Excavation or Accretion from Classical Novae (or related objects)

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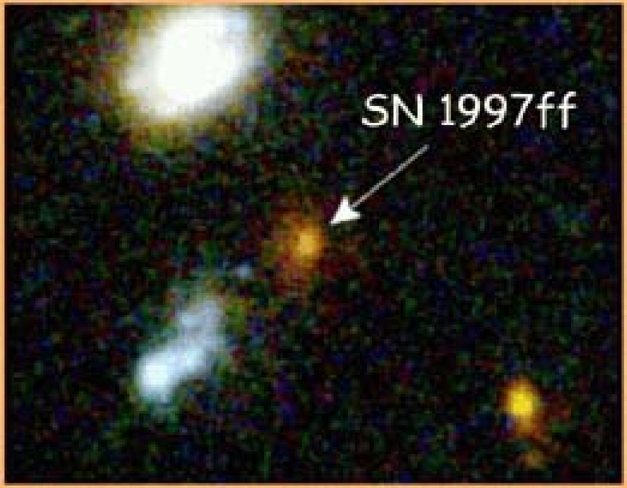
