Overview of Accreting Neutron Stars

We see accreting neutron stars as bright X-ray sources. Their luminosity is set by gravitational energy released by the infalling matter:

$$L_{accr} = \left(\frac{GM}{R}\right)\dot{M} \qquad \text{—}(*)$$

↑ this is 200 MeV/nucleon for $1.4 M_\odot$, 10 km ($\sim 10^{20}$ erg/g)

Contrast nuclear energy scale 1 MeV $\sim 10^{18}$ erg/g

Even a small amount of accretion can drive a large luminosity

eg. $\dot{M} = 10^{-13} M_\odot/yr$ gives $L \simeq 10^{33}$ erg/s $\approx L_\odot$

[To show this, (*) is often written in the form $L = \dot{M}c^2\eta$ where $\eta = \frac{GM}{Rc^2}$ is the accretion efficiency $\simeq 0.2$ for neutron stars.]

Eddington luminosity — A natural limit to the accretion rate.

The accretion luminosity exerts an outwards force on the electrons

$$\underbrace{\left(\frac{L}{4\pi r^2}\right)}_{\text{Flux}} \frac{\sigma_T}{c}$$

σ_T ← Thomson cross-section for photon scattering

$\sigma_T = \frac{8\pi}{3} r_0^2$

factor of c gives the momentum flux

gravity acts on the protons $\quad \frac{GM}{r^2} m_p = m_p g$

An electric field couples the e^- and p.

When the two forces balance, $L = \boxed{L_{Edd} = \frac{4\pi GMc}{\kappa}}$

where we've defined the opacity $\kappa = \sigma_T/m_p = 0.4\ \mathrm{cm^2/g}$ "cross-section per gram"

$$L_{Edd} = 1.3 \times 10^{38}\,\mathrm{erg/s}\left(\frac{M}{M_\odot}\right)$$

For a neutron star, $L_{acer} = L_{Edd}$ for $\dot{M} \equiv \dot{M}_{Edd} \simeq 10^{-8}\,M_\odot/yr$
$(10^{18}\,g/s)$

Emission temperature

Blackbody emission $L = 4\pi R^2 \sigma_{SB} T_{eff}^4$

$$\Rightarrow \quad T_{eff} = 2\times10^7 K \, \frac{L_{38}^{1/4}}{R_6^{1/2}}$$

or photon energies $\approx$ keV X-rays

(This assumes the accreting particles deposit their energy at a depth below the photosphere, so the energy thermalizes.)

Types of NS X-ray binaries

[These are close binaries! $\left(\frac{2\pi}{P_{orb}}\right)^2 = \frac{GM_{tot}}{a^3}$

$\Rightarrow a = 9\times10^{10}\,cm \left(\frac{M_{tot}}{1 M_\odot}\right)^{1/3}\left(\frac{P_{orb}}{4h}\right)^{2/3}$

$\approx R_\odot$!!]

Two flavors:

$\boxed{LMXB}$

(Low mass X-ray binary)

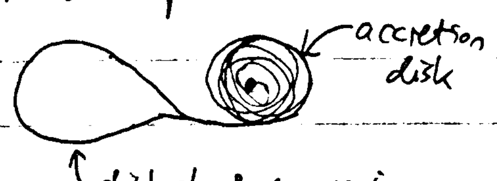
orbital periods ~ 10 mins to days to year

low mass companion star ($< M_\odot$)

long-lived systems $10^8 - 10^9$ yrs

$\dot{M} \sim 10^{-11} - 10^{-8}\,M_\odot/yr$

Roche lobe overflow from a low mass companion — stable accretion



Show X-ray bursts, few show pulsations

$\boxed{HMXB}$

(High mass X-ray binary)

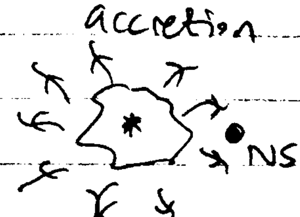
$P_{orb} \sim 1d - 100$'s days

high mass companion star ($> M_\odot$)

young systems $10^6 - 10^7$ yrs

Similar range of $\dot{M}$'s

Roche lobe overflow or wind accretion



No X-ray bursts! Often show accretion pulsations

Why LMXBs are interesting:

1) they live long enough they can replace their entire crust

eg. $\dot{M} = 10^{-9} M_\odot/yr$

time to accrete $0.01 M_\odot$ = 10^7 yrs << lifetime.

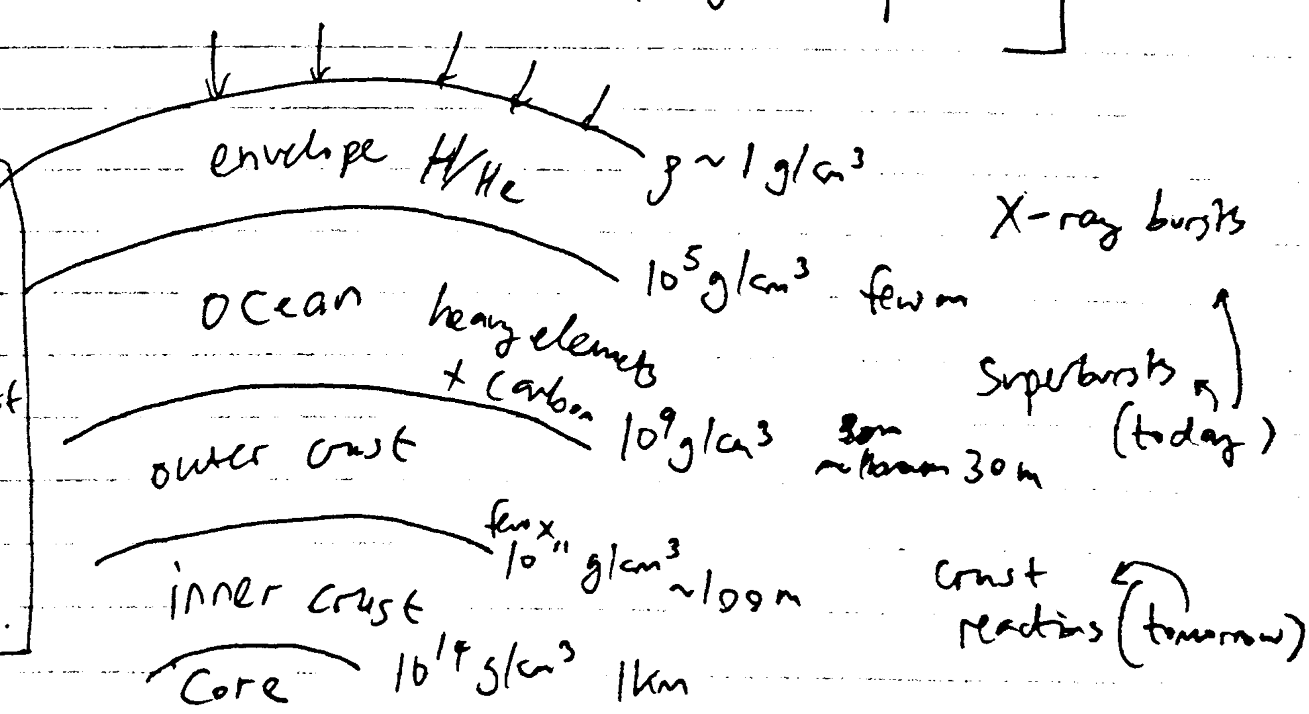
2) We can see the neutron star, either
- during thermonuclear flashes
- during periods of quiescence in transient systems

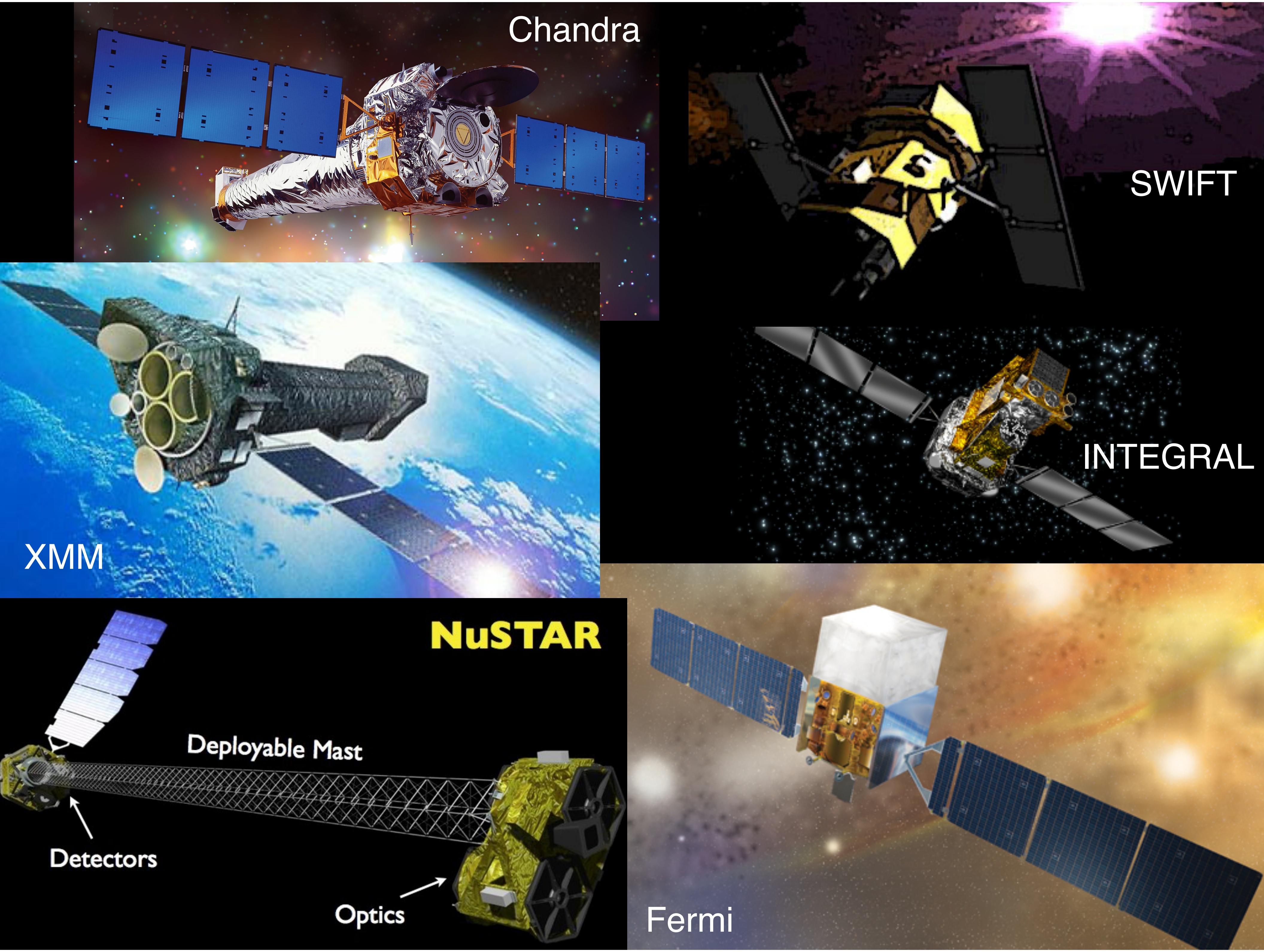
this means that the accreted matter is processed across the entire nuclear chart from proton drip line to neutron drip and beyond.

this heats the star as we will see
so even though neutron stars cool quickly in isolation (on timescales of ~ 10^6 yrs — see D. Page lectures) the LMXB neutron stars remain hot — as Ed Brown will describe.

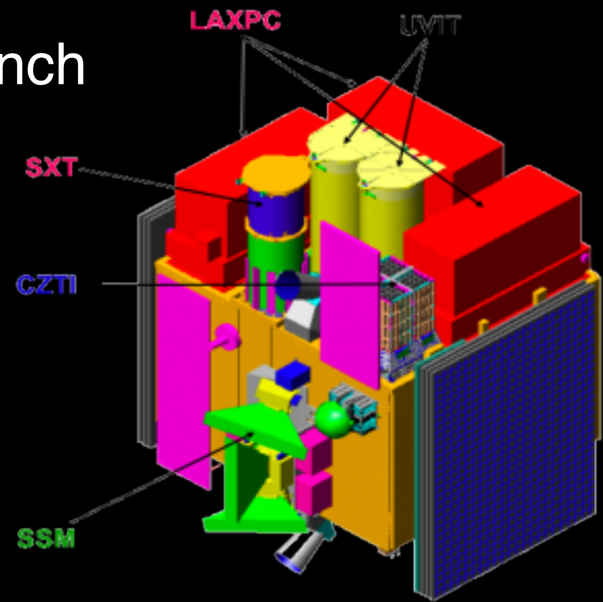
[Show some slides on current and future X-ray telescopes.]

