Lecture 9

Hydrogen Burning Nucleosynthesis, Classical Novae, and X-Ray Bursts

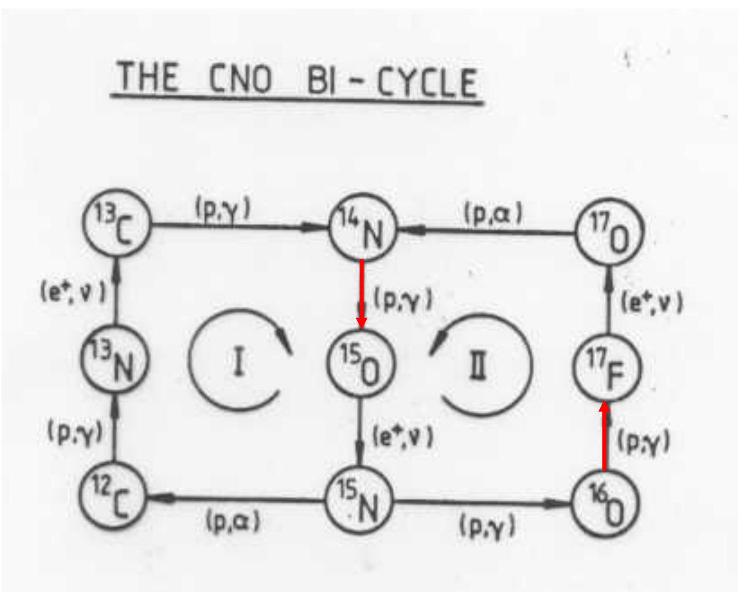
Once the relevant nuclear physics is known in terms of the necessary rate factors, $\lambda = N_A\langle\sigma v\rangle$ = *function* (T,ρ), the evolution of the composition can be solved from the coupled set of rate equations. For the species I:

$$\frac{dY_I}{dt} = -\overbrace{\sum_{j,k} Y_I\, Y_j\, \rho\, \lambda_{jk}(I)}^{\text{destruction}} \; + \overbrace{\sum_{k,j,L \,\ni\, L+k=I+j} Y_L\, Y_k\, \rho\, \lambda_{kj}(L)}^{\text{creation}}$$

The rather complicated looking restriction on the second summation simply reflects the necessary conservation conditions for the generic forward reaction, $I(j,k)L$ and its reverse, $L(k,j)I$.

k and j are typically n, p, α, or γ.

In the special case of weak decay one substitutes for $Y_j\rho\lambda$ the inverse mean lifetime against the weak interaction, $\lambda = 1/\tau_{beta}$. The mean lifetime is the half-life divided by ln 2 = 0.693. Then one has a term with a single Y_i times λ.



red = slow

Suppose we write the differential equation for ^{14}N in the CNO-1 cycle. In general ^{14}N might be created and destroyed by a large variety of reactions, $(\alpha,\gamma),(n,p),(\alpha,p),(n,\gamma),(p,\alpha),(p,n),(\gamma,\alpha),etc.$ But here there are just two:

$$\frac{dY(^{14}N)}{dt} = Y(^{13}C)Y_p\,\lambda_{p,\gamma}(^{13}C) - Y(^{14}N)Y_p\,\lambda_{p,\gamma}(^{14}N)$$

Now suppose ^{13}C and ^{14}N are in steady state. That is every time $^{13}C(p,\gamma)^{14}N$ creates a ^{14}N, $^{14}N(p,\gamma)^{15}O$ destroys it.

Then $\quad \frac{dY(^{14}N)}{dt} \approx 0 \Rightarrow \frac{Y(^{13}C)}{Y(^{14}N)} \approx \frac{\lambda_{p\gamma}(^{14}N)}{\lambda_{p\gamma}(^{13}C)}$

and by similar reasoning   Everywhere that $\frac{dY_i}{dt} \approx 0$

$$\frac{Y(^{13}C)}{Y(^{12}C)} = \frac{\lambda_{p\gamma}(^{12}C)}{\lambda_{p\gamma}(^{13}C)} \qquad \frac{Y(^{15}N)}{Y(^{14}N)} = \frac{\lambda_{p\gamma}(^{14}N)}{\lambda_{p\gamma}(^{15}N)+\lambda_{p\alpha}(^{15}N)}$$

and if the entire first loop was in steady state

$$\frac{Y(^{12}C)}{Y(^{14}N)} = \frac{\lambda_{p\gamma}(^{14}N)}{\lambda_{p\gamma}(^{12}C)}$$

$$i.e., \quad \frac{Y(^{14}N)}{Y(^{12}C)} = \left(\frac{Y(^{14}N)}{Y(^{13}C)}\right)\left(\frac{Y(^{13}C)}{Y(^{12}C)}\right) = \left(\frac{\cancel{\lambda_{p\gamma}(^{13}C)}}{\lambda_{p\gamma}(^{14}N)}\right)\left(\frac{\lambda_{p\gamma}(^{12}C)}{\cancel{\lambda_{p\gamma}(^{13}C)}}\right)$$

That is, the ratio of the abundances of any two species in steady state is the inverse ratio of their destruction rates

Integrating and assuming $Y_{13} = 0$ at $t = 0$ and $\frac{Y_{13}}{Y_{12}} = \frac{\lambda_{12}}{\lambda_{13}}$

after a time τ_{ss} = time required to reach steady state, one has with some algebra

$$\tau_{ss} = \frac{\ln\left(\frac{\lambda_{12}}{\lambda_{13}}\right)}{(\lambda_{12}-\lambda_{13})}$$

nb. always > 0
since ln of a number < 1
is negative

which says steady state will be reached on the faster of the two reaction time scales, $1/\lambda_{12}$ or $1/\lambda_{13}$

How long does it take for a pair of nuclei to reach steady state?

The time to reach steady state is approximately the reciprocal of the *destruction rate for the more fragile nucleus.*

Eg. for ^{12}C and ^{13}C   [absorb ρY_p into λ for simplicity];

i.e. $\lambda_{12} = \rho Y_p \lambda_{p\gamma}(^{12}C)$; $\lambda_{13} = \rho Y_p \lambda_{p\gamma}(^{13}C)$]

$$\frac{dY_{13}}{dt} = -Y_{13}\lambda_{13} + Y_{12}\lambda_{12} \qquad \frac{dY_{12}}{dt} \approx -Y_{12}\lambda_{12}$$

Ignore any reactions that create ^{12}C

Let $u = Y_{13}/Y_{12}$ then

$$\frac{du}{dt} = \frac{1}{Y_{12}}\frac{dY_{13}}{dt} - \frac{Y_{13}}{Y_{12}^2}\frac{dY_{12}}{dt} = \lambda_{12} - \frac{Y_{13}}{Y_{12}}\lambda_{13} + \frac{Y_{13}}{Y_{12}}\lambda_{12}$$
$$= \lambda_{12} + u\,(\lambda_{12} - \lambda_{13})$$

A sampling of Rates from Caughlan and Fowler (1988)

T6	12C(pg)	13C(pg)	14N(pg)
2	8.51(-39)	2.69(-38)	9.88(-44)
4	2.95(-29)	9.71(-29)	4.17(-33)
6	1.24(-24)	4.15(-24)	5.85(-28)
8	1.01(-21)	3.44(-21)	1.02(-24)
10	1.19(-19)	4.07(-19)	2.06(-22)
12	4.51(-18)	1.55(-17)	1.17(-20)
15	2.86(-16)	9.90(-16)	1.18(-18)
20	3.85(-14)	1.34(-13)	2.73(-16)
25	1.26(-12)	4.39(-12)	1.30(-14)
30	1.79(-11)	6.27(-11)	2.46(-13)
40	8.57(-10)	3.01(-9)	1.76(-11)
50	3.88(-11)	4.71(-8)	3.64(-10)
	15N(pa)	16O(pg)	17O(pa)
2	1.92(-39)	2.68(-48)	2.64(-49)
4	8.69(-29)	1.23(-36)	1.36(-37)
6	1.28(-23)	5.52(-31)	6.70(-32)
8	2.32(-20)	2.00(-27)	2.65(-28)
10	4.81(-18)	6.79(-25)	9.68(-26)
12	2.82(-16)	5.75(-23)	8.82(-24)
15	2.95(-14)	9.11(-21)	1.55(-21)
20	7.23(-12)	3.60(-18)	1.06(-18)
25	3.62(-10)	2.51(-16)	4.07(-16)
fastest at 30 * 30	7.18(-9)	6.35(-15)	3.47(-14)
40	5.60(-7)	6.94(-13)	9.11(-12)
50	1.25(-5)	1.93(-11)	2.43(-10)

At $T_6 = 30$ $\rho Y_p = 100$

$$\left(\rho Y_p \lambda_{p\gamma}(^{15}N)\right)^{-1} = 1.4\times10^6 \text{ sec} \qquad {}^{15}N \leftrightarrow {}^{14}N \text{ (quickest)}$$

$$\left(\rho Y_p \lambda_{p\gamma}(^{13}C)\right)^{-1} = 1.5\times10^8 \text{ sec} \qquad {}^{12}C \leftrightarrow {}^{13}C \text{ (}2^{nd}\text{ quickest)}$$

