Surface Hydrogen-Burning Modeling of Super Soft X-ray Binaries AND Pulsations of Hot, Luminous White Dwarfs:

Possible SN Ia Progenitors ?

Sumner Starrfield, ASU

KITP_ UCSB : May 2005

Collaborators:

Frank Timmes: LANL

Raph Hix: UTK and ORNL

Ed Sion: Villanova

Warren Sparks: LANL

Peter Hauschildt: Hamburg

There is
High Speed
Calcium,
Silicon,
And
Magnesium
Observed
Early in
The Spectral
Evolution.

Is it already
present in the
outer layers or
produced
by the shock?

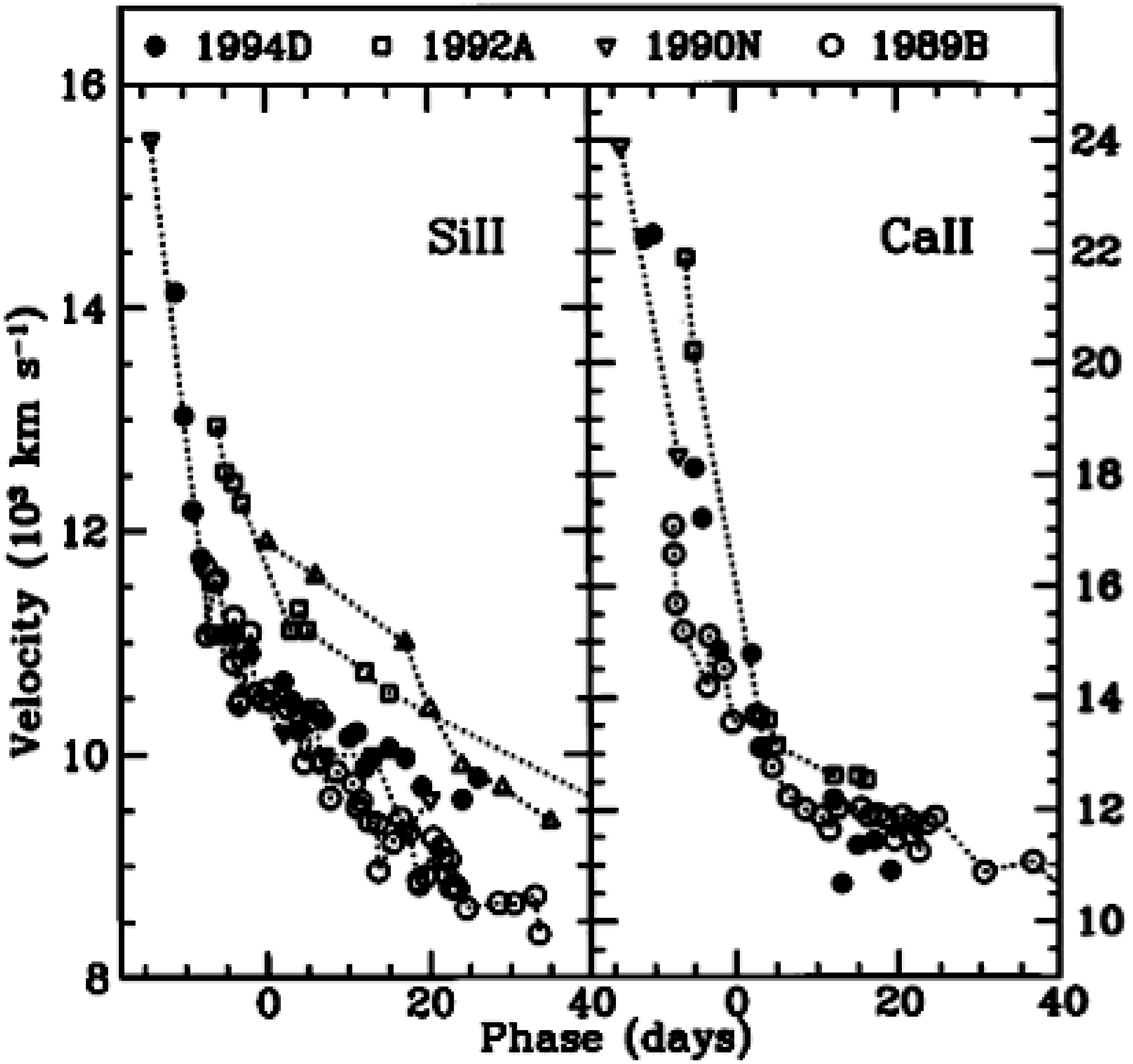


Figure 5 Evolution of the expansion velocity as deduced from the minima of the Si II λ6355 (*left panel*) and Ca II H&K (*right panel*) absorption troughs for SNe Ia 1994D, 1992A, 1990N, 1989B, and 1981B. From Patat et al (1996); reproduced with permission.

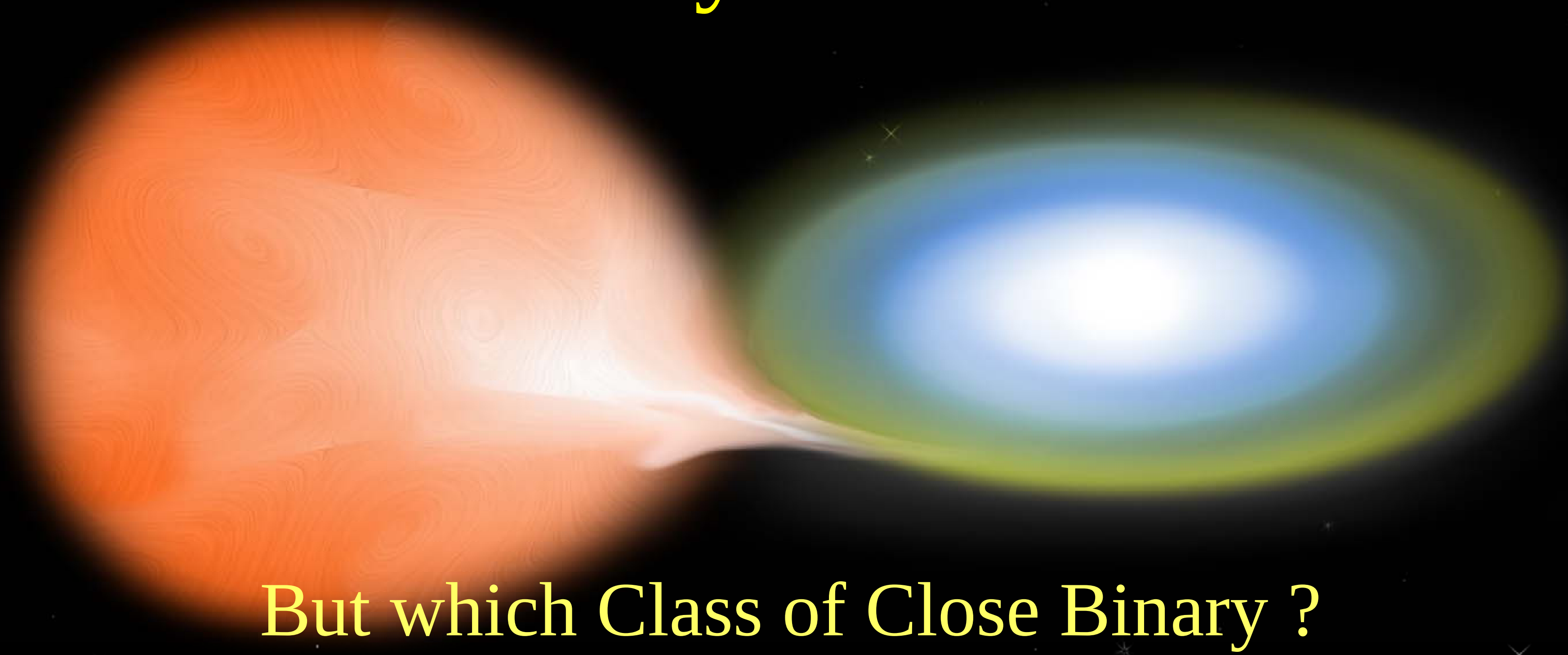
Filippenko 1997

The Defining Property of a SN Ia is:

There is NO evidence for
Hydrogen
or Helium
in the Ejecta.

SN Ia are Thought to Occur on the WD Component of a Close Binary Stellar System

(Whelan and Iben 1973)



But which Class of Close Binary ?

and

How do we get rid of the hydrogen and helium?

Chandrasekhar Mass Models:

- Only a TNR in a Chandrasekhar Mass (~$1.4M_{\odot}$) Carbon-Oxygen White Dwarf (WD) can match the observations.
- Stellar theory predicts a CO WD forms with $M_* < 1.2\ M_{\odot}$
- Need accretion from a binary companion to grow the WD to the Chandrasekhar mass.
- Classical, Recurrent, Symbiotic or Dwarf Novae have all been proposed
- Unless the secondary has a strange composition (double degenerate systems, for example) it is transferring H and He.

HOW DO WE GET RID OF THE H and He?

- PROPOSAL: By thermonuclear burning in the surface layers while they are accreting material.
- Steady Burning: H burns to He as fast as it accretes
- But Steady Burning predicts that it works for only one mass accretion rate for a given WD mass
- About 3 x 10^{-7} $M_{\odot}$ yr^{-1} for a 1.35 $M_{\odot}$ WD (van den Heuvel et al.)
- Steady burning has not been tested with evolution codes.

THE NOVA CODE:

- Lagrangian, fully implicit, 1-D hydro
- Radiation transport by diffusion
- OPAL opacities plus Iben fit
- EOS: Timmes et al. (get from his web site)
- Time dependent, mixing-length, convection
- Elements mixed by diffusion in convective region
- 34 nuclei reaction network from Timmes (web site)
- Accretion via a fast rezoning algorithm
- Boundary layer heating (not important for WDs)

The Initial Models:

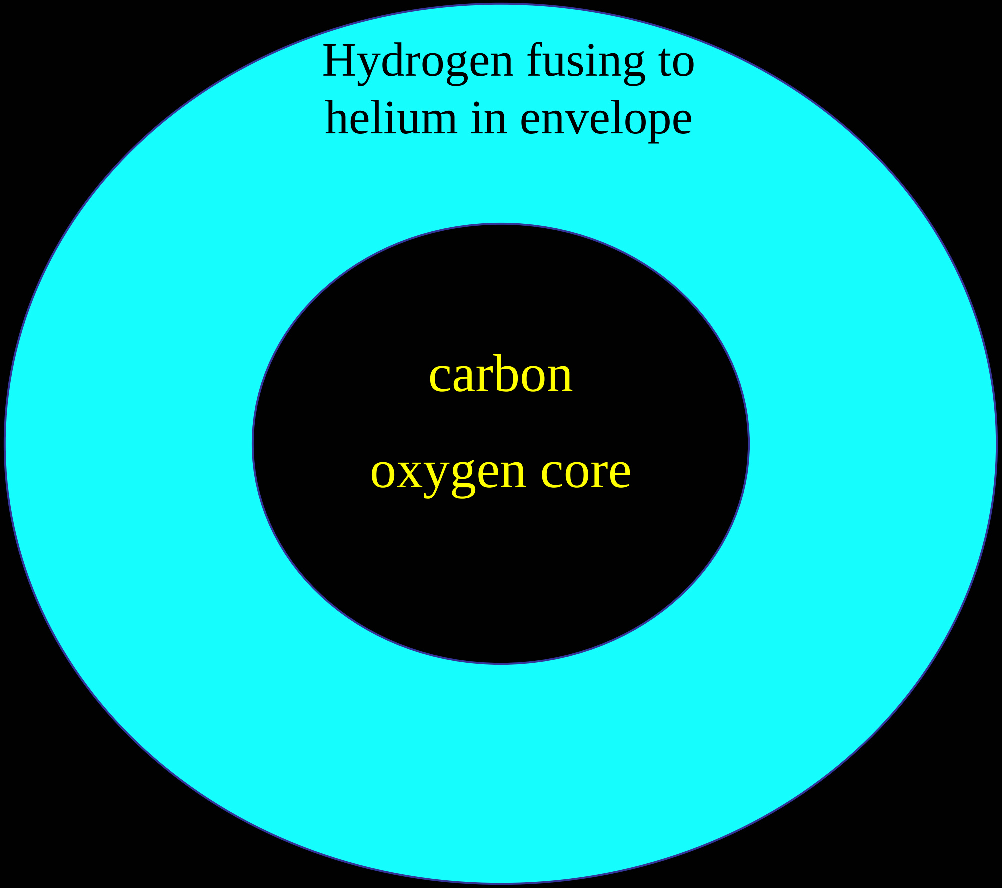
1) Evolve a simulation through three nova outbursts
2) Assume matter expanding faster than escape speed is "ejected" when radius exceeds 10^{13}cm and optically thin.
3) Allow to cool until luminosity is 30 $L_{\odot}$ (~3 years after outburst: Nova Cyg 92).
4) Start accreting and assume no mixing with core (accreting gas has either solar or LMC metallicity)

5) Include accretion, compression, and thermonuclear energy.

