

Life of an Accreted Nucleon on a Neutron Star

Lars Bildsten (Kavli ITP, UCSB)

- General Properties of Accreting Neutron Stars
 - ↳ Type I X-Ray Bursts every few hours
- H/He Burning to Heavy Elements
 - ↳ ^{12}C Flashes in rp-process ashes
 - ↳ Superbursts every ~decade
- Electron Captures and Pycnonuclear Reactions in Crust
 - ↳ Powers Thermal Emission in Quiescence

X-Ray Binaries

Matter is supplied at $\dot{M} \approx 10^{-10} \rightarrow 10^{-8} M_{\odot}/\text{yr}$

$$\Rightarrow L_{\text{accr}} = \frac{GM_{\text{NS}}}{R_{\text{NS}}} \dot{M} \approx 10^{36} \rightarrow 10^{38} \frac{\text{ergs}}{\text{sec}}$$

Neutron Star

$[M \approx 1.3 \rightarrow 2 M_{\odot}, R \approx 10 \text{ km}]$

$k_B T_{\text{eff}} \approx \text{keV}$

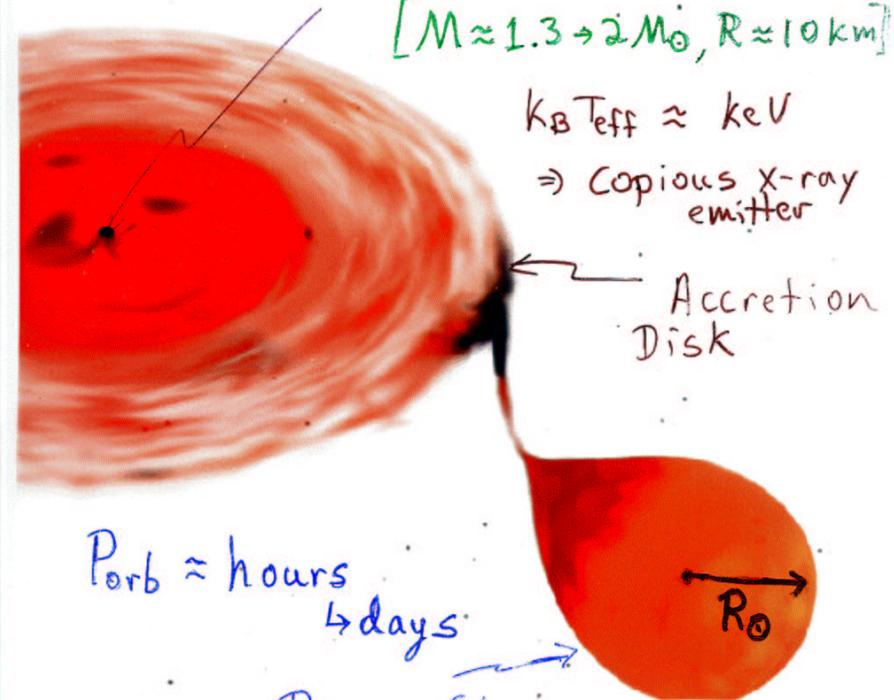
⇒ Copious X-ray emitter

Accretion Disk

$P_{\text{orb}} \approx \text{hours}$

↳ days

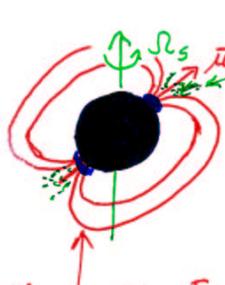
Donor Star mostly consists of H + He.



Two Types of Neutron Star Systems

3

1) Accreting X-Ray Pulsars.



Accreting Matter at $10^{-11} - 10^{-8} M_{\odot}/\text{yr}$ from wind or Roche-Lobe overflow from $M \approx 5 M_{\odot}$ companion.

Magnetic Field $B_s \approx 10^{11} \text{ G}$ Spin Periods $\approx 10^{-1} - 10^3$ seconds measured easily due to magnetic field misalignment with spin.

2) Low-Mass X-Ray Binaries

- No overt evidence for a magnetic field (i.e. No Pulse!)
 $B_s \leq 10^9 - 10^{10} \text{ G}$ \uparrow B_{neutr} exceptions!
- Low Mass ($M \leq M_{\odot}$) companions, so system is old and has accreted lots of matter ($\Delta M \approx 10^{-2} M_{\odot}$)
 \Rightarrow Should be rapidly rotating
($\nu_s \sim 100 \text{ Hz} \Rightarrow$ millisecond radio pulsar)

Gravitational Versus Nuclear Energy

A proton accreting onto a neutron star releases

$$E_{\text{GR}} \sim \frac{GMm_p}{R}$$

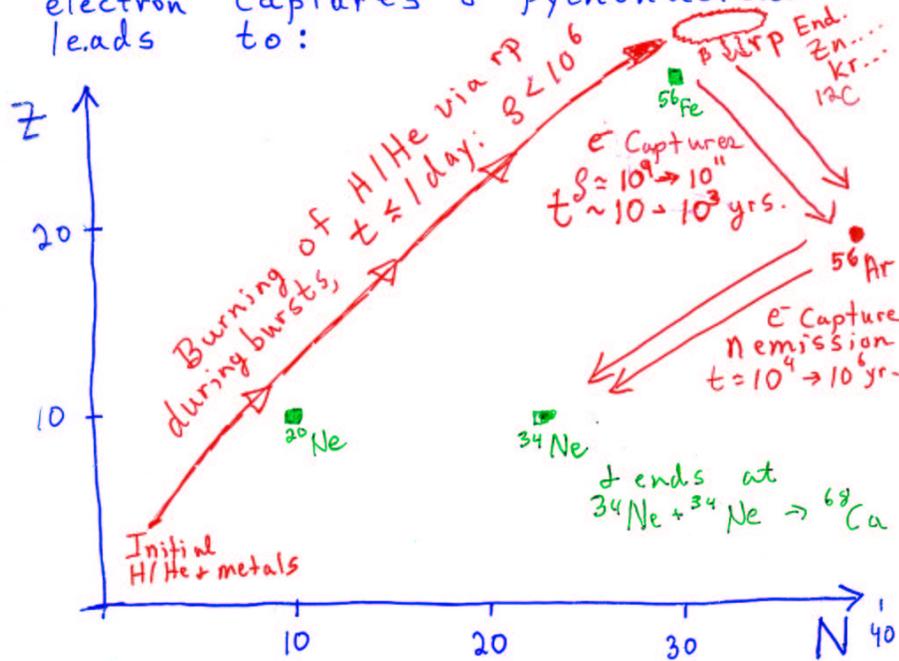
or $\approx 200 \text{ MeV}$ per baryon; much larger than $\sim 7 \text{ MeV}$ / baryon from nuclear fusion

\Rightarrow Nuclear Physics is only observable if either:

- Nuclear fuel is stored for a long time and then burns rapidly (Type I Bursts, Superbursts)
- Accretion basically shuts off (quiescent emission from NS)