* The different layers know about each other: eg. burst ashes form the crust; crust reactions heat the outer layers.

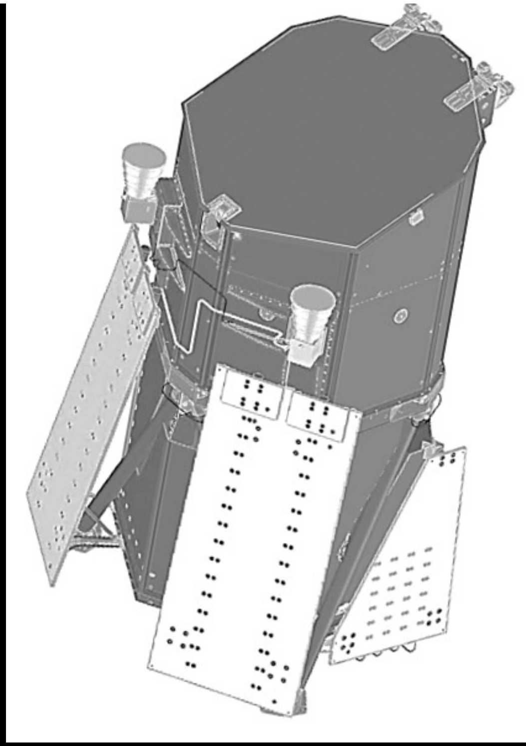



Chandra
SWIFT
XMM
INTEGRAL
NuSTAR
Deployable Mast
Detectors
Optics
Fermi

ASTROSAT
Oct 2015 launch

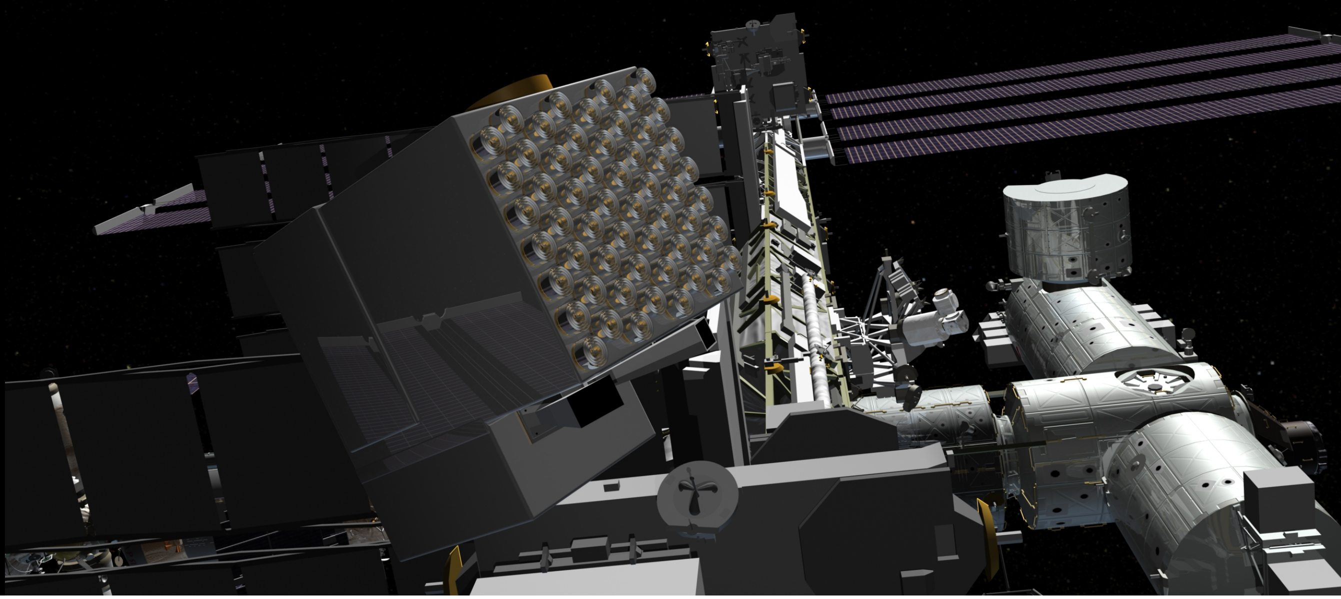


eROSITA
2017



ASTRO-H
2016 launch

NICER
Dec 2016 launch



Physics of thin shell flash

In a thin layer, the pressure is fixed by the weight of the overlying layers

$$P = \underbrace{g}_{\frac{GM}{R^2}\ \text{gravity}} \ \underbrace{y}_{\text{column depth } g/cm^2}$$

[an example of hydrostatic balance
$$\frac{dP}{dz} = -\rho g \Rightarrow \frac{dP}{dy} = g \Rightarrow P = gy$$]

[eg. on Earth $g \simeq 10^3\ cm/s^2$
$y \simeq (10^{-3} g/cm^3)(10\ km)$
$\Rightarrow P = 10^6\ dynes/cm^2 = 1\ atm$ ✓]

As matter begins to burn, it burns under constant pressure conditions

Entropy equation $\quad TdS = dU + PdV = c_p dT$

$$c_p \underbrace{\frac{dT}{dt}}_{\text{rate of heat gain/loss}} = \varepsilon_{heat} - \varepsilon_{cool}$$

c_p: eg ideal gas $\frac{5}{2}\frac{k_B}{\mu m_p}$

ε_{heat}: erg/cm³/s from nuclear reactions

ε_{cool}: cooling (conduction, radiation, convection...) neutrinos..

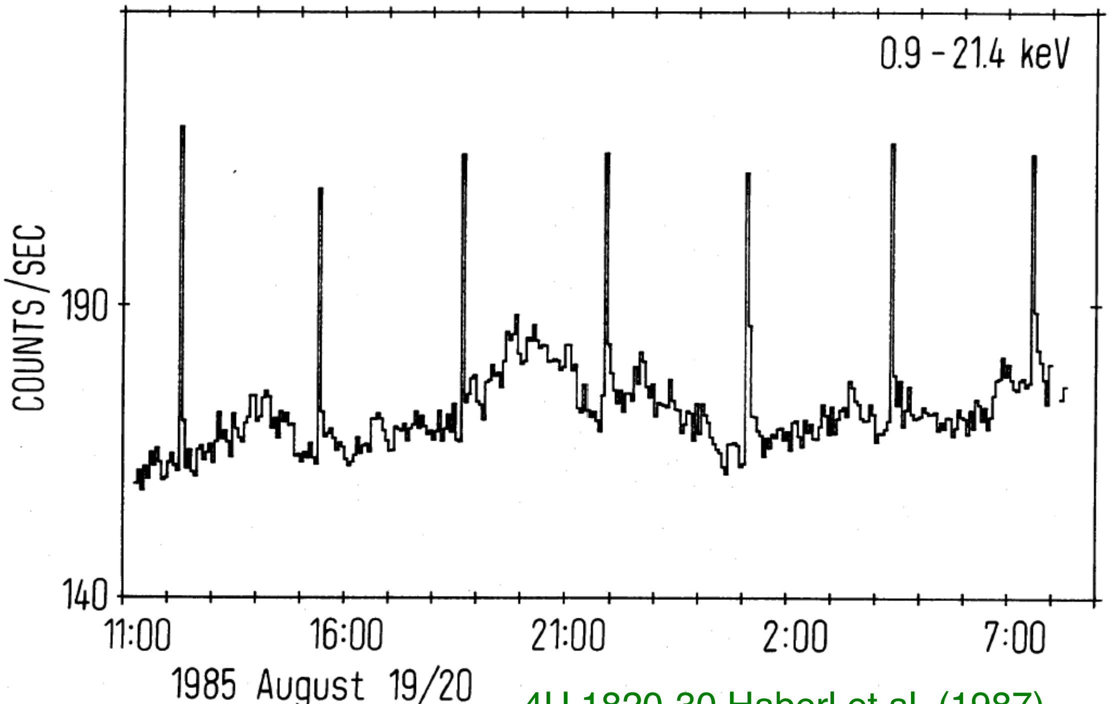
Now perturb this equation $T \to T + \delta T$

$$c_p \frac{\partial}{\partial t}\delta T = \frac{\delta T}{T}\left(\frac{d\varepsilon_{heat}}{d\ln T} - \frac{d\varepsilon_{cool}}{d\ln T}\right)$$

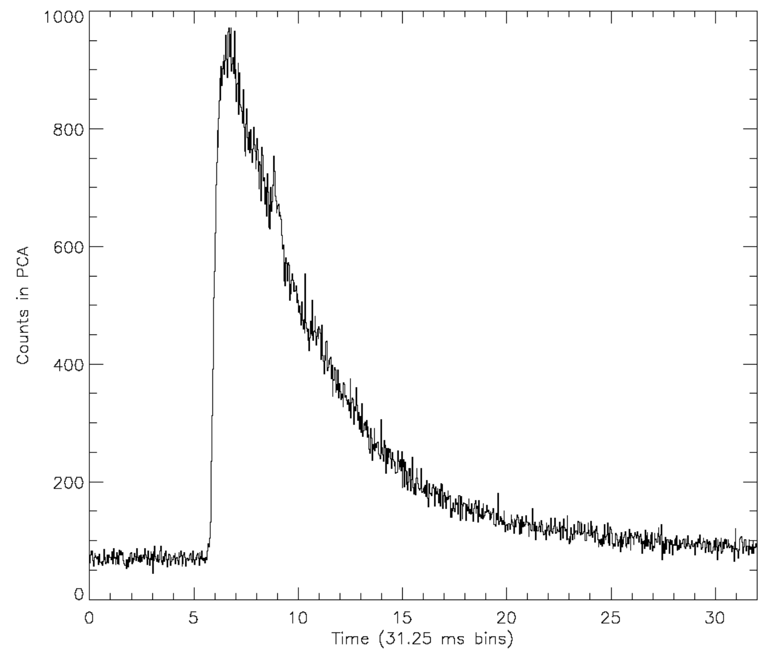
Note: degeneracy can also give conditions under which pressure does not respond to temperature changes eg. He core flash

will get a thermal instability if $\boxed{\dfrac{d\varepsilon_{heat}}{d\ln T} > \dfrac{d\varepsilon_{cool}}{d\ln T}}$

In general this is satisfied because nuclear reactions are very temperature sensitive!