6) Nuclear energy far exceeds accretion energy for a WD (opposite for a neutron star)

7) Evolve $1.25M_{\odot}$ and $1.35M_{\odot}$ WDs at many mass accretion rates

“Steady” Burning White Dwarf Composition:


Hydrogen fusing to
helium in envelope

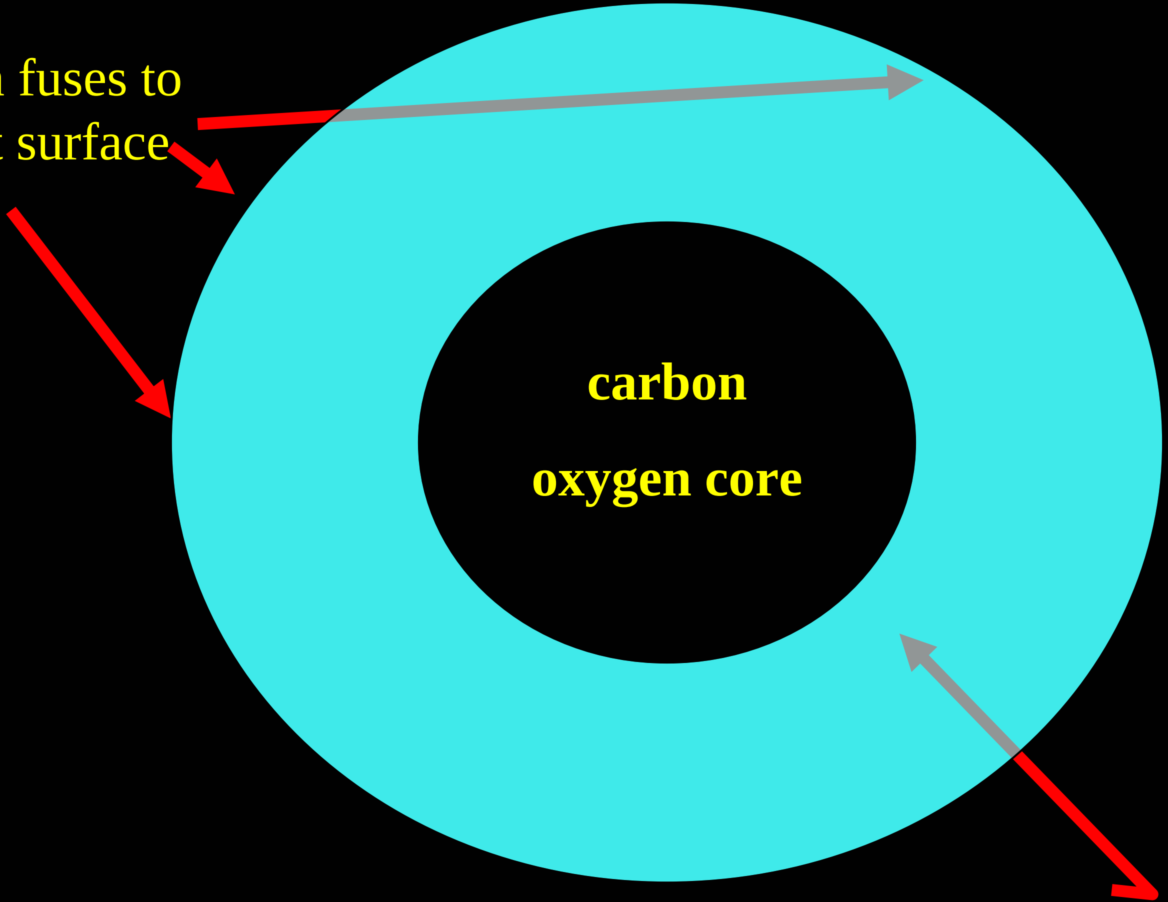
carbon

oxygen core

Works for only 1 mass accretion rate: ~3 x 10^{-7} $M_\odot$ /yr

What We Find:

Surface Hydrogen Burning White Dwarf Composition:



Hydrogen fuses to
helium at surface

carbon

oxygen core

helium fuses to
carbon, oxygen
and more
massive nuclei
below the
surface

TABLE 1

1.35 $M_\odot$ HOT WD EVOLUTIONARY SEQUENCES[a]

PARAMETER	SEQUENCE 1[b]	2	3	4	5
$\dot{M}$ ($M_\odot$ yr^{-1})	1.6×10^{-9}	1.6×10^{-8}	1.6×10^{-7}	3.5×10^{-7}	8.0×10^{-7}
$\tau_{\rm evol}$ (yr)	8.3×10^{5}	2.2×10^{5}	1.3×10^{5}	3.8×10^{4}	4.8×10^{4}
$\delta M_{\rm acc}$ ($M_\odot$)	1.3×10^{-3}	3.5×10^{-3}	2.1×10^{-2}	1.3×10^{-2}	3.8×10^{-2}
$T_{\rm ss}$ (10^6 K)	114	177	319	347	516
$\epsilon_{\rm ss}$ (10^8 ergs g^{-1} s^{-1})	0.15	1.5	16.6	36.8	91.0
$L_{\rm SHB}$ (ergs s^{-1})	5.4×10^{35}	5.9×10^{36}	6.3×10^{37}	1.4×10^{38}	3.6×10^{38}
$T_{\rm eff}$ (K)	3.6×10^{5}	6.6×10^{5}	1.2×10^{6}	1.4×10^{6}	2.0×10^{6}
$T_{\rm eff}$ (eV)	32	57	107	125	175
^{1}H (CI)	0.0	0.0	0.0	0.0	0.0
^{4}He (CI)	<0.01	0.0	0.0	0.0	0.0
^{12}C (CI)	0.11	0.45	0.31	0.22	0.06
^{13}C (CI)	0.01	0.05	0.13	0.14	0.12
^{14}N (CI)	0.02	0.35	0.13	0.10	0.06
^{16}O (CI)	0.01	0.15	0.42	0.49	0.07
$A > 19$ (CI)	0.77	<0.01	<0.01	<0.01	0.60

[a] The initial model for all evolutionary sequences had $M_{\rm WD} = 1.35\ M_\odot$, $L_{\rm WD} = 30\ L_\odot$, $T_{\rm eff} = 2.3 \times 10^5$ K, and $R_{\rm WD} = 2391$ km.

[b] Sequence 1 experienced a helium TNR in which the temperature exceeded 7×10^8 K.

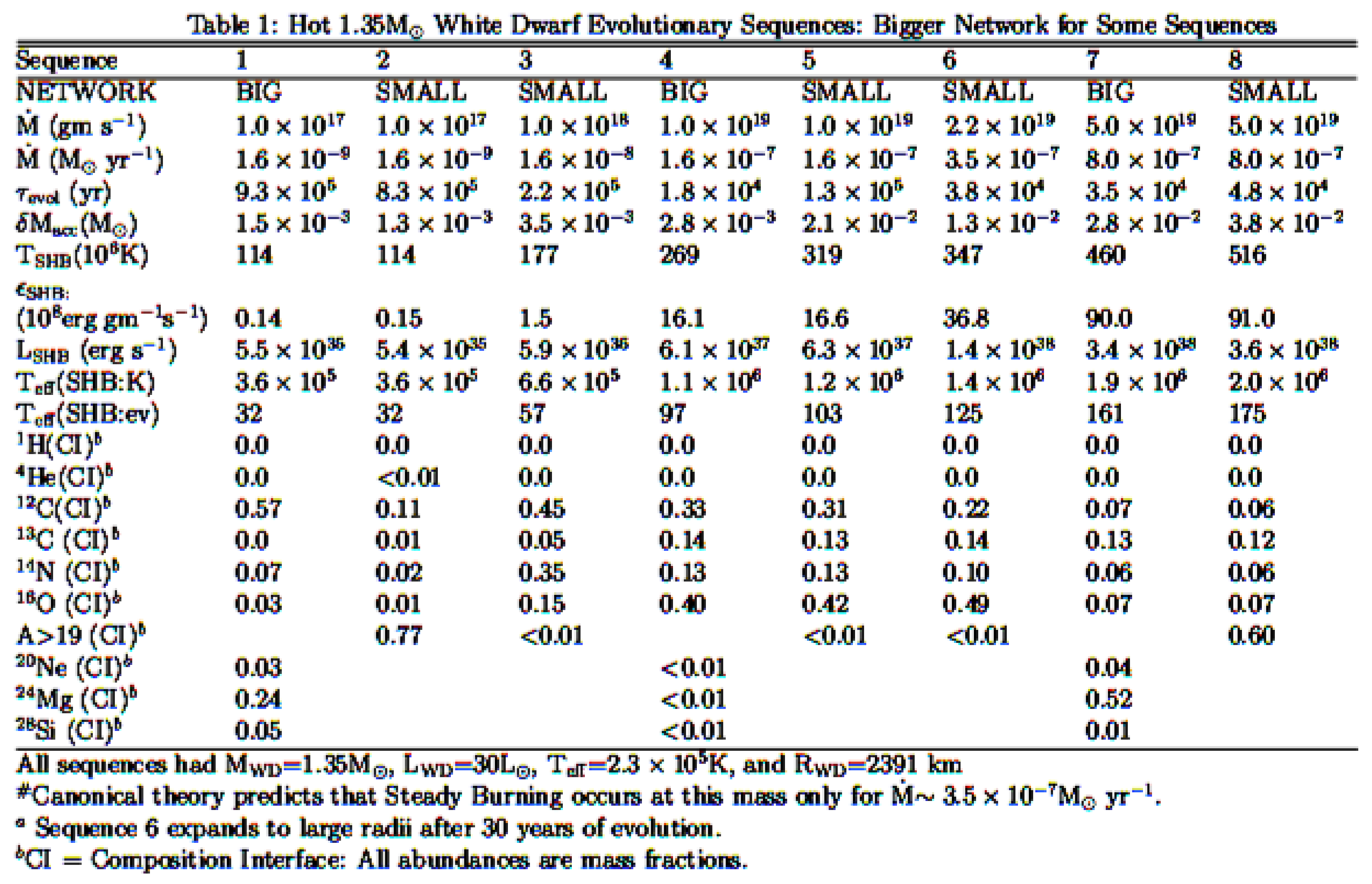


Table 1: Hot $1.35M_\odot$ White Dwarf Evolutionary Sequences: Bigger Network for Some Sequences

Sequence	1	2	3	4	5	6	7	8
NETWORK	BIG	SMALL	SMALL	BIG	SMALL	SMALL	BIG	SMALL
$\dot{M}$ (gm s^{-1})	1.0×10^{17}	1.0×10^{17}	1.0×10^{18}	1.0×10^{19}	1.0×10^{19}	2.2×10^{19}	5.0×10^{19}	5.0×10^{19}
$\dot{M}$ ($M_\odot$ yr^{-1})	1.6×10^{-9}	1.6×10^{-9}	1.6×10^{-8}	1.6×10^{-7}	1.6×10^{-7}	3.5×10^{-7}	8.0×10^{-7}	8.0×10^{-7}
τ_{evol} (yr)	9.3×10^{5}	8.3×10^{5}	2.2×10^{5}	1.8×10^{4}	1.3×10^{5}	3.8×10^{4}	3.5×10^{4}	4.8×10^{4}
$\delta M_{acc}(M_\odot)$	1.5×10^{-3}	1.3×10^{-3}	3.5×10^{-3}	2.8×10^{-3}	2.1×10^{-2}	1.3×10^{-2}	2.8×10^{-2}	3.8×10^{-2}
$T_{SHB}(10^6K)$	114	114	177	269	319	347	460	516
ϵ_{SHB}: (10^8erg $gm^{-1}s^{-1}$)	0.14	0.15	1.5	16.1	16.6	36.8	90.0	91.0
L_{SHB} (erg s^{-1})	5.5×10^{36}	5.4×10^{35}	5.9×10^{36}	6.1×10^{37}	6.3×10^{37}	1.4×10^{38}	3.4×10^{38}	3.6×10^{38}
T_{eff}(SHB:K)	3.6×10^{5}	3.6×10^{5}	6.6×10^{5}	1.1×10^{6}	1.2×10^{6}	1.4×10^{6}	1.9×10^{6}	2.0×10^{6}
T_{eff}(SHB:ev)	32	32	57	97	103	125	161	175
^{1}H(CI)^b	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
^{4}He(CI)^b	0.0	<0.01	0.0	0.0	0.0	0.0	0.0	0.0
^{12}C(CI)^b	0.57	0.11	0.45	0.33	0.31	0.22	0.07	0.06
^{13}C (CI)^b	0.0	0.01	0.05	0.14	0.13	0.14	0.13	0.12
^{14}N (CI)^b	0.07	0.02	0.35	0.13	0.13	0.10	0.06	0.06
^{16}O (CI)^b	0.03	0.01	0.15	0.40	0.42	0.49	0.07	0.07
A>19 (CI)^b		0.77	<0.01		<0.01	<0.01		0.60
^{20}Ne (CI)^b	0.03			<0.01			0.04	
^{24}Mg (CI)^b	0.24			<0.01			0.52	
^{28}Si (CI)^b	0.05			<0.01			0.01	

All sequences had $M_{WD}=1.35M_\odot$, $L_{WD}=30L_\odot$, $T_{eff}=2.3 \times 10^5$K, and $R_{WD}=2391$ km

[#] Canonical theory predicts that Steady Burning occurs at this mass only for $\dot{M} \sim 3.5 \times 10^{-7} M_\odot$ yr^{-1}.

[a] Sequence 6 expands to large radii after 30 years of evolution.

