Exposing Nuclear Burning Ashes During Radius Expansion X-ray Bursts

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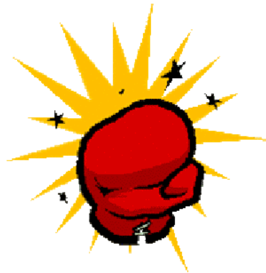
Outline

I. Punch-line
II. Brief overview of X-ray bursts
III. Convection during X-ray bursts
IV. Ash ejection by winds from super-Eddington bursts
V. Composition of ejected ashes & detectability (Chandra, XMM, Con-X?)
VI. Conclusions + Future plans

Punch-line



Ashes of nuclear burning are ejected in the radiative wind of photospheric radius expansion bursts and exposed

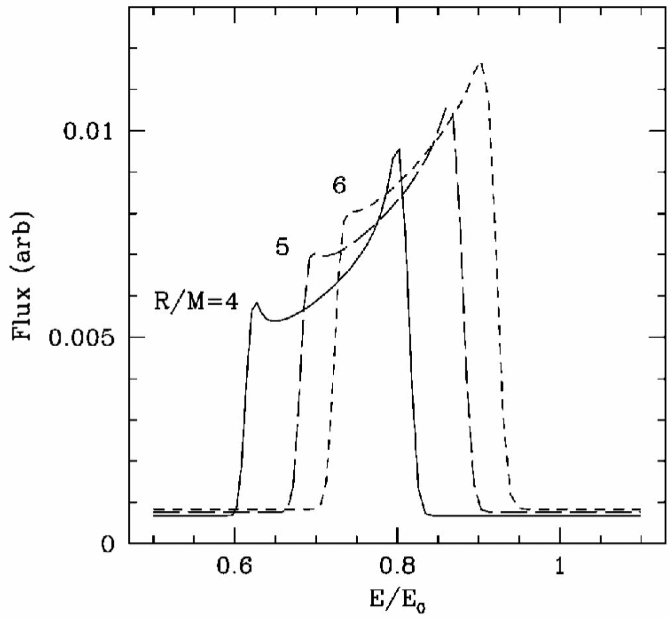
⇒ Detect spectral lines of ashes

Our study motivated by numerical results from Woosley, Heger et al.:

⇒ they showed ashes can be brought high up in atmosphere by convection.

Why is this interesting?

- By detecting spectral lines from ashes:
  1. Can measure gravitational redshift $z = \Delta\lambda / \lambda$ if lines formed near neutron star surface…measure NS equation of state.
  2. Probe nuclear processing even if lines not formed near surface



Ozel & Psaltis 2003

ν_{spin} = 400 Hz
spot radius = 20 degree

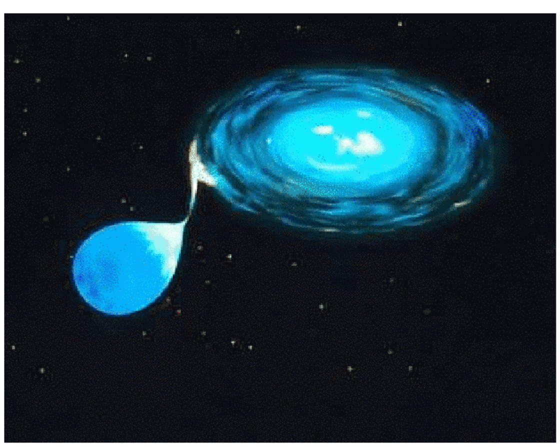
E_0 line center in lab frame

Cottam, Paerels, & Mendez 2002 report detection of redshifted H-like and He-like Fe absorption lines from bursts in EXO 0748-676… z ~ 0.35

Fe from accretion material not ashes of burning

Overview of X-Ray Bursts

Low-Mass X-ray Binary



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

Donor star: two possible types

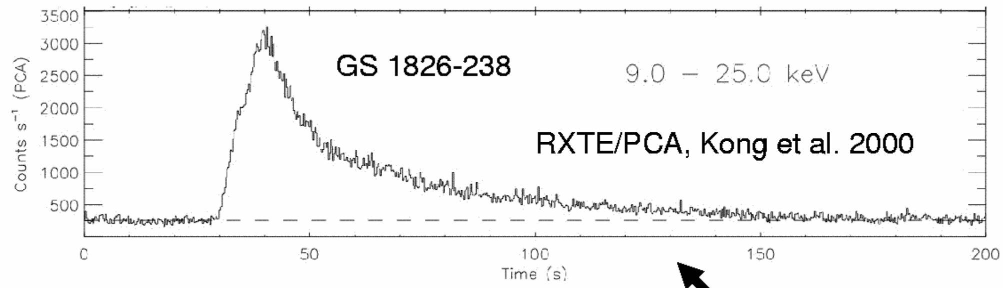
1. ~0.5 M_{sun} main sequence star…H/He accretion OR
2. He white dwarf or He core red giant…He accretion