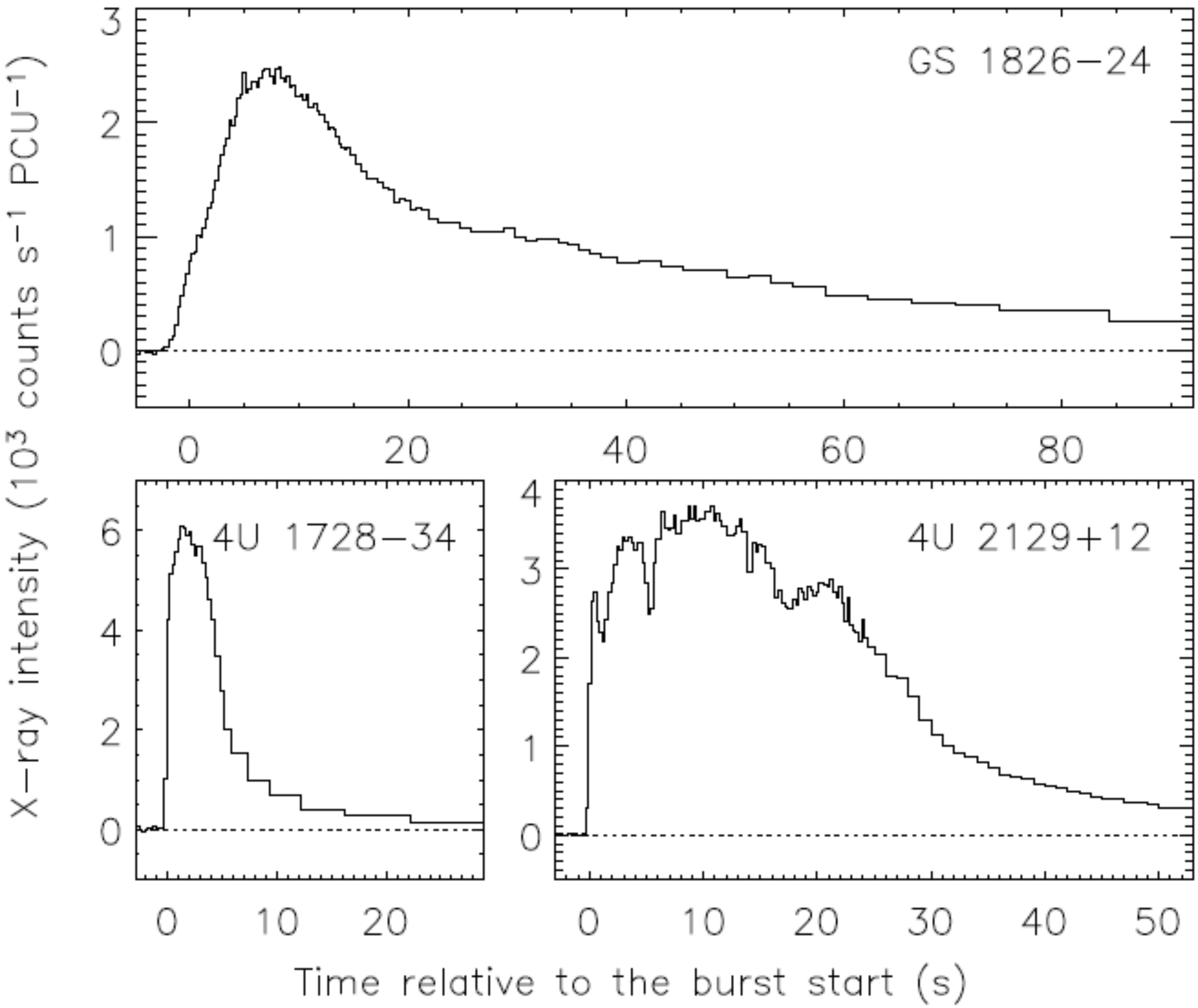


4U 1820-30 Haberl et al. (1987)



4U 1728-34 Strohmayer et al. (1996)

Variety of X-ray burst lightcurves



Galloway et al. (2008)

Questions

- we saw that the bursts were happening every few hours. How much mass accumulates in that time if the accretion rate is 10% of the Eddington accretion rate?
- if I burn that much helium into heavy elements, how much energy is released?
- what determines the duration of the burst?
- do you think a lot of mass is ejected in bursts?
- what should the X-ray spectrum look like and will it change during the burst?

Type I X-ray bursts

Basic energetics and timescales

Hydrogen and helium accreted onto a neutron star at rates 10^{-10} – 10^{-8} $M_\odot$/yr burns unstably in a thin shell flash, observed as a Type I X-ray burst.

Typical properties:

- energies 10^{39} – 10^{40} ergs
- recurrence times hours to days
- durations few seconds – minutes

Does this make sense in a picture of recurrent shell flashes, where material accumulates and burns in a limit cycle?

Questions to consider:

how much mass accumulates in a few hours?

if I burn that much helium into heavy elements, how much energy is released?

what physics will determine the burst duration?

what should the X-ray spectrum look like?

Bonus: (do you think a lot of mass is ejected in bursts?)

$$\Delta M = \dot{M}\Delta t = \underset{\text{(0.1 Eddington accretion rate)}}{10^{17}\,\mathrm{g/s}} \times \underset{\text{(few hours)}}{10^{4}\,\mathrm{s}} = 10^{21}\,\mathrm{g}$$

$$\mathrm{He} \rightarrow \mathrm{C} \text{ gives } 0.6\ \mathrm{MeV/nucleon} \simeq 6\times 10^{17}\,\mathrm{erg/g}$$

$$10^{21}\,\mathrm{g} \times 10^{18}\,\mathrm{erg/g} = 10^{39}\,\mathrm{ergs} \quad ✓$$

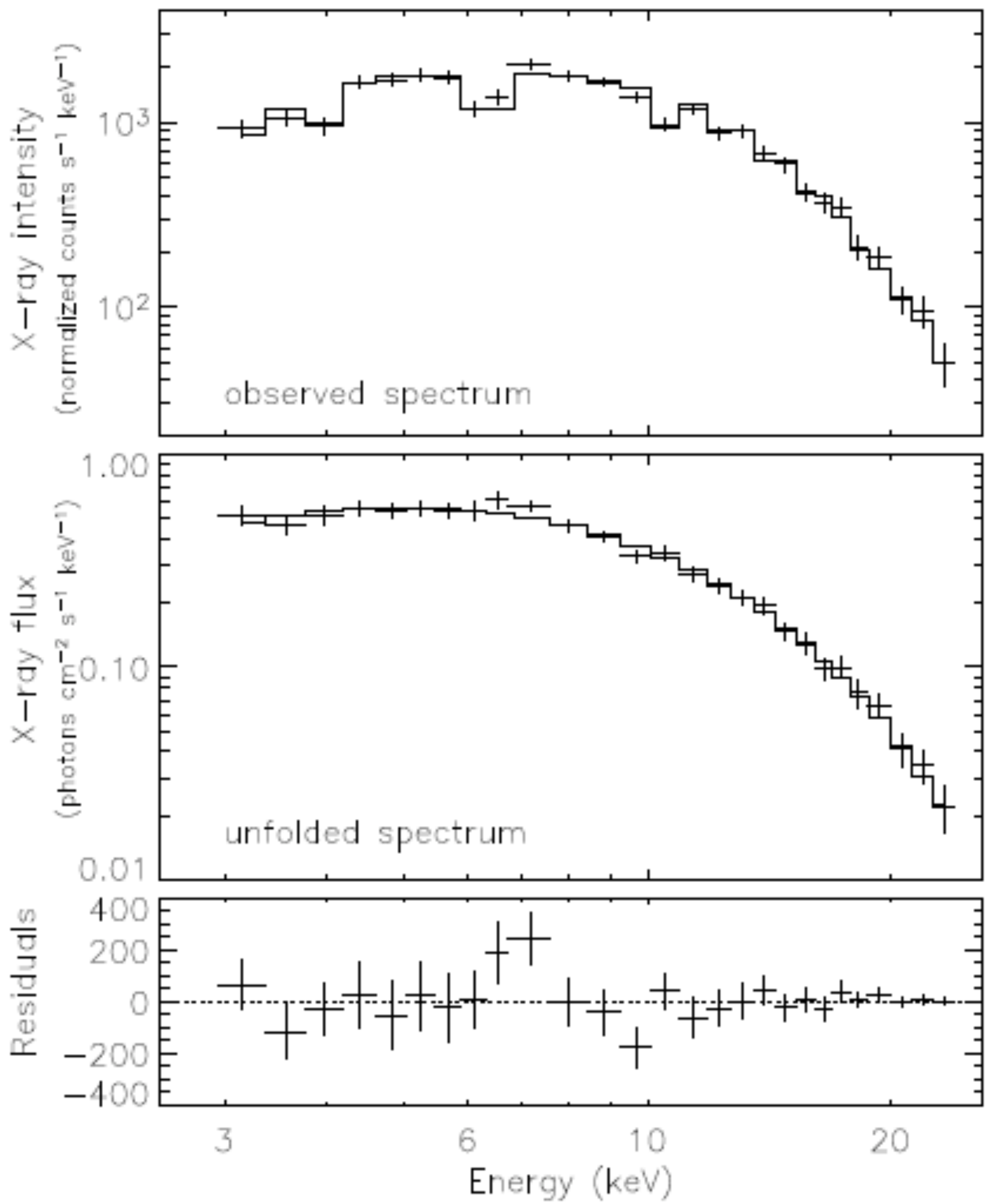
Alternative way to look at this

"alpha parameter"

$$\alpha = \frac{\int F_p\,dt}{\int F_b\,dt} \quad \begin{matrix} \leftarrow \text{between bursts} \\ \leftarrow \text{during burst} \end{matrix}$$

should be $\simeq \dfrac{200\,\mathrm{MeV/nucleon}}{(1-5)\,\mathrm{MeV/nucleon}} \simeq 40-200.$

Example of the spectrum of a Type I XRB

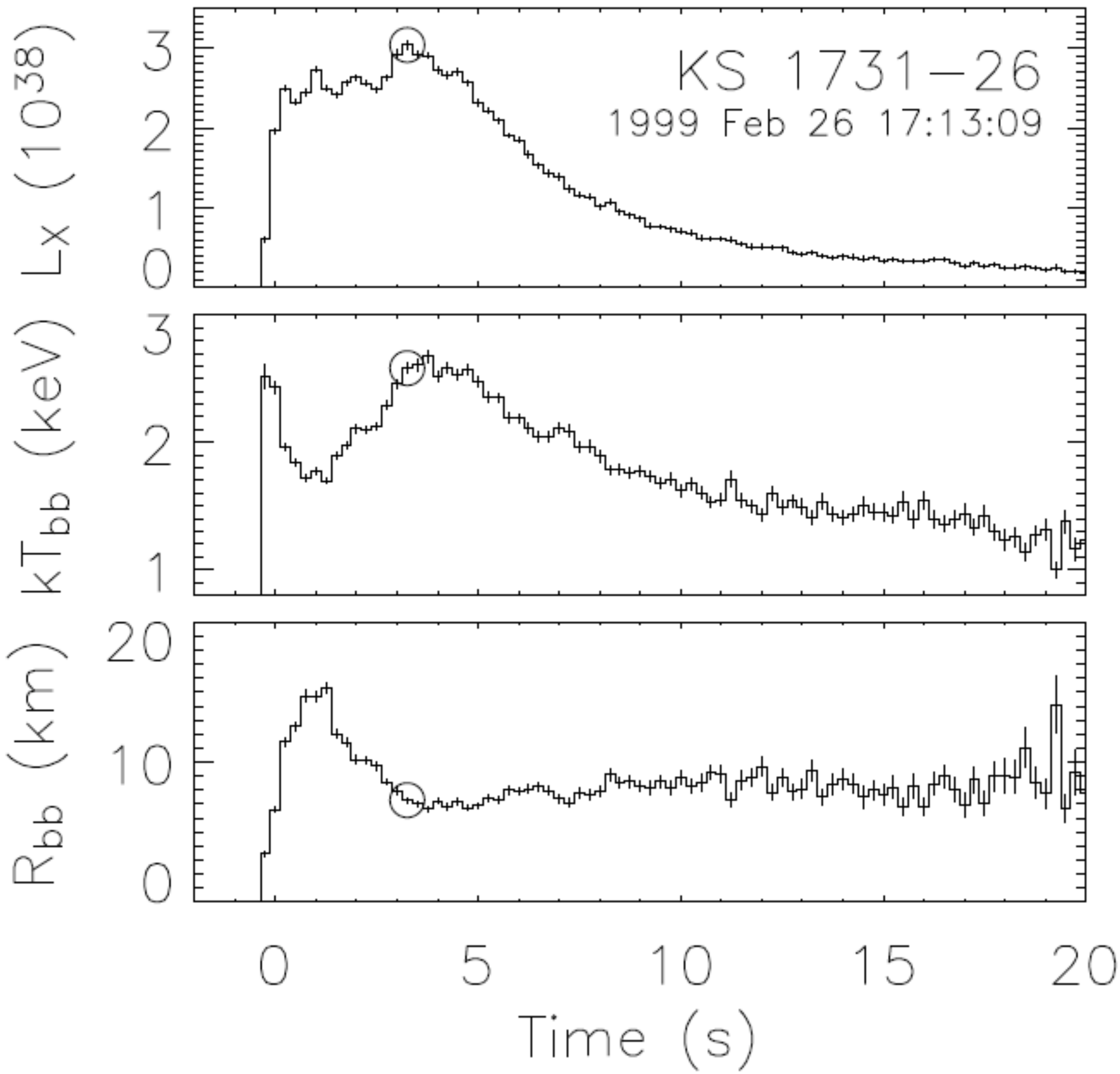


$$kT = 2.99 \pm 0.04 \text{ keV}$$

$$\text{radius } 5.09^{+0.13}_{-0.12} \text{ km}$$

Galloway et al. (2008)