Nuclear Trajectory in an Accreting Neutron Star

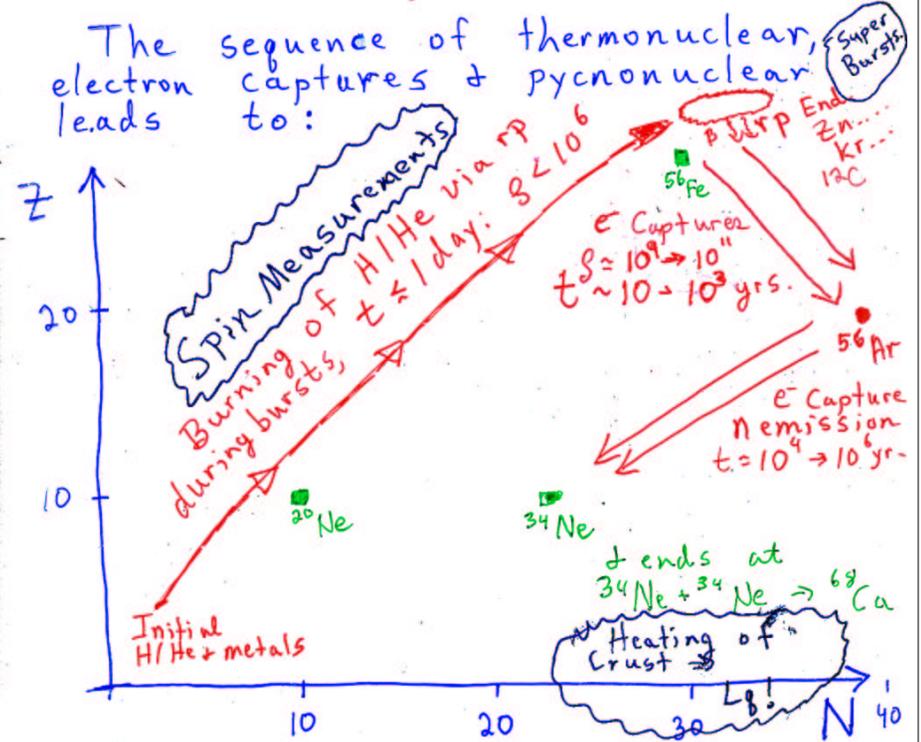
The sequence of thermonuclear, electron captures & pycnonuclear leads to:



Trajectory and times for
 $\dot{M} \approx 10^{-8} M_{\odot}/\text{yr}$
 All this action in outer 100-500m

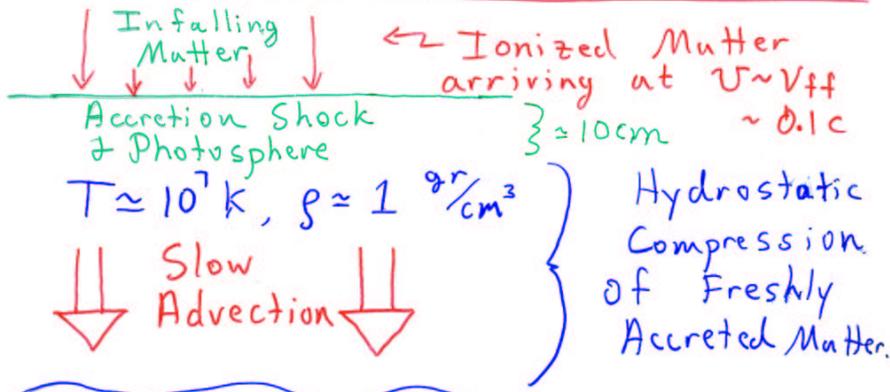
Nuclear Trajectory in an Accreting Neutron Star

The sequence of thermonuclear, electron captures & pycnonuclear leads to:



Trajectory and times for
 $\dot{M} \approx 10^{-8} M_{\odot}/\text{yr}$
 All this action in outer 100-500m

Accretion and Burning of Matter on the Neutron Star



Burning Zone

$T \approx (1-3) \times 10^8 \text{ K}; \rho \approx 10^{5-6} \frac{\text{g}}{\text{cm}^3}$
 Helium Ignition First!
 $3\alpha \rightarrow {}^{12}\text{C}$
 3 meters

- It takes an hour - day for fresh fuel to reach the burning location
- Burning is confined to a thin shell when a steady-state model is constructed. (Hansen & Van Horn '75)
 \Rightarrow UNSTABLE

JAN VAN PARADIJS Type I X-Ray Bursts

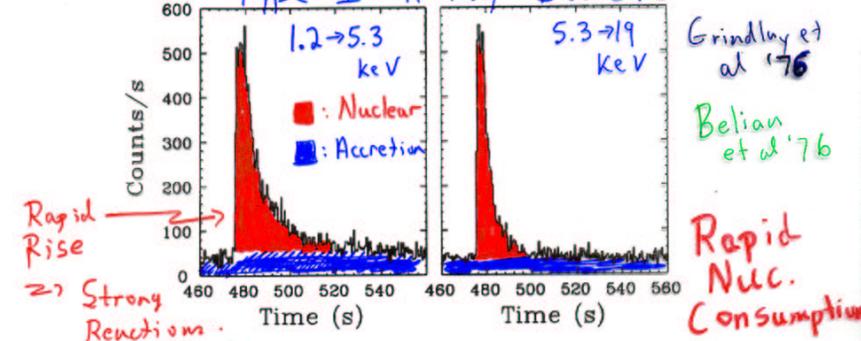


Figure 8. Type I X-ray burst from 1702-42 as observed with Exosat in the 1.2 - 5.3 keV band (left) and the 5.3 - 19.0 keV band (right); the softening of the X-ray burst spectrum is apparent as a longer tail in the low-energy burst profile (courtesy T. Oosterbroek).

Many (Woosley & Taam '76; Maraschi & Cavaliere '77; Joss '77; Lamb & Lamb '78)

successfully associated the thermal instabilities with Bursts, where:

<u>Observable</u>	<u>Interpretation</u>
$t_{\text{rec}} \approx \text{hours} - \text{days}$	Time to accumulate critical fuel pile

$$E_{\text{Burst}} \approx 10^{39} \text{ ergs} = [\dot{M} t_{\text{rec}}] \left(\frac{7 \text{ MeV}}{\text{nucleon}} \right)$$

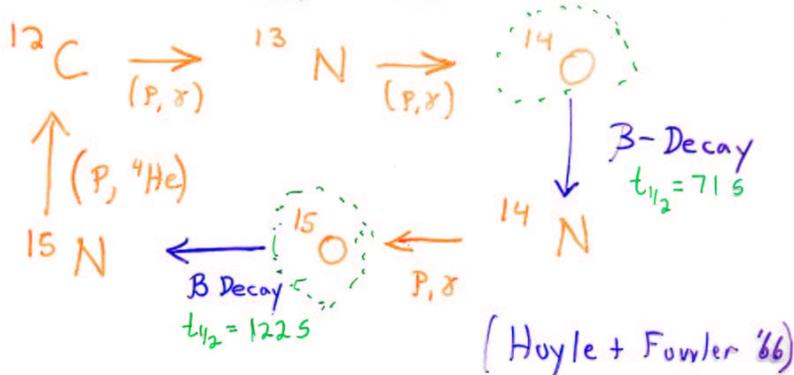
$t_{\text{decay}} \approx 10 \text{ sec.}$
 Time for cooling the envelope after burn.

\Rightarrow Limit cycle of accumulation for hours followed by Ignition

Hydrogen versus Helium

Why Helium First?