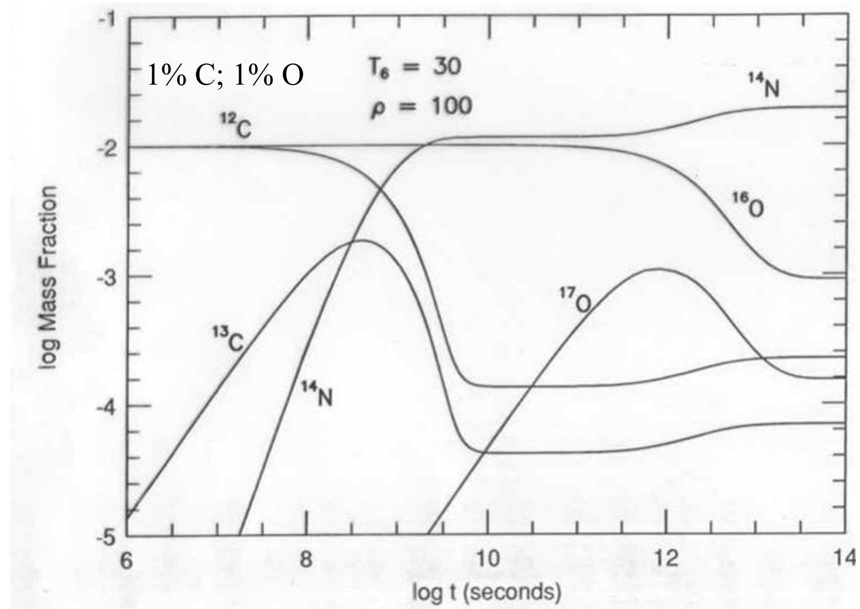
$$\left(\rho Y_p \lambda_{p\gamma}(^{12}C)\right)^{-1} = 5.6\times10^8 \text{ sec} \qquad {}^{12}C \leftrightarrow {}^{14}N \text{ (quick)}$$

$$\left(\rho Y_p \lambda_{p\gamma}(^{14}N)\right)^{-1} = 4.2\times10^{10} \text{ sec} \qquad \text{one cycle of the main CNO cycle}$$

$$\left(\rho Y_p \lambda_{p\alpha}(^{17}O)\right)^{-1} = 2.9\times10^{11} \text{ sec} \qquad {}^{17}O \leftrightarrow {}^{16}O \text{ (slow)}$$

$$\left(\rho Y_p \lambda_{p\gamma}(^{16}O)\right)^{-1} = 1.6\times10^{12} \text{ sec} \qquad {}^{16}O \leftrightarrow {}^{14}N \text{ (very slow)}$$

Steady state after several times these time scales.



ρ = 10 would be more appropriate for massive stars where T is this high, so the real time scale should be about 10 times greater. Also lengthened by convection.

Provided steady state has been achieved the abundance ratios are just given by the λ' s.

E. g. ^{13}C

$$\left(\frac{^{12}C}{^{13}C}\right)_{SS} = \left(\frac{\lambda_{p\gamma}\left(^{13}C\right)}{\lambda_{p\gamma}\left(^{12}C\right)}\right)$$

T(10^6 K)	^{13}C/^{12}C
10	1/3.48
20	1./3.50
30	1./3.51

but $\left(\frac{^{13}C}{^{12}C}\right)_\odot = \frac{1}{89}$

In steady state the abundance ratio ^{13}C/^{12}C is much greater than in the sun.

And this is sometimes observed…

Giant stars in the globular cluster M4

Suntzeff and Smith (ApJ, 381, 160, (1991)

TABLE 2

STELLAR PARAMETERS AND DERIVED ABUNDANCES

Star	T_{eff} (K)	log g	log $\epsilon(^{12}C)$	$^{12}C/^{13}C$	[C/M]
		M4			
1403	4200	1.3	6.70	5	−0.67
1408	4350	1.6	6.65	5	−0.72
1412/V4	4100	0.5	$\lesssim$5.6	…	$\lesssim$ −1.85
1514	3800	0.4	6.25	5	−1.12
1608	4600	2.0	6.75	6	−0.63
1617	4350	1.6	6.40	3:	−0.93
1622	4650	2.1	7.00	3–5:	−0.35
1625	4200	1.3	6.30	5:	−1.07
1701	4500	1.9	7.10	4	−0.25
2206	4150	1.2	6.75	4	−0.60
2307	3950	0.9	6.40	4	−0.95
2406/V13	3950	0.6	6.30	3	−1.02
2410	4350	1.6	6.80	5–10:	−0.59
2422	4300	1.5	6.50	3	−0.83
2519	4200	1.3	6.85	4	−0.50
2608	4300	1.5	6.85	5	−0.52
2617	4050	1.1	6.60	5	−0.77
2623	4500	1.9	6.65	3–5:	−0.70
3309	4700	2.2	7.15	…	−0.30
3404	4700	2.2	7.05	…	−0.40
3612	4150	1.2	6.60	3	−0.73
3624	4100	1.1	6.70	5	−0.67
4201	4300	1.5	6.70	5	−0.67
4310	4250	1.4	6.90	5	−0.47
4404	4650	2.1	7.10	…	−0.35
4413	4550	1.9	7.00	3	−0.32
4415	4300	1.5	6.70	5:	−0.67
4416	4450	1.8	6.50	5–10:	−0.89
4421	4350	1.6	6.55	6:	−0.83
4509	4650	2.1	6.95	5–10:	−0.44
4511	4050	1.0	6.55	6	−0.83
4630	4200	1.4	6.75	5	−0.62

But it doesn't always work so well. E.g. $\frac{^{15}N}{^{14}N}$ in the sun has a ratio

$$\left(\frac{^{15}N}{^{14}N}\right)_{\odot} = 3.7 \times 10^{-3}$$

But the steady state abundance is

T_H	$(^{15}N/^{14}N)_{SS}$
20	3.8(-5)
30	3.4(-5)
50	2.9(-5)

$$\left(\frac{^{15}N}{^{14}N}\right)_{\odot} = \frac{\lambda_{p\gamma}(^{14}N)}{\lambda_{p\alpha}(^{15}N)} \approx 3 \times 10^{-5}$$

Will have to make ^{15}N somewhere else not in steady state with ^{14}N

Also $\left.\frac{^{13}C}{^{14}N}\right)_{\odot} = 0.035$ but

T_6	$\left.\frac{^{13}C}{^{14}N}\right)_{SS} = \frac{\lambda_{p\gamma}(^{14}N)}{\lambda_{p\gamma}(^{12}C)}$
20	2.0(-3)
30	7.9(-3)
40	7.7(-3)

So one can make $\frac{^{13}C}{^{12}C}$ large but cannot make $\frac{^{13}C}{^{14}N}$ big compared with its solar value. Cardinal rule of nucleosynthesis - you must normalize to your biggest overproduction, nitrogen in this case.

Way out: Make ^{13}C in a CN process that has not reached steady state (because of the longer life of $^{13}C(p,\gamma)^{14}N$, e.g., make ^{13}C in a region where just a few protons are mixed in with the carbon and then convection cools the material.

Hydrogen Burning Nucleosynthesis Summary

^{12}C - destroyed by hydrogen burning. Turned into ^{13}C if incomplete cycle. ^{14}N otherwise.

^{13}C - produced by incomplete CN cycle. Made in low mass stars. Ejected in red giant winds and planetary nebulae

^{14}N - produced by the CNO cycle from primordial ^{12}C and ^{16}O present in the star since its birth. A secondary element. Made in low mass ($M < 8\ M_{\odot}$) stars and ejected in red giant winds and planetary nebulae. Exception: Large quantities of "primary" nitrogen can be made in very massive stars when the helium convective core encroaches on the hydrogen envelope.

^{15}N - Not made sufficiently in any normal CNO cycle> Probably made in classical novae as radioactive ^{15}O

^{16}O - Destroyed in the CNO cycle. Made in massive stars by helium burning

^{17}O - Used to be made in massive stars until the rate for $^{17}O(p,\alpha)^{14}N$ was remeasured and found to be large. probably made in classical novae

^{18}O - made in helium burning by $^{14}N(\alpha,\gamma)^{18}F(e^{+}\nu)^{18}O$

^{23}Na - Partly made by a branch of the CNO cycle but mostly made by carbon burning in massive stars.

^{26}Al - long lived radioactivity made by hydrogen burning but more by explosive neon burning in massive stars

Hydrogen burning at high temperature (T > 10^8 K)

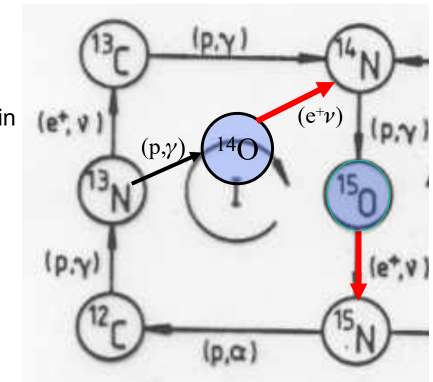
Sites:

- Nova explosions on accreting white dwarfs
  ($T_9 \sim 0.4$)
- X-ray bursts on accreting neutron stars
  ($T_9 \sim 1$ - 2)
- Supermassive stars
- neutrino driven wind in core collapse supernovae ?

Suppose keep raising the temperature of the CNO cycle. Is there a limit how fast it can go? Suppose ^{13}N(p,γ)^{14}O faster than 10 min?

Eventually one gets hung up on the finite life times for ^{14}O (70.6 s) and ^{15}O (122 s) to decay by positron emission. This has several interesting consequences:

10 min



^{15}F and ^{16}F are not bound

Slowest rates are weak decays of ^{14}O and ^{15}O.

