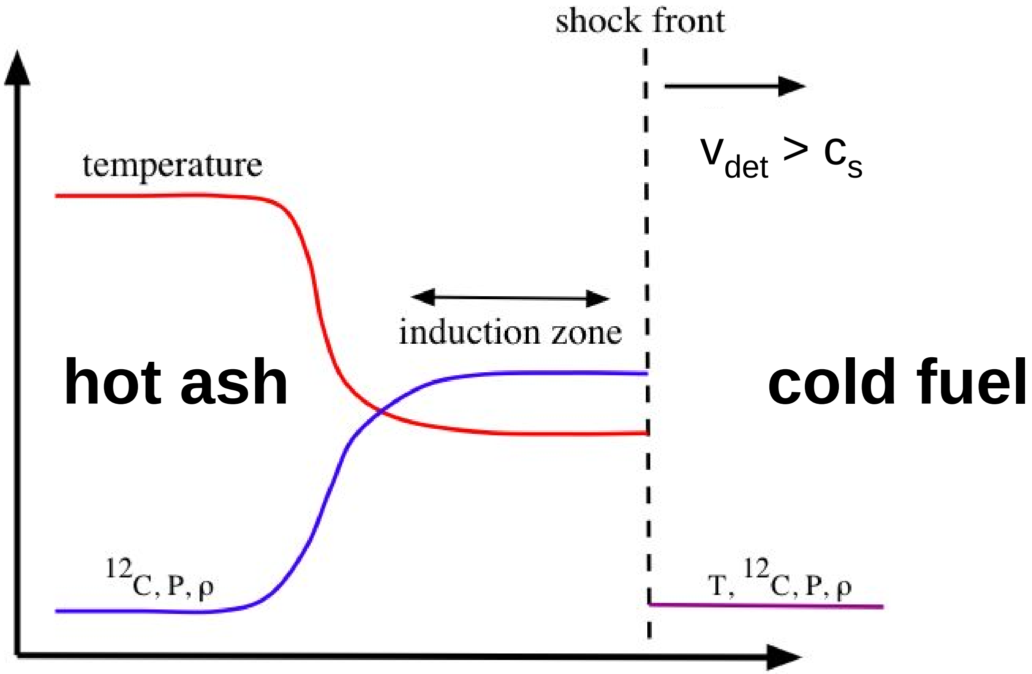
time

Base of ^{12}C layer

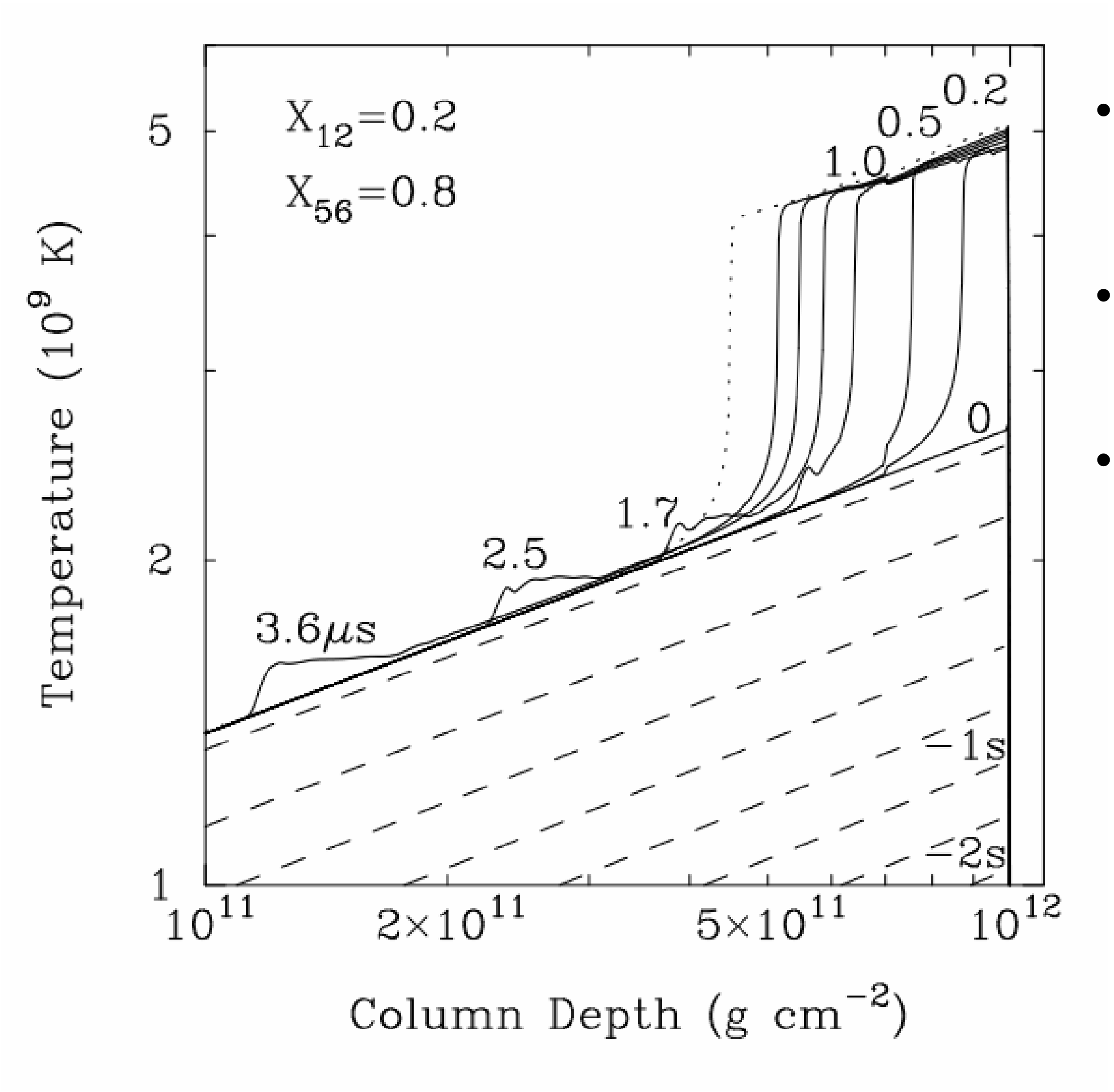
Modeling the burn: II. the detonation

- Solve propagation of detonation and shocks using a 1D finite difference, Lagrangian, hydro code.

- Couple the hydrodynamics to a 13 isotope α-reaction network: (includes α-chain, heavy-ion, and (α,p)(p,γ) reactions).