Simple Chain when Hot



For the $T \geq 7 \times 10^7$ K environment, the time around the chain is not T sensitive as the β -decays are the rate limiting step

\Rightarrow ① H Burning is stable at high T 's, as burning is T independent $\dot{M} \geq 10^2 \dot{M}_{\text{Edd}}$

\Rightarrow ② Burning of H is so slow relative to compression that Helium ignites prior to H depletion. (Taam) \rightarrow next

Mixed Burning Regime

(Taam, Lamb + Lamb, Woosley Wallace + Weisberg)

If H is burning via hot CNO, then all CNO \rightarrow ^{14}O + ^{15}O

Cosmic Abundance $\Rightarrow \sim 10^3$ protons seed.

So must go around cycle

$$N \approx \frac{10^3}{4} \text{ times}$$

$$\Rightarrow t \sim \left(\frac{10^3}{4}\right) (3000) \approx \text{day!}$$

\Rightarrow If $Z \leq Z_0$ it takes a day to burn all H \rightarrow He via Hot CNO

However, the accreted helium ignites when roughly

$$y \equiv \int \rho dz \approx 10^8 \frac{\text{gr}}{\text{cm}^2} \text{ has accumulated.}$$

Takes $t = \text{hr} \left(\frac{\dot{M}_{\text{Edd}}}{\dot{M}} \right)$

$\Rightarrow \dot{M} \geq \frac{1}{24} \dot{M}_{\text{Edd}} \Rightarrow$ Helium ignites before H depletion. Lower $\dot{M} =$ Pure He

Mixed Ignition Conditions

(Fujimoto + Hanawa; Fushiki + Lamb...)

$$- Z_{\text{CNO}} = 0.01$$

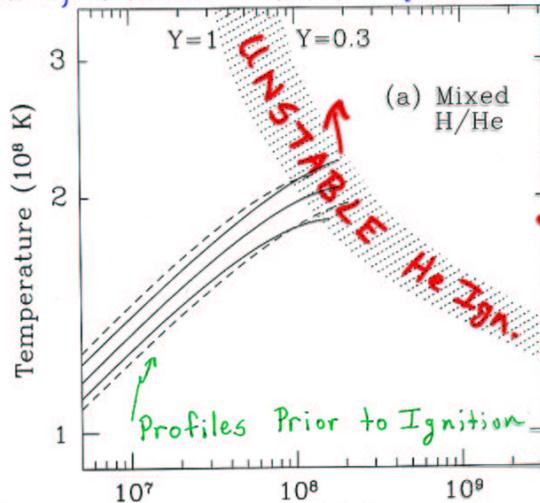
$$\frac{\dot{m}}{\dot{m}_{\text{Edd}}} = 0.03, 0.1$$

$$+ 0.3$$

$$- \dot{m} = 0.1 \dot{m}_{\text{Edd}}$$

$$Z_{\text{CNO}} = 0.005$$

$$+ 0.02$$



$$\frac{P}{g} = \int \rho dz = \text{Column Depth (g cm}^{-2}\text{)}$$

$$\text{Typical } y_{\text{ign}} \approx 2 \times 10^8 \text{ gr/cm}^2$$

$$t_{\text{rec}} \approx \frac{y_{\text{ign}}}{\dot{m}} = 6 \text{ hr} \left(\frac{0.1 \dot{m}_{\text{Edd}}}{\dot{m}} \right)$$

Typical Conditions are

$$\rho_{\text{in}} \approx 10^6 \frac{\text{gr}}{\text{cm}^3}; T_{\text{in}} \approx 2 \times 10^8 \text{ K and}$$

thickness of 500 cm.

Rapid Proton (rp) Process

Hydrogen Burning

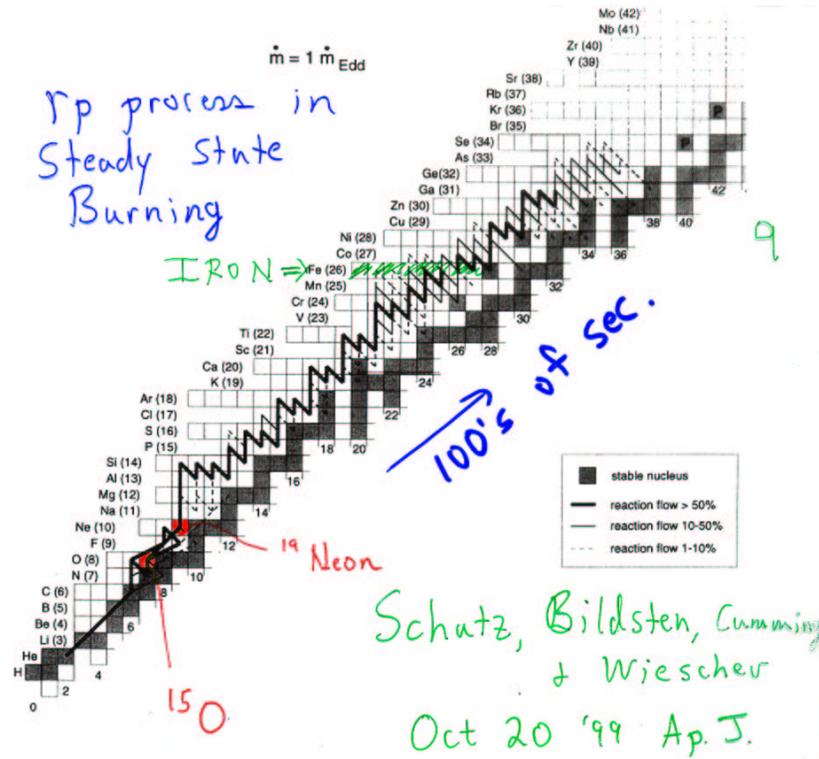
[Wallace + Woosley]
During the flash initiated by the $3\alpha \rightarrow {}^{12}\text{C}$ reactions, the T gets high enough that:



are faster than the β decays, removing O from the catalytic cycle

- These nuclei then burn H via the rp-process, (p, γ) reactions followed by β -decays, no cycles.
- The initial ${}^4\text{He}$ content determines the # of seeds for rp.





Schutz, Bildsten, Cumming & Wiescher
 Oct 20 '99 Ap.J.

Agreeing with Fujimoto, Wallace & Woosley, we find that the burning can easily go far beyond ^{56}Fe .

rp process takes $\sim 100\text{s}$ to complete burning....