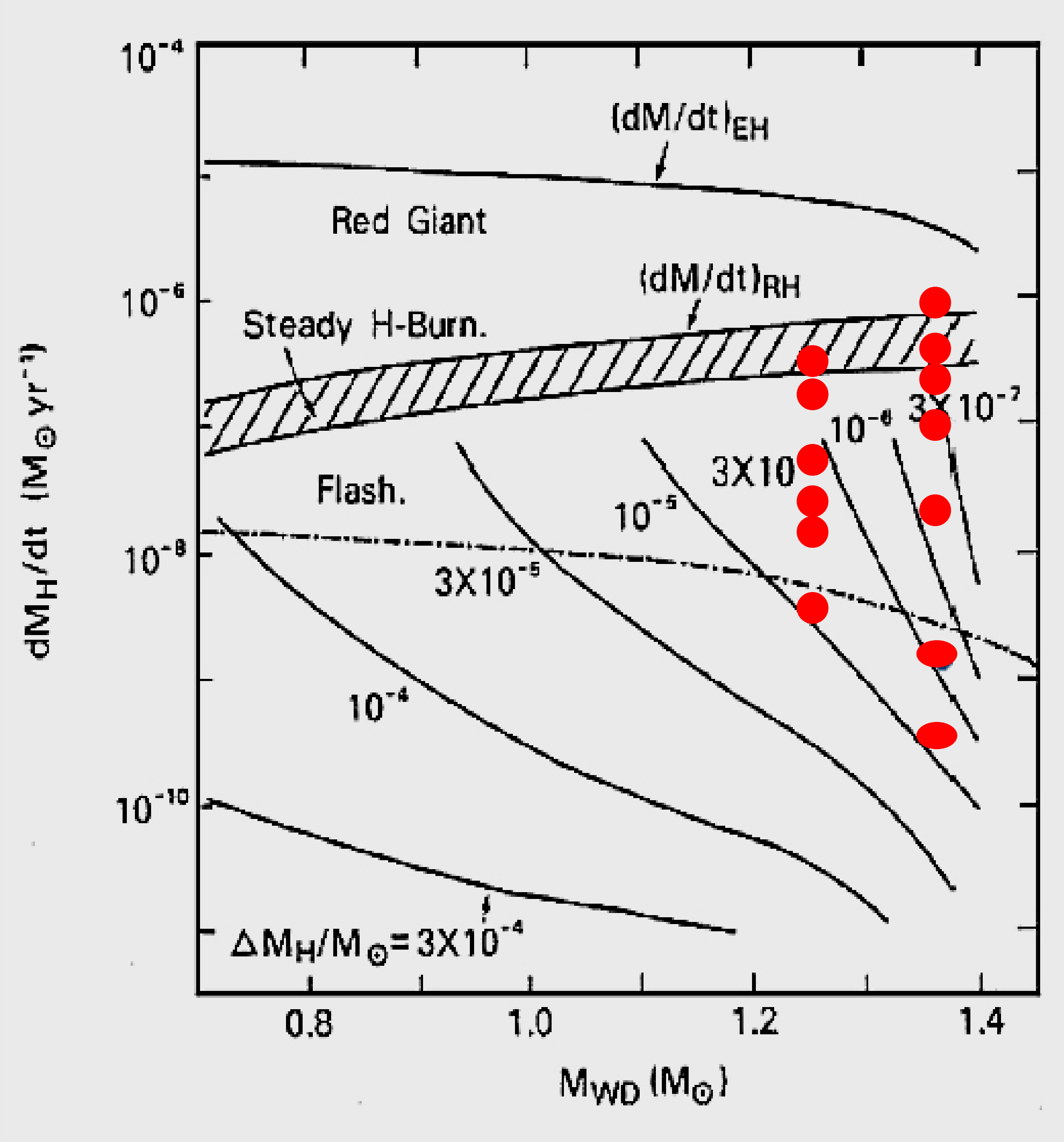
[b] CI = Composition Interface: All abundances are mass fractions.

RESULTS:

- We start with a bare CO core
- For surface zone (sz) mass ~ $10^{-5}M_\odot$
- After 15 yrs of evolution, $T_{sz} = 3 \times 10^8$K
- H burns to He in less than the time step ~ 10^6 sec
- Some of the He is already burning to Carbon in surface zone
- He mass fraction declines to zero somewhat deeper into WD
- Have accreted ~ $3 \times 10^{-2}M_\odot$ and WD mass reached $1.38M_\odot$

- For finer mass zoning: sz ~ $10^{-7}M_\odot$
- Hydrogen reaches to a depth of ~ $10^{-6}M_\odot$
- But it takes 95,000 time steps to go ~70 years

We have expanded the range of mass accretion rates where complete burning of Hydrogen and Helium occurs in the surface layers



Our Simulations resemble the Super Soft X-ray Binaries:

Discovered as soft X-ray sources in Rosat Survey of LMC

1. Later Realized that CAL 83 and CAL 87 were also SSS
2. Typical luminosities ~ 10^{37} erg/sec
3. Typical temperatures about: 3 – 7 x 10^5 K
4. "Close Binaries" with orbital periods (hours to days)
5. Spectra show jets (how much mass is lost is unknown)
6. WDs accreting at high rates with ongoing nuclear burning near surface and no TNR ("Steady Burning").
    1. Proposed by van den Heuvel et al. 1992;
    2. See also: Kahabka and van den Heuvel, ARAA, 1997
7. Assumed rates: a few times 10^{-7} $M_{\odot}$/yr

Table 1 Summary of all known luminous supersoft X-ray sources[a]

Name	Count rate (cts/s)	T (eV)	L_{bol} (erg/s)	Type	Period	Ref.[b]
LMC						
RX J0439.8-6809	1.35	21–27 (wd)	$0.6\text{–}1.5 \times 10^{37}$	CV	3.37 h	1–4
RX J0513.9-6951	<0.06–2.0	34–54 (wd)	$1.2\text{–}4.8 \times 10^{37}$	CBSS	18.3 h	2, 5–10
RX J0527.8-6954	0.004–0.25	27–68 (wd)	$0.038\text{–}3.0 \times 10^{37}$	CBSS?		2, 7, 11–15
RX J0537.6-7034	0.02	18–30 (bb)	$0.6\text{–}2 \times 10^{37}$			16–17
CAL 83	0.98	34–54 (wd)	$0.38\text{–}4.8 \times 10^{37}$	CBSS	1.04 day	12, 18–19
CAL 87	0.09	68–86 (wd)	$1.2\text{–}9.5 \times 10^{37}$	CBSS	10.6 h	18–22
RX J0550.0-7151	<0.02–0.9	25–40 (bb)				2, 7
SMC						
1E0035.4-7230	0.33	34–54 (wd)	$0.38\text{–}1.2 \times 10^{37}$	CV	4.1 h	23–25
RX J0048.4-7332	0.19	25–45 (wd)	$0.48\text{–}1.2 \times 10^{37}$	Sy-N		22, 26–29
RX J0058.6-7146	<0.001–0.7	15–70 (bb)	2×10^{36}			22
1E0056.8-7154	0.29	27–43 (wd)	$1.5\text{–}3.8 \times 10^{37}$	PN		30
Milky Way						
RX J0019.8+2156	2.0	21–27 (wd)	$3\text{–}9 \times 10^{36}$	CBSS	15.8 h	43–45
RX J0925.7-4758	1.0	70–100 (wd)	$3\text{–}7 \times 10^{35}$	CBSS	3.8 day	40–42
Nova 1983 Mus	0.1	25–35 (bb)	$1\text{–}2 \times 10^{38}$	CV-N	85 min	31, 32–36
1E 1339.8+2837	0.01–1.1	20–45 (bb)	$0.12\text{–}10 \times 10^{35}$			46–47
AG Dra	1.0	10–15 (bb)	1.4×10^{36}	Sy	554 day	49–50
RR Tel	0.18	14 (wd)	1.3×10^{37}	Sy-N	387 day	29, 48
Nova V1974 Cygni	0.03–76		2×10^{38}	CV-N	1.95 h	38, 39
M31						
a. RX J0037.4+4015	0.3×10^{-3}	43 (bb)				51
b. RX J0038.5+4014	0.8×10^{-3}	45 (bb)				51
c. RX J0038.6+4020	1.7×10^{-3}	43 (bb)				51

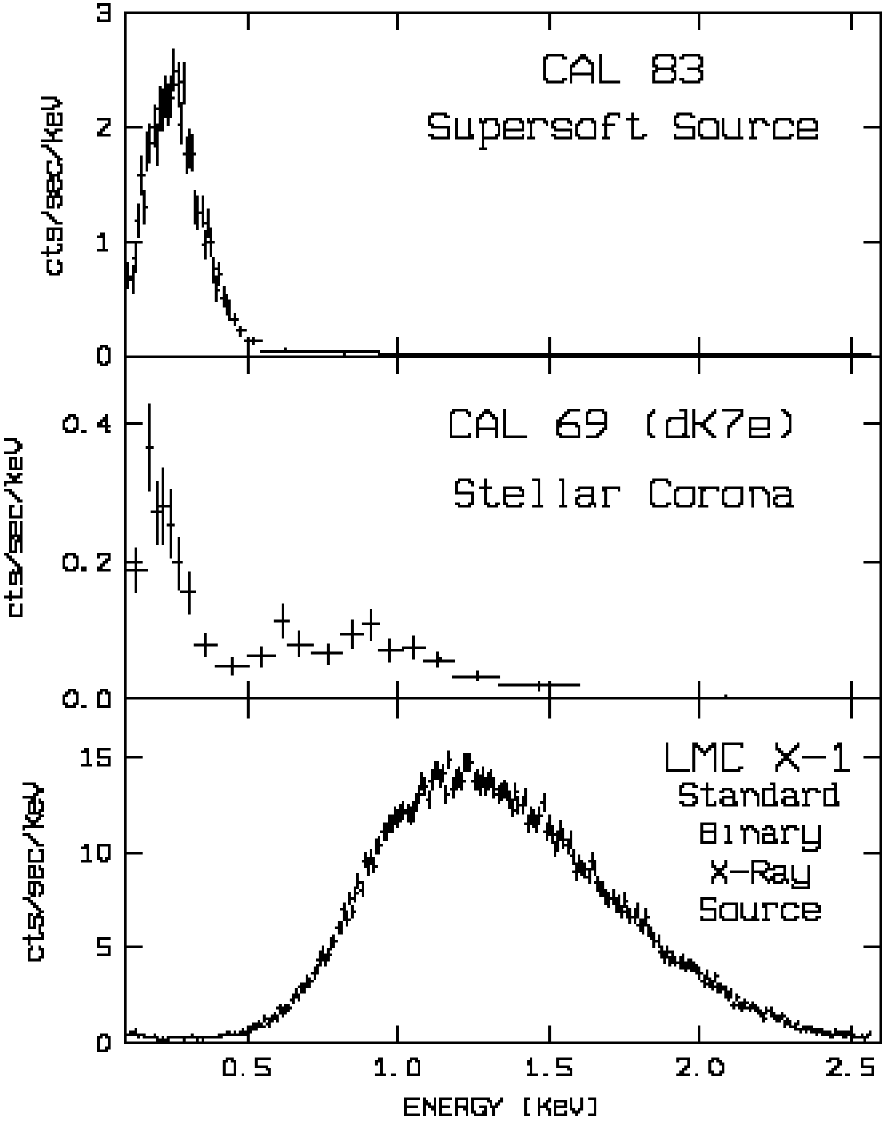


Figure 1 ROSAT PSPC count spectra of three objects in the Large Magellanic Cloud (LMC) field: the SSS CAL 83, the dK7e foreground star CAL 69, and the black hole candidate LMC X-1 (similar to Figure 2 of Trümper et al 1991)