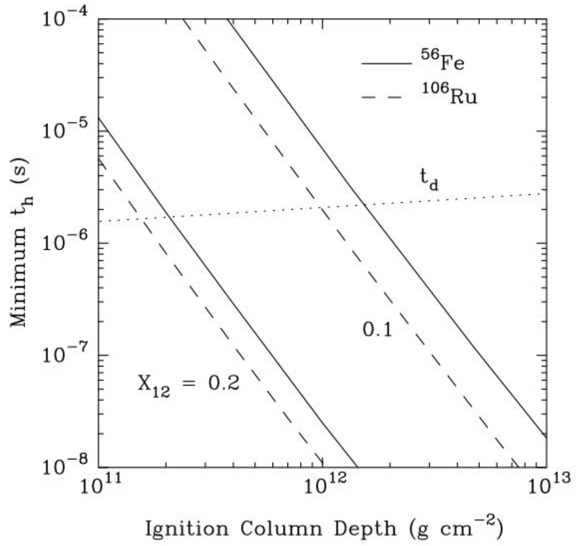
Modeling the burn: II. the detonation



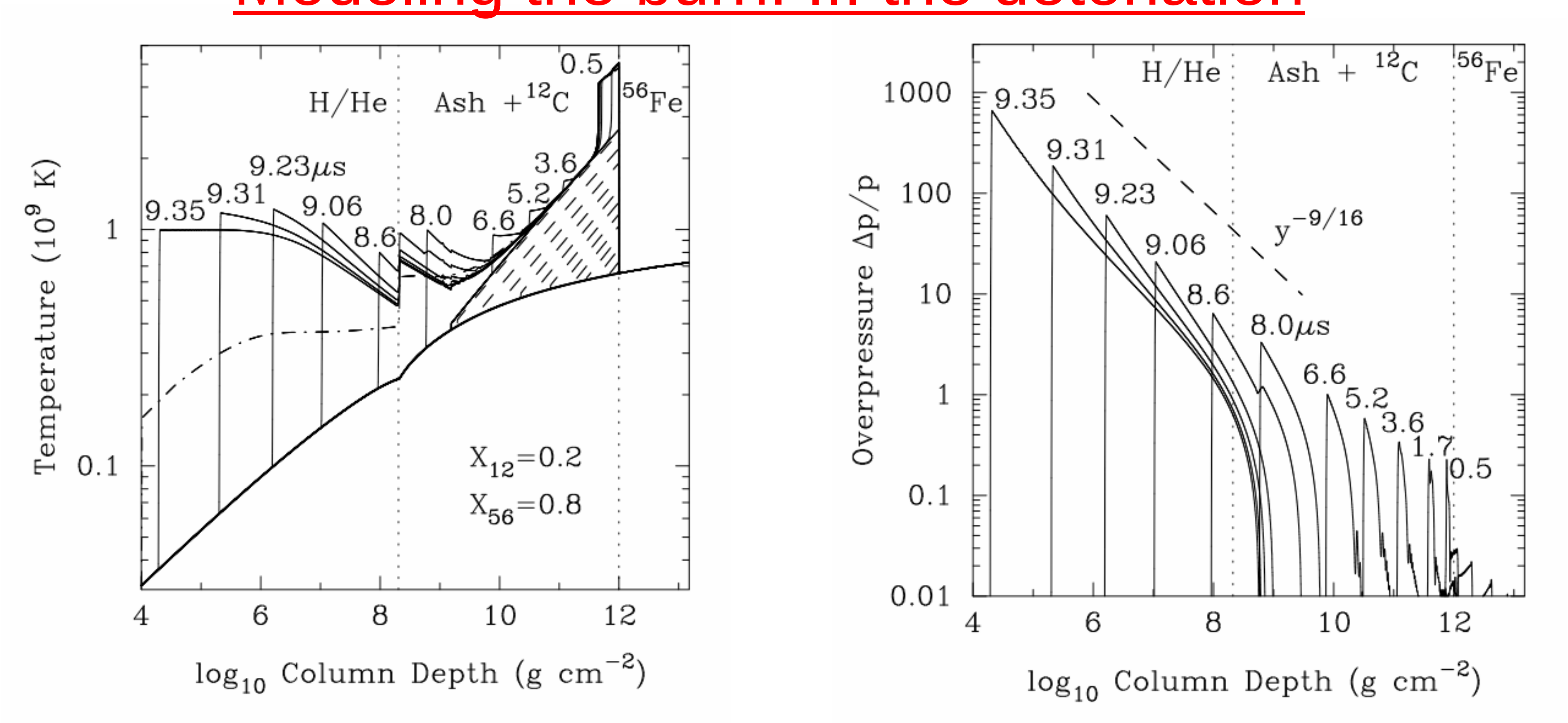
- Detonation moves outward into lower density, colder fuel.

- At ~$4\text{x}10^{11}$ g cm^{-2} detonation dies since $t_{heat} > t_{dyn}$

- But shock keeps moving out and steepening!