Previous Plot with $\tau = 10\text{s}$ decay likely He-rich

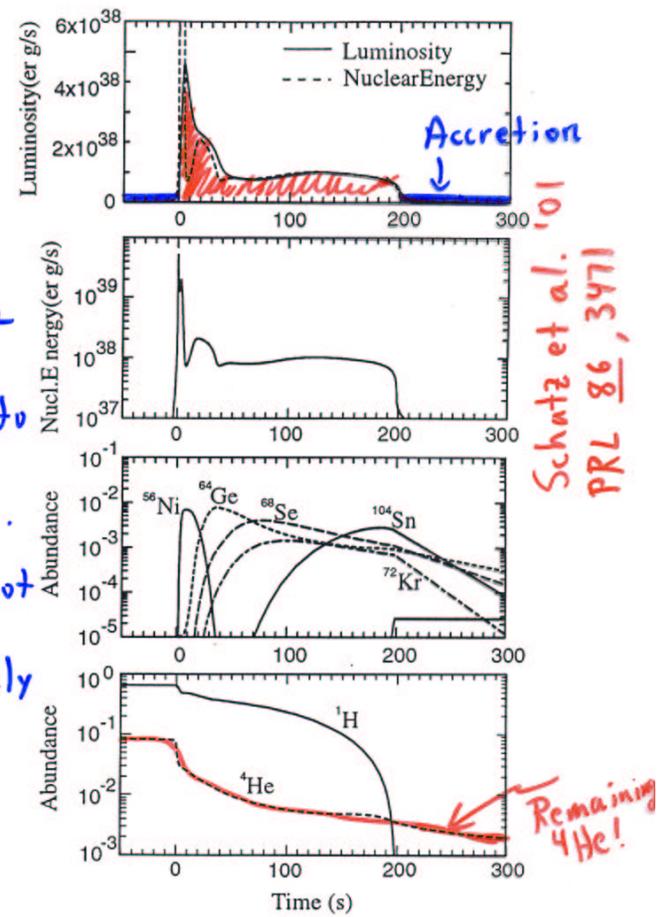
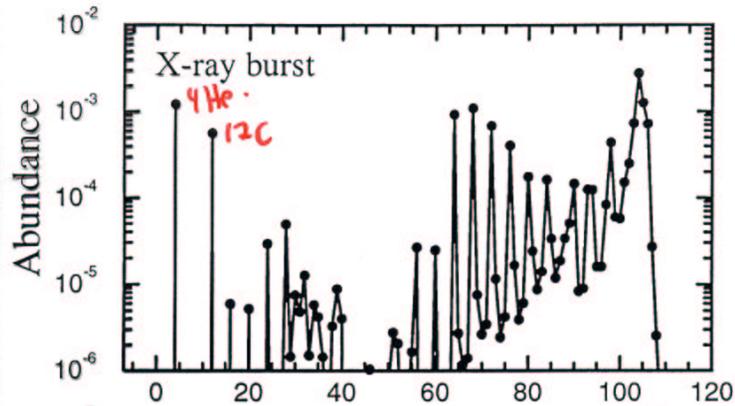


FIG. 3. Luminosity, nuclear energy generation rate, and the abundances of hydrogen, helium, and the important waiting point nuclei as functions of time during an x-ray burst. For comparison, the nuclear energy generation rate is also shown as a dashed line together with the luminosity, though it is out of scale during the peak of the burst. The mass of the accreted layer is 4.9×10^{21} g.

^{12}C Remains in Ashes.



Schatz et al. '01

Textbook Burster

GS 1826-238

- 70 bursts detected in 2.5 yrs monitoring with Beppo-SAX wfc, nearly periodic at $t_{\text{rec}} = 5.76 \pm 0.62$ hrs (Ubertini et al '99, In't Zand et al '99, Kong et al. '00) $\dot{M} = \text{const.}$
- Global Rate $\dot{M} \approx 10^{-9} \text{ Mo/yr}$
 $R_{\text{app}}/d = 9 \text{ km}/8 \text{ kpc}$ (Kong et al '00)
 $\Rightarrow \dot{m} \approx 8 \times 10^3 \frac{\text{g}}{\text{cm}^2 \cdot \text{s}}$
 Safely in mixed H/He Regime
- Accumulated Column Density $y = \dot{m} t_{\text{rec}} \approx 1.6 \times 10^8 \frac{\text{g}}{\text{cm}^2}$
 agrees with theory!
- Energy, $\alpha = 50$
 $4 \text{ MeV/accr. nucleon}$ for 10km 1.4 Mo NS
 \Rightarrow Clearly Burning Hydrogen/Helium

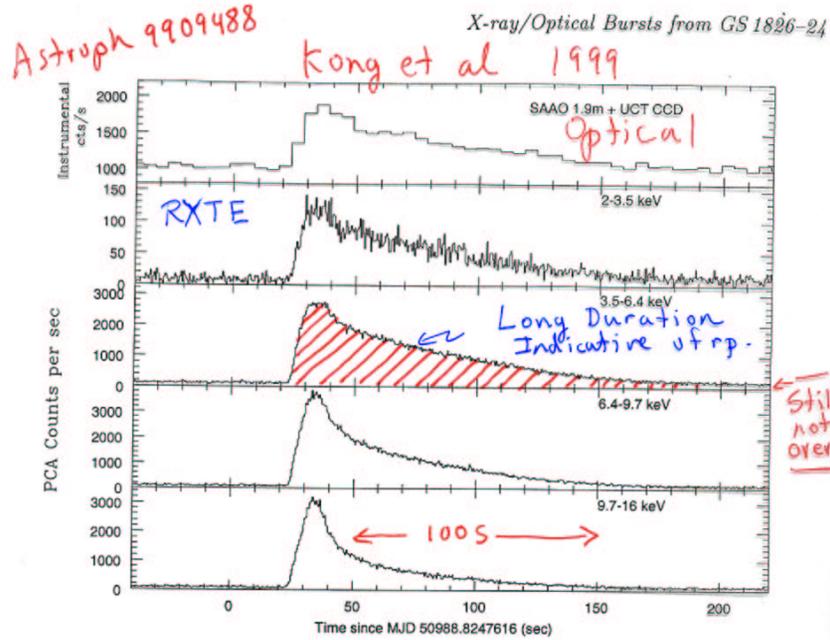


Figure 5. The optical (SAAO) and X-ray (RXTE) burst profiles in various energy bands. The timing resolution is 5 s (optical) and (RXTE/PCA). The decay times strongly depend on photon energy with decays being shorter at higher energies.

! No Oscillations!

5.76 hr periodic!

$\alpha \approx 50$

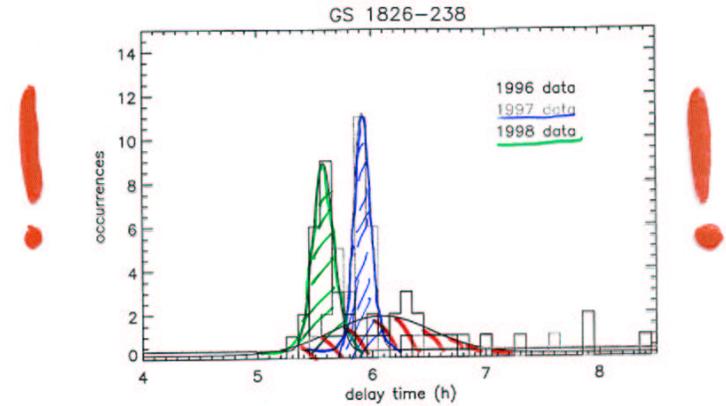


FIGURE 1. Burst wait times distribution in 1996,1997,1998.

Cocchi et al '00

Table 1. Burst wait times and persistent emission distributions in 1996,1997,1998

	1996	1997	1998
Recurrence time (h)	6.08 ± 0.14	5.92 ± 0.01	5.58 ± 0.01
Dispersion (h, 1 sigma)	0.44 ± 0.15	0.07 ± 0.01	0.09 ± 0.01
WFC 2-28 keV average intensity (mCrab)	30.3 ± 2.2	31.4 ± 2.3	31.9 ± 2.0
Dispersion (1 sigma)	5.5 mCrab	4.5 mCrab	2.9 mCrab
ASM 2-10 keV average intensity (mCrab)	24.6 ± 0.2	28.1 ± 0.3	27.8 ± 0.5
Dispersion (1 sigma)	9.2 mCrab	12.0 mCrab	11.9 mCrab

Very Regular Burster!!