P_{orb} ~ hour to days

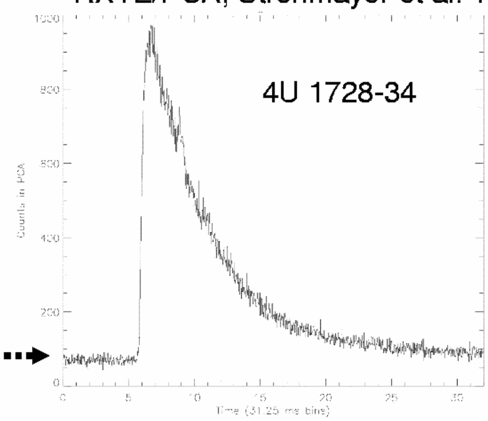
$$\dot{M} \sim 10^{-10} - 10^{-8} M_{sun} \mathrm{yr}^{-1}$$

$$L_{acc} = \frac{G M_{NS} \dot{M}}{R_{NS}} \sim 10^{36} - 10^{38} \text{ erg s}^{-1}$$

⇨ kT ~ keV
X-ray emitter



RXTE/PCA, Strohmayer et al. 1996



Long duration… mixed H/He burning

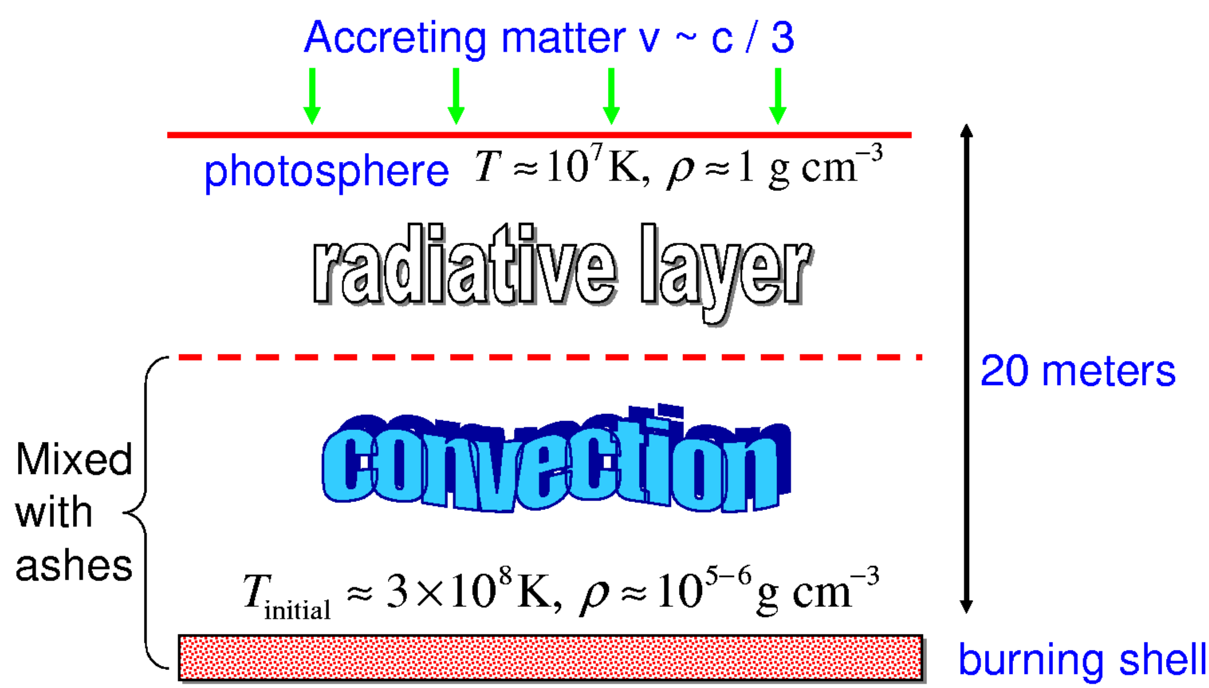
short duration… pure He burning

L_{acc}

E_G ~ 200 MeV/nucleon
E_{nuc} ~ few MeV/nucleon

Observe burst because nuclear fuel accumulated for hrs - days, burned rapidly in seconds - minutes

NS Atmosphere during an X-ray burst

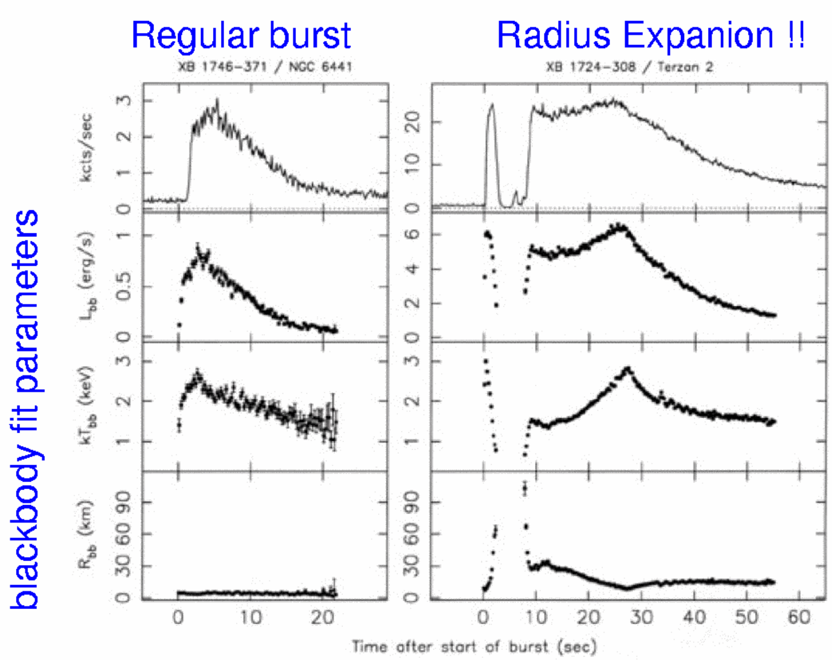


Burst properties sensitive to $\dot{m} = \frac{\dot{M}}{4\pi R^2}$

- Hot CNO burning during fuel accumulation… H → He
- $t_{\mathrm{burn\ H}} \sim 1$ day $t_{\mathrm{ignition\ mass}} \sim \mathrm{hr}\ (\dot{m}/\dot{m}_{\mathrm{Edd}})$