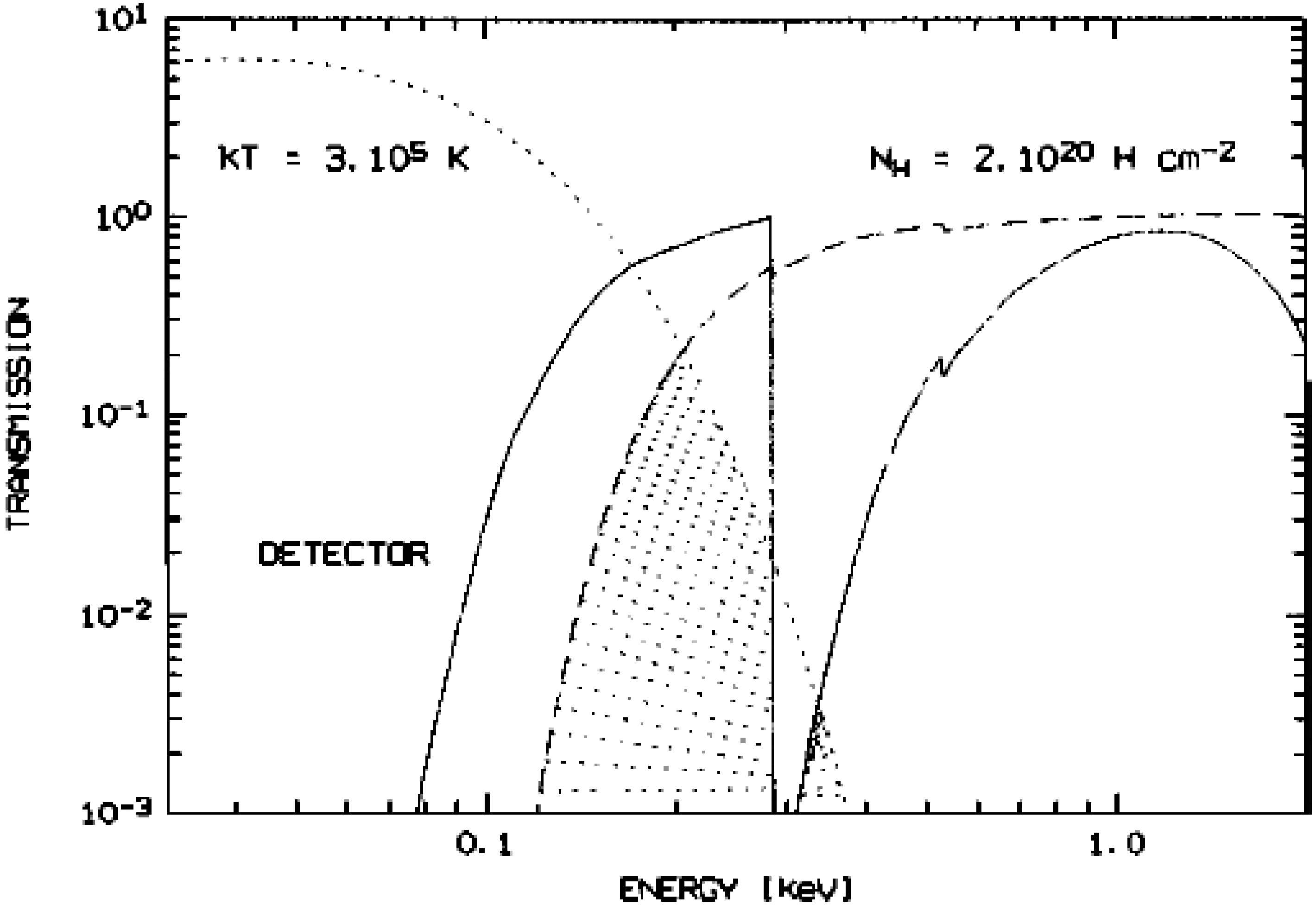
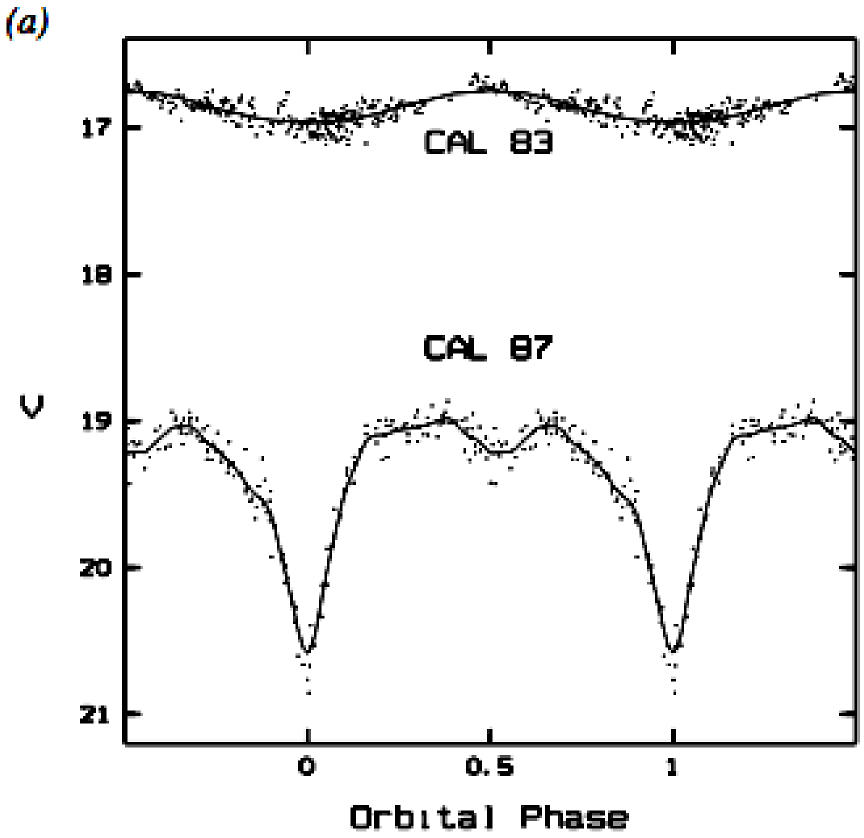
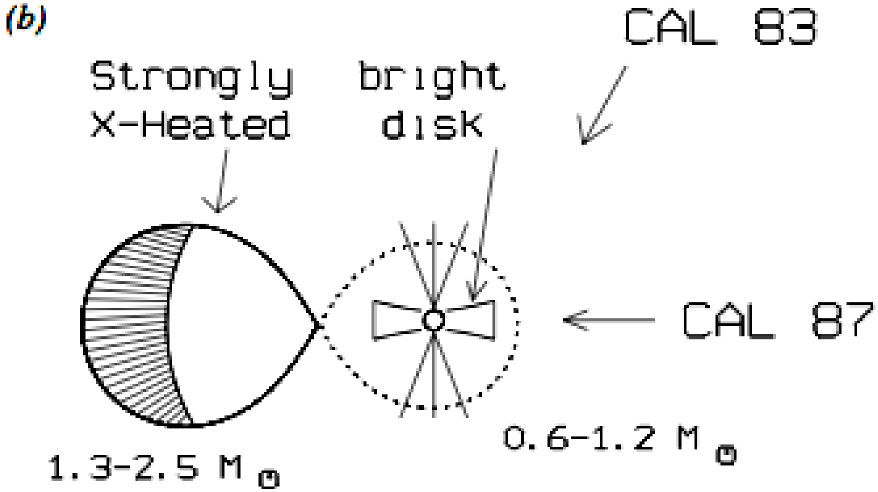
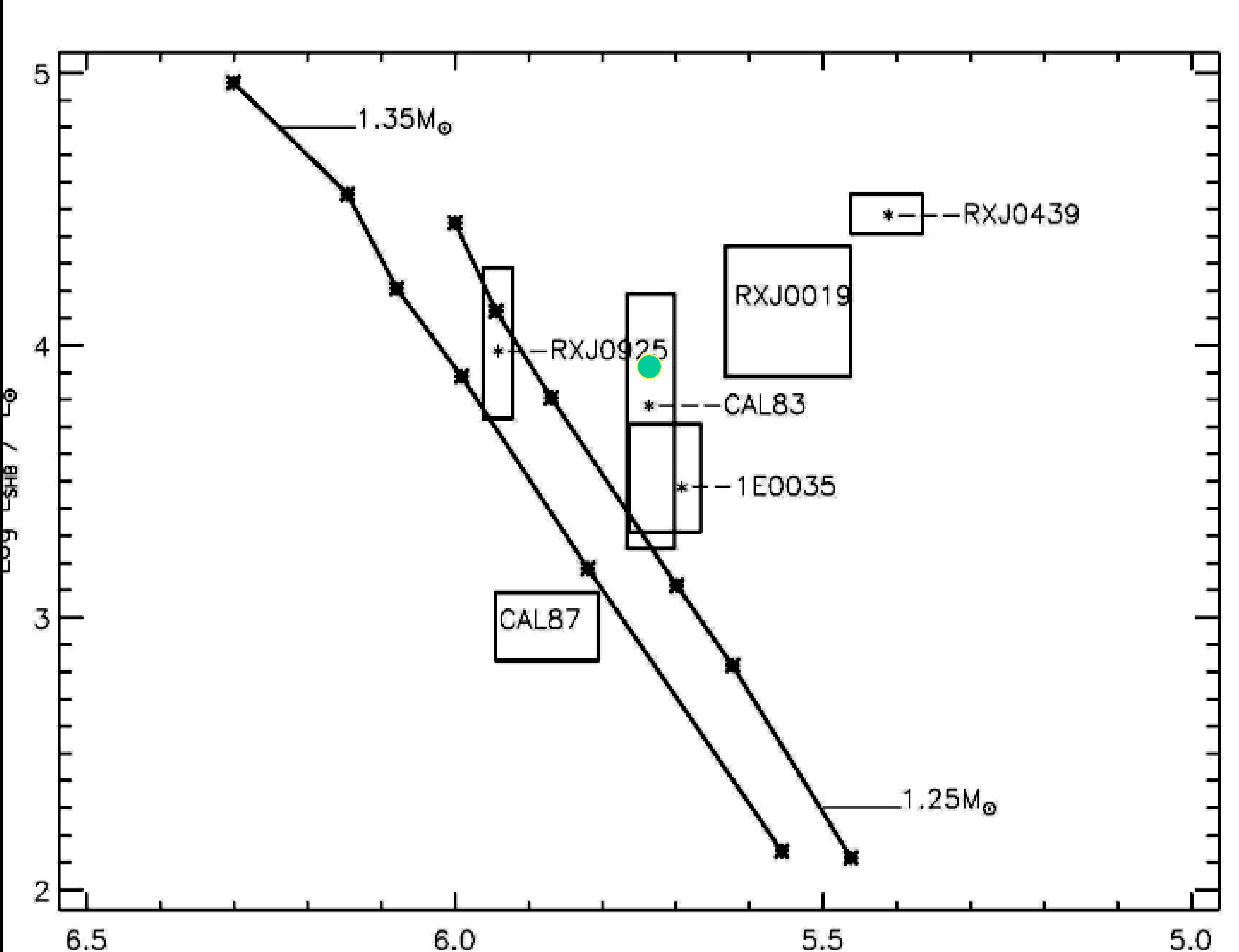


Figure 2 ROSAT PSPC efficiency (*solid curve*), transmission of ISM for hydrogen column of 2.10^{20} H atoms cm^{-2} (*dashed line*), distribution of a 3.10^5-K blackbody spectrum (*dotted line*) and folded (observed) distribution (*hatch marks*) (SA Rappaport, private communication).


(a)
CAL 83
CAL 87
V
17
18
19
20
21
0
0.5
1
Orbital Phase

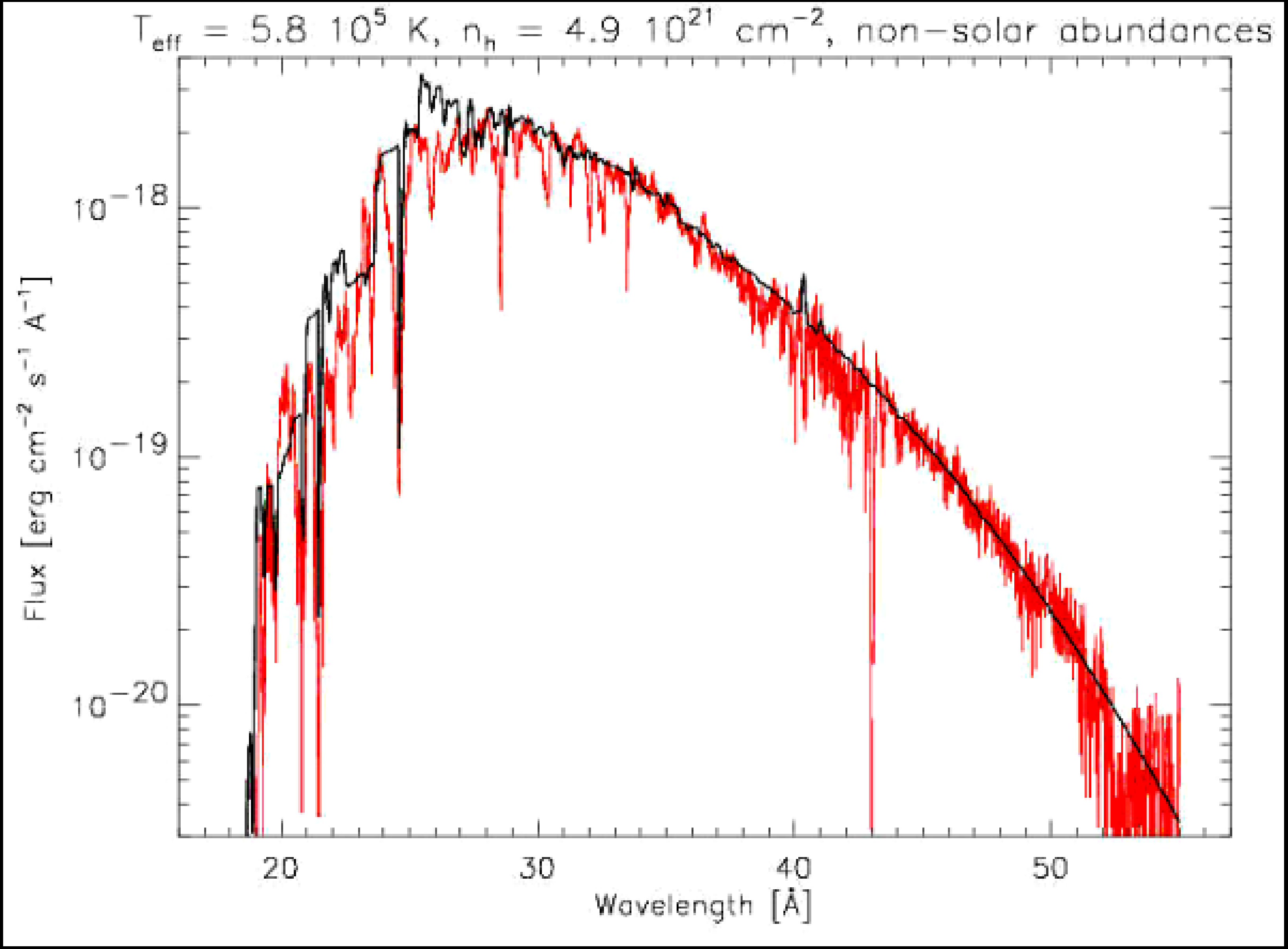

(b)
CAL 83
Strongly X-Heated
bright disk
CAL 87
1.3–2.5 $M_\odot$
0.6–1.2 $M_\odot$



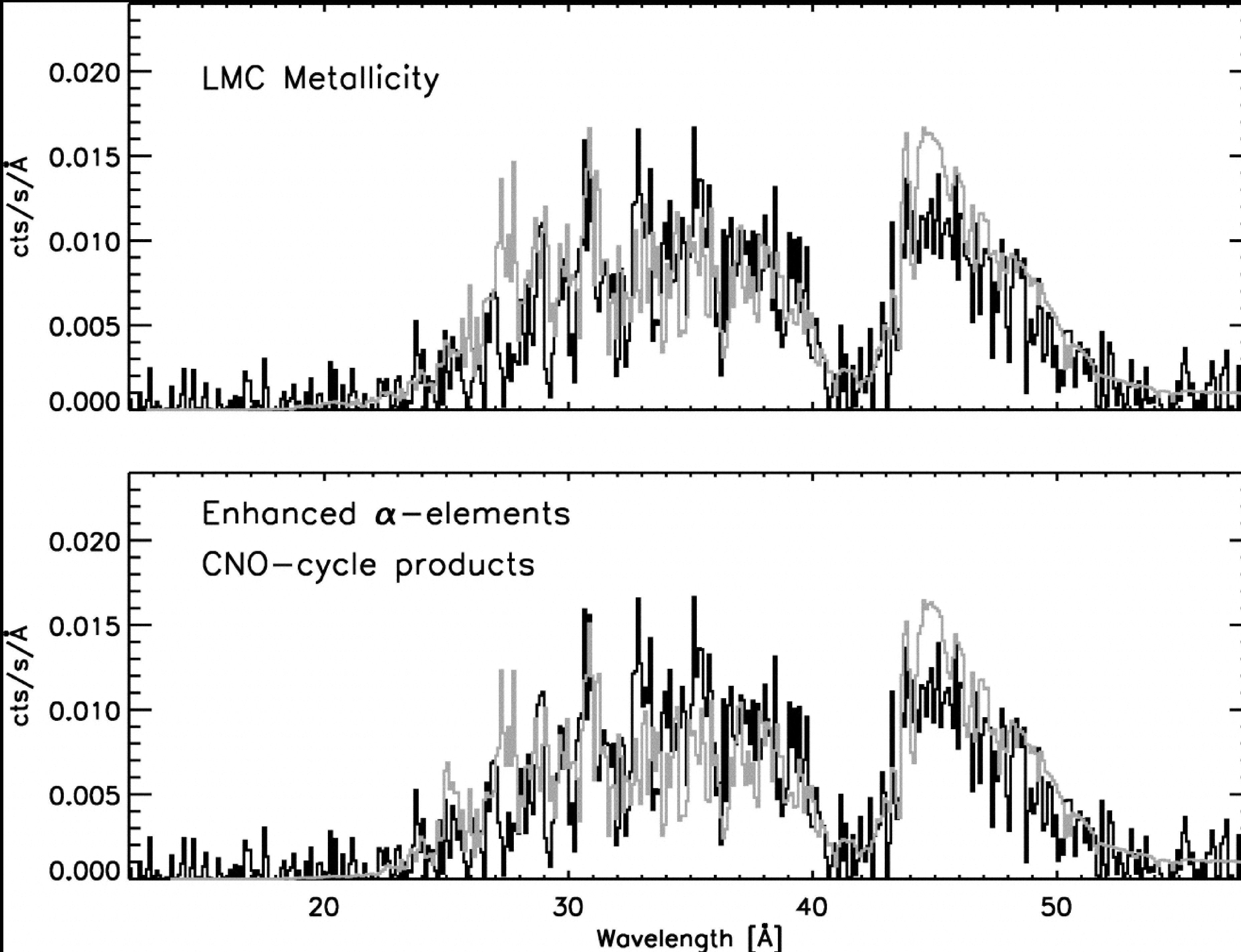
Log $L / L_{\odot}$

Log T_{eff}

Stellar Atmosphere fit to X-ray Spectrum:



More Sophisticated and Enriched C, N, O -- Petz et al. 2005


LMC Metallicity
Enhanced α−elements
CNO−cycle products
cts/s/Å
0.000
0.005
0.010
0.015
0.020
20
30
40
50
Wavelength [Å]

Parameter	Value
Effective temperature, T_{eff}...	$5.5 \pm 0.25\ 10^5$ K
Surface gravity, log g...	8.5 ± 0.1 (cgs)
WD radius, R_{WD}...	$0.01 \pm 0.001\ R_\odot$
WD luminosity, L_{WD}...	$9 \pm 3\ 10^3\ L_\odot$
WD mass, M_{WD}...	$1.3 \pm 0.3\ M_\odot$

Table 1: Hot 1.35$M_\odot$ White Dwarf Evolutionary Sequences: Effect of Metallicity

Sequence	1	2	3	4	5	6	7	8	9
Network	Big	Big	Small	Big	Big	Small	Big	Big	Big
Composition	Solar	LMC	Solar	Solar	LMC	Solar	LMC	Solar	LMC
$\dot{M}$ (gm s^{-1})	1.0×10^{17}	1.0×10^{18}	1.0×10^{18}	1.0×10^{19}	1.0×10^{19}	2.2×10^{19}	2.2×10^{19}	5.0×10^{19}	5.0×10^{19}
$\dot{M}$ ($M_\odot$ yr^{-1})	1.6×10^{-9}	1.6×10^{-8}	1.6×10^{-8}	1.6×10^{-7}	1.6×10^{-7}	3.5×10^{-7}	3.5×10^{-7}	8.0×10^{-7}	8.0×10^{-7}
τ_{evol} (yr)	9.3×10^{5}	7.8×10^{4}	2.2×10^{5}	1.8×10^{4}	2.7×10^{4}	3.8×10^{4}	2.7×10^{4}	3.5×10^{4}	3.6×10^{4}
δM_{acc}($M_\odot$)	1.5×10^{-3}	1.2×10^{-3}	3.5×10^{-3}	2.8×10^{-3}	4.3×10^{-3}	1.3×10^{-2}	9.5×10^{-3}	2.8×10^{-2}	2.8×10^{-2}
T_{SHB}(10^6K)	114	174	177	269	275	347	333	460	460
ϵ_{SHB}:									
(10^8erg gm^{-1}s^{-1})	0.14	1.5	1.5	16.1	16.2	36.8	37.1	90.0	89.0
L_{SHB} (erg s^{-1})	5.5×10^{35}	6.0×10^{36}	5.9×10^{36}	6.1×10^{37}	6.1×10^{37}	1.4×10^{38}	1.4×10^{38}	3.4×10^{38}	3.4×10^{38}
T_{eff}(SHB:K)	3.6×10^{5}	6.5×10^{5}	6.6×10^{5}	1.1×10^{6}	1.2×10^{6}	1.4×10^{6}	1.4×10^{6}	1.9×10^{6}	1.9×10^{6}
T_{eff}(SHB:ev)	32	56	57	97	99	125	122	161	162
^{1}H(CI)^{b}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
^{4}He(CI)^{b}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
^{12}C(CI)^{b}	0.57	0.45	0.45	0.33	0.31	0.22	0.17	0.07	0.06
^{13}C (CI)^{b}	0.0	0.05	0.05	0.14	0.14	0.14	0.13	0.13	0.13
^{14}N (CI)^{b}	0.07	0.35	0.35	0.13	0.12	0.10	0.08	0.06	0.06
^{16}O (CI)^{b}	0.03	0.15	0.15	0.40	0.41	0.49	0.46	0.07	0.07
A>19 (CI)^{b}			<0.01			<0.01			
^{20}Ne (CI)^{b}	0.03	<0.01		<0.01	<0.01		0.07	0.04	0.04
^{24}Mg (CI)^{b}	0.24	<0.01		<0.01	<0.01		0.07	0.52	0.54
^{28}Si (CI)^{b}	0.05	<0.01		<0.01	<0.01		<0.01	0.01	0.01

All sequences had M_{WD}=1.35$M_\odot$, L_{WD}=30$L_\odot$, T_{eff}=2.3 × 10^5K, and R_{WD}=2391 km

[#] Canonical theory predicts that Steady Burning occurs at this mass only for $\dot{M} \sim 3.5 \times 10^{-7} M_\odot$ yr^{-1}.

[a] Sequence 6 expands to large radii after 30 years of evolution.

[b] CI = Composition Interface: All abundances are mass fractions.

Table 1: Results of the Hot 1.25$M_\odot$ White Dwarf Evolutionary Sequences

Sequence	1	$2^\dagger$	$3^\dagger$	4	5	$6^\#$	$7^\dagger$	$8^\%$
Mass ($M_\odot$)	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
L(init)(erg s^{-1})	1.1×10^{35}	1.1×10^{35}	1.1×10^{35}	1.1×10^{35}	1.1×10^{35}	1.1×10^{35}	1.1×10^{35}	1.1×10^{35}
$T_{\rm eff}$K (init)	1.8×10^5	1.8×10^5	1.8×10^5	1.8×10^5	1.8×10^5	1.8×10^5	1.8×10^5	1.8×10^5
R (km)	3745	3745	3745	3745	3745	3745	3745	3745
$\dot{M}$ (gm s^{-1})	1.0×10^{17}	5.0×10^{17}	1.0×10^{18}	5.0×10^{18}	1.0×10^{19}	1.9×10^{19}	5.0×10^{19}	1.0×10^{20}
$\dot{M}$ ($M_\odot$ yr^{-1})	1.6×10^{-9}	8.0×10^{-9}	1.6×10^{-8}	8.0×10^{-8}	1.6×10^{-7}	3.0×10^{-7}	8.0×10^{-7}	1.6×10^{-6}
$\tau_{\rm evol}$ (yr)	9.1×10^5	9.4×10^4	1.0×10^5	6.9×10^4	5.8×10^4	2.9×10^4	4.0×10^3	25
$\delta M_{\rm acc}$($M_\odot$)	1.4×10^{-3}	7.4×10^{-4}	1.7×10^{-43}	5.5×10^{-3}	9.2×10^{-3}	8.9×10^{-3}	3.2×10^{-3}	4.0×10^{-5}
$T_{\rm SHB}$(10^6K)	79	102	114	156	182	190	169	230
$\epsilon_{\rm nuc}$(SHB:) 10^8erg gm^{-1}s^{-1})	.2	.8	1.6	7.8	15.6	29.6	78.	~30.
$L_{\rm SHB}$ (erg s^{-1})	5.1×10^{35}	2.6×10^{36}	5.1×10^{36}	2.5×10^{37}	5.2×10^{37}	1.1×10^{38}	$1.1 \times 10^{38} V^b$	$\sim 3 \times 10^{38}$
$L_{\rm acc}$ (erg s^{-1})	4×10^{34}	2×10^{35}	4×10^{35}	2×10^{36}	4×10^{36}	8×10^{36}	2×10^{37}	4×10^{37}
$T_{\rm eff}$(SHB:K)	2.9×10^5	4.2×10^5	5.0×10^5	7.4×10^5	8.8×10^5	1.0×10^6	$5.8 \times 10^3 V$	$\sim 5 \times 10^5$
$T_{\rm eff}$(SHB:ev)	25	36	423	64	76	86	95V	~43
^{1}H(CI)^a	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
^{4}He(CI)^a	0.98	0.0	0.0	0.0	0.0	0.0	0.0	
^{12}C(CI)^a	<0.01	0.71	0.65	0.56	0.50	0.58	0.69	
^{14}N (CI)^a	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
^{16}O (CI)^a	<0.01	0.07	0.10	0.11	0.28	0.39	0.38	
A>19 (CI)^a	<0.01	0.20	0.24	0.32	0.21	0.02	<0.01	

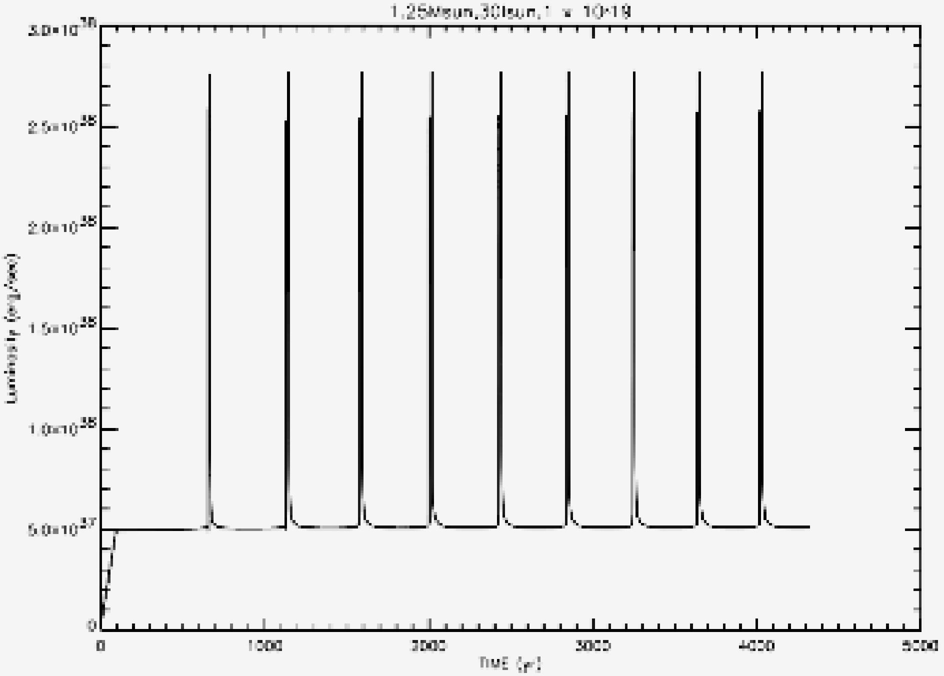
† Sequences 2,3, and 7 underwent helium runaways at the evolution time listed in the table. Only a small fraction of accreted material ($\sim 10^{-5} M_\odot$) was ejected.

$^\#$ Canonical theory predicts that Steady Burning occurs at this mass only for $\dot{M} \sim 3 \times 10^{-7} M_\odot$ yr^{-1}.

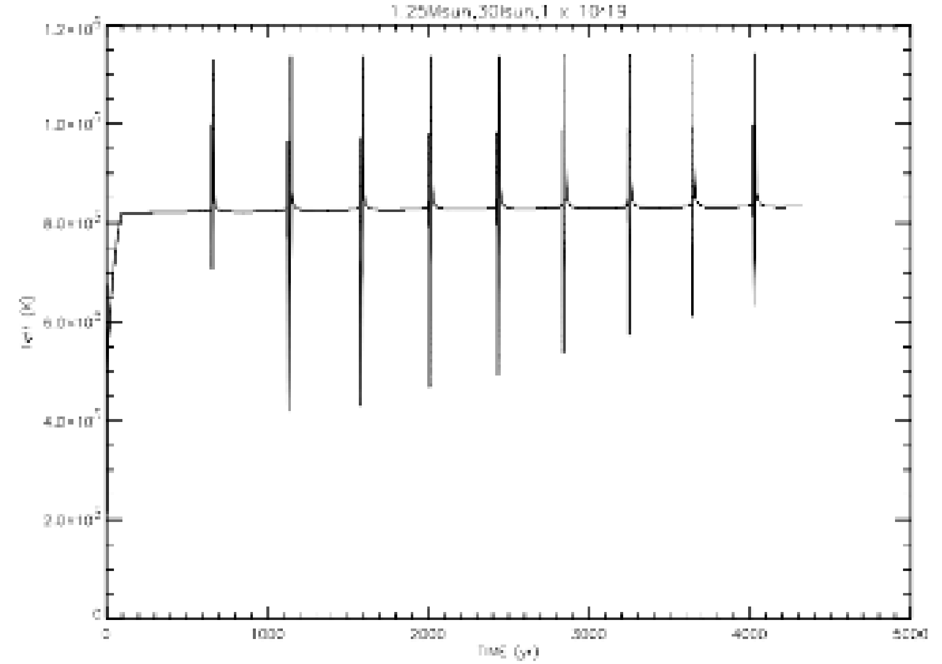
$^\%$ This sequence expanded to large radii after 25 yr of evolution.

^{a} CI = Composition Interface: All abundances are mass fractions.