The β-limited CNO cycle

- Material accumulates in ^{14}O and ^{15}O rather than ^{14}N, with interesting nucleosynthetic consequences for ^{15}N. But can the material cool down fast enough that ^{15}N is not destroyed by ^{15}N(p,α)^{12}C in the process?
- The nuclear energy generation rate becomes temperature insensitive and exceptionally simple

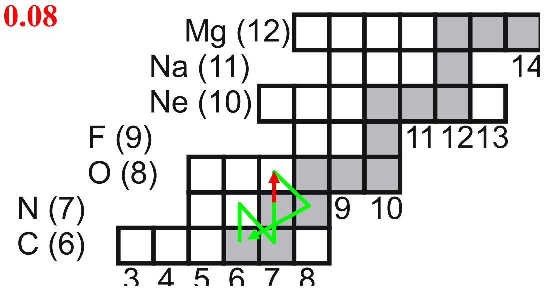
$$\varepsilon_{nuc} = 5.9 \times 10^{15} \ \ Z \ \ \mathrm{erg\ g^{-1}\ s^{-1}}$$

- As the temperature continues to rise matter can eventually break out of ^{14}O and ^{15}O especially by the reaction ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na(p,γ)^{21}Mg(e$^+\nu$) …. The *rp*-process (Wallace and Woosley 1981).

"Cold" CN(O)-Cycle **$T_9 < 0.08$**

Energy production rate:

$\varepsilon \propto <\sigma v>_{14N(p,\gamma)}$



Hot CN(O)-Cycle **$T_9 \sim 0.08$-0.1**

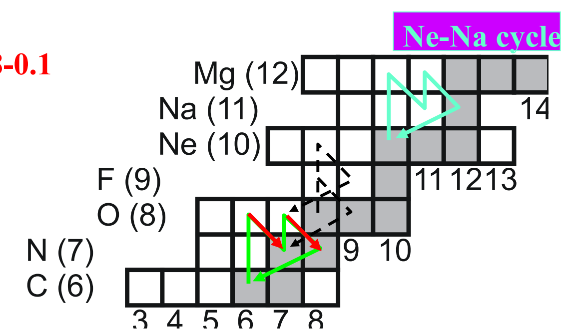
aka "beta limited CNO cycle"

$\varepsilon \propto 1/(\lambda^{-1}_{14O(\beta+)} + \lambda^{-1}_{15O(\beta+)}) = \mathrm{const}$

Note: condition for hot CNO cycle depends on density and Y_p:

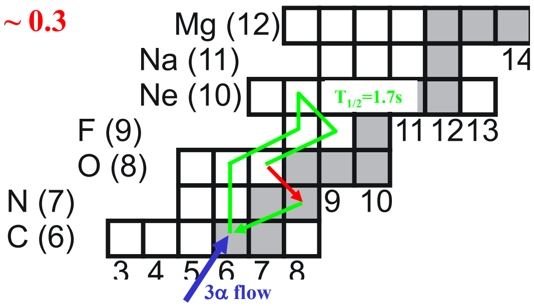
on ^{13}N: $\lambda_{p,\gamma} > \lambda_\beta$

$\Leftrightarrow Y_p \rho N_A < \sigma v > \ > \lambda_\beta$



Very Hot CN(O)-Cycle $T_9 \sim 0.3$

still “beta limited” but other nuclei involved

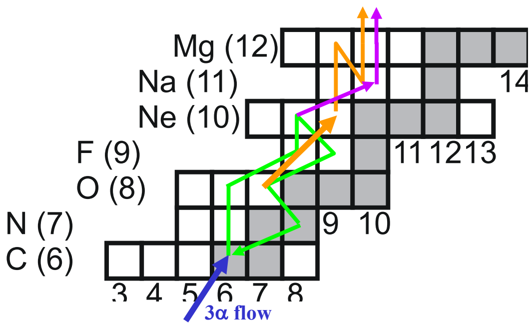


Breakout

processing beyond CNO cycle after breakout via:

$T_9 >\sim 0.3$ $^{15}O(\alpha,\gamma)^{19}Ne$

$T_9 >\sim 0.6$ $^{18}Ne(\alpha,p)^{21}Na$



One place where the β-limited CNO cycle is important is classical novae. Another is in x-ray bursts on neutron stars.

Classical Novae

- Distinct from “dwarf novae” which are probably accretion disk instabilities (lower L, shorter recurrence times)
- Thermonuclear explosions on accreting white dwarfs. Unlike supernovae, they recur, usually (but not always) on long (>1000 year) time scales.
- Rise in optical brightness by > 9 magnitudes
- Significant brightness change thereafter in < 1000 days
- Evidence for mass outflow from 100’s to 5000 km s^{-1}
- Anomalous (non-solar) abundances of elements from carbon to sulfur

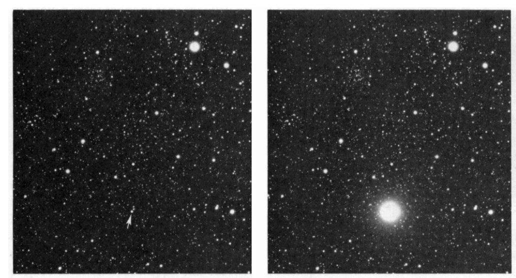
- Typically the luminosity rises rapidly to the Eddington luminosity for one solar mass (~10^{38} erg s^{-1}) and stays there for days (fast nova) to months (slow nova)
- In Andromeda (and probably the Milky Way) about 40 per year. In the LMC a few per year.
- Evidence for membership in a close binary –

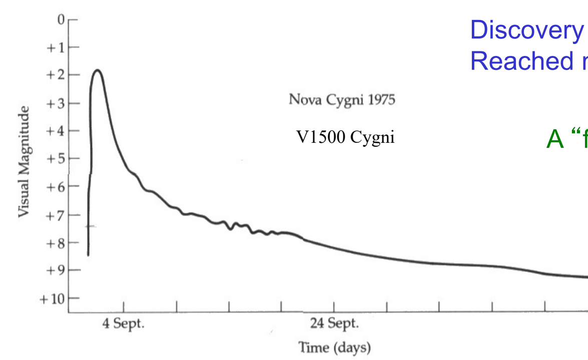
Nova Aquila (1918) – Kraft (1964)
0.06 days (GQ-Mus 1983)
2.0 days (GK Per 1901)
see Warner, *Physics of Classical Novae*, IAU Colloq 122, 24 (1990)

For a list of novae and their characteristics see

https://en.wikipedia.org/wiki/List_of_novae_in_the_Milky_Way_galaxy

V603 Aquila (1918) m = -0.5; brightest in modern times

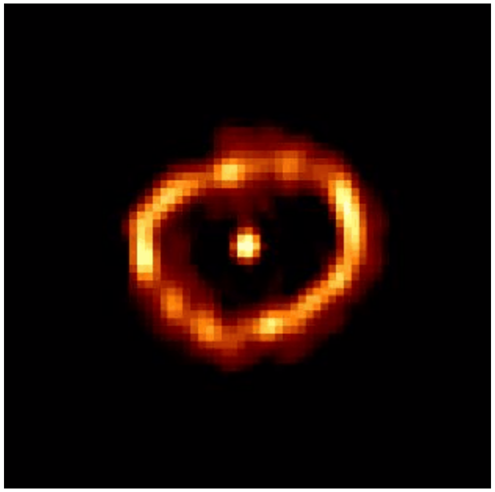




Discovery Aug 29, 1975
Reached magnitude 1.7.

A “fast” nova

Nova Cygni 1992



Visible to the unaided eye (m = 4.4).
Photo at left is from HST in 1994.
Discovered Feb. 19, 1992.
Spectrum showed evidence
for ejection of large amounts
of neon, oxygen, and magnesium,

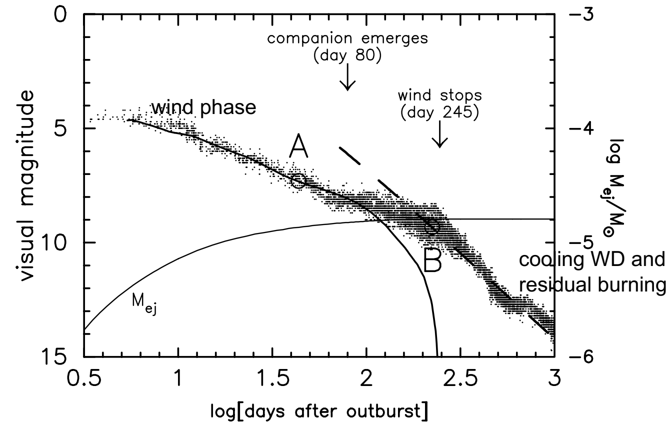
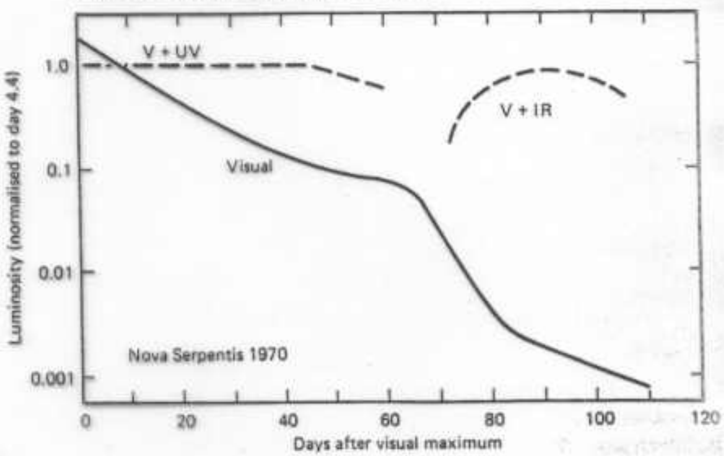


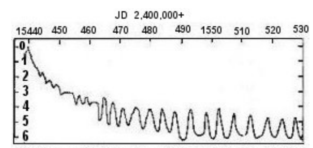
FIG. 4.—*Thick solid line*: visual magnitude of free-free emission from the optically thin ejecta, based on eq. (1), scaled to fit at day 43 (*point* A). The flux decays with a slope of $\sim t^{-1.5}$ until day ~100. *Dashed line*: free-free emission with a slope of $\sim t^{-3}$ after the wind stops, scaled to fit at day 224 (*point* B). *Thin solid line*: ejected mass (M_{ej}) from the WD by the optically thick winds. Here we assume JD 2,448,665.0 as the date of the outburst. *Points*: observational magnitudes taken from the AAVSO archive. Two epochs of the nova outburst are indicated by arrows: the companion emerges from the WD photosphere, and the optically thick nova wind stops. [*See the electronic edition of the Journal for a color version of this figure.*]

Nova Cygni (1992)
from Hachisu and Kato (2005)

DUST FORMATION

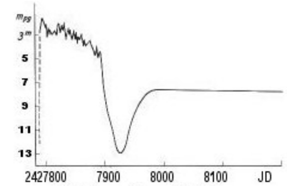
Fig. 4.1.2. The luminosity of the nova FH Serpentis as a function of time since its outburst. The visible light declined soon after outburst, to be replaced by ultraviolet radiation and later by infrared radiation. Thus the total (bolometric) luminosity of FH Ser remained high for several months (adapted from J. S. Gallagher & S. Starrfield, 1978, *Ann. Rev. Astr. Astrophys.*, 16, 171).