Example of spectral evolution during a burst

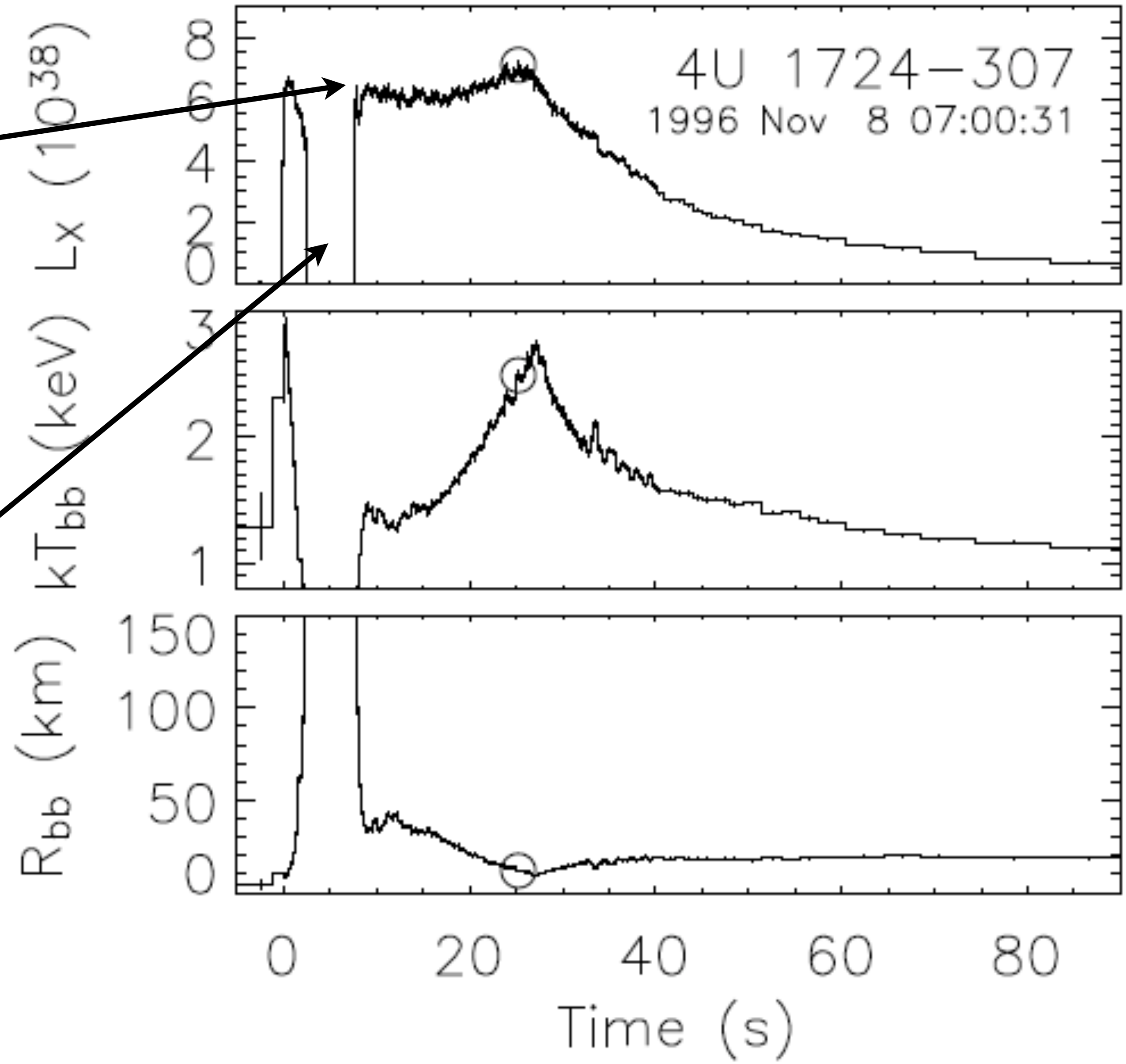


Galloway et al. (2008)

An extremely strong photospheric radius expansion burst

Flat-topped burst profile at ~L_{Edd}

During the expansion phase, the spectrum shifts to lower energies, out of the X-ray band



Galloway et al. (2008)

Cooling time of the burning layer

Helium burning reactions are fast — assume energy deposited instantaneously: then

$$\int_{T_i}^{T_f} c_p \, dT = E_{deposited}$$

$$\Rightarrow \quad T_f \simeq \frac{E_{dep}}{\frac{5}{2} k_B / A m_p} \longleftarrow \text{(degeneracy is lifted; use ideal gas } c_p\text{)}$$

$$\simeq \frac{10^{18} \text{ erg/g}}{2e8 \text{ erg/g/K}} = 5 \times 10^9 \text{K}$$

in fact, radiation pressure limits the temperature to 2×10^9K.

$$\left(\frac{1}{3} a T^4 = g y \right)$$

How quickly will the layer cool?

Radiation transports heat $\quad F \simeq \frac{1}{3} c \lambda \frac{d}{dr}(aT^4)$

mean free path $\lambda = \frac{1}{n\sigma} = \frac{1}{\rho K}$

$$\Rightarrow \quad F = -\frac{4acT^3}{3K\rho} \frac{dT}{dr} \simeq \frac{4acT^4}{3Ky}$$

$$= 4 \times 10^{38} \text{ erg/s } \frac{T_9^4}{y_8 \left(\frac{K}{0.1 \text{ cm}^2/\text{g}}\right)}$$

Cooling timescale $\quad y c_p \frac{\partial T}{\partial t} = F$

$$\Rightarrow \quad t_{cool} \simeq \frac{y c_p T}{F}$$

$$= \frac{y c_p T}{4acT^4} 3Ky = \frac{3Ky^2 c_p}{4acT^3}$$

$$= 0.7 \text{ seconds } \frac{y_8^2}{T_9^3} \left(\frac{K}{0.1 \text{ cm}^2/\text{g}}\right)$$

One zone model

The one zone approach allows us to make a simple numerical model of the flashes. We follow a single temperature T and thickness y of the fuel layer that evolve according to

$$\varepsilon_{cool} = \frac{acT^4}{3\kappa y^2} = \frac{F}{y}$$

$$c_p \frac{dT}{dt} = \varepsilon - \varepsilon_{cool}$$

$$\frac{dy}{dt} = \dot{m} - \frac{\varepsilon_{3\alpha}\, y}{E_{3\alpha}/12m_p}$$

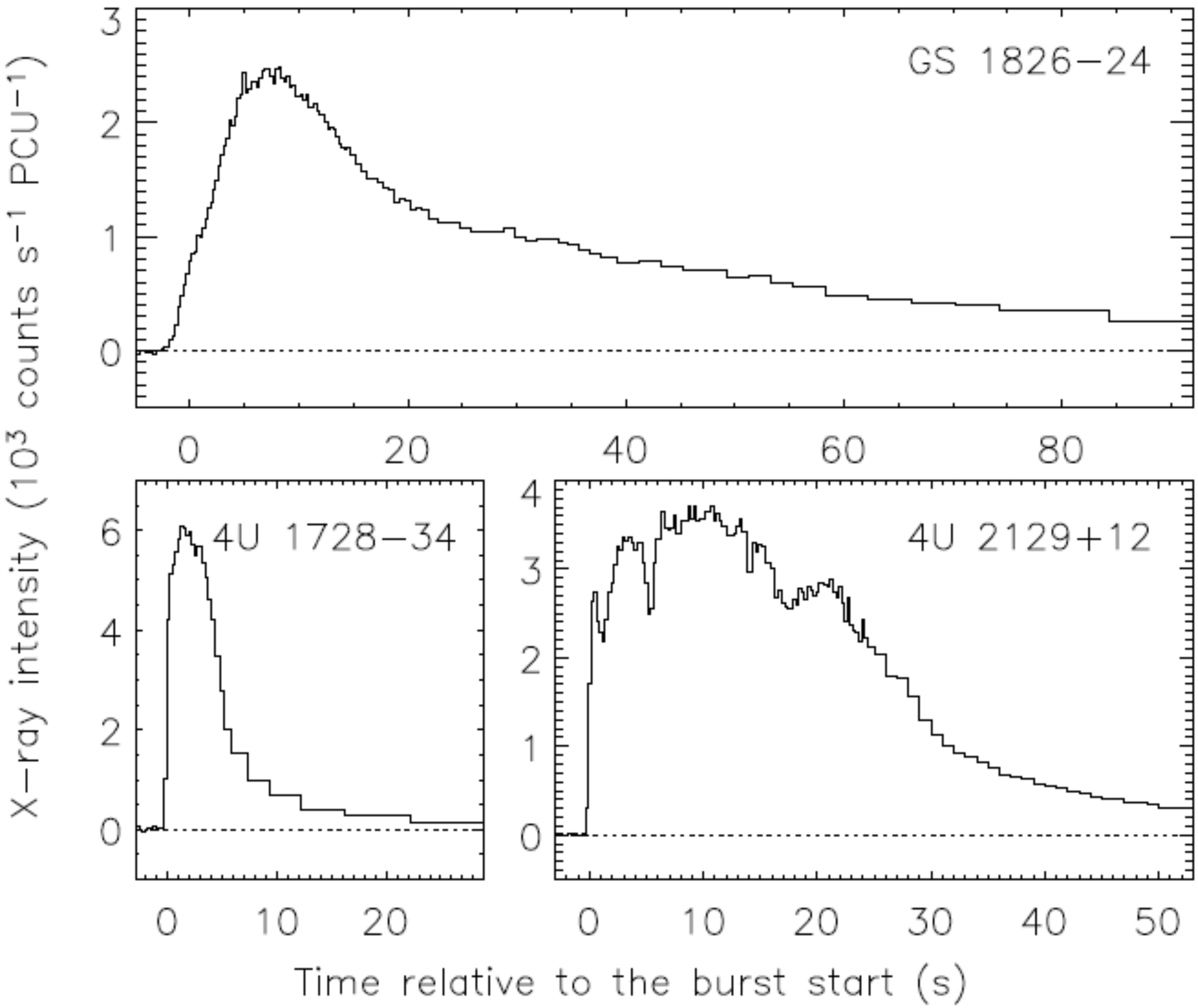
7.275 MeV energy release per reaction.

These equations were written down by Paczynski (1983).

$$\varepsilon_{3\alpha} = 5.3\times 10^{21}\ \mathrm{erg/g/s}\ f\,\frac{\rho_5^2 Y^3}{T_8^3}\exp\left(-\frac{44}{T_8}\right)$$

Points to note:
- basic properties: light curve shape; ignition depth; recurrence times
- how things change with $\dot{m}$
- stabilization at $\dot{m} > \dot{m}_{Edd}$.
- base flux add a term $c_p \frac{dT}{dt} = + \frac{F_b}{y}$ to heat the layer from below.

Variety of X-ray burst lightcurves

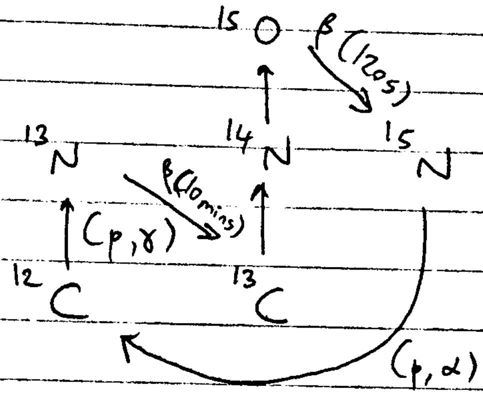


Galloway et al. (2008)

Hydrogen burning by the hot CNO cycle

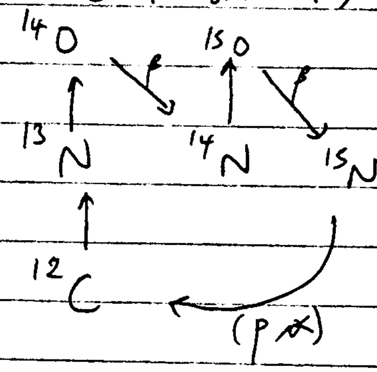
As the H/He accumulate on the NS surface, the temperature is $\gtrsim 8\times10^7$ K in most of the layer and the H-burning occurs by the β-limited hot CNO cycle.

Cold CNO cycle



hot CNO ($T \gtrsim 8\times10^7$K)

(Hoyle & Fowler 1965)



$\tau(^{14}O \rightarrow {}^{14}N) = 102s$

$\tau(^{15}O \rightarrow {}^{15}N) = 176s$

^{14}N proton capture limits the cycle rate (eg in the Sun)

The proton captures are so fast that the beta decays limit the rate

the rate is <u>temperature-independent</u>, and therefore <u>thermally-stable</u>

$$\varepsilon = 6\times10^{15}\ \mathrm{erg/g/s}\ Z_{CNO}$$

This is why X-ray bursts are triggered by He burning. The H burning cannot respond to temperature fluctuations!