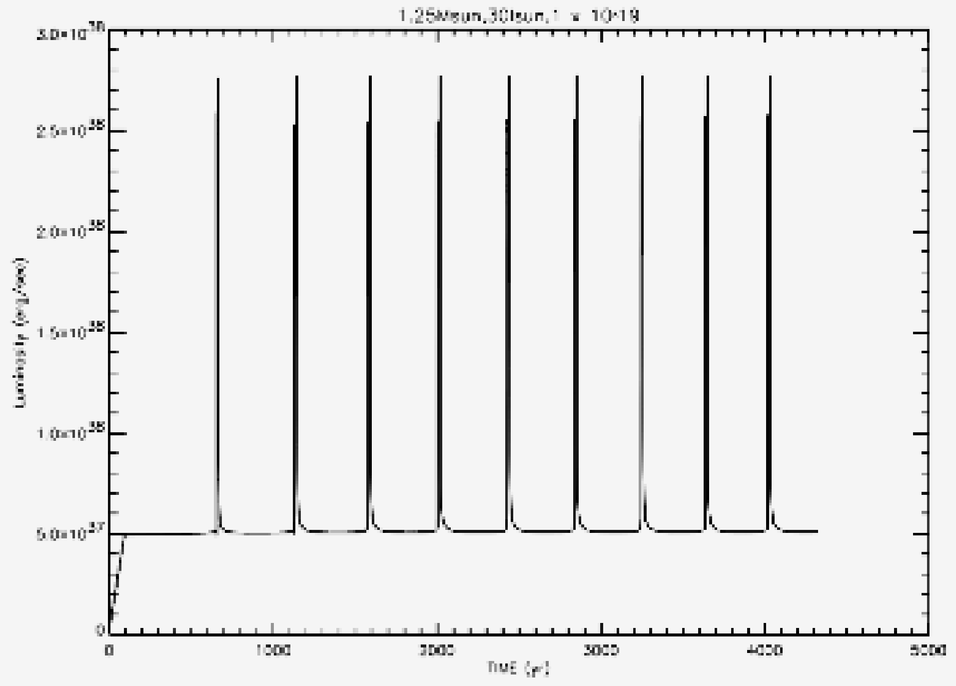
^{b} V stands for variable.

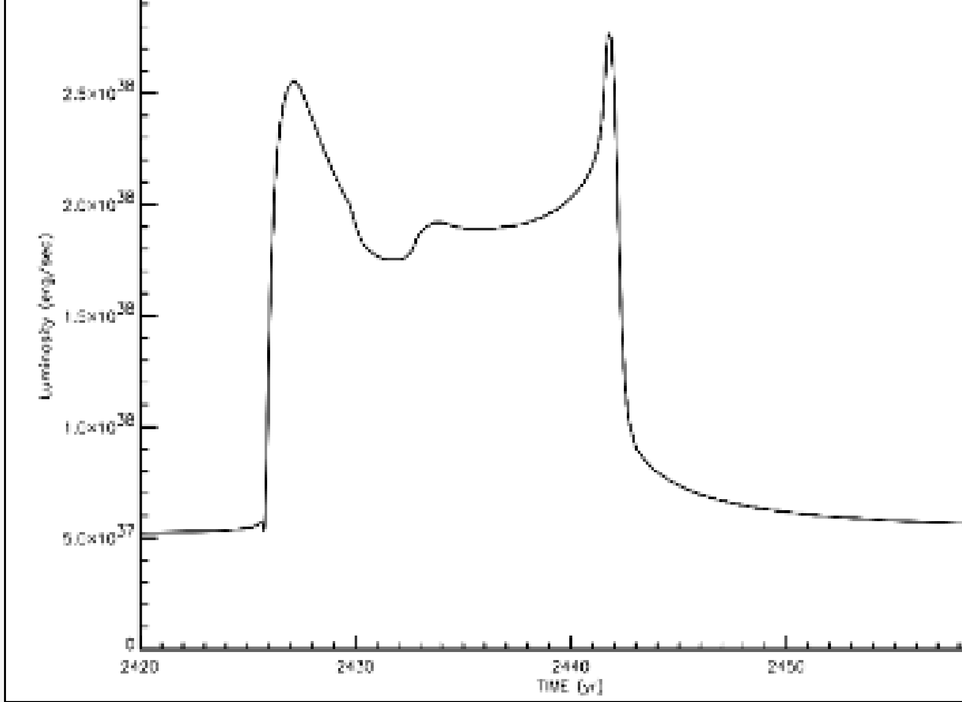


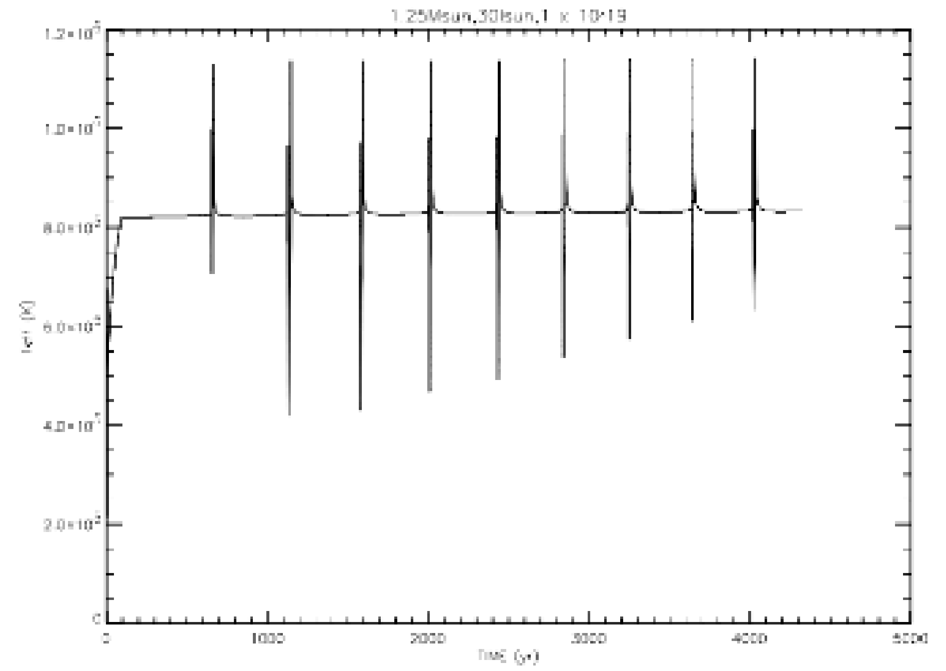
1.25Msun,30lsun,1 x 10-19
3.0×10^{38}
2.5×10^{38}
2.0×10^{38}
1.5×10^{38}
1.0×10^{38}
5.0×10^{37}
0
Luminosity (erg/sec)
0
1000
2000
3000
4000
5000
TIME (yr)

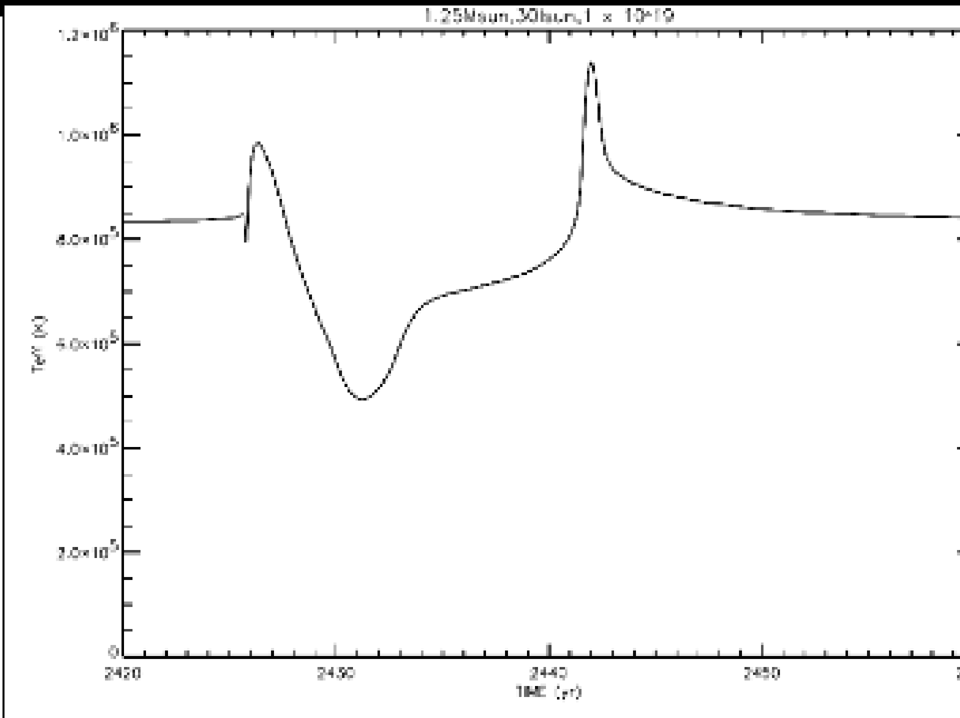


1.25Msun,30lsun,1 x 10-19
1.2×10^{5}
1.0×10^{5}
8.0×10^{5}
6.0×10^{5}
4.0×10^{5}
2.0×10^{5}
0
Teff (K)
0
1000
2000
3000
4000
5000
TIME (yr)


1.25Msun,30lsun,1 x 10^19
3.0×10^38
2.5×10^38
2.0×10^38
1.5×10^38
1.0×10^38
5.0×10^37
0
Luminosity (erg/sec)
0
1000
2000
3000
4000
5000
TIME (yr)


2.5×10^38
2.0×10^38
1.5×10^38
1.0×10^38
5.0×10^37
0
Luminosity (erg/sec)
2420
2430
2440
2450
TIME (yr)


1.25Msun,30lsun,1 x 10^19
1.2×10^6
1.0×10^6
8.0×10^5
6.0×10^5
4.0×10^5
2.0×10^5
0
Teff (K)
0
1000
2000
3000
4000
5000
TIME (yr)


1.25Msun,30lsun,1 x 10^19
1.2×10^6
1.0×10^6
8.0×10^5
6.0×10^5
4.0×10^5
2.0×10^5
0
Teff (K)
2420
2430
2440
2450
TIME (yr)

What We Have Found:

1) Hot white dwarfs can accrete at high mass accretion rates.
2) Hydrogen fuses to helium in the surface layers.
3) Helium fuses to carbon, oxygen, and higher mass nuclei in the accreted layers below the surface.
4) This is NOT canonical Steady Burning.
5) However, the luminosity and effective temperature remain constant for thousands of years.
6) We call it "Surface Hydrogen Burning (SHB)."
7) The range of mass accretion rates at which SHB occurs is much larger than the "single" value assumed for Steady Burning.
8) Changing to a lower metallicity does not change the results.

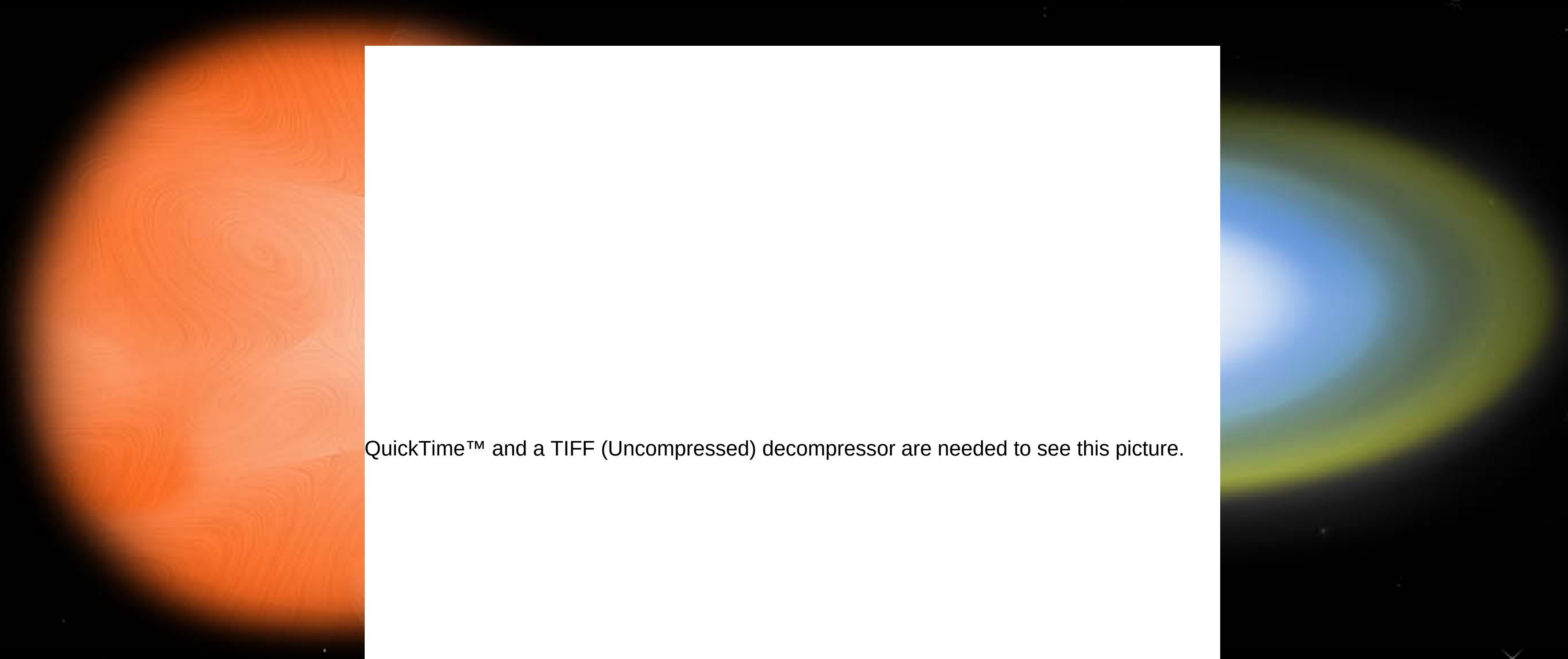
What We Explain/Predict:

1) Type Ia Supernovae are similar because they are explosions on accreting white dwarfs.
2) Their outbursts differ slightly possibly because their surface abundances depend on the rate of mass accretion as the white dwarf approaches the Chandrasekhar Limit ($\sim 1.4 M_\odot$).
3) The explosions from high mass accretion white dwarfs should have more oxygen near the surface than carbon.
4) The carbon/oxygen abundance ratio can be measured and should vary among Ia explosions.
5) Super Soft Xray Sources have surface conditions which can be understood on the basis of Surface Hydrogen Burning <u>not Steady Burning.</u>

Where Do We Go From Here?