  If $\dot{m} < \dot{m}_{\mathrm{Edd}}/24$ ⇒ pure He layer in burning shell ($Y_{he} \sim 1$)
- Since $\varepsilon_{3\alpha} \propto (Y_{he})^3$ low accretion rate yield more energetic bursts

$\dot{m} < \dot{m}_{\mathrm{Edd}}/24$ ⇒ Super-Eddington luminosity which drives a radiative wind (photospheric radius expansion)

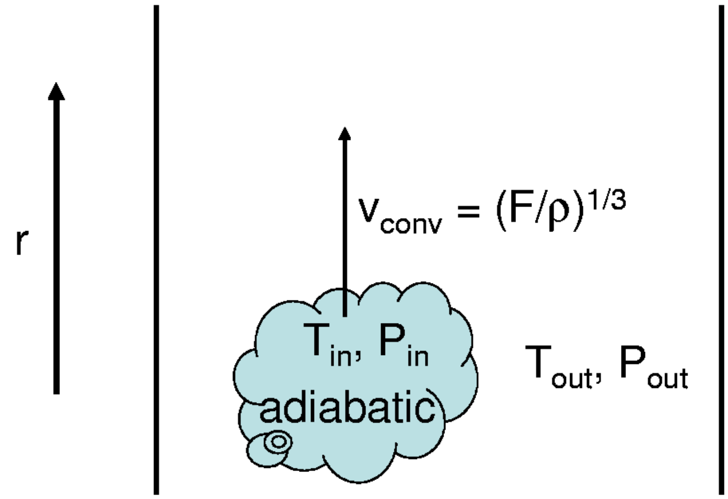


Kuulkers et al. 2002

$M_{wind}/M_{accreted} \sim E_{nuclear}/E_{gravity} \sim 2\,/\,200 \sim 1\%$

We show that convection reaches low enough pressures that wind from RE burst can eject ashes.

Convection during X-ray Bursts



$P_{in} = P_{out}$

$T_{in} > T_{out}$

$\therefore\ \rho_{in} < \rho_{out}$

buoyancy force

Convectively unstable if $\left|\left(\frac{dT}{dr}\right)_{in}\right| < \left|\left(\frac{dT}{dr}\right)_{out}\right|$

Convection during X-ray Bursts

- Why is atmosphere convective?

  $t_{thermal}$(at base) = $C_P T_b y_b / F = (10^{8+8+8} / 10^{24}) \sim 1$s

  $t_{dynamical}$(at base) = H_P / c_s
  $= (y_b / \rho_b g)^{1/2} = (10^8 / 10^{6+14})^{1/2} \sim 10^{-6}$ s

  where $y = P / g$ = column depth (g cm^{-2})

- Convection subsonic:

  $v_{conv} \sim (F / \rho)^{1/3} = (10^{24} / 10^6)^{1/3} = 10^6$ cm/s

  $C_s = (g\, y / \rho)^{1/2} = (10^{14+8} / 10^6)^{1/2} = 10^8$ cm/s

⇒ Thermal profile in convective region very nearly follows an adiabat: $T \propto y^n$, $n \sim 2/5$

The extent of the convective region

- Upper bound: Joss 1977

$$S \propto \ln(T^{5/2} / P) = \ln(T^{5/2} / g\,y)$$

Photosphere: $([10^7]^{5/2} / 10^{14+0}) \sim 3000$

Burning shell: $([10^9]^{5/2} / 10^{14+8}) \sim 3$

⇒ Entropy barrier of photosphere prevents convection from reaching surface

The extent of the convective region

- Order of Magnitude estimate: find where entropy of radiative region equals entropy of convective region

$$S \propto \ln(T^{5/2} / P) = \ln(T^{5/2} / g\,y)$$
$$= \ln(3) \text{ in convective region}$$

In radiative region temperature profile follows

$$T(y) \sim T_{surface} (y_{surface} / y)^{1/4}$$

So extent of convective region y_c:

$$3 \sim T_{surface}^{5/2} (y_s / y_c)^{5/8} / g\,y_c$$

$$y_c = (T_{surface} / 3)^{8/13}\, y_{surface}^{5/13} = (10^7 / 3)^{8/13} = 10^4 \text{ g/cm}^2$$

Pretty good estimate… but ignores heating up of radiative region, etc., and doesn't give evolution