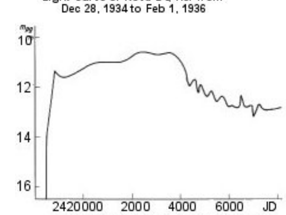
Light Curve of GK Persei from Feb 24, 1901 to May 25, 1901

Fast nova – rise is very steep and the principal display lasts only a few days. Falls > 3 mag within 110 days



Light Curve of Nova DQ Her from Dec 28, 1934 to Feb 1, 1936

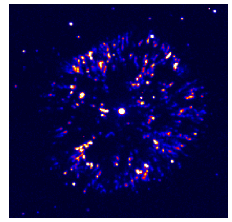
Slow nova – the decline by 3 magnitudes takes at least 100 days. There is frequently a decline and recovery at about 100 days associated with dust formation.



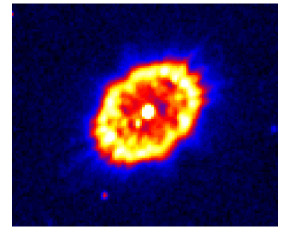
Light Curve of Nova RT Ser from the beginning of 1908 to July 16, 1935

Very slow nova – display lasts for years.

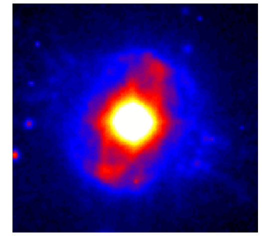
An earth mass or so is ejected at speeds of 100s to 1000s of km/s. Years later the ejected shells are still visible. The next page shows images from a ground-based optical survey between 1993 and 1995 at the William Hershel Telescope and the Anglo-Australian Telescope.



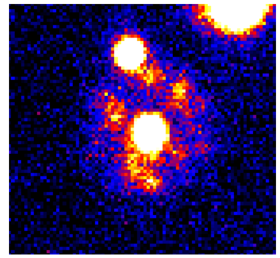
Nova Persei (1901)
GK Per



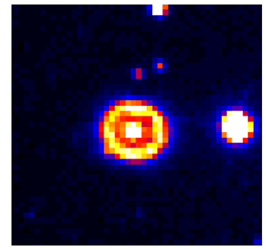
Nova Hercules (1934)
DQ - Her



Nova Pictoris (1927)
RR Pic



Nova Cygni (1975)
V1500 Cygni



Nova Serpentis (1970)
FH Ser

http://www.jb.man.ac.uk/~tob/novae/

Models

A white dwarf composed of either C and O (usually $< 1.06\ M_\odot$) or O, Mg, and Ne (usually $> 1.06\ M_\odot$) accretes hydrogen-rich material from a companion star at a slow rate of $10^{-8.5\pm1}\ M_\odot$ / yr

As the matter piles up, it becomes dense and hot. It is heated at its base chiefly by gravitational compression, though the temperature of the white dwarf itself may play a role.

Ignition occurs at a critical pressure of 2×10^{19} dyne cm^{-2} (Truran and Livio 1986 - assumptions R, M constant, $\Delta R << R$); basically this is the condition that $T_{base} \sim 10^7\ K = T_{H-ignition}$

This implies a certain critical mass since

$$i.e.,\ \frac{dP}{dm} = \frac{-GM}{4\pi r^4};$$

$$dm = 4\pi r^2 \rho\, dr$$

$$\boxed{\Delta M_{ign} \approx \frac{4\pi P_{ign}}{G}\frac{R_{WD}^{\ 4}}{M_{WD}} \sim 10^{-6}\text{-}10^{-4}\ M_\odot}$$

Addendum:

2 x 10^{19} dyne cm^{-2} ? 10^7 K?

Prialnik in his textbook says 2 x 10^{18} dyne cm^{-2} ; 2 x 10^7 K

I ran a half dozen models with Kepler to check. Found 2 x 10^7 K is a better temperature for the onset of the runaway. The pressure ranged from 3 x 10^{18} to 9 x 10^{18} dyne cm^{-2} at runaway. The density was around 5 x10^3 g cm^{-3} and went down as the runaway developed. Mildly degenerate. Burning continued throughout the nova, not just at the beginning.

Runaway is when the rise time for the temperature at the base becomes much shorter than the time for the accreted mass to increase. It is not a degeneracy condition as described in Prialnik's text.

Thermal inertia effects are important at high accretion rates.

Models

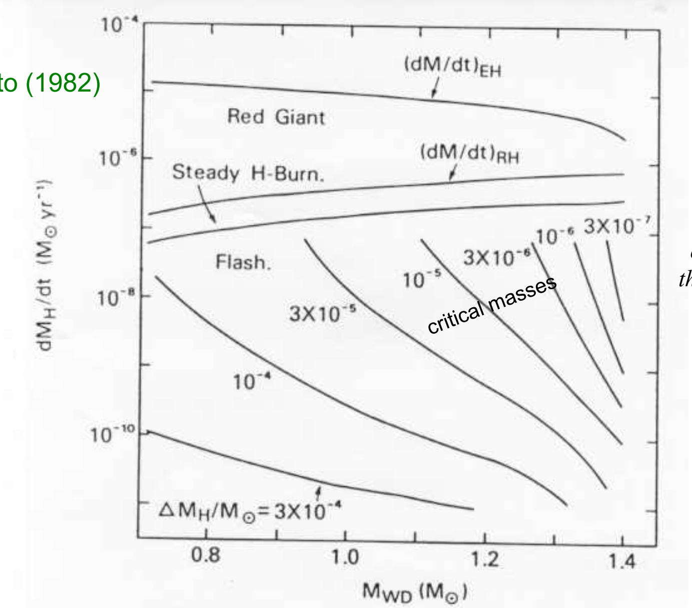
$$R_{WD} \approx 8.5\times10^{8}\left[1.286\left(\frac{M_{WD}}{M_\odot}\right)^{-2/3} - 0.777\left(\frac{M_{WD}}{M_\odot}\right)^{2/3}\right]^{1/2} \text{cm}$$

Approximately,
$R \propto M^{-1/3}$
for low M

Eggleton (1982) as quoted in Politano et al (1990)

This gives a critical mass that decreases rapidly (as $M^{-7/3}$) with mass. Since the recurrence interval is this critical mass divided by the accretion rate, bursts on high mass white dwarfs occur more frequently even though they are rarer by number.

Nomoto (1982)



For a given accretion rate the critical mass is smaller for larger mass white dwarfs

The mass of the accreted hydrogen envelope at the time the hydrogen ignites is a function of the white dwarf mass and accretion rate.

Truran and Livio (1986) using Iben (1982) –

Mass WD	Interval (10^5 yr)
0.60	12.9
0.70	7.3
0.80	4.2
0.90	2.4
1.00	1.2
1.10	0.64
1.20	0.28
1.30	0.09
1.35	0.04

Politano et al (1990) in *Physics of Classical Novae*

Even though the average mass white dwarf is 0.6 – 0.7 solar masses the most often observed novae have masses around 1.14 solar masses.

These would be white dwarfs composed of Ne, O, and Mg. It is estimated that ~ 1/3 of novae, by number, occur on NeOMg WDs even though they are quite rare.

see also Ritter et al, ApJ, 376, 177, (1991)

Iben 1982 gives

$$t_{rec} = 570\text{ yr}\left(\frac{1.5\times10^{-8}}{\dot{M}}\right)^{1/3} 10^{-4.38(M_{WD}-1.)} X_H^{-1} \times\left[1-0.29\left(\frac{\dot{M}}{1.5\times10^{-8}}\right)^{0.3}\right]$$

which could be as low as 6 years for 10^{-7} $M_\odot$ yr^{-1} on a 1.35 $M_\odot$ white dwarf.

This week in Nature!