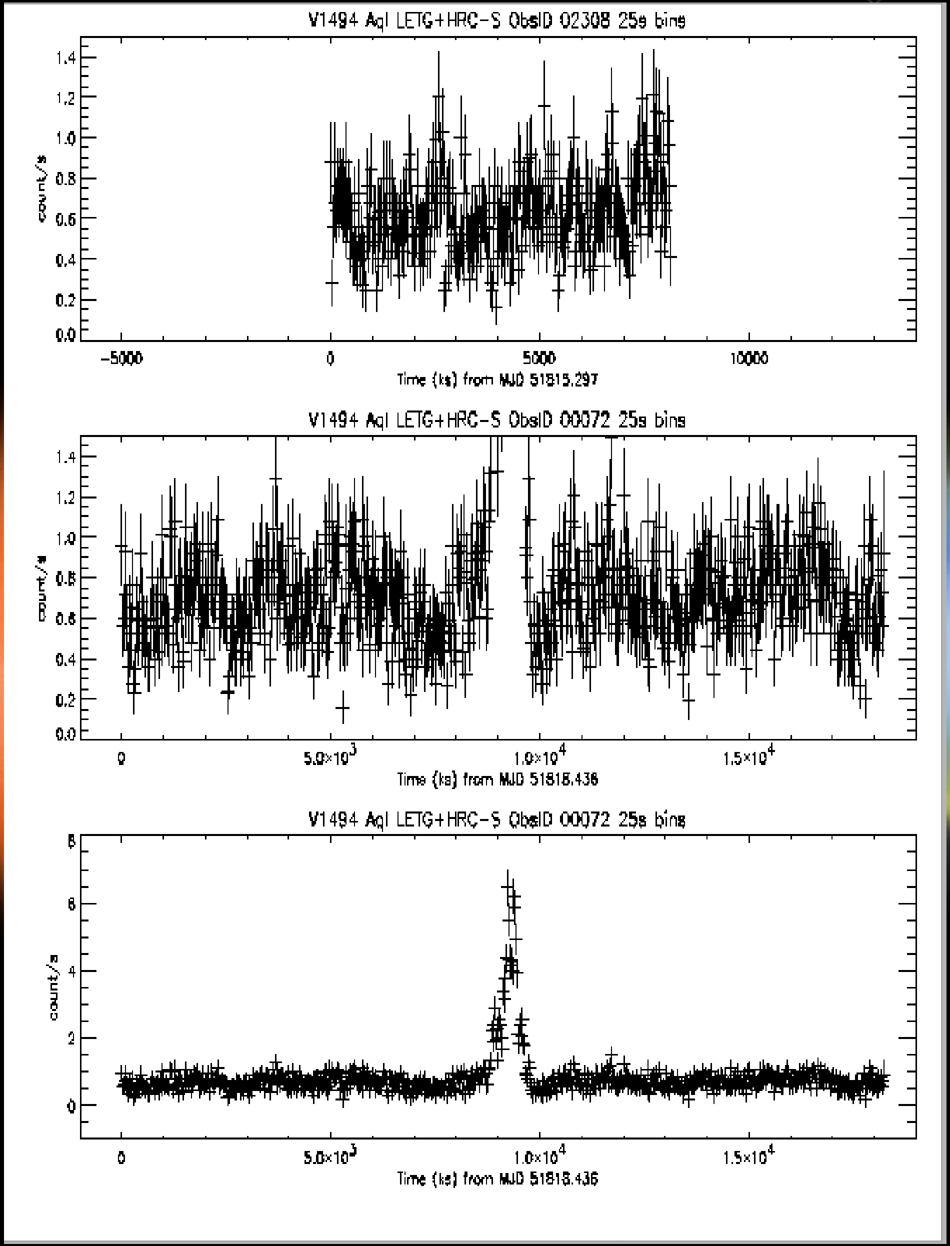
1) Allow a sequence to accrete until the explosion occurs.
2) Vary the initial luminosity of the white dwarf to determine its effects on the evolution.
3) Go to lower mass CO white dwarfs ($1.0M_{\odot}$ for example) although such studies are in the literature (Sion and Starrfield, Iben et al.)
4) Use our sequences for explosion studies.
5) Improve the observational determinations of SSS surface properties.

Let’s SEGway to Pulsations:

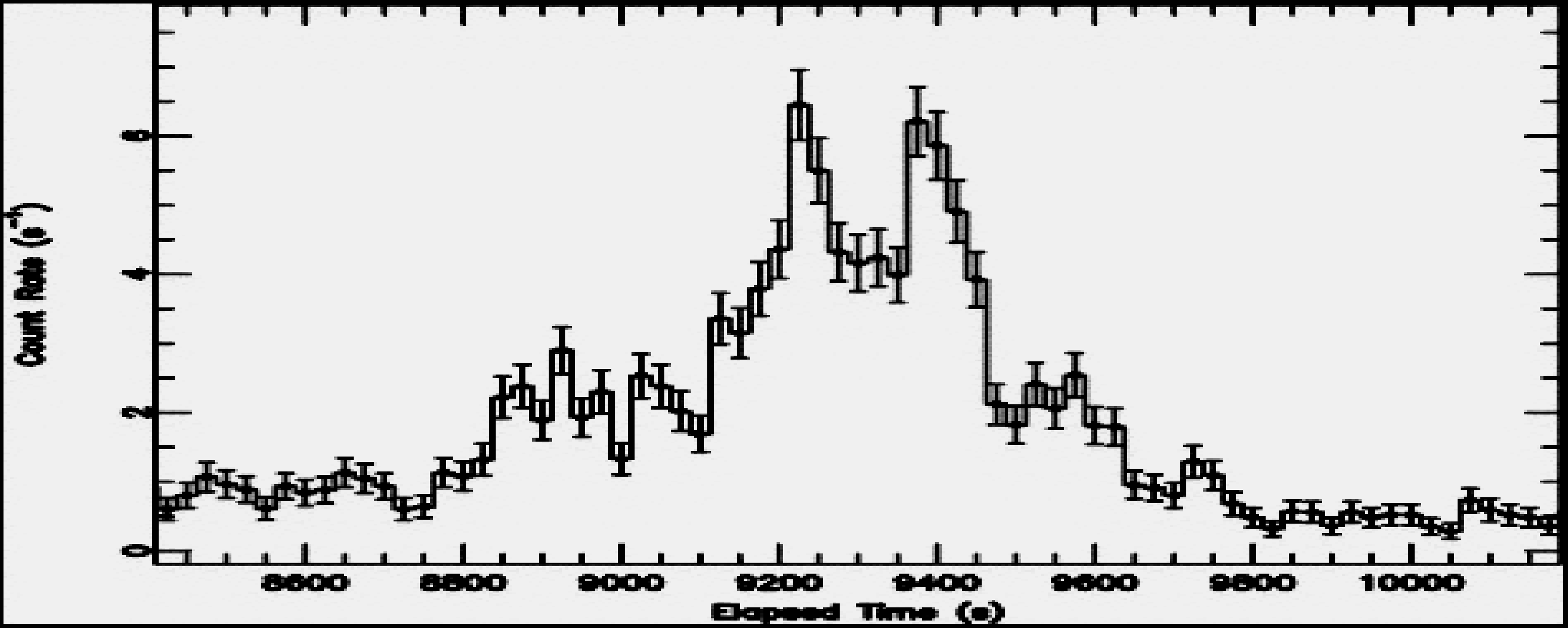


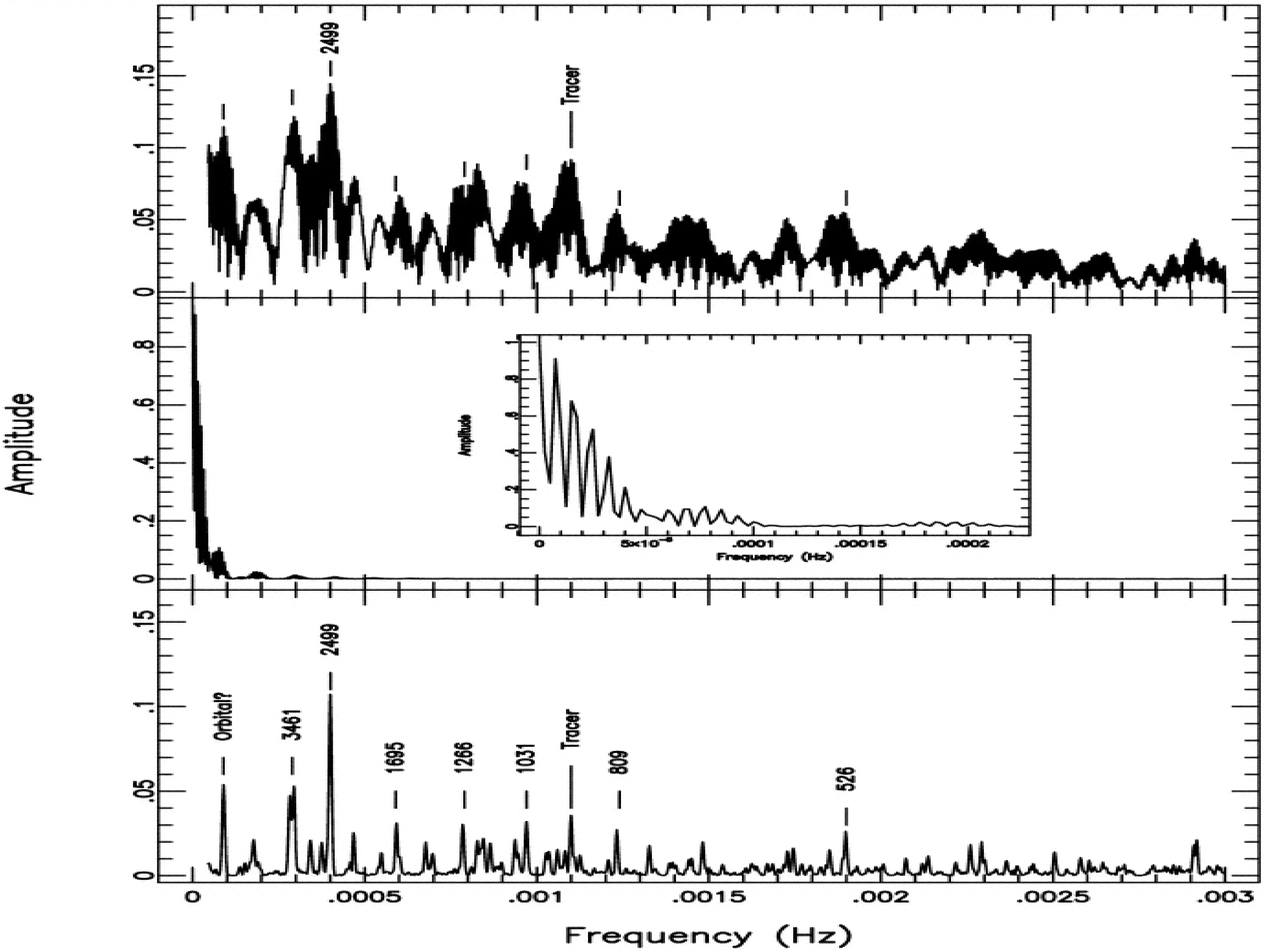
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

The CHANDRA X-ray light curve of V1494 Aql (in its SSS Phase)

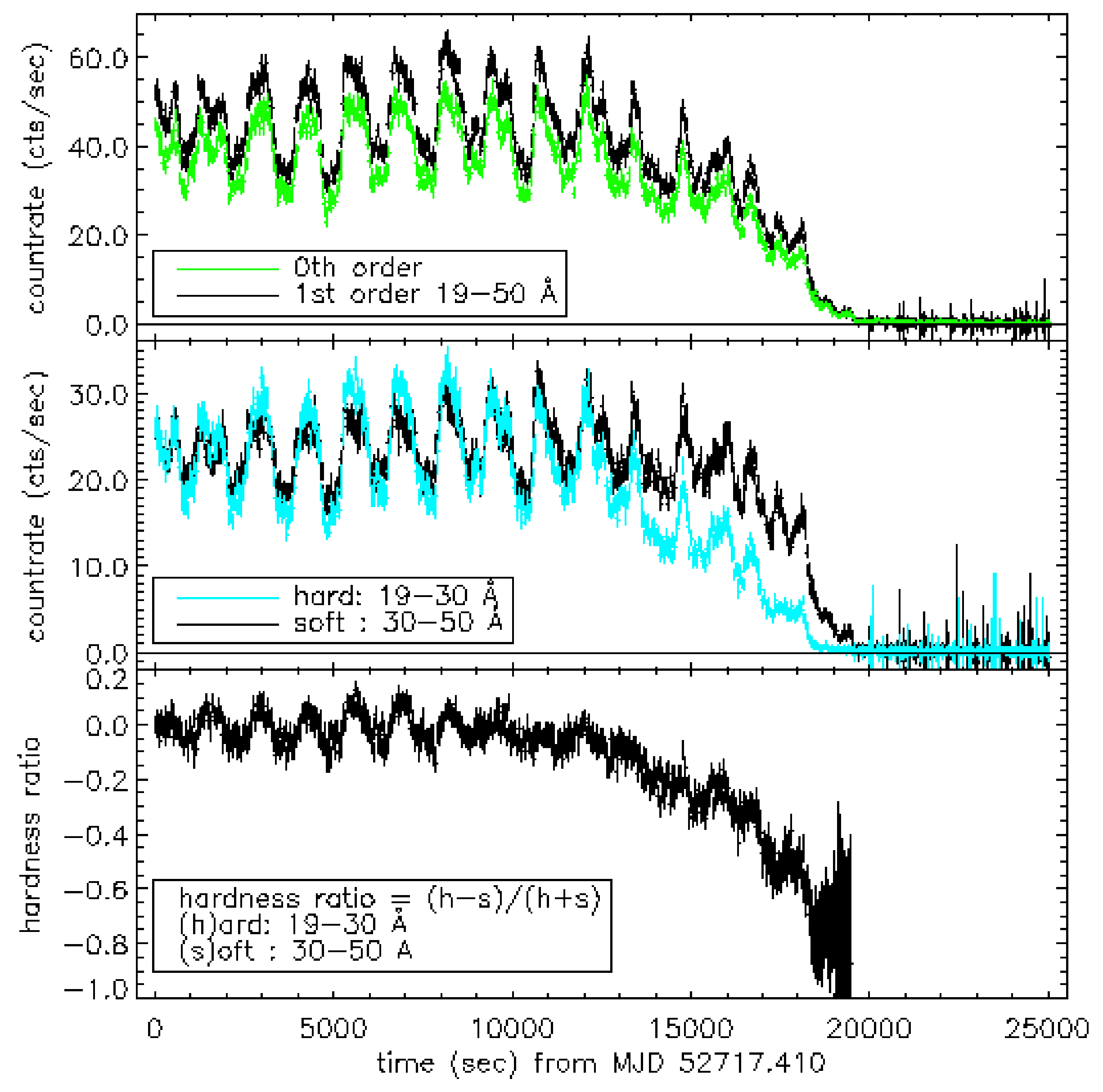


A blow-up of the X-ray “Burst”