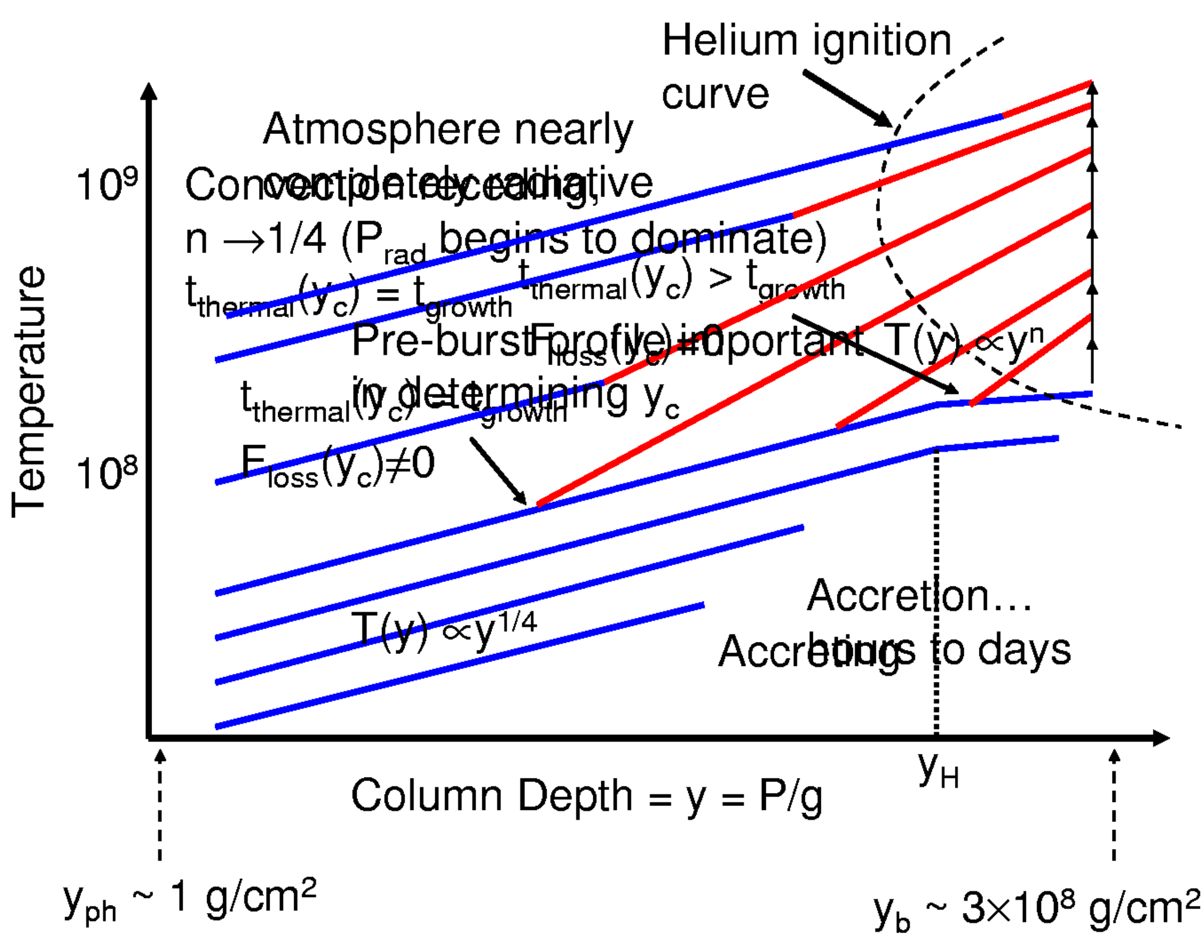
The extent of the convective region

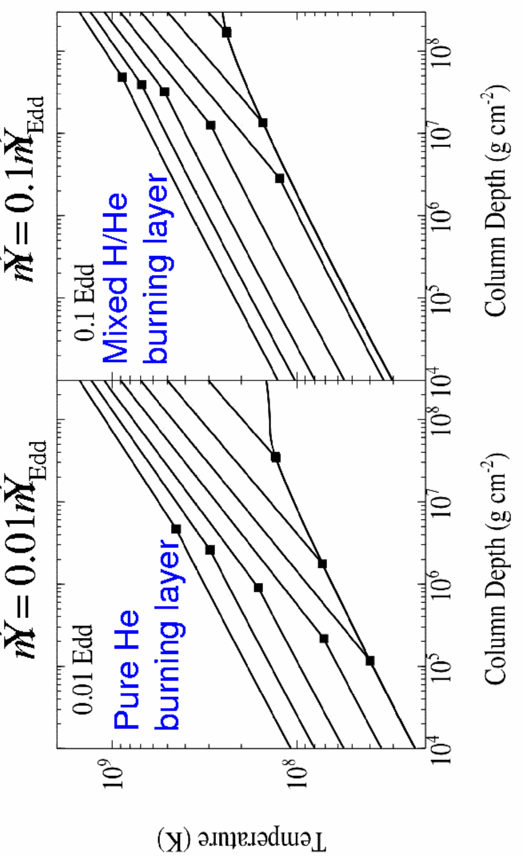
- Solve the entropy equation: $T\frac{dS}{dt} = \frac{dF}{dy} + \varepsilon_{\text{nuclear}}$
- Convective region adiabatic: $T(y) = T_b(y/y_b)^{n(y)}$
- Use $T\frac{dS}{dt} = C_P\frac{dT}{dt}$ and integrate over convective region:

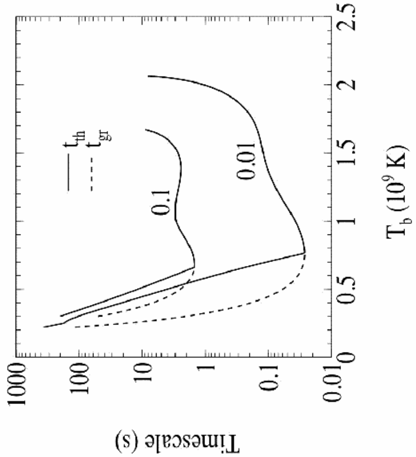
$$\frac{dT_b}{dt} = \frac{\int_{y_c}^{y_b} \varepsilon_{\text{nuclear}} dy + F_{\text{crust}} - F_{\text{loss}}(y_c)}{\int_{y_c}^{y_b} C_P (y/y_b)^{n(y)} dy}$$