See Darnley et al (*Nature* 2019 – January 29) for evidence of a nova recurring on time scales of years for millions of years (supershell – 100 pc in diameter – in Andromeda). M31N 2008-12a is the most frequently recurring nova. $M_{crit} \sim 10^{-7}$ M_O. Authors speculate it could be growing to the Chandraseekhar mass (but presumably NeOMg WD not CO so not SN Ia)

A Kepler model (2019):

$M_{WD} = 1.0\ M_\odot \quad \dot{M} = 1.\times10^{-9}\ M_\odot\ y^{-1}$

$R_{WD} \approx 5500\,\mathrm{km} \quad L_{WD} = 0.01\ L_\odot$

Accreted layer $\Delta R \approx\ 170\ \mathrm{km}$

$X_H = 0.70 \quad X_{He} = 0.28 \quad X_C = 0.01 \quad X_O = 0.01$

$$\Delta M \approx \frac{4\pi R^4 P_{crit}}{GM} = 4\times10^{-5}\ M_\odot$$

$\rho_{base} = 2900\ \mathrm{g\ cm^{-3}}\ T_{base} = 1.8\times10^7\ \mathrm{K} \quad P_{base} = 9\times10^{18}\ \mathrm{dyne\ cm^{-2}}$

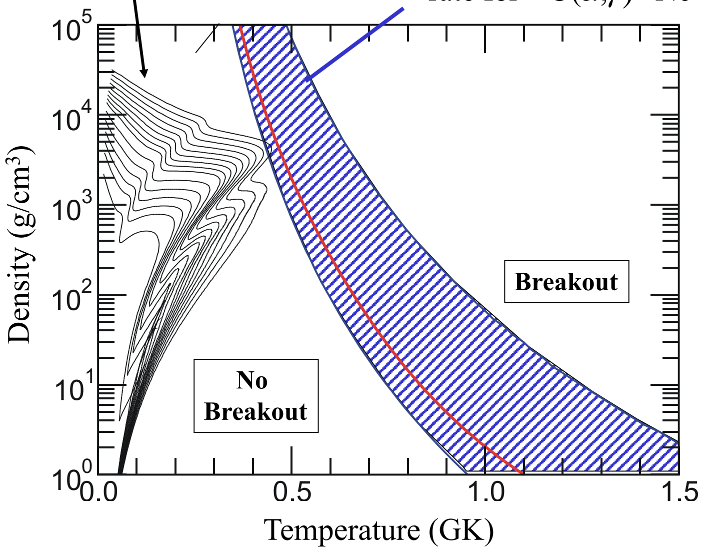
$$\bar{\rho} \sim \frac{\Delta M}{4\pi R^2 \Delta R} \sim 1500\ \mathrm{g\ cm^{-3}}$$

degeneracy parameter $\eta = 2.7$

Partially degenerate

Multizone Nova model (Starrfield 2001)

Breakout depends on uncertain rate for $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$



Nature of the burning:

Confusing statements exist in the literature. A nova is not a degenerate flash that happens in seconds and then is over (like a SN Ia). The ignition is partly degenerate but actually resembles a thin shell instability more than a nuclear runaway. So long as the radius of the center of mass of the burning layer does not increase dramatically, the pressure at the base stays constant. Some expansion occurs but not enough to put the burning out. At constant P, when density goes down, T goes up.

So the hydrogen continues to burn for a long time, dredging up C and O as it proceeds. Hydrostatic equilibrium maintains the luminosity at near the Eddington value. Matter is lost as a “super-wind”, not as a blast wave.

The dredge up of C and O is very important to the energetics and nucleosynthesis

For the beta-limited CNO cycle

$$\varepsilon_{nuc} = 5.9\times10^{15}\ Z\ \mathrm{erg\ g^{-1}\ s^{-1}} \qquad Z \sim 0.01 - 0.1$$

for $M = 10^{-5}\ M_\odot$; $Z = 0.01$

$$L = \varepsilon_{nuc}\, M \sim 10^{42}\ \mathrm{erg\ s^{-1}}$$

So the initial power is quite super-Eddington, but that drives convection and expansion until a smaller region is burning and the observed peak $L \sim 10^{38} - 10^{39}\ \mathrm{erg\ s^{-1}}$.

The binding energy per gram of material at the white dwarf edge is about

$$\frac{GM}{R} \approx \frac{(6.67E-8)(2E33)}{5E8} \approx 2\times10^{17}\ \text{erg gm}^{-1}$$

To eject e.g., 3 x 10^{-5} solar masses takes about 10^{46} erg. The kinetic energy (e.g., 1000 km/s) is about 10^{45} The integral of the Eddington luminosity for 10^7 s is also about 10^{45} erg. So the binding energy dominates the energy budget ad the light and kinetic energy are a small fraction of that.

In some cases common envelope effects may also be important. The companion star is inside the nova.

Nucleosynthesis in Novae

Basically ^{15}N and ^{17}O

The mass fraction of both in the ejecta is ~0.01, so crudely …

$$M_{nova}(^{15}\text{O}) \sim (0.01)(3\times10^{-5})(30)(10^{10}) \sim 10^5\, M_\odot$$

Woosley (1986)

$$X_{\text{Pop I}}(^{15}\text{N}) \sim 10^5 / \underbrace{3\times10^{10}}_{\substack{\text{approximate Pop I}\\ \text{material in the Galaxy}\\ \text{within solar orbit}}} \sim 4\times10^{-6} \approx \text{the solar mass fraction of } ^{15}\text{N and } ^{17}\text{O in the sun.}$$

Novae also make interesting amounts of ^{22}Na and ^{26}Al for gamma-ray astronomy

TABLE 2

HEAVY-ELEMENT MASS FRACTIONS IN NOVAE FROM OPTICAL AND ULTRAVIOLET SPECTROSCOPY

Object	Year	Reference	H	He	C	N	O	Ne	Na-Fe	Z	$(Z/Z_\odot)$	$(Ne/Ne_\odot)$	CNO/Ne-Fe
Solar	...	1	0.71	0.27	0.0031	0.001	0.0097	0.0018	0.0034	0.019	1.0	1.0	2.7
T Aur	1891	2	0.47	0.40	...	0.079	0.051	...	...	0.13	6.8	...	...
RR Pic	1925	3	0.53	0.43	0.0039	0.022	0.0058	0.011	...	0.043	2.3	6.3	2.9
DQ Her	1934	4	0.34	0.095	0.045	0.23	0.29	...	...	0.57	30.	...	...
DQ Her	1934	5	0.27	0.16	0.058	0.29	0.22	...	...	0.57	30.	...	...
HR Del	1967	6	0.45	0.48	...	0.027	0.047	0.0030	...	0.077	4.1	1.7	25.
V1500 Cyg	1975	7	0.49	0.21	0.070	0.075	0.13	0.023	...	0.30	16.	13.	12.
V1500 Cyg	1975	8	0.57	0.27	0.058	0.041	0.050	0.0099	...	0.16	8.4	5.6	15.
V1668 Cyg	1978	9	0.45	0.23	0.047	0.14	0.13	0.0068	...	0.32	17.	3.9	47.
V1668 Cyg	1978	10	0.45	0.22	0.070	0.14	0.12	...	...	0.33	17.	...	...
V693 CrA	1981	11	0.40	0.21	0.004	0.069	0.067	0.023	...	0.39	21.	128.	...
V693 CrA	1981	12	0.29	0.32	0.046	0.080	0.12	0.17	0.016	0.39	21.	97.	1.3
V693 CrA	1981	10	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66	35.	148.	1.2
V1370 Aql	1982	13	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86	45.	296.	0.36
V1370 Aql	1982	10	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86	45.	296.	0.48
GQ Mus	1983	14	0.37	0.39	0.0081	0.13	0.095	0.0023	0.0039	0.2 4	13.	1.2	38.
PW Vul	1984	15	0.69	0.25	0.0033	0.049	0.014	0.00066	...	0.067	3.5	0.38	100.
PW Vul	1984	10	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30	16.	2.3	34.
PW Vul	1984	16	0.617	0.247	0.018	0.069	0.0443	0.001	0.0027	0.14	7.7	1.	31.
QU Vul	1984	17	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10	5.3	23.	1.3
QU Vul	1984	10	0.33	0.26	0.0095	0.074	0.17	0.086	0.063	0.40	21.	49.	1.7
QU Vul	1984	18	0.36	0.19	...	0.071	0.19	0.18	0.0014	0.44	23.	100.	1.4
V842 Cen	1986	10	0.41	0.23	0.12	0.21	0.030	0.00090	0.0038	0.36	19.	0.51	77.
V827 Her	1987	10	0.36	0.29	0.087	0.24	0.016	0.00066	0.0021	0.35	18.	0.38	124.
QV Vul	1987	10	0.68	0.27	...	0.010	0.041	0.00099	0.00096	0.053	2.8	0.56	26.
V2214 Oph	1988	10	0.34	0.26	...	0.31	0.060	0.017	0.015	0.40	21.	9.7	12.
V977 Sco	1989	10	0.51	0.39	...	0.042	0.030	0.026	0.0027	0.10	5.3	15.	2.5
V433 Sct	1989	10	0.49	0.45	...	0.053	0.0070	0.00014	0.0017	0.062	3.3	0.80	33.
V351 Pup	1991	19	0.37	0.25	0.0056	0.076	0.19	0.11	...	0.38	20.	63.	2.4
V1974 Cyg	1992	18	0.19	0.32	...	0.085	0.29	0.11	0.0051	0.49	27.	68.	3.2
V1974 Cyg	1992	20	0.30	0.52	0.015	0.023	0.10	0.037	0.075	0.18	9.7	21.	3.1
V838 Her	1991	11	0.60	0.31	0.012	0.012	0.004	0.056	...	0.09	0.11	31.	...

REFERENCES.—(1) Grevesse & Anders 1989; (2) Gallagher et al. 1980; (3) Williams & Gallagher 1979; (4) Williams et al. 1978; (5) Petitjean et al. 1990; (6) Tylenda 1978; (7) Ferland & Shields 1978b; (8) Lance et al. 1988; (9) Stickland et al. 1981; (10) Andreä et al. 1994; (11) Vanlandingham et al. 1997; (12) Williams et al. 1985; (13) Snijders et al. 1987; (14) Morisset & Péquignot 1996; (15) Saizar et al. 1991; (16) Schwarz et al. 1997c; (17) Saizar et al. 1992; (18) Austin et al. 1996; (19) Saizar et al. 1996; (20) Hayward et al. 1996.

H mildly depleted

He/H mildly enhanced

CNO enhanced

Some have very large Ne

Gehrz et al (2002)

Some issues

- Burning is not violent enough to give fast novae unless the accreted layer is significantly enriched with CNO prior to or early during the runaway.