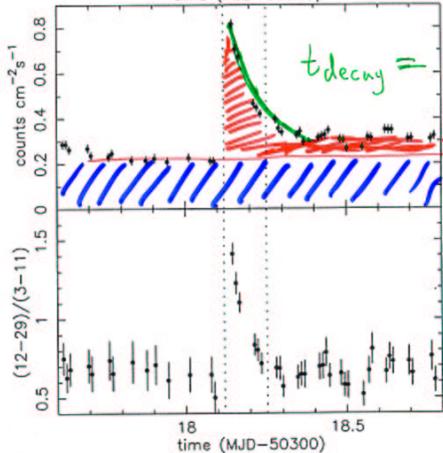
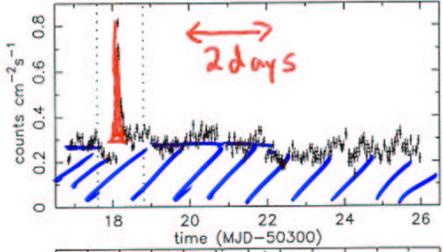
The dispersion in recurrence times is smaller than that in $F_x \Rightarrow$ as we know from other contexts F_x is not a great \dot{M} indicator

Newest Profound Puzzle!

Cornelisse et al. '00
day in August 1996

Superbursts!

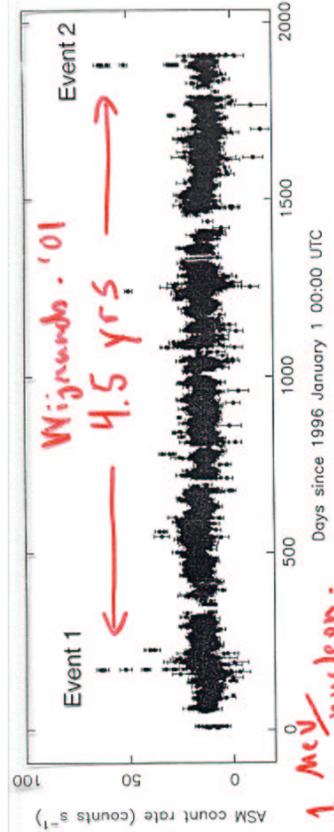
Now
Seen
in
6
Sources.
(kulkers)



$L_{peak} \approx 10^{38} \frac{\text{erg}}{\text{sec}}$
 $E_{burst} \approx 10^{42} \text{ erg}$
 $\sim 10^3 E_{type I}$

Cause?
Likely
thermonuclear
energy release
from deep
in NS.

Fig. 1. Top: The nine day lightcurve of 4U 1735-44 as observed with the WFC in August 1996. Count rates are for channels 1-31 (energy range 2-28 keV). Each time bin corresponds to 15 minutes. A large enhancement in intensity starts near MJD 50318.1 and ends about ≈ 4.0 hours later. The vertical dotted lines indicate the time interval for which the count rate and hardness ratio are shown in the expanded view of the lower frames. The hardness ratio shown is the ratio of the count rate in channels 12-29 (5-20 keV) to that in channels 3-11 (2-5 keV). During the flux enhancement the exponential softening expected for a type-I X-ray burst is clearly visible. The vertical dotted lines indicate the time interval for which we add the data to obtain the burst spectrum.



$L \approx 1 \text{ MeV/nucleon}$

Fig. 1.— The 1.5-12 keV ASM light curve of 4U 1636-53 showing the two very long X-ray events.

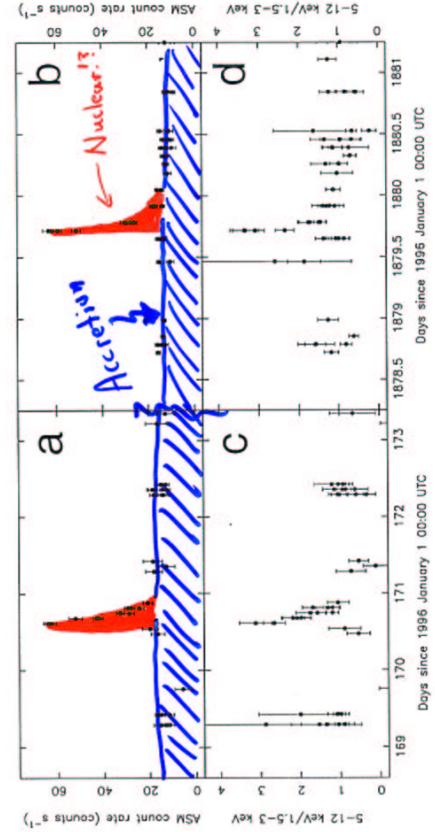


Fig. 2.— The 1.5-12 keV ASM light curve of 4U 1636-53 showing the two very long X-ray events. The 1.5-3 keV count rate curve of event 1 (a) and 2 (b), and the 5-12 keV/1.5-3 keV count rate curve of event 1 (c) and 2 (d).

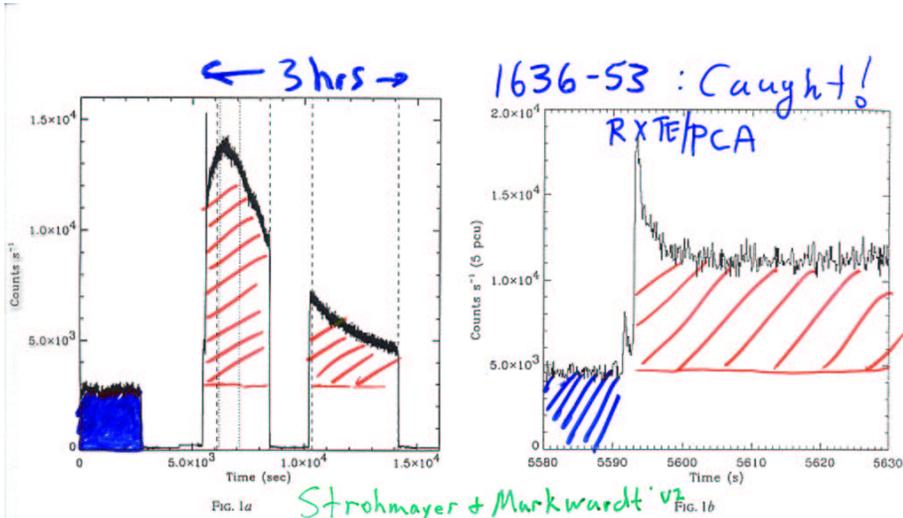


Fig. 1—(a) Light curve of the superburst from 4U 1636–53 observed on 2001 February 22. The data are the 2–60 keV PCA count rates from the Standard1a mode. The time resolution is 1 s. The dashed vertical lines denote the intervals with high time resolution event mode data. The ~800 s interval in which isotations are detected is shown by the vertical dotted lines. (b) An exploded view of the sharp rise near the start of the burst is also shown. Here the time resolution is 1/8 s. Note the double-peaked profile that shows timescales typically seen in normal type I X-ray bursts (~10 s). Time is measured from 15:19:00 UTC 2001 February 22.