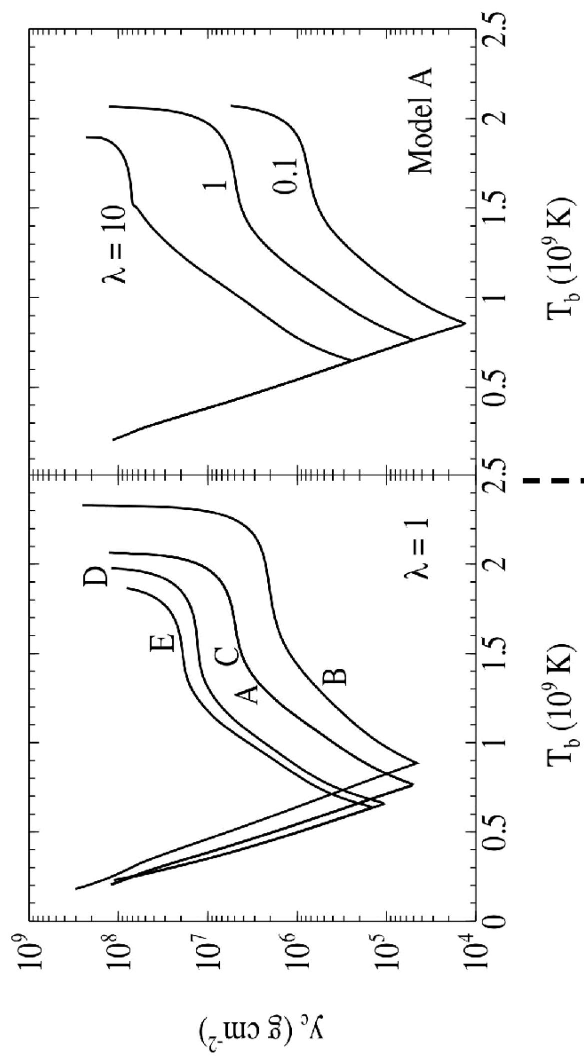
Similar to calculation in Hanawa & Fujimoto 1984

F_{crust} = flux escaping from crust ~ 0.1 MeV/nucleon
$F_{loss}(y_c)$ = flux lost to overlying radiative region
(get from mixing length theory)







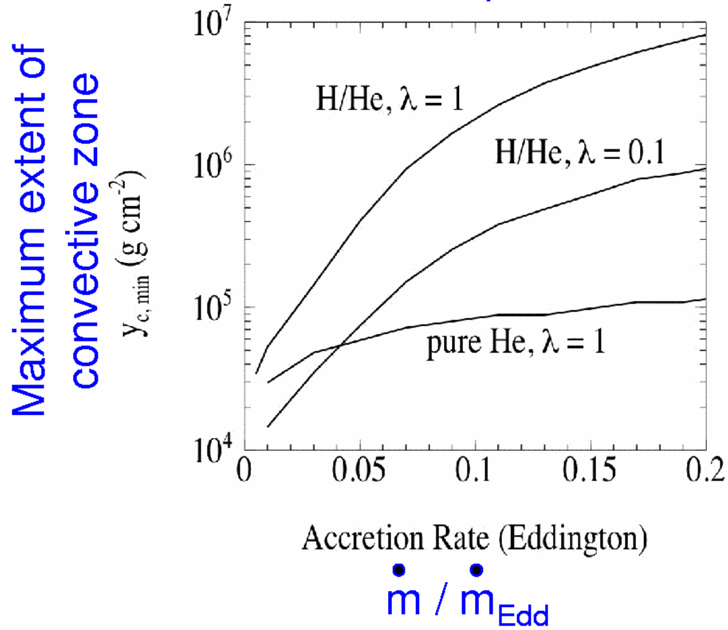


A, B, C: solar-abundance accretion

D, E: He donor star (like 4U 1820-30)