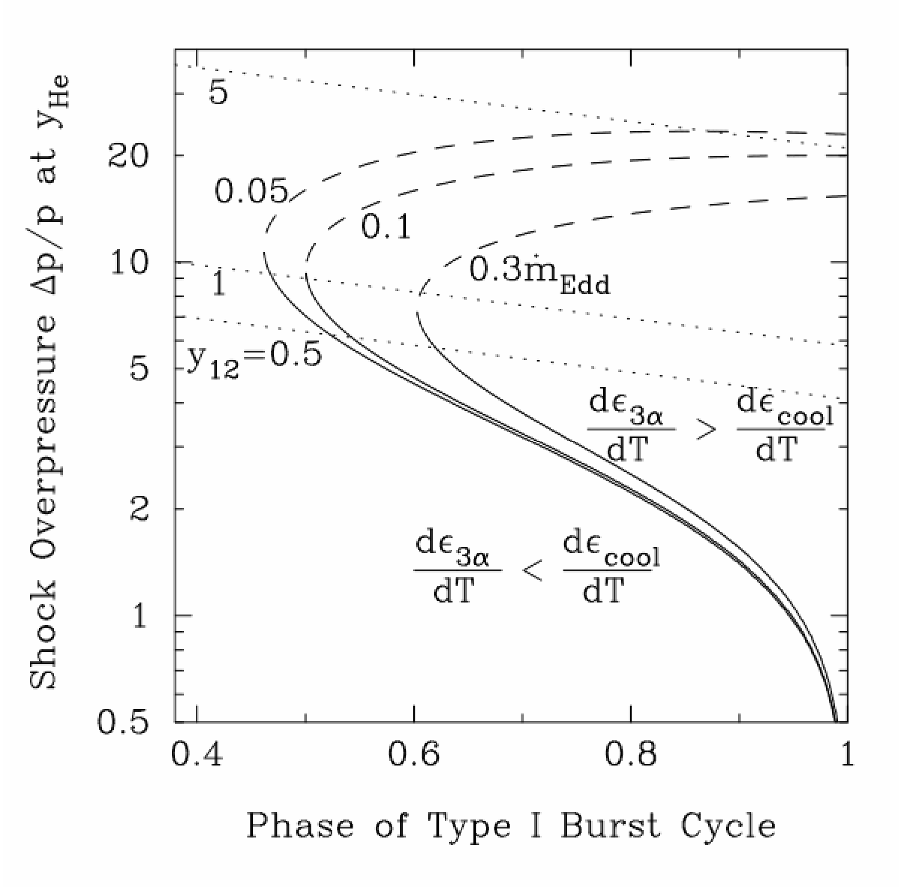


Modeling the burn: II. the detonation



- Shock steepens as power-law with column depth ($\Delta p/p \sim y^{-9/16}$)
- deposits lots of entropy in H/He layer… by the time shock hits the H/He at $y=10^8$ g cm^{-2}, $\Delta p/p \sim$ 5-10.
- H/He layer adiabatically expands in dynamical time (~μs) to cooler T.
- depending on how deep the H/He layer, shock can ignite the ^{4}He… and trigger a Type I precursor burst.