Strohmayer + Markwardt '02
Strohmayer + Brown '03

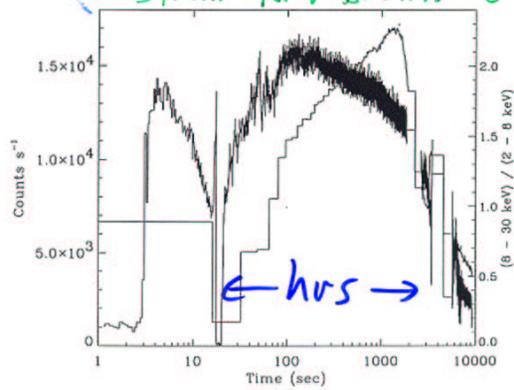


Fig. 2.—Time history of the X-ray flux from 4U 1820–30 during the superburst. The PCA light curve (2–60 keV) at 1/8 s resolution is the higher time resolution trace (left-hand axis). The lower time resolution curve is the (8–30)/(2–8) keV hardness ratio from Standard2 data with 16 s resolution (right-hand axis).

E. Kuulkers et al.: A superburst from KS1731–260

509

Kuulkers et al '02

Table 3. Properties of superbursts ordered along their exponential decay time^a.

source	instrument	energy range	duration (hr)	precursor?	τ_{exp} (hr)	L_{pers} (L_{Edd}) ^b	kT_{max} (keV)	L_{peak} (10^{38} erg s) ^{c,d}	$\tau \equiv E_b/L_{\text{peak}}$ (hr) ^d	$\gamma \equiv L_{\text{pers}}/L_{\text{peak}}$ ^d	$t_{\text{no bursts}}$ (days) ^e	H/He or He donor	references/ ^f
4U 1820–30	PCA	2–60 keV	>2.5	yes	≈ 1	≈ 0.1	≈ 3.0	3.4 ± 0.1	$\gtrsim 1.4$	≈ 0.1	?	He	S00, SB01
Ser X-1	WFC	2–28 keV	~ 4	?	1.2 ± 0.1	≈ 0.2	2.6 ± 0.2	1.6 ± 0.2	≈ 0.8	≈ 1.4	≈ 0.4	H/He	C01
4U 1735–44	WFC	2–28 keV	~ 7	?	1.4 ± 0.1	≈ 0.25	2.6 ± 0.2	1.5 ± 0.1	$\gtrsim 0.5$	$\gtrsim 0.9$	≈ 0.4	H/He	C00
4U 1636–53	ASM, PCA	1.5–12 keV	$\gtrsim 1-3$?	$1.5 \pm 0.1/3.1 \pm 0.5$	~ 0.1	~ 0.1	1.6 ± 0.2	$\sim 0.5-1$	$\gtrsim 1.5$	~ 0.2	H/He	W01
GX 3+1	ASM	1.5–12 keV	>4.4	?	1.6 ± 0.2	~ 0.2	~ 0.2	1.6 ± 0.2	$\gtrsim 0.5$	$\gtrsim 1.5$	~ 0.2	?	K01
KS 1731–260	WFC, ASM	2–28 keV	~ 12	yes	2.7 ± 0.1	≈ 0.1	≈ 0.1	2.7 ± 0.1	≈ 1.0	≈ 2.0	≈ 0.4	?	this paper

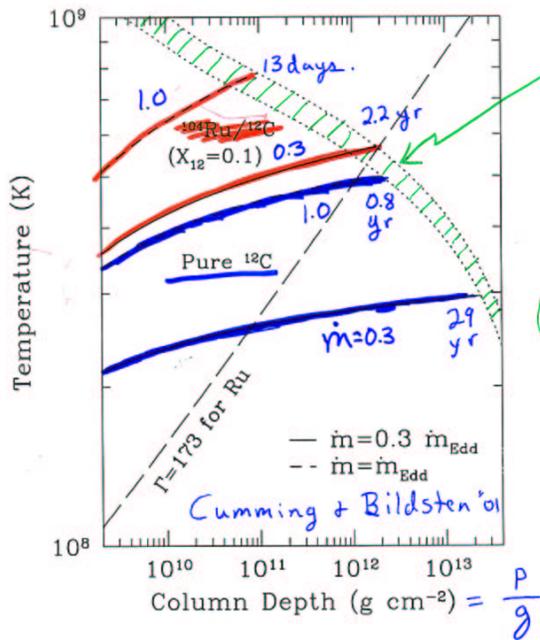
Handwritten notes in red: $\approx 0.2 L_{\text{Edd}}$ and $\approx 10^{42}$ erg.

^a A question mark denotes an unknown value.
^b We used the 0.01–100 keV unabsorbed flux from spectral fits and the observed maximum flux during radius expansion bursts.
^c Unabsorbed bolometric peak (black-body) luminosity.
^d Since the rise to maximum was only observed for 4U 1820–30, the values for the other sources are to be used with caution.
^e Time of cessation of normal X-ray bursts after the superburst.
^f C00 = Cornillese et al. (2000), C01 = Cornillese et al. (2001), K01 = Kuulkers (2001a,b), S00 = Strohmayer (2000), S01 = Strohmayer & Brown (2001), W01 = Wijngaards (2001).

$E \approx 10^{42}$ ergs, lasts many hours, objects accreting at $\sim 0.2 L_{\text{Edd}}$

"Settling" Solutions

Since $K_{\text{cond}} \propto \frac{1}{Z^{2/3} \mu^{1/3}}$, the rp-ashes reduce $K \Rightarrow$ Hotter at base than pure ^{12}C . for same deep flux $F = 10^{17} \frac{\text{erg}}{\text{gr}} \cdot \dot{m}$.



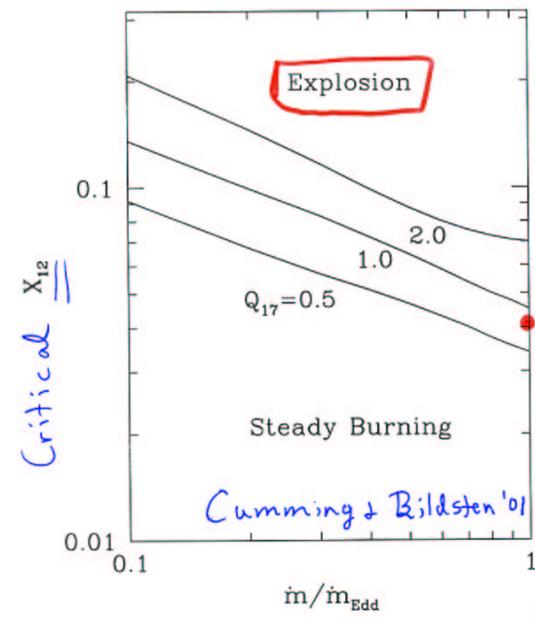
^{12}C Ignition
 $\frac{d\epsilon_{\text{nuc}}}{d \ln T} > \frac{d\epsilon_{\text{cool}}}{d \ln T}$
 $\epsilon_{\text{cool}} \approx \frac{8kT}{y^2}$
 (unlike Ia's where v -cooling matters)
 $\dot{m} \approx \frac{1}{3} \dot{m}_{\text{Edd}}$
 Preferred.