$$F_{\rm loss}(y_c) = \lambda \frac{4acnT_c^4}{3\kappa y_c}$$

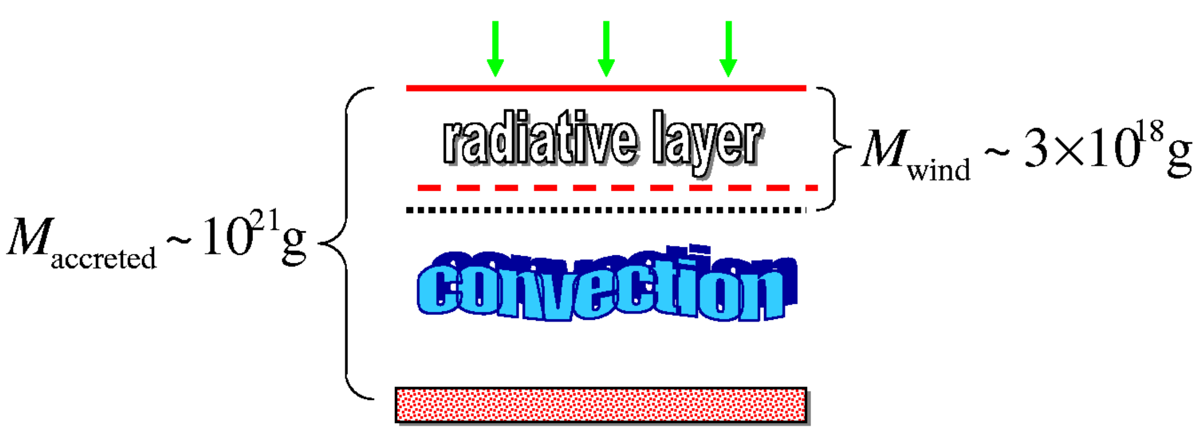
The BIG picture



$y_{c,min}/y_b$ = fraction of mass above convective zone
= 0.01% at 0.01 Edd
= 1% at 0.1 Edd

Winds During Radius Expansion Bursts

- The ashes mixed throughout convective region do not reach photosphere (entropy barrier).
- But do the ashes reach low enough pressures at an early enough times (before $L>L_{Edd}$) to get ejected by the wind? $M_{wind}/M_{accreted} \sim E_{nuclear}/E_{gravity} \sim 1\%$



Estimate of $M_{wind} = M_{acc}\, y_w/y_b$

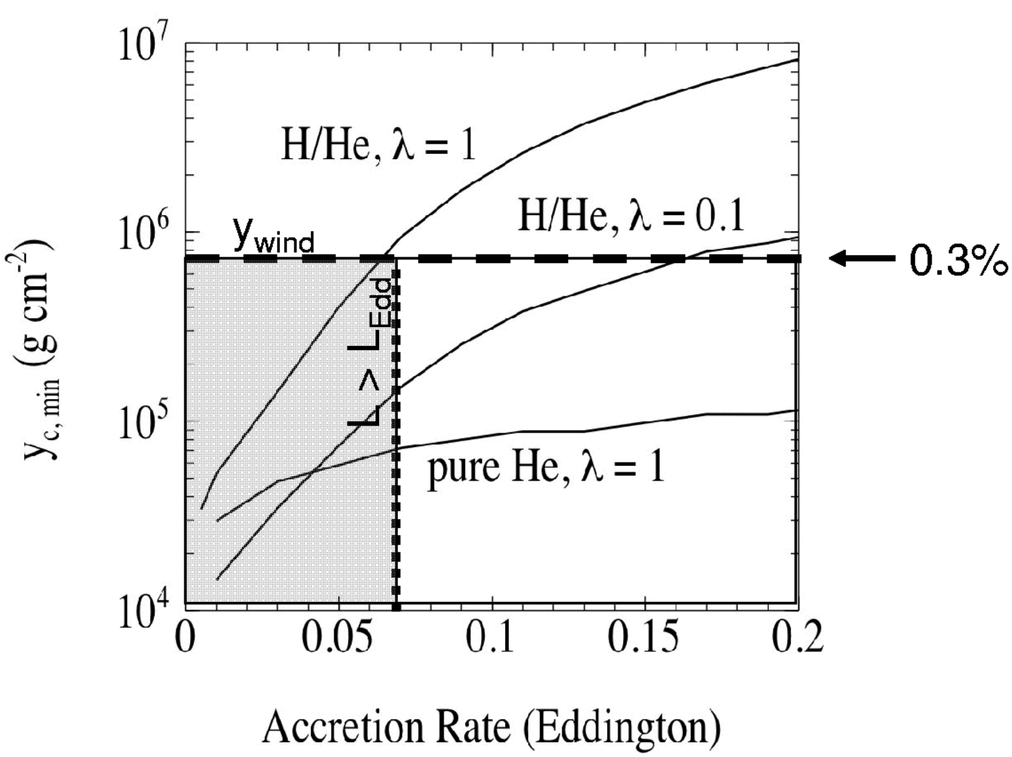
Suppose $L > L_{edd} = 4\pi GMc/\kappa$

Force $= (L - L_{edd})/c \approx v_{esc}\, dM_{wind}/dt$

$$dM_{wind}/dt \approx 10^{18} \text{ g/s } (0.2 / \kappa)\, (L/L_{edd} - 1)$$

Burst duration: $\Delta t \sim M_{acc} Q_{nuc}/L$,
where $Q_{nuc} = 1.6 + 4\, X_H$ MeV/nucleon

$$\Delta M_{wind}/M_{acc} \approx \Delta t\, (dM_{wind}/dt) / M_{acc} = (1 - L_{edd}/L) Q_{nuc} / v_{esc}\, c = 0.003\, (1 - L_{Edd}/L)$$