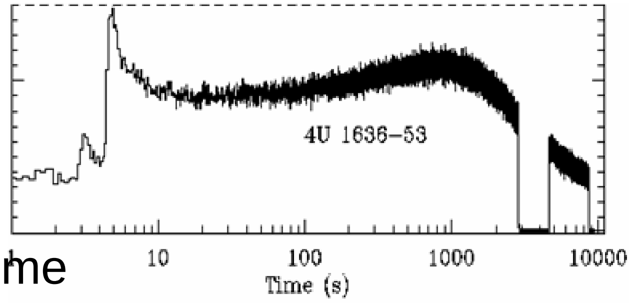
Shock-triggered helium burning



- about 1/2 the time there is enough H/He around that the shock ignites the ^{4}He and triggers a precursor burst
- precursors have been found in 4 out of 4 cases in which the onset was observed… (uh oh?)

Light curve:

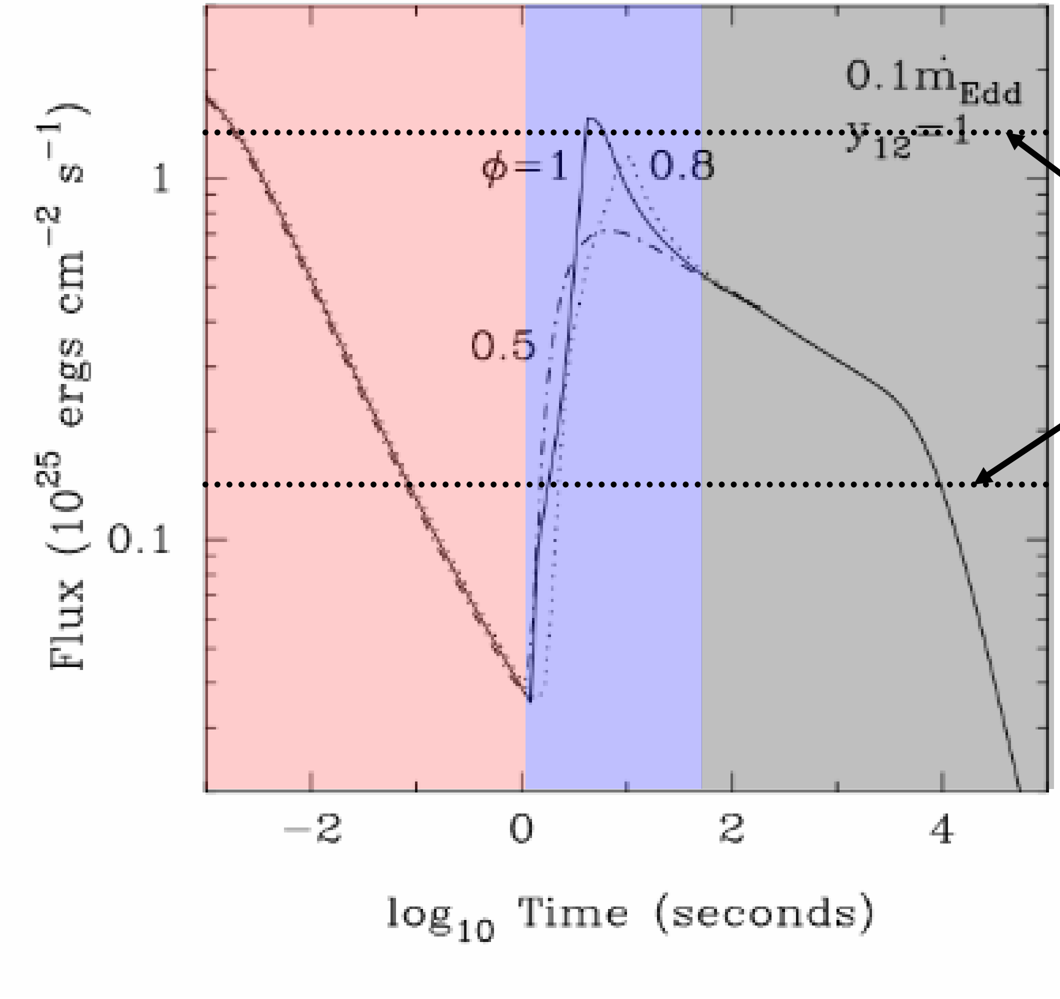
$$C_p \frac{\partial T}{\partial t} = \frac{\partial F}{\partial y} - \epsilon_\nu$$