  Shear mixing during accretion

  Convective "undershoot" during burst

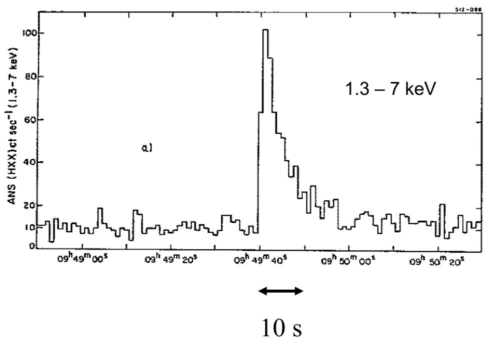
- CO vs NeO white dwarf

- Making ^{15}N and ^{17}O

- Relation to Type Ia supernovae. How to grow M_{WD} when models suggest it is actually shrinking?

Type I X-Ray Bursts

First **X-ray burst**: 3U 1820-30 (Grindlay et al. 1976) with ANS (Astronomical Netherlands Satellite)



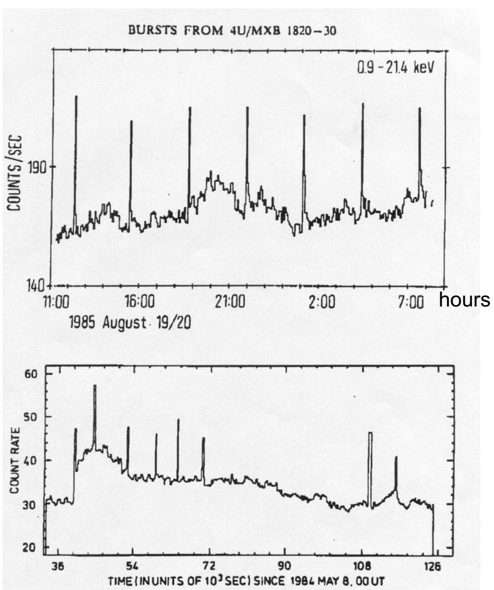


Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820–303 (from Haberl et al. 1987). (b) Irregular burst recurrence, observed from 1636–536 (from Sztajno et al. 1985).

Typical X-ray bursts:

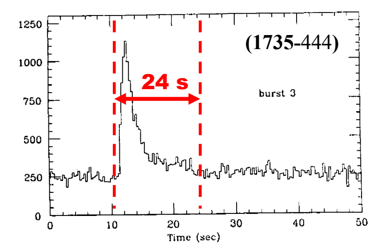
- recurrence: hours-days
- regular or irregular

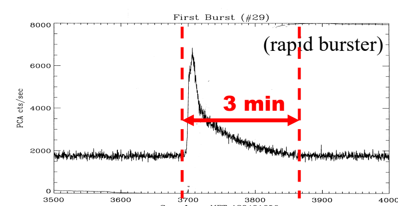
Frequent and very bright phenomenon !

Type I X-Ray Bursts

(e.g., Strohmayer & Bildsten 2003)

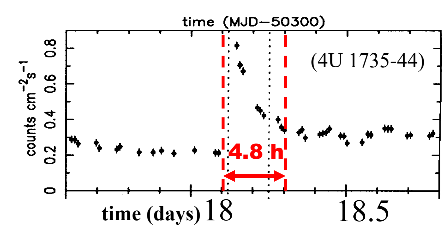
- Burst rise times < 1 s to 10 s
- Burst duration 10's of seconds to minutes (some much longer "superbursts")
- Occur in low mass x-ray binaries
- Persistent luminosity from <0.01 Eddington to 0.2 Eddington (i.e., 10^{36}- 10^{38} erg s^{-1})
- Spectrum softens as burst proceeds. Spectrum thermal. A cooling blackbody
- L_{peak} < 4 x 10^{38} erg s^{-1}. i.e., about Eddington. Evidence for radius expansion in some bursts. T initially 3 keV, decreases to 0.5 keV, then gets hotter again.





Normal type I bursts:

- duration 10-100 s
- ~10^{39} erg



Superbursts:

(discovered 2001, so far 24 seen – Keek et al (2015))

- ~10^{43} erg
- rare (every 3.5 yr ?)

- Of 13 known luminous globular cluster x-ray sources, 12 show x-ray bursts. Over 70 total X-ray bursters were known in 2002.
- Distances 4 – 12 kpc. Two discovered in M31 (Pietsch and Haberl, *A&A,* **430**, L45 (2005).
- Low B-field < $10^{8\text{-}9}$ gauss
- Rapid rotation (at break up? due to accretion?). In transition to becoming ms pulsars?
- Very little mass lost (based upon models). Unimportant to nucleosynthesis

- Back-of-the envelope calculation:

$E_{burst} \sim 10^{39}$ erg;
$E_{nuclear} \sim 1$ MeV/nucleon
($\sim 10^{18}$ erg/g)
$\Rightarrow$ fuel $\Delta M \sim 10^{21}$ g;
for $\dot{M} \sim 10^{-10}$ to 10^{-9} $M_\odot$/yr
$\Rightarrow t_{recur} \sim$ hrs–days

But 1 MeV/nucleon << BE at edge of neutron star (~200 MeV/nucleon)

X-ray burst theory predicts three regimes of burning:

1) intermediate accretion rates;
$2 \times 10^{-10}\, M_\odot\, yr^{-1} \lesssim \dot{M} \lesssim 4\text{–}11 \times 10^{-10}\, M_\odot\, yr^{-1}$:
pure He shell ignition after steady H burning

2) high accretion rates;
$4\text{–}11 \times 10^{-10}\, M_\odot\, yr^{-1} \lesssim \dot{M} \lesssim 2 \times 10^{-8}\, M_\odot\, yr^{-1}$:
mixed H/He burning triggered by thermally unstable He ignition

3) Accretion rates near Eddington ~ few x 10^{-9}
carbon fusion powered superbursts. Rare.

During pure helium flashes the fuel is burned rapidly; they last only ~5-30 s

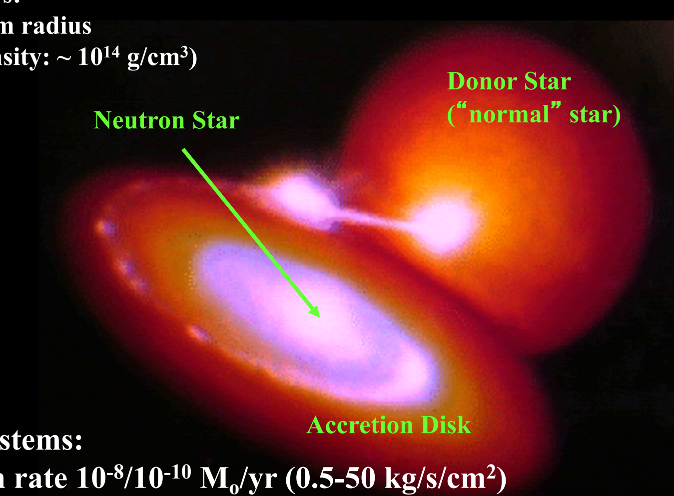
Bursts with unstable mixed H/He burning release their energies on a longer, 10–100 s, timescale, due to the long series of β decays in the rp-process

Superbursts last ~ 1000 s

The Model

Woosley and Taam (1976)

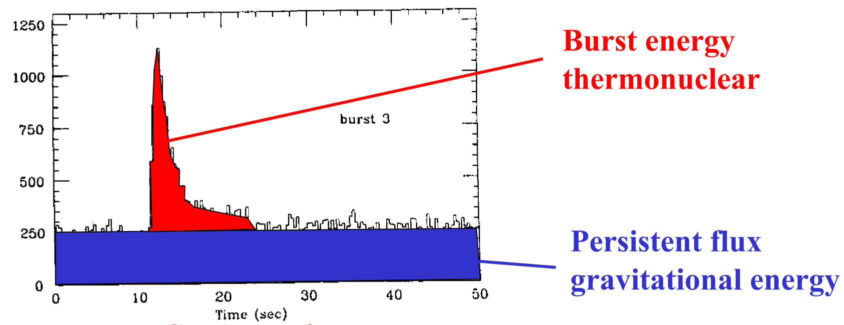
Neutron stars:
1.4 M_o, 10 km radius
(average density: ~ 10^{14} g/cm^3)



Typical systems:
- **accretion rate $10^{-8}/10^{-10}$ M_o/yr (0.5-50 kg/s/cm^2)**
- **orbital periods 0.01-100 days**
- **orbital separations 0.001-1 AU's**

Observation of thermonuclear energy:

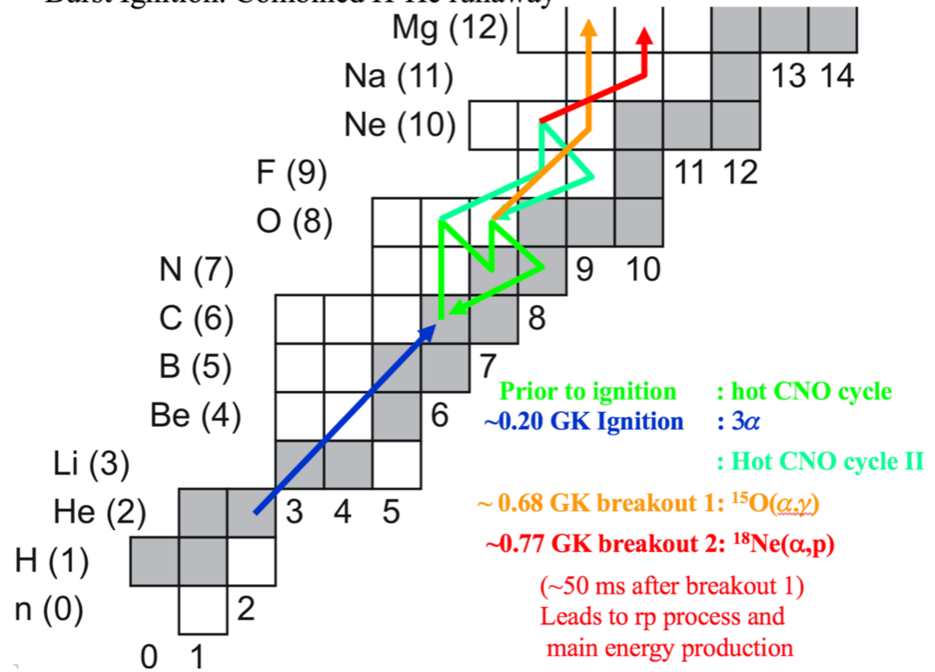
Unstable, explosive burning in bursts (release over short time)