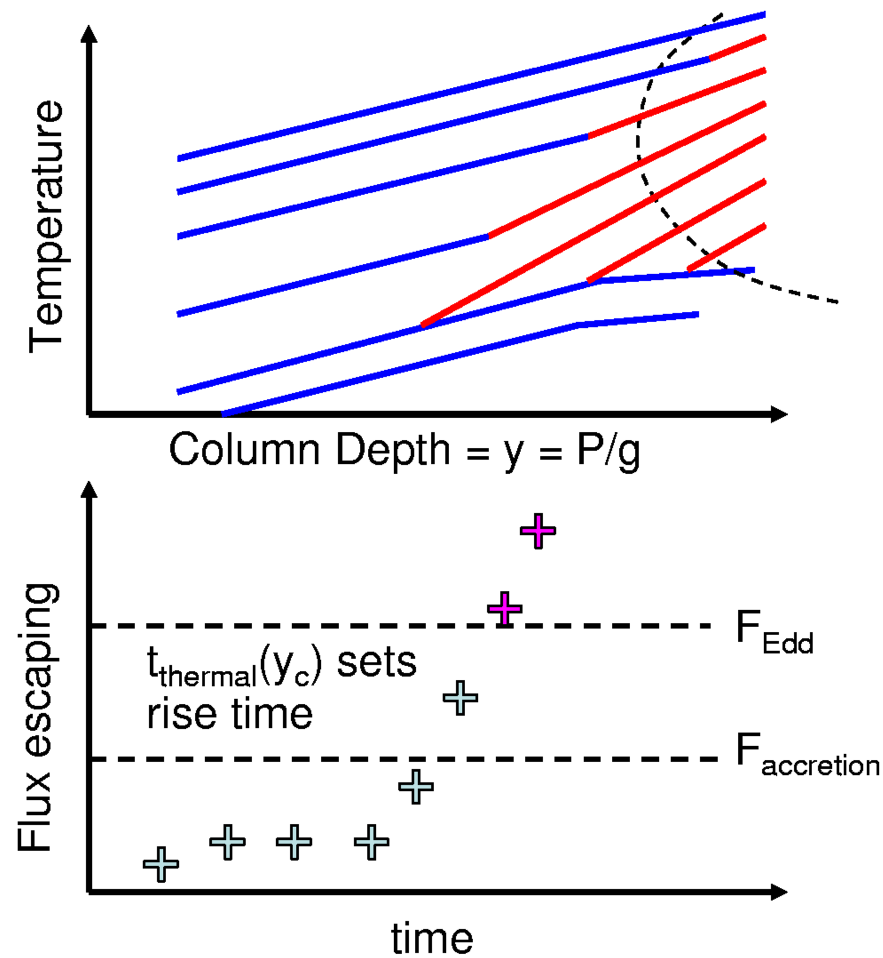


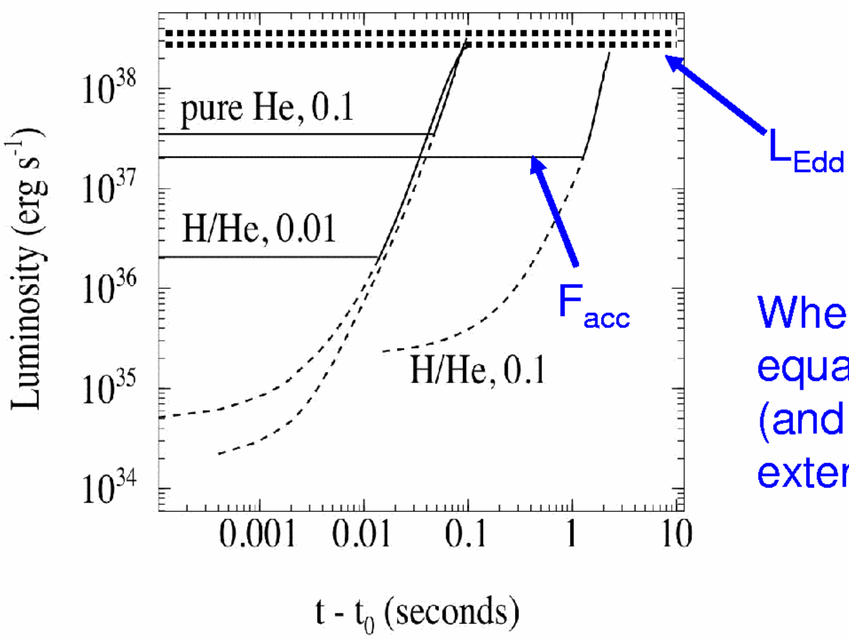
Timescale Question:

Does wind turn on after $y_c < y_{wind}$?

I.e., When $y_c < y_{wind}$ is $L < L_{edd}$?

⇒ Must calculate rise times of burst light curves





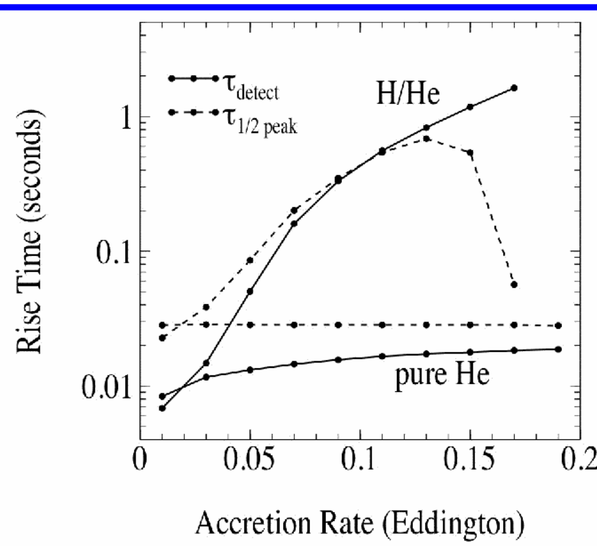
When $t = t_0$ thermal time equals growth time (and convection at max. extent)

Reach $L > L_{edd}$ well after $y_c < y_{wind}$… so ashes ejected.

burst rise times

Since photons diffuse out on the thermal timescale $t_{thermal}(y_{c,min})$ sets the timescale of the burst rise

⇨ The extent of convection sets the burst rise time



Ejected Ash Composition & Detectability

- Our current calculations of $\varepsilon_{nuclear}$ only account for α-captures…reasonable if only have helium around
- Do not burn to very heavy metals
- Can get spectral lines during cooling in radius expansion
- Difficult to get lines at surface…no redshift (?)