\Rightarrow The rp-ashes allow for:
 (a) earlier ignition
 (b) energies more consistent with superbursts.

Survival of ^{12}C

For this case we must have the ^{12}C survive to the ignition depth

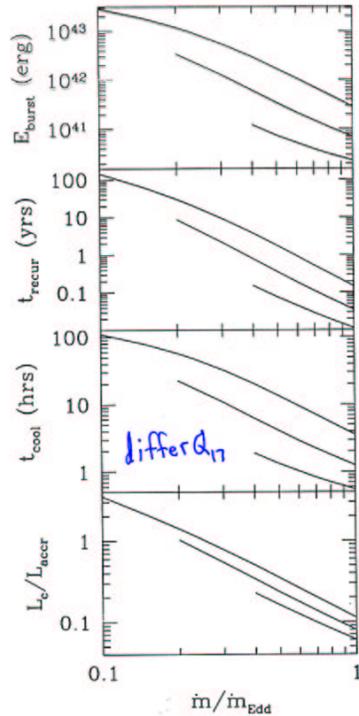
$$t_{\text{nuc}} \approx \frac{E_{\text{nuc}} X_{12}}{E_{\text{nuc}}} > t_{\text{accrue}} = \frac{y}{\dot{m}} \text{ at ignition.}$$



Calculated Value (Schutz et al. '99)

$F_{\text{deep}} = 10^{17} \frac{\text{erg}}{\text{gr}} Q_{17} \dot{m}$
 Q_{17} = measure of flux coming thru deep ocean
 Measured at $Q_{17} \approx 0.3$ in KS1731-270.

Resulting Predictions



Once unstable, burns rapidly to
 $T_{\text{peak}} \approx 2 \times 10^9 \text{K} \left(\frac{E_F}{\text{MeV}} \right)^{1/2} * \left(\frac{X_{12}}{0.1} \right)^{1/2}$

On longer times, decays $L \propto e^{-t/t_c}$

$$t_{\text{cool}} \approx 4 \text{hrs} \frac{g_8}{g_{14}} \left(\frac{Z}{44} \right)^4 \left(\frac{104}{A} \right)^3$$

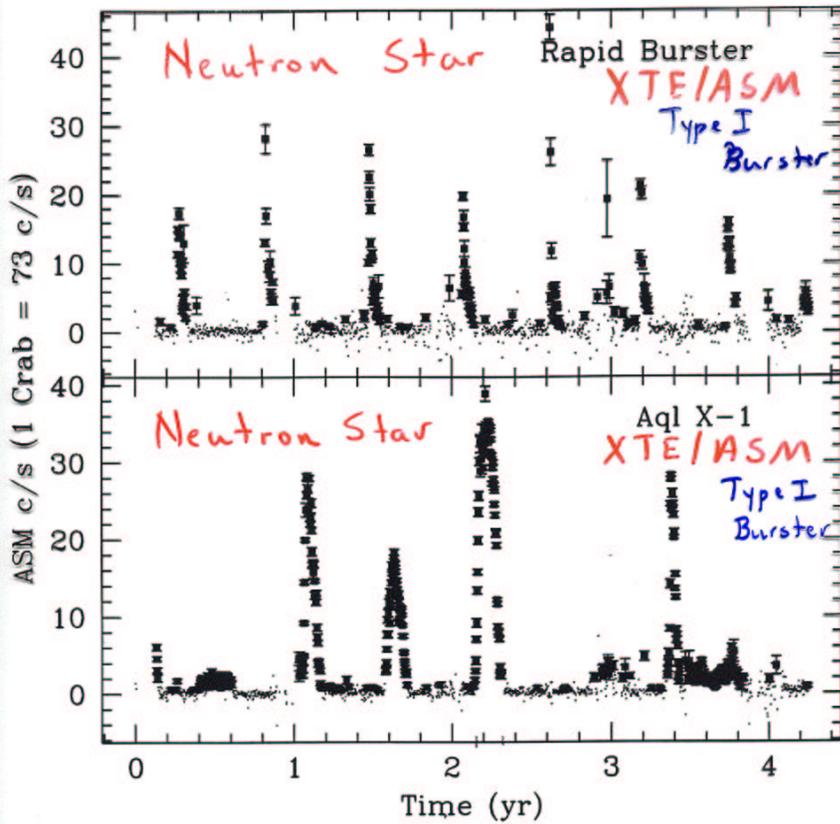
and the characteristic lumin is

$$\frac{L_c}{L_{\text{Edd}}} \approx 0.8 X_{12} g_8^{1/3} \left(\frac{A}{104} \right)^{5/3} \left(\frac{44}{Z} \right)^{8/3}$$

“Superburst Puzzles “Ashes to Ashes”

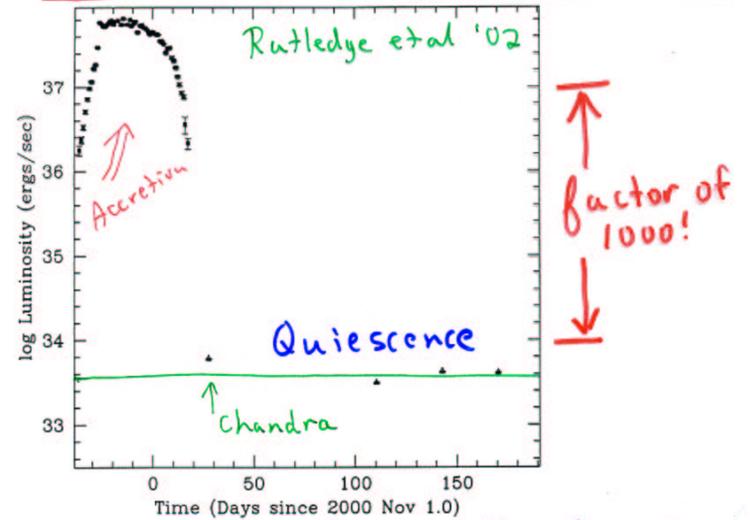
- Are the ashes from the hourly bursts ^{12}C rich enough?
- Is there interesting nucleosynthesis during a Superburst since $T > 10^9 \text{K}$?
- Why are some X-ray binaries more likely than others for the event?

Transient Accretors. Day Average ≈ 730 have error bars < 30 ; little points from transient/plots/asm lc.ps April 15, 2000

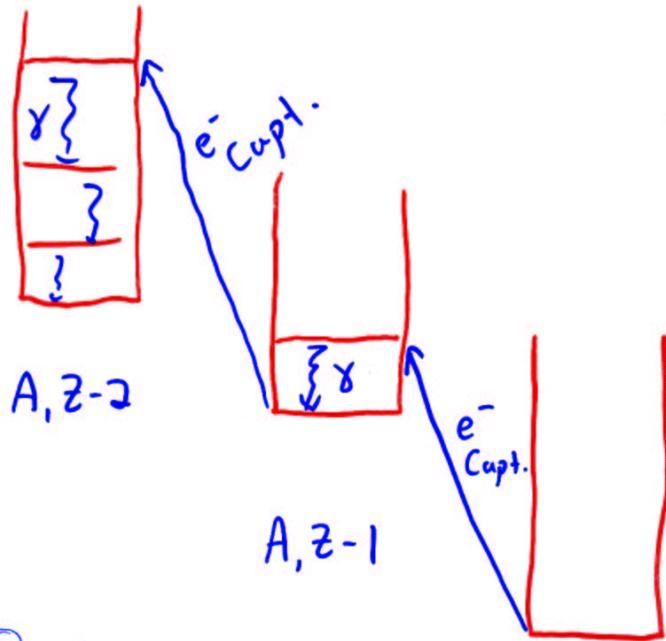


For both NS + BH Binaries the transient accretion is thought to arise from an accretion disk instability, as in dwarf novae