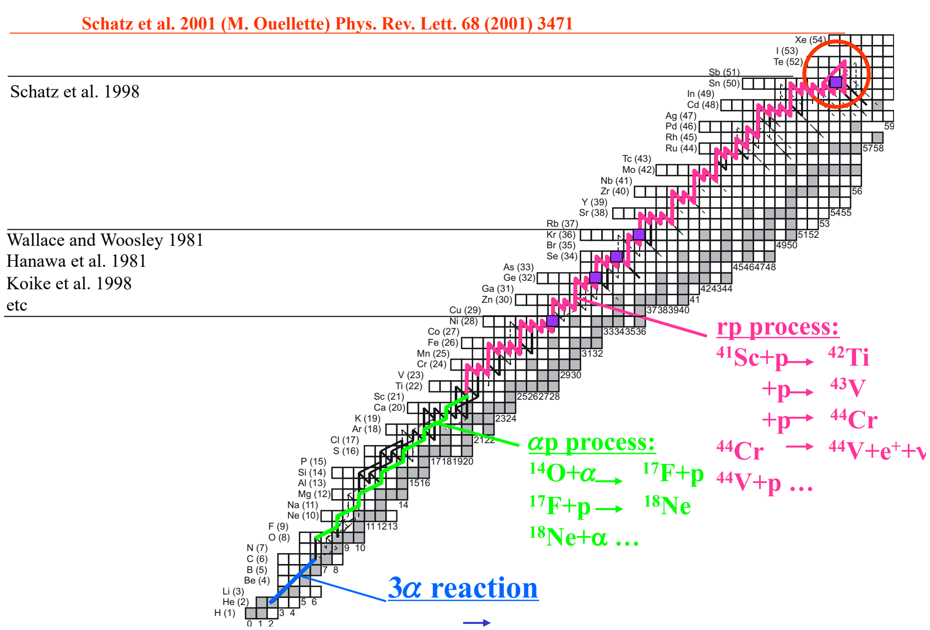
$$\frac{\textit{Gravitational energy}}{\textit{Nuclear energy}} \sim 30-40$$

Very little matter if any is ejected by
a x-ray burst. Nucleosynthetically sterile.

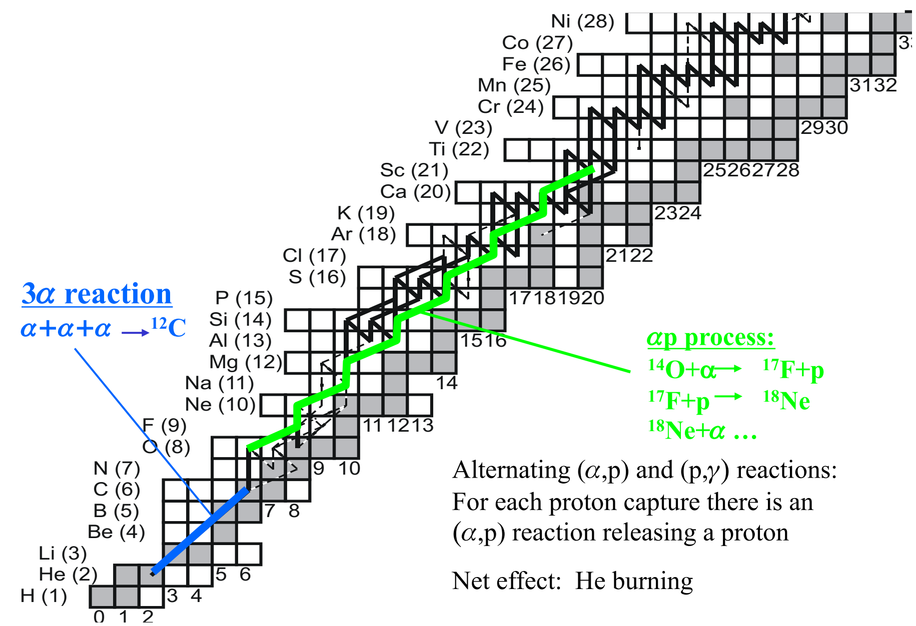
Burst Ignition: Combined H-He runaway



Models: Typical reaction flows



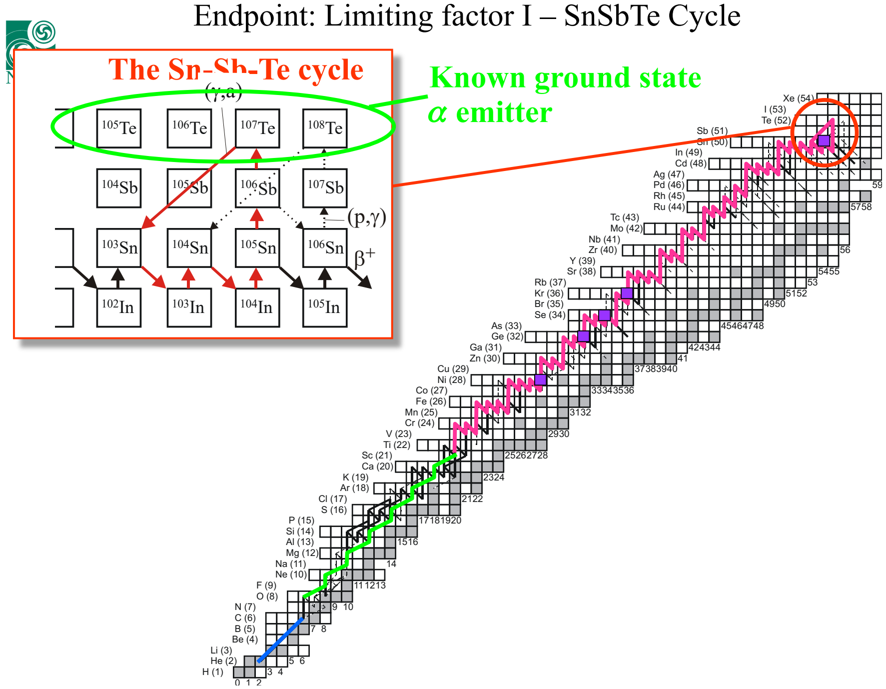
At still higher T: αp process

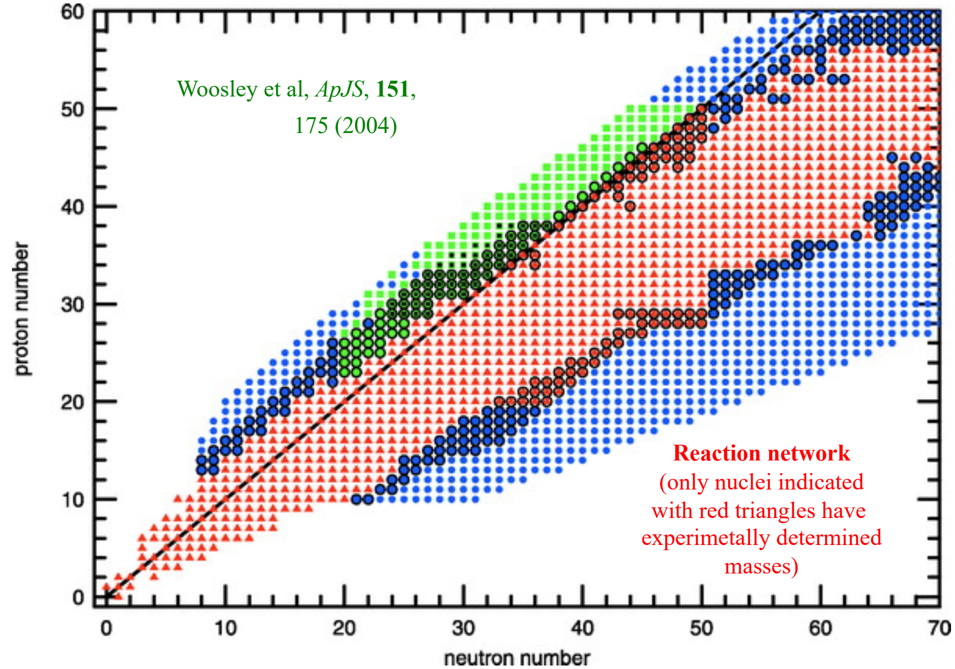


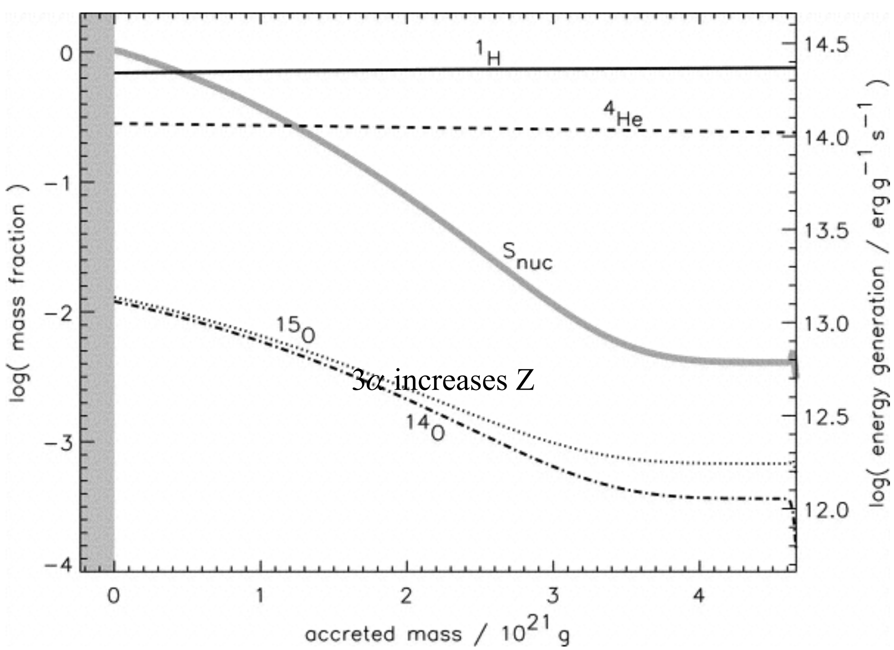
Alternating (α,p) and (p,γ) reactions:
For each proton capture there is an
(α,p) reaction releasing a proton