New calculations with Hendrik Schatz's full nuclear reaction network suggest there may be protons around even in initially pure He layer…changes $\varepsilon_{nuclear}$ and ash composition

Ejected Ash Composition & Detectability

Where might protons come from?

The reaction $^{12}C(a,g)^{16}O$ is a bottleneck

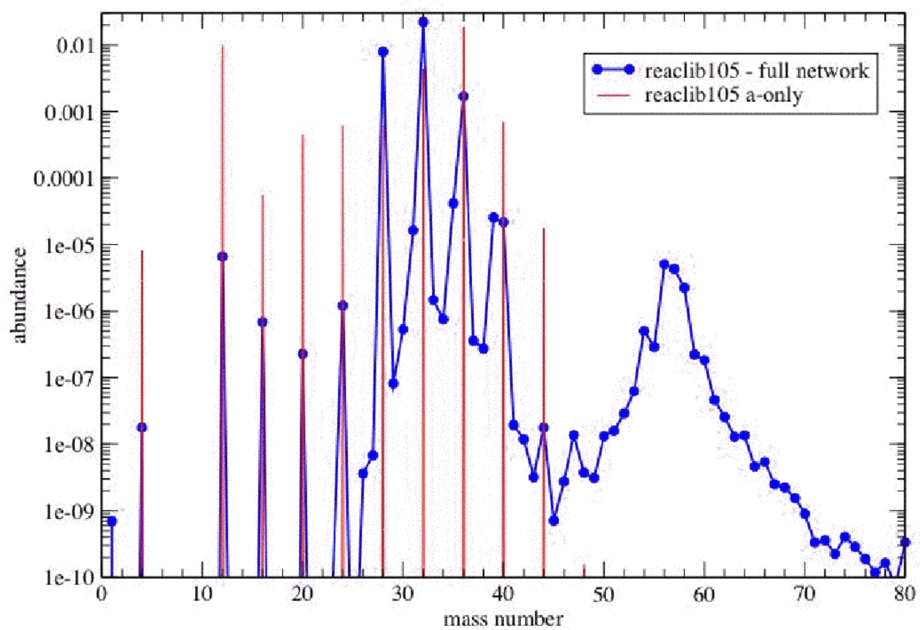
If have protons around can overcome bottleneck with the reaction $^{12}C(p,g)^{13}N(a,p)^{16}O$

Where might protons come from if have initially pure He layer?

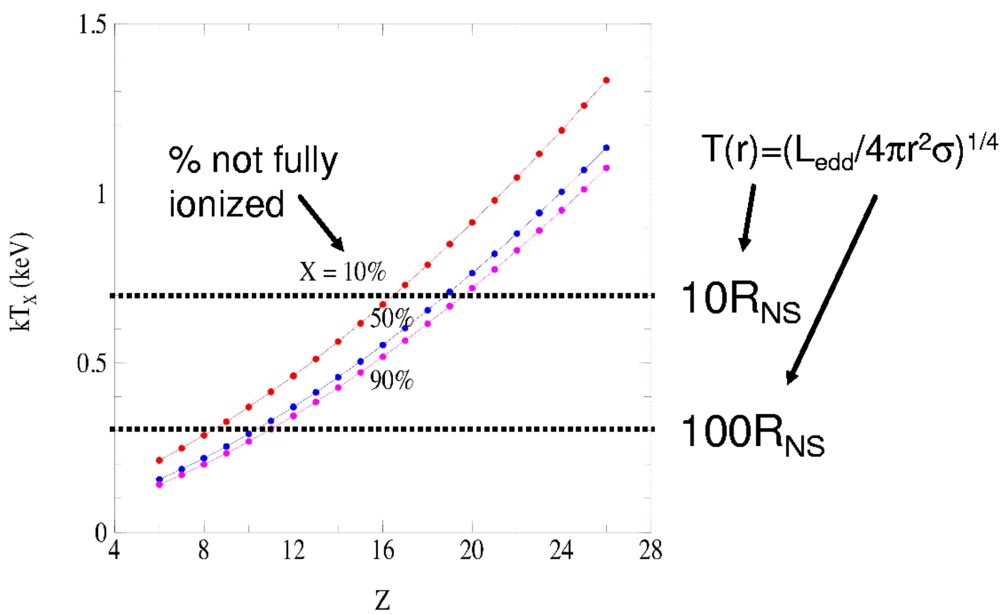
E.g., $^{24}Mg(a,p)^{27}Al(a,p)$
occurs if burning hot enough to reach ^{24}Mg but not so hot that overcome $^{12}C(a,g)$ bottleneck

⇒ Will there be heavy metals even in low accretion rate, radius expansion bursts? Redshift measurement?

Ejected Ash Composition & Detectability



Saha Ionization Equation:



Conclusions & Future Work

- Ashes of nuclear burning ejected during radius expansion bursts
- Detection of atomic spectral features would probe the neutron star equation of state and the nuclear burning
- Hope to soon have a better idea of the ash composition and address the detectability of lines with e.g., XMM, Astro-E2, Chandra, Constellation-X
- Putting together a proposal with D. Galloway for Chandra time