Evolution of Aql X-1 Outburst



- Comparable Declines of L are seen in other NS's and are even more dramatic in BH systems (Narayan et al '97, Asai et al. '98)
- Quiescent NS spectra consistent with large thermal contribution (Rutledge et al., '99, '00...)
- Energy source for thermal emission likely has large nuclear contribution (Brown, Bildsten, + Rutledge '98)



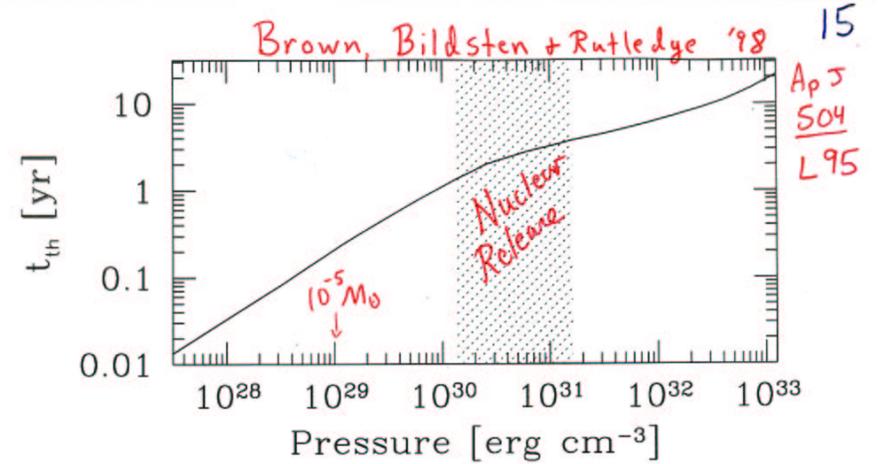
Once

$$E_F > Q,$$

Captures Proceed.

A, Z

\Rightarrow Energy Deposited and eventually so neutron rich, fusion can occur.



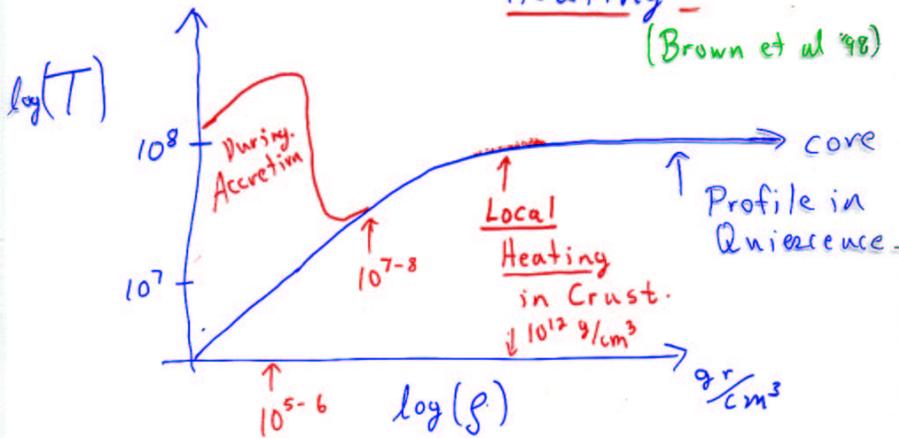
Accreted Crust undergoes:

- Electron Captures
- Neutron Emission
- Pycnonuclear Reactions

[Sato, Haensel + Zdunik]

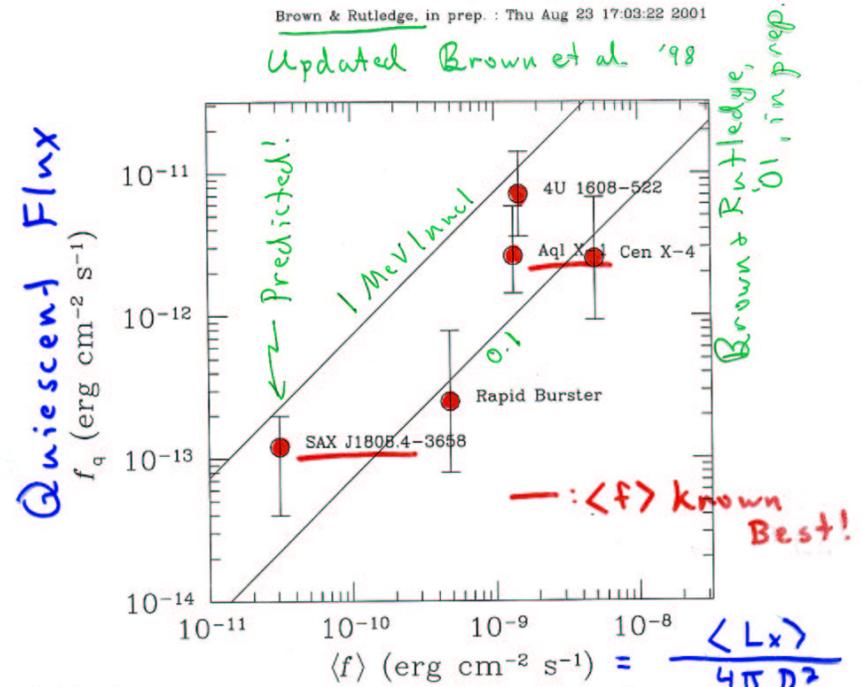
From Haensel + Zdunik, the sum of the energy released is $\approx 1 \text{ MeV/nucleon}$, but depends on nuclear composition initially.

Role of Deep Crustal Heating 15a



⇒ Outer envelope heats to $\approx 10^8$ k during outburst, but that heat escapes back out on a timescale of days (Hanawa et al.)

⇒ The deep heating in the crust and core maintains it at a $T \approx 10^8$ k, hot enough to make it luminous in quiescence at $L_q \approx 10^{33}$ erg/s (Brown et al. '98)



⇒ Time averaged heat deposited during outbursts exits as thermal

$$L_q \approx \left(\frac{\text{MeV}}{\text{nucleon}} \right) \langle \dot{M} \rangle = 6 \times 10^{32} \frac{\text{erg}}{\text{s}} \frac{\langle \dot{M} \rangle}{10^{-11} \frac{M_\odot}{\text{yr}}}$$

Future + Open ?'s

Despite it's energetic disadvantage, nuclear physics plays an impit role on accreting NS's and allows us to probe their properties (spin, $\vec{B} + R$).

BIG Puzzles Remain:

? ● Are rp process elements ejected $\rightarrow \infty$

The NS potential well is deep, so at best only a fraction of the accreted material can escape.

? ● Can we see the elements?

Maybe so, especially during the more violent + long lasting superbursts, if convection brings ashes to photosphere.

? ● Are there asymmetries?

Yes! Spins have been measured underlying cause of symmetry breaking still unknown.