It takes about 3 mins to go around the cycle, $\Rightarrow$ time to burn all the hydrogen in a fluid element is

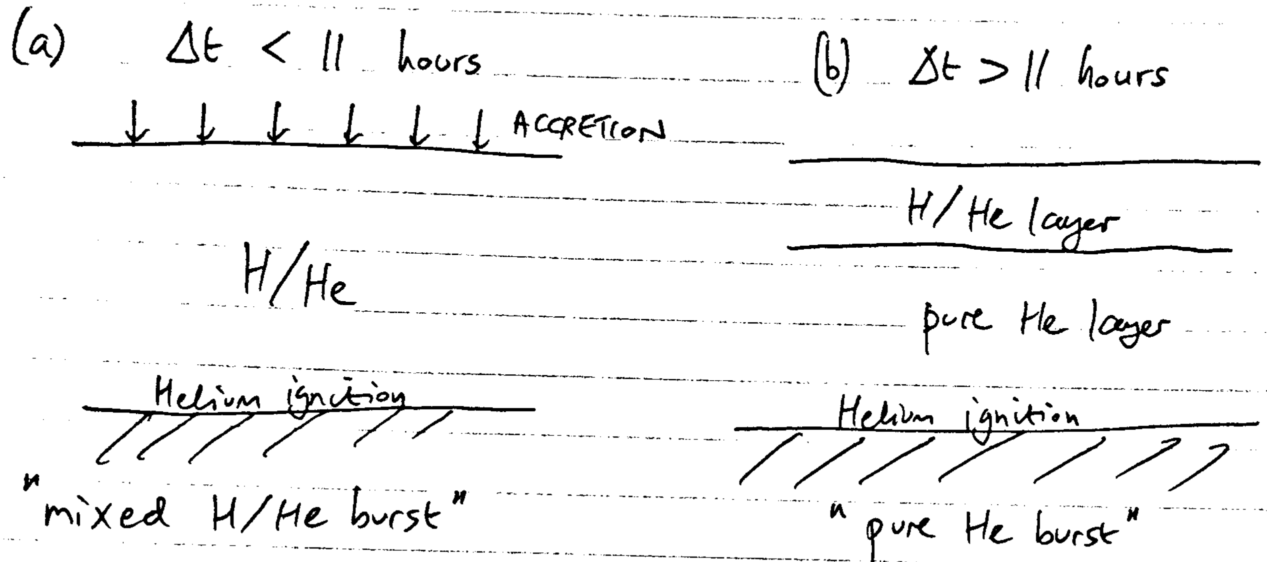
$$t_H = 11\ \text{hours} \left(\frac{0.02}{Z_{CNO}}\right)\left(\frac{X_0}{0.7}\right)$$

CNO mass fraction

initial H mass fraction

H burning ~~is~~ always involves weak reactions and so is always very <u>slow</u> compared to He burning.

The fact that H burns stably gives two regimes of burning:



<u>rp-process H burning</u>

At temperatures $\gtrsim 3 \times 10^8$K α-mediated reactions become possible. First, $\boxed{\text{BREAKOUT}}$ from the CNO cycle occurs via $^{14}O(\alpha, p)$ and $^{15}O(\alpha, \gamma)$

A series of $(\alpha,p)(p,\gamma)$ reactions ensues $\boxed{\alpha p\text{- PROCESS}}$

This produces seeds for the $\boxed{\text{rp-process}}$ (rapid proton capture process) which involves a series of proton captures and β decays along the proton drip line. (The proton equivalent of the r-process).

Heavy elements beyond the iron group are produced. How heavy? If the mass of the αp seed is $A_{\alpha p}$ then counting nuclei gives

$$A_{rp} = A_{\alpha p}\left(1 + \frac{X}{Y}\right)$$

eg. $A_{\alpha p} = 22$ (Mg) $X = 0.7, Y = 0.3 \Rightarrow A_{rp} = 73$ (eg. ^{73}Kr)

- in practise, there is an endpoint at $A \simeq 104$ because of a closed SbSnTe cycle (Schatz et al. 2001)
- the amount of time before the burst cools is another factor determining A_{rp}. Waiting points along the path mean that the rp-process can take hundreds of seconds to complete
- How far the αp-process goes is determined by the temperature since the Coulomb barrier increases for heavier nuclei.

How can we test these ideas observationally?

① Burst lightcurves. Do we see the diversity of lightcurves we expect? Yes! Some bursts show long $\simeq 100$s tails powered by rp-process burning. The best source for this comparison is GS1826-24, an extremely regular and consistent burster.

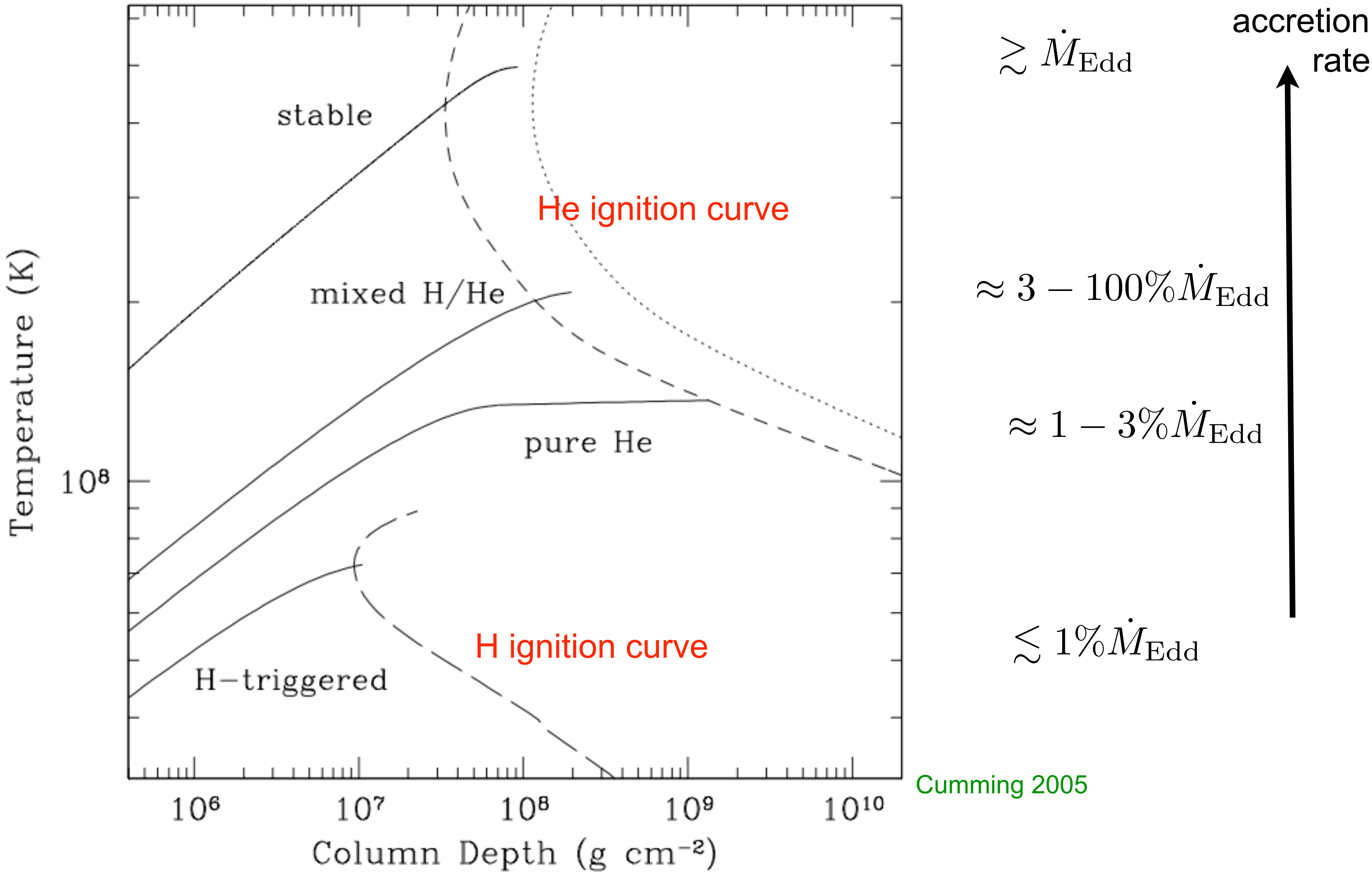
② SUPERBURSTS Rare ($\Delta t \sim 1$ year) energetic ($\sim 10^{42}$ ergs) long ($\sim$hours) flashes we believe are due to carbon burning in the neutron star ocean. The carbon is left over in the ashes of rp-process burning, produced by 3α after the H runs out.

$$A_{rp} = A_{\alpha p} + \begin{pmatrix}\text{number of}\\ \text{H per seed}\end{pmatrix} = A_{\alpha p} + \frac{n_p}{n_\alpha}\frac{n_\alpha}{n_{seed}}$$

$$n_{seed} = \left(\frac{A_{\alpha p}}{4}\right)^{-1} n_\alpha \qquad = A_{\alpha p} + \frac{4X}{Y}\frac{A_{\alpha p}}{4} \quad ✓$$

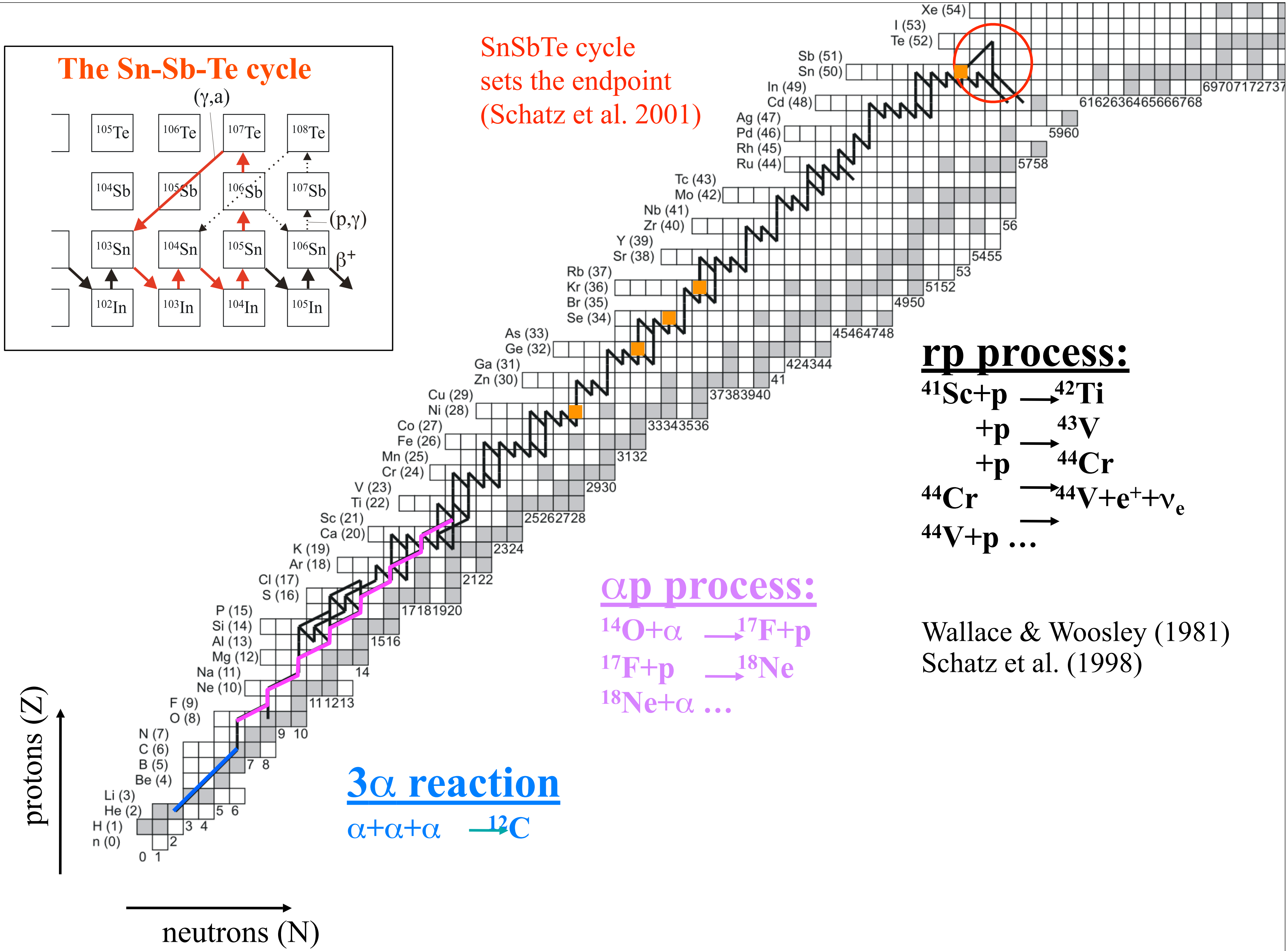
$$\frac{n_p}{n_\alpha} = \frac{4X}{Y}$$

Four different regimes of H/He burning



Cumming 2005

Taam, Woosley, Joss, Fujimoto (late 1970s, 1980s), Bildsten (1998)