2499
Tracer
Amplitude
0
.05
.1
.15
0
.2
.4
.6
.8
Amplitude
0
5×10⁻⁵
.0001
.00015
.0002
Frequency (Hz)
Orbital?
3461
2499
1695
1266
1031
Tracer
809
526
0
.0005
.001
.0015
.002
.0025
.003
Frequency (Hz)

V4743 Sgr on 19 March 2003



Light curve:

Black = 0th order

Green = 1st order

Black = 19 - 30 Å

“Blue” = 30 - 50 Å

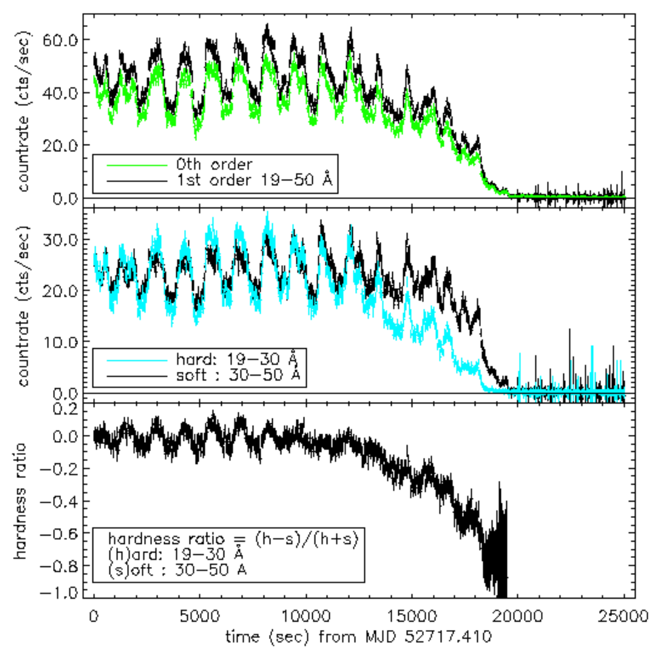
Hardness Ratio:

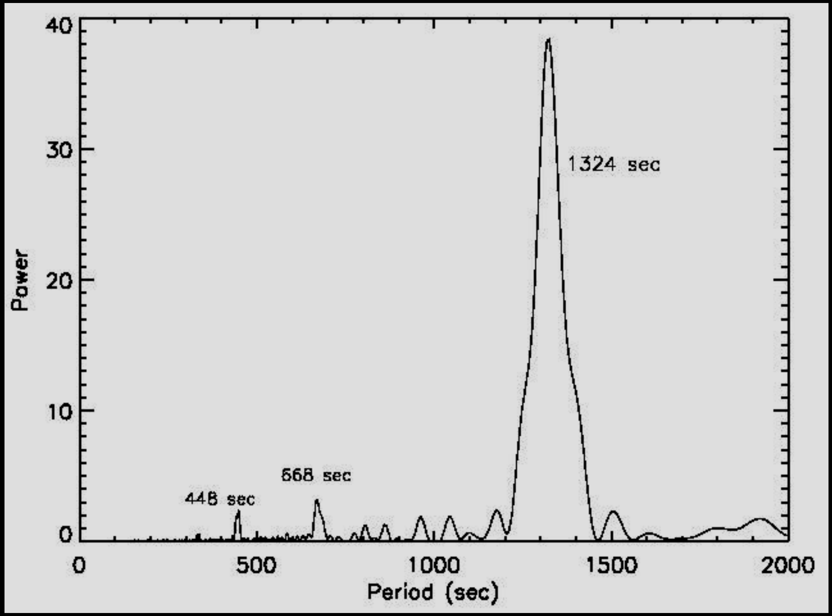
19 - 30 Å

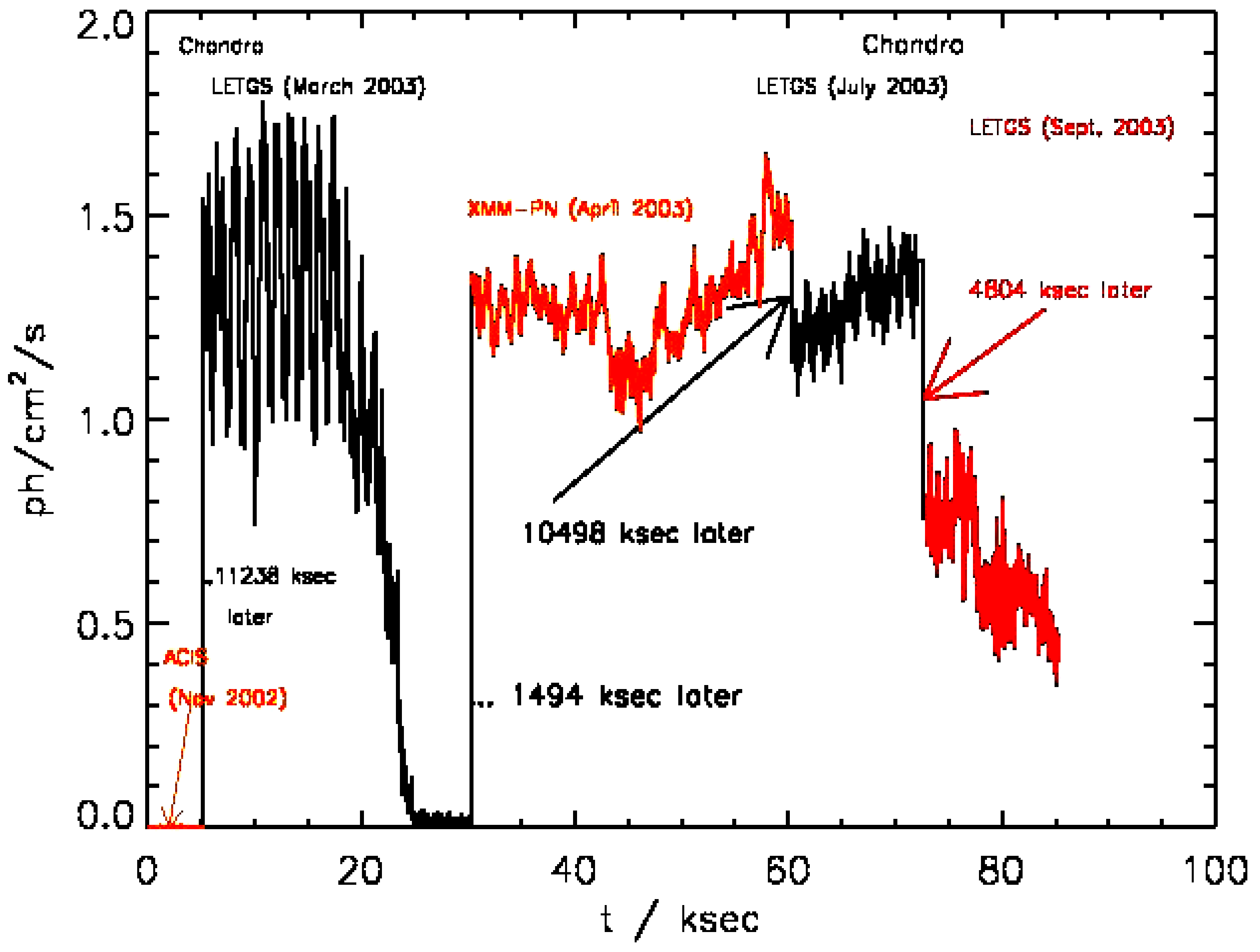
30 - 50 Å

The Light Curve:

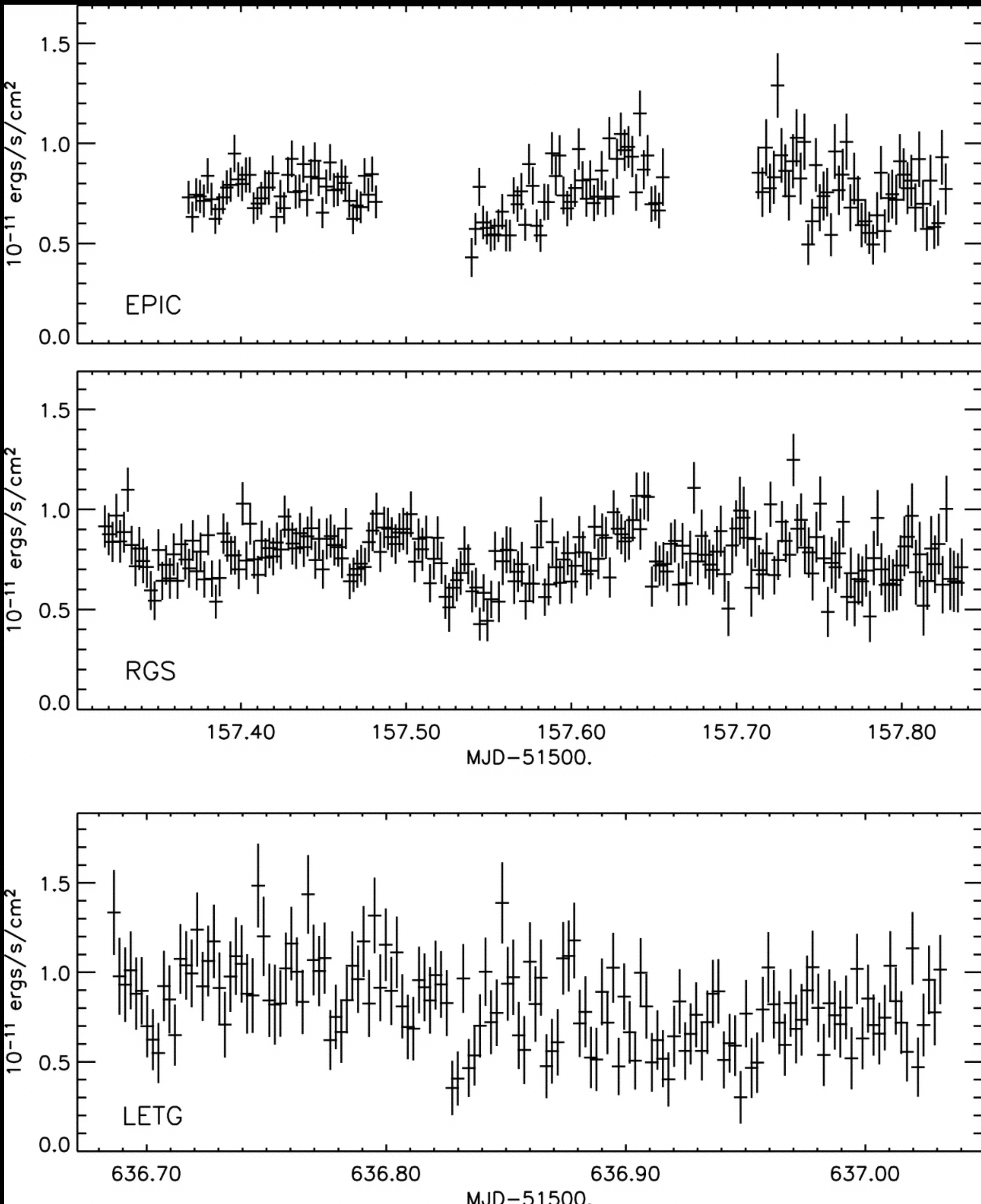
1) V4743 was bright in X-rays
2) The light curve exhibits oscillations with a period ~22min
3) After 15 ksec it begins to decline - first “soft” then “hard”
4) By 20 ksec it has dropped to nearly zero.






Chandra
LETGS (March 2003)
Chandra
LETGS (July 2003)
LETGS (Sept. 2003)
XMM-PN (April 2003)
4804 ksec later
10498 ksec later
..11238 ksec
later
ACIS
(Nov 2002)
... 1494 ksec later
ph/cm^2/s
t / ksec
0.0
0.5
1.0
1.5
2.0
0
20
40
60
80
100

X-ray Light Curves Of CAL 83: IT ALSO OSCILLATES



HOT WHITE DWARFS WITH NUCLEAR BURNING NEAR THE SURFACE ARE PULSATING IN NON-RADIAL g^+ MODES

Analysis of These Modes Will Provide Another Means of Studying the Interiors of These Stars!

QuickTime™ and a Sorenson Video 3 decompressor are needed to see this picture.

Credit: NASA: Greg Bacon and Bryan Preston (STScI/AVL)