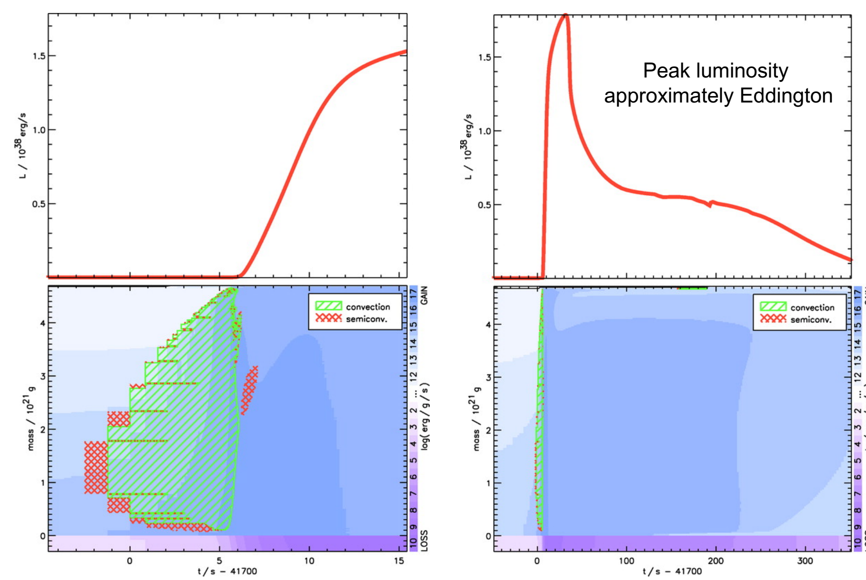
Net effect: He burning

Endpoint: Limiting factor I – SnSbTe Cycle

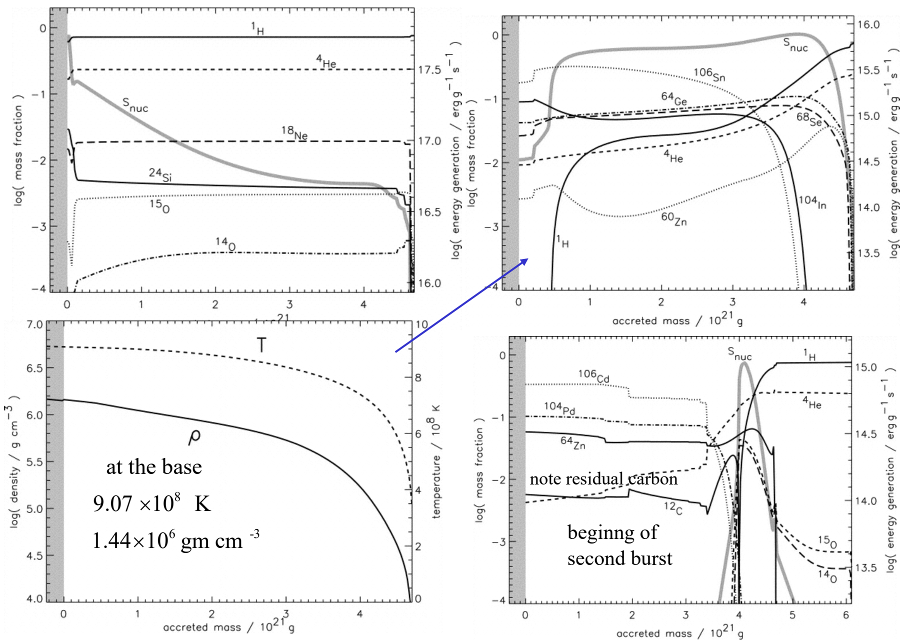


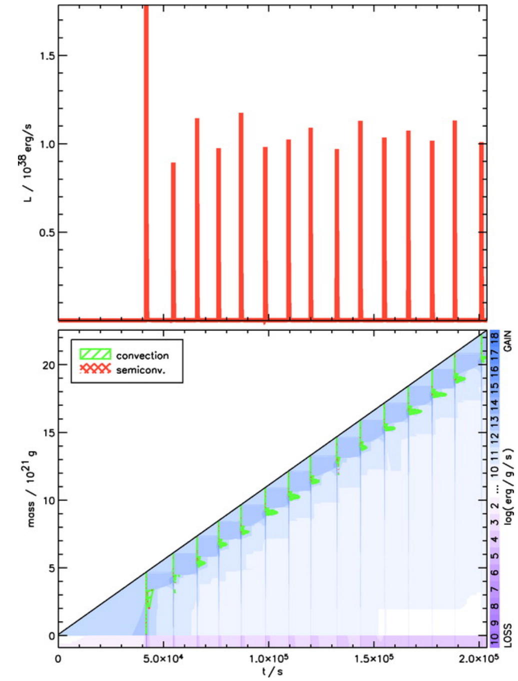






Times offset by 41,700 s of accretion at 1.75 x 10^{-9} solar masses/yr



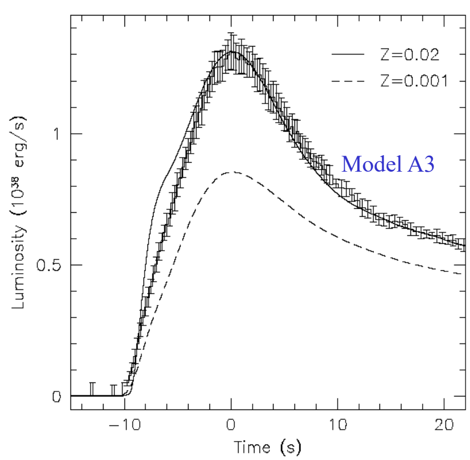


Fourteen consecutive flashes at about a 4 hours interval.

The first is a start up transient.

$$\dot{M} = 1.75\times10^{-9}\ M_\odot\ yr^{-1}$$

$$Z = Z_\odot / 20$$



GS 1826-24

Heger, Cumming, Gallaoway and Woosley (2005)

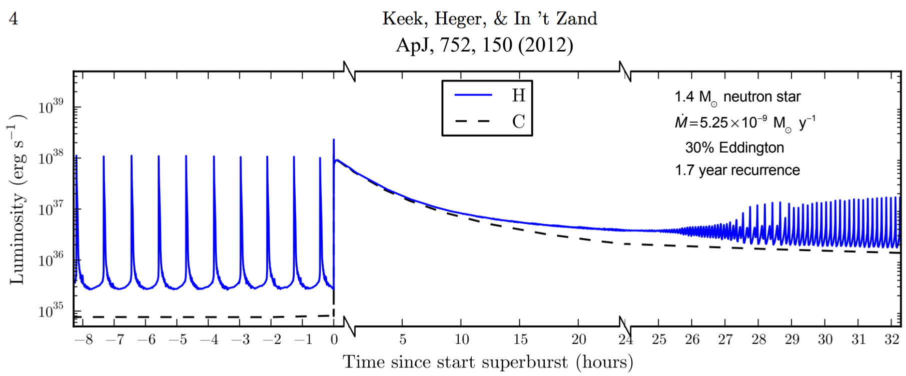
TABLE 1. AVERAGE BURST PROPERTIES[a]

Model	Z	$\dot{M}$ ($10^{-9}\ M_\odot\ yr^{-1}$)	Δt (h)	E_{burst} (10^{39} ergs)	α	ΔM (10^{21} g)
A1	0.02	1.17	5.4	4.52	60	1.15
A2	0.02	1.43	4.3	4.55	57	1.11
A3	0.02	1.58	3.9	4.61	55	1.10
A4	0.02	1.75	3.4	4.64	54	1.08

Current Issues:

- Superbursts
- Detailed comparison with an accumulating wealth of observational data, especially time histories of multiple bursts and the effects of thermal inertia
- Large volume of uncertain, yet important reaction rates (FRIB)
- Multi-D models with B fields and rotation – spreading of the burning
- Can XRB's be used to obtain neutron star radii, crustal structure, and/or distances

"Superbursts"



About 2 dozen superbursts have been observed. They are thought to be produced by carbon runaways as predicted by Woosley and Taam (1976). The fine structure in the above simulation has not yet been observed

Recent 2D simulations from Chris Malone using MAESTRO

http://www.astro.sunysb.edu/cmalone/research/pure_he4_xrb/index.html

XRB models by Alex Heger et al.

http://2sn.org/xrb/movie/