SnSbTe cycle
sets the endpoint
(Schatz et al. 2001)

rp process:

^{41}Sc+p $\longrightarrow$ ^{42}Ti

+p $\longrightarrow$ ^{43}V

+p $\longrightarrow$ ^{44}Cr

^{44}Cr $\longrightarrow$ ^{44}V+e^{+}+ν_e

^{44}V+p …

αp process:

^{14}O+α $\longrightarrow$ ^{17}F+p

^{17}F+p $\longrightarrow$ ^{18}Ne

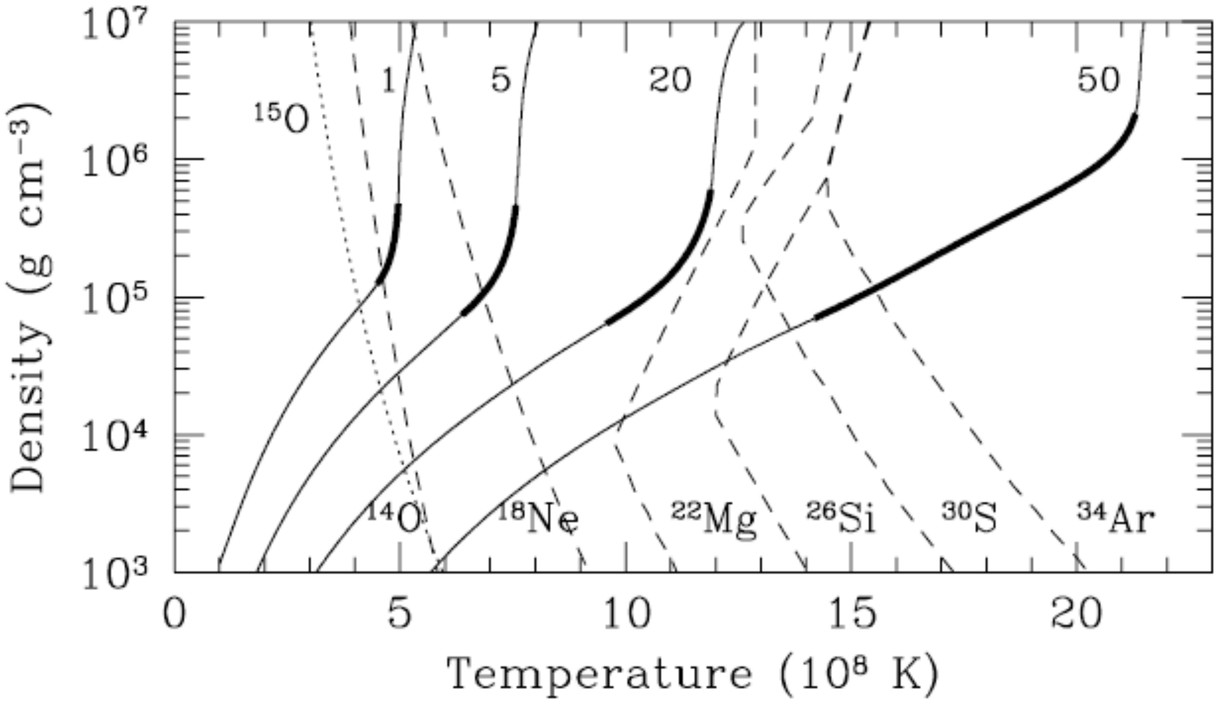
^{18}Ne+α …

Wallace & Woosley (1981)
Schatz et al. (1998)

3α reaction

α+α+α $\longrightarrow$ ^{12}C

alpha-p process



how far the αp process gets depends on the burning temperature

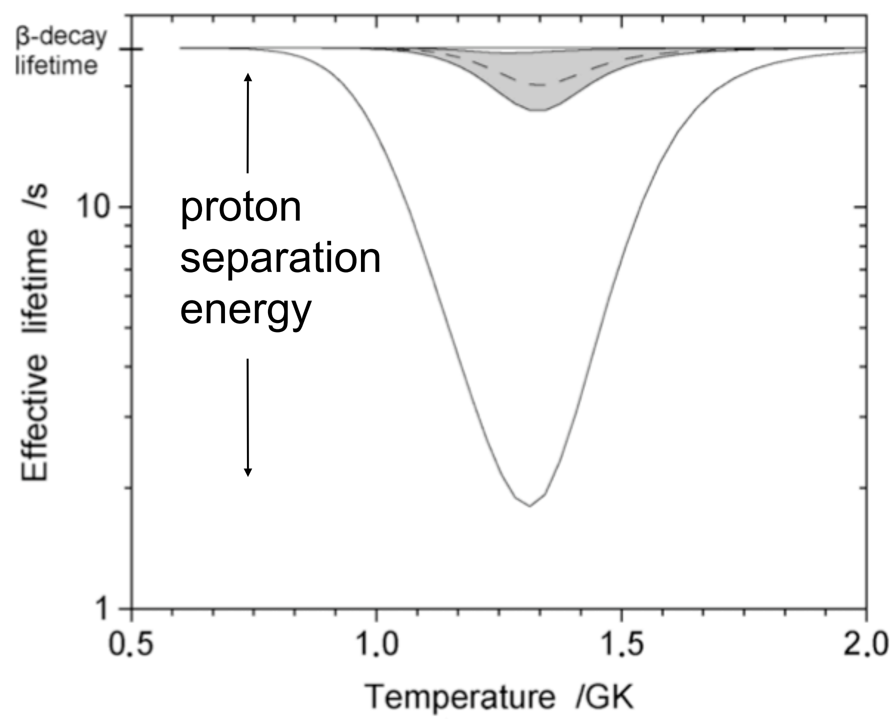
FIG. 5.—Tracks of a fluid element in the T-ρ plane for various accretion rates. The accretion rate is indicated by the number near the end of the track in units of $\dot{m}_{\mathrm{Edd}}$. The thick line segment shows where hydrogen burns from 90% down to 10% of its initial abundance. The dotted line marked "^{15}O" shows the conditions where the $^{15}\mathrm{O}(\alpha, \gamma)^{19}\mathrm{Ne}$ rate equals the ^{15}O β^+-decay rate. The dashed lines show where the (α, p) reaction rates on ^{14}O, ^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar equal the other destruction mechanisms (β^+ decays and proton captures) on these isotopes. In the temperature and density region to the right of these dashed (or dotted) lines, the (α, p) [or (α, γ)] reactions dominate the destruction reactions of the respective isotopes.

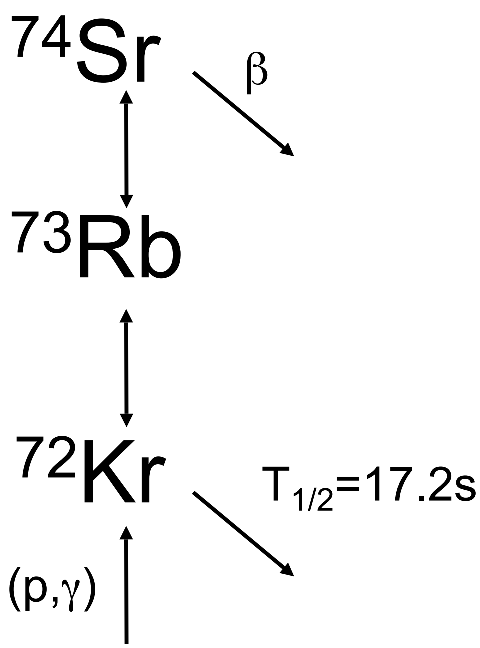
Schatz et al. (1999)

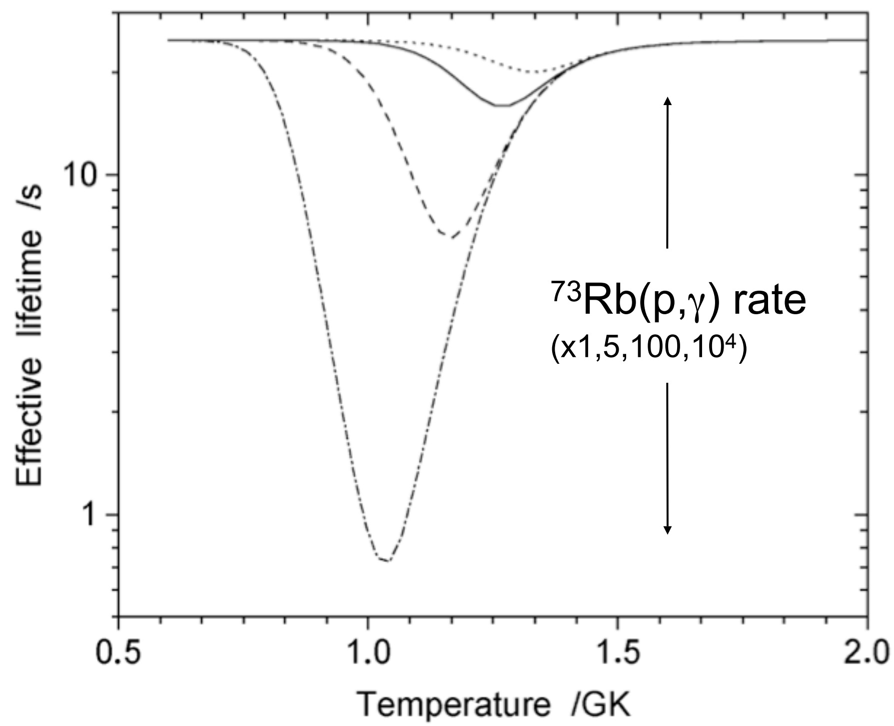
Mass measurements of
rp-process waiting point nuclei