shock breakout

precursor burst

late-time cooling wave



F_{Edd}

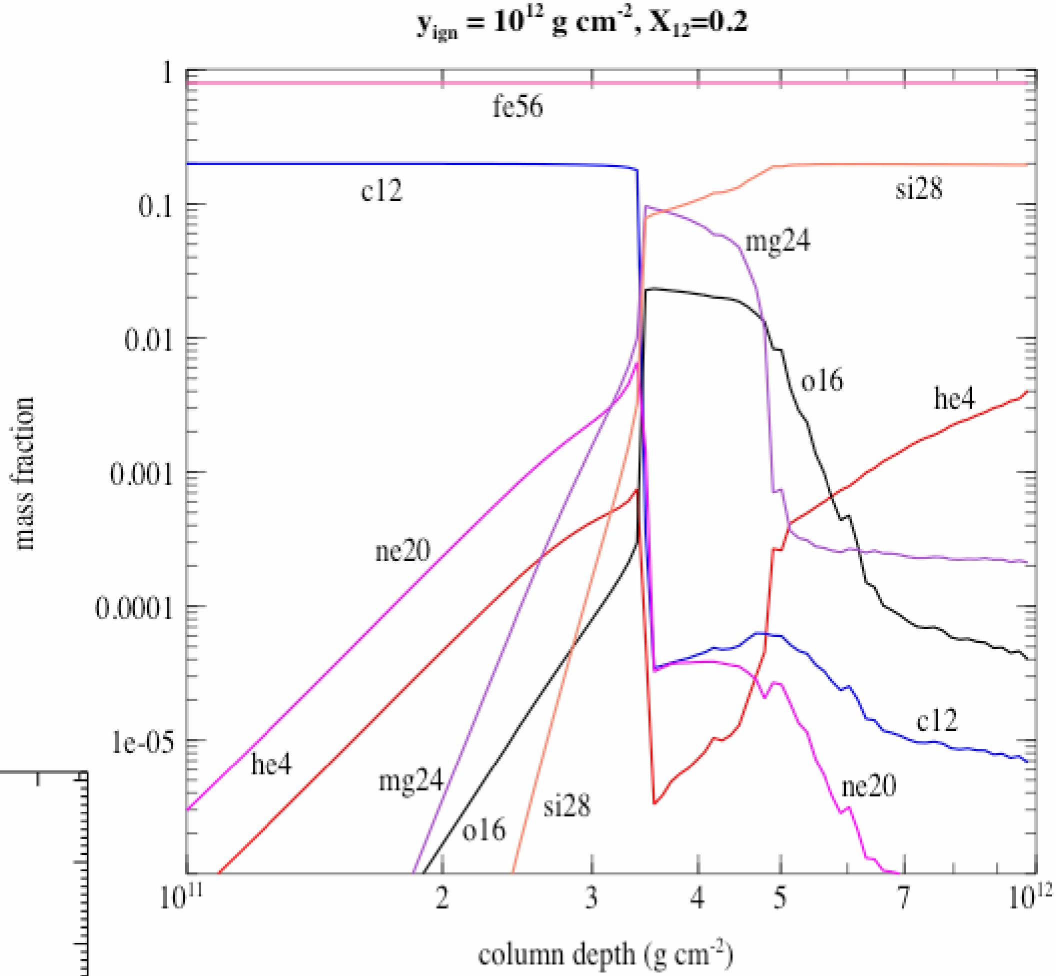
F_{accr}

Summary & questions

- strong degeneracy of ^{12}C ignition layer => $t_{heat} < t_{dyn}$ => detonation.
- detonation drives a shock that steepens as it moves upward.
- shock hits H/He layer, triggering He burning 1/2 the time
- accounts for precursor burst (He burning) and pre-precursor burst (shock breakout).

- have seen precursor 4/4… should we worry?
- what would it look like if it was a deflagration instead of a detonation?
- what about 2D propagation effects? sliding detonation…

Composition:



Gupta et al. 2006