^{72}Kr; Rodriguez et al. (2004)
ISOLTRAP/ISOLDE

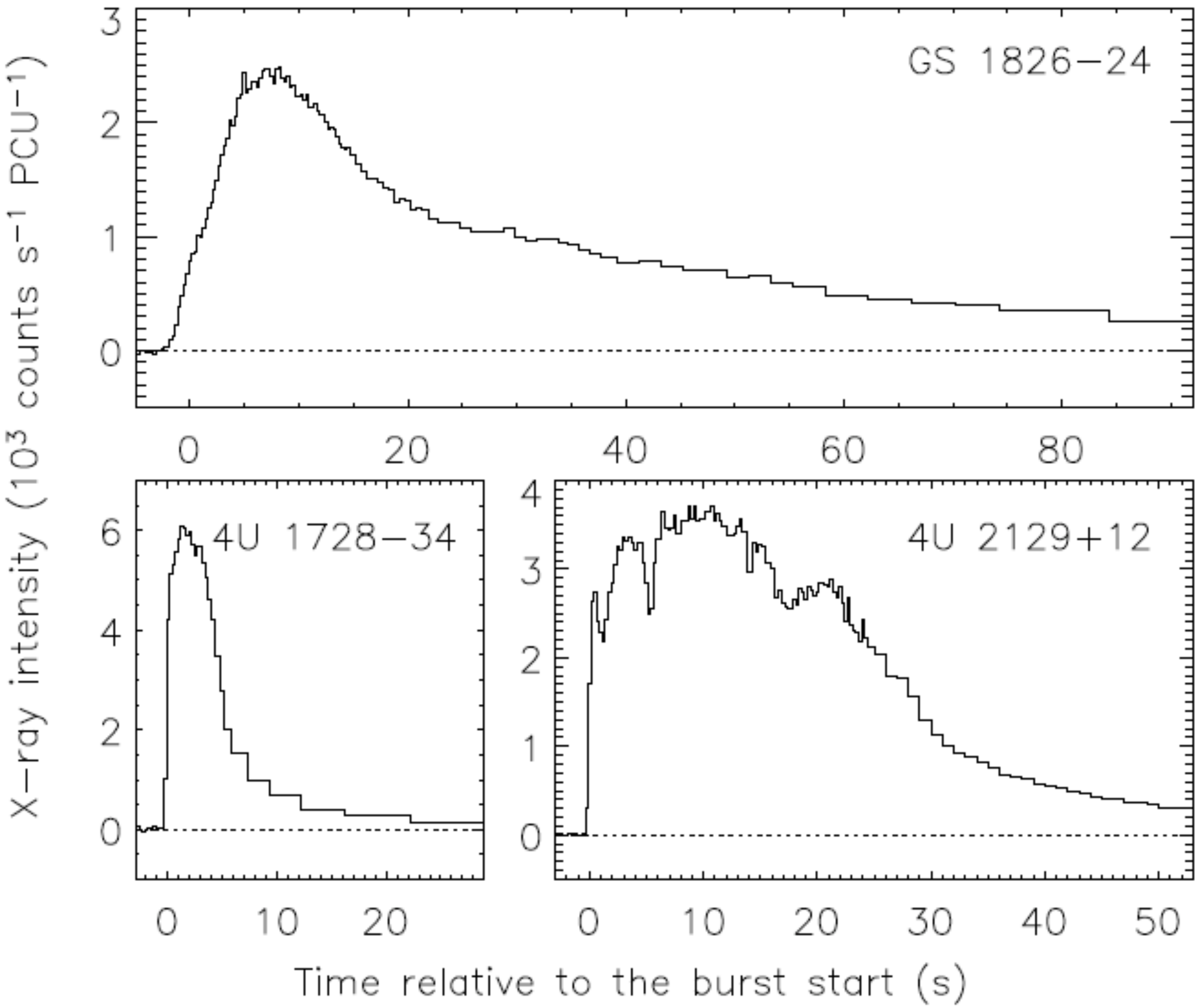
^{68}Se; Clark et al. (2004)
CPT/ATLAS





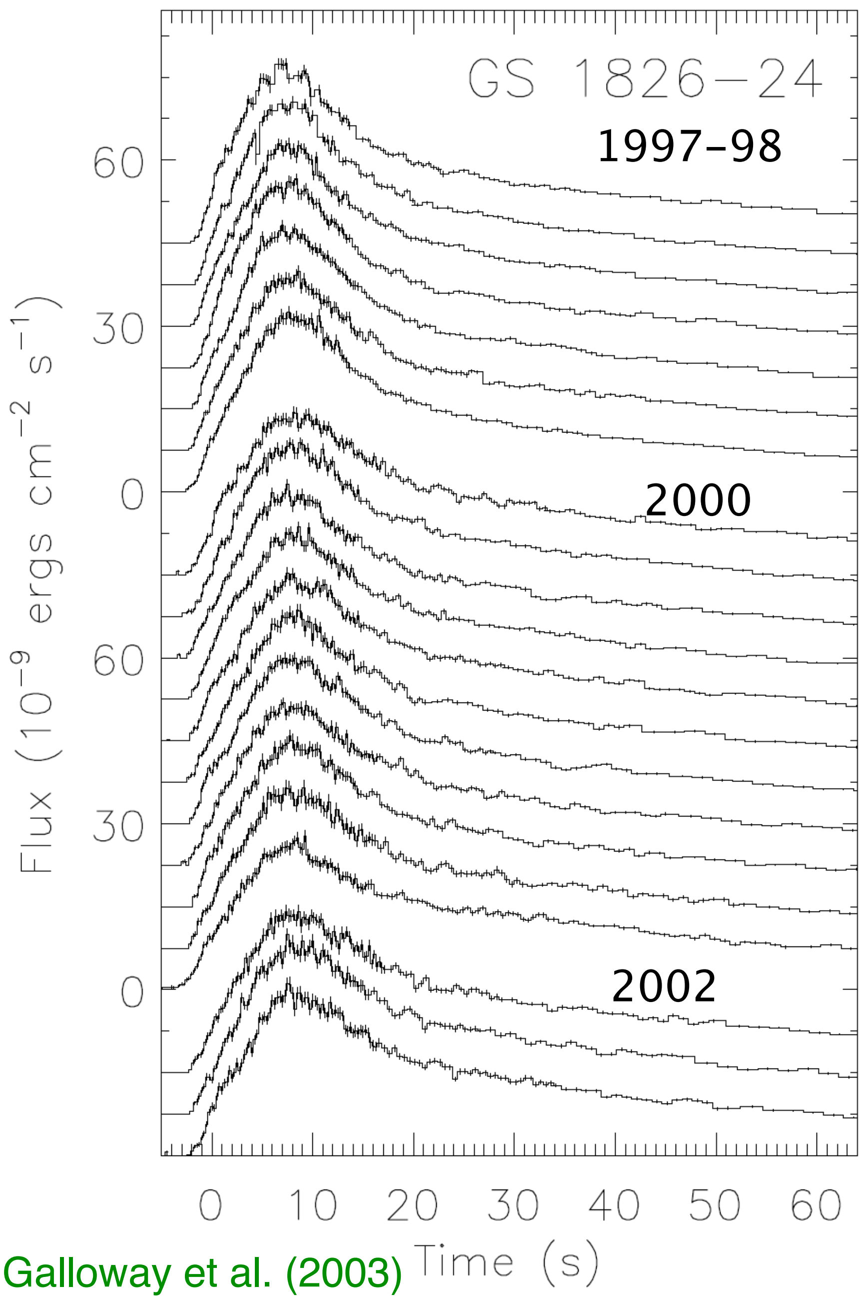


Variety of X-ray burst lightcurves



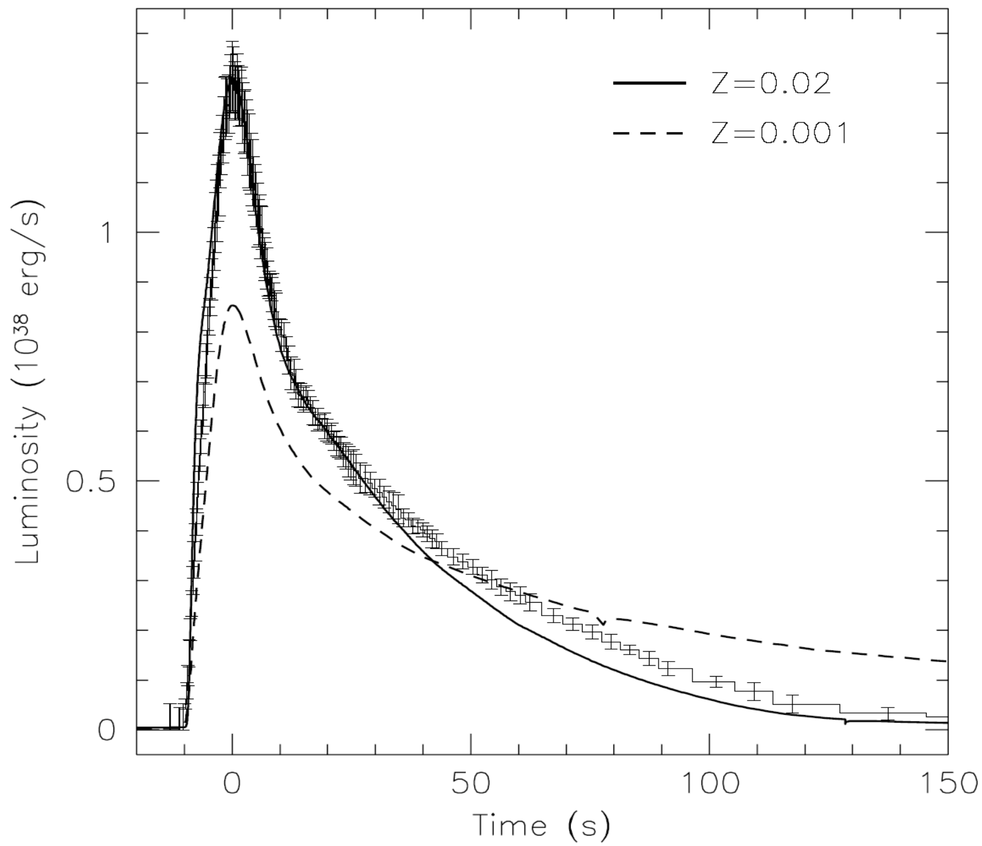
Galloway et al. (2008)

He ignition in a H-rich environment: GS 1826-24

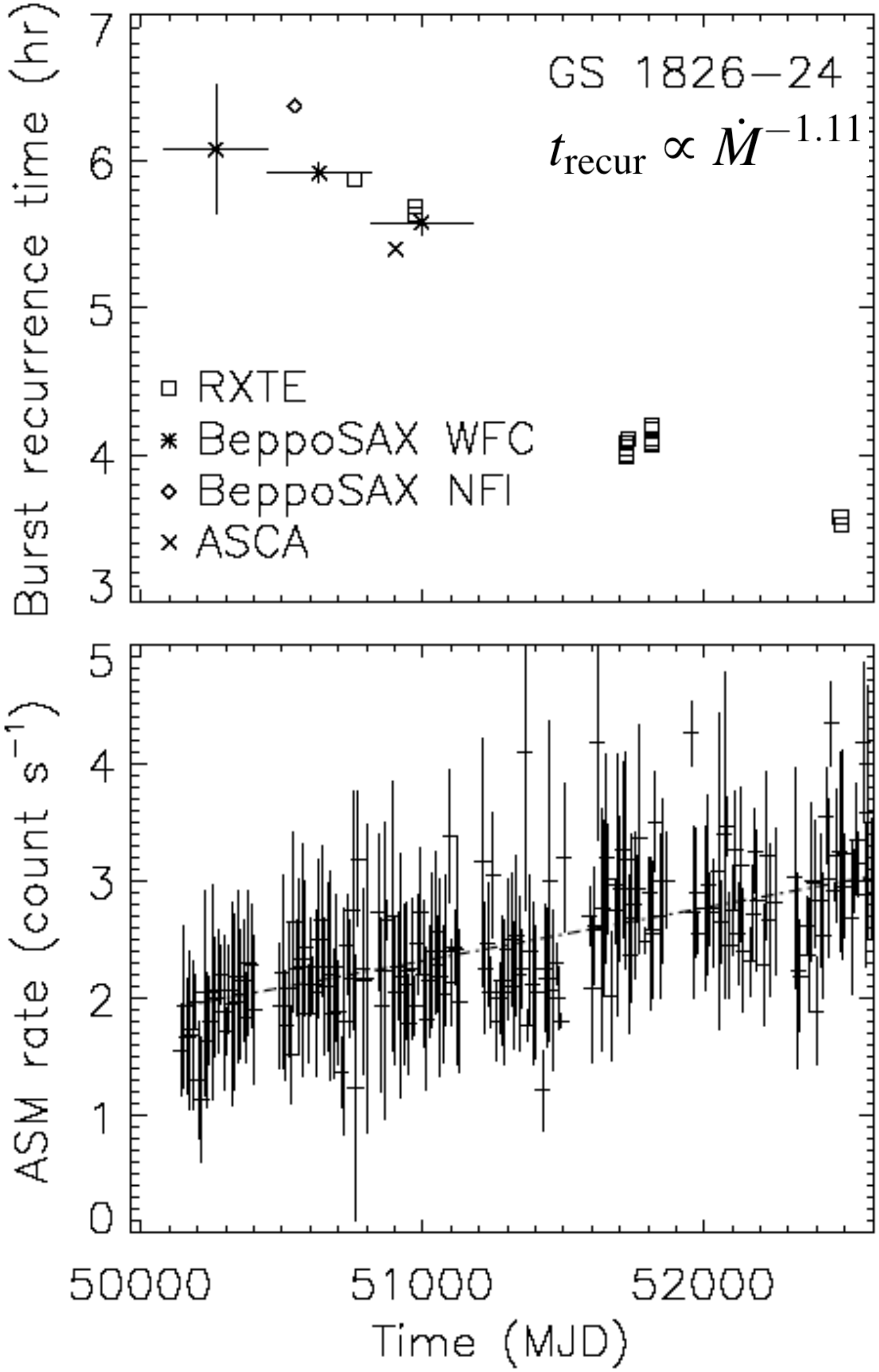


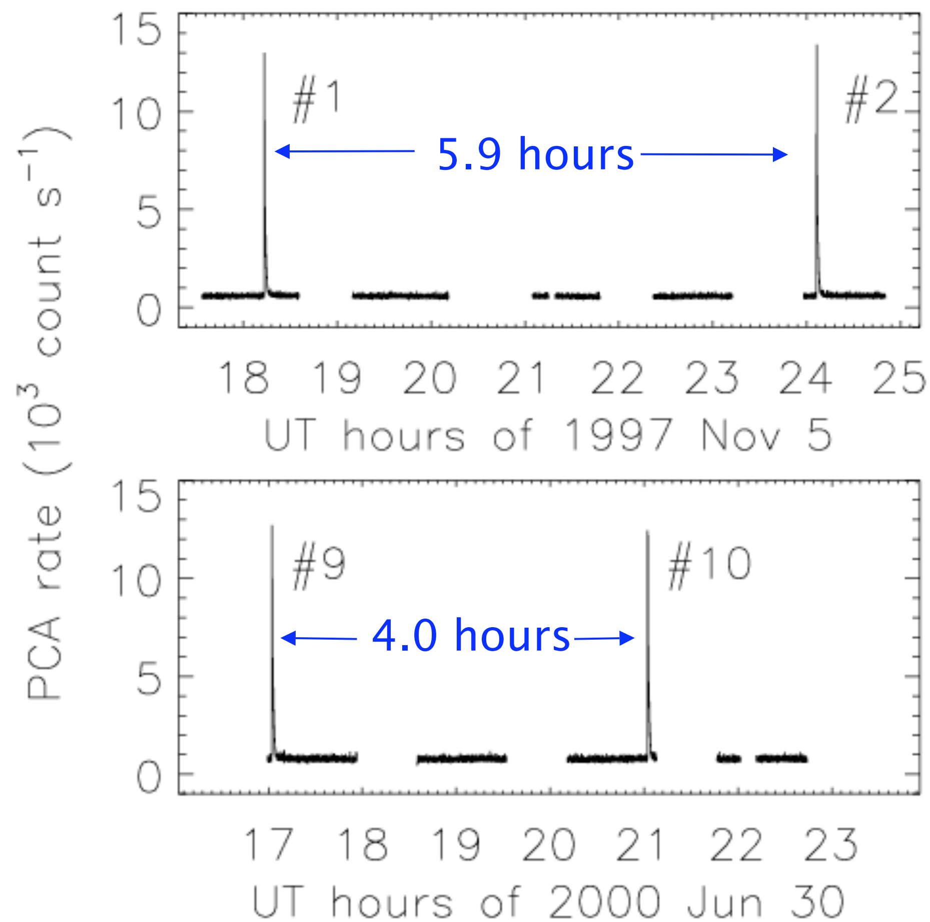
Galloway et al. (2003)

- very regular burster, recurrence times 3-6 hours
- rp-process gives long ~100 second tail
- recurrence time goes down as 1/Mdot as expected



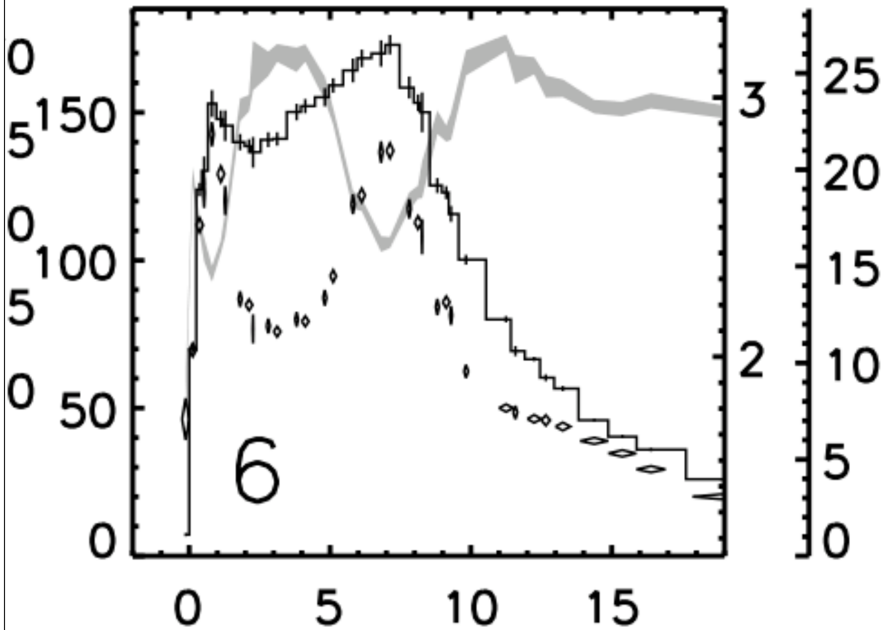
Heger et al. (2007) comparison with Woosley et al. (2004) models





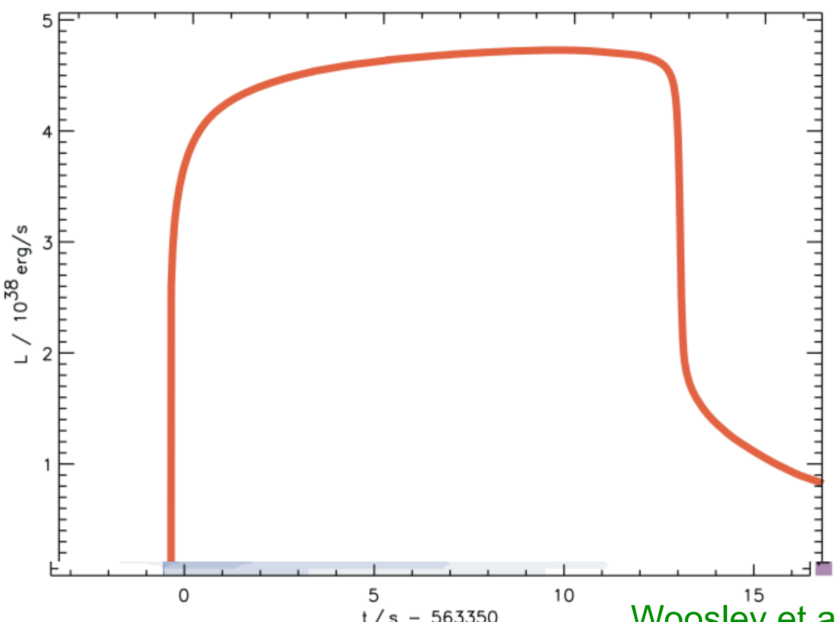
Galloway et al. (2003)

He ignition after H depletion: SAX J1808.4-3658

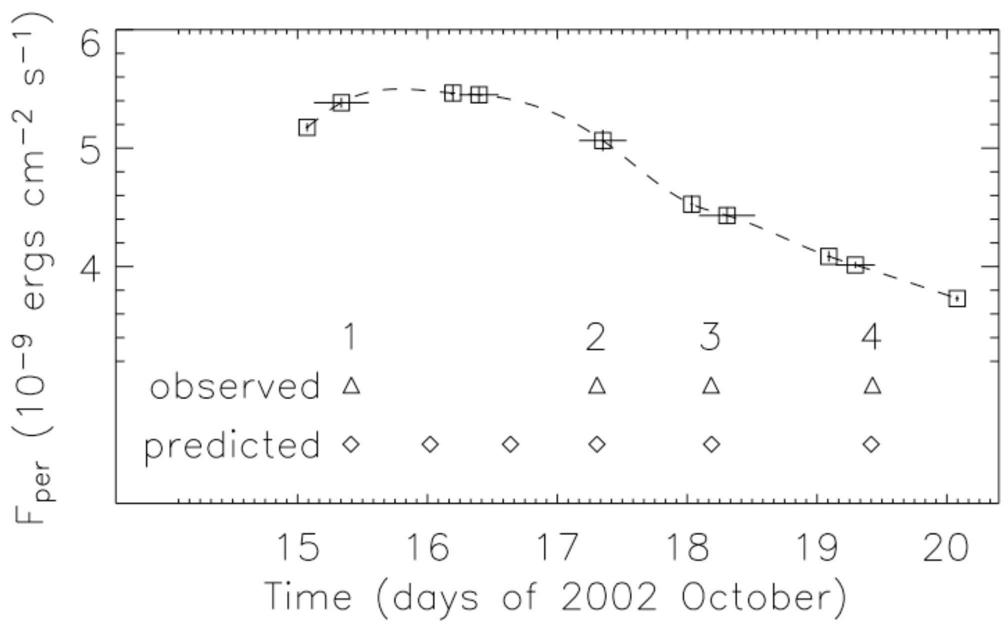


Galloway et al 2007 RXTE catalog

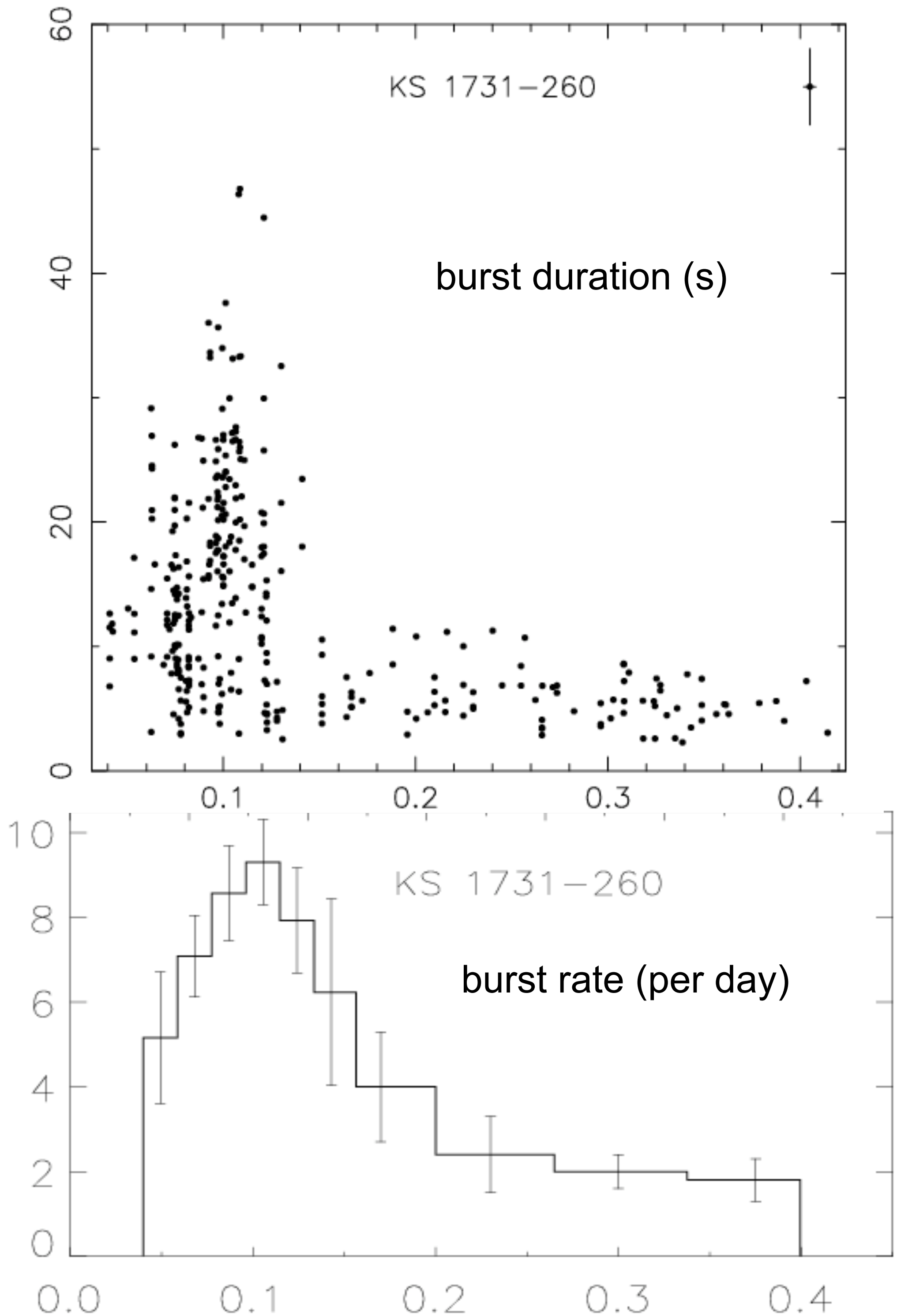
- Transiently accreting millisecond X-ray pulsar, accreting at ~6% Eddington during outburst
- Hydrogen burns away before ignition => pure He layer (t_{burn} = 12 hours for solar material; observed Δt ~ 24 hours)



Woosley et al. 2004 ApJS



Galloway & Cumming (2006)



Transition to stable burning

above ~10^{37} erg/s (about 10% Eddington), bursts become short, irregular, and only burn ~10% of the accreted fuel
=> evidence for some other kind of burning, stable burning?

transition occurs ~ factor of ten below the theoretically expected value

Cornelisse et al. (2003)
see also van Paradijs et al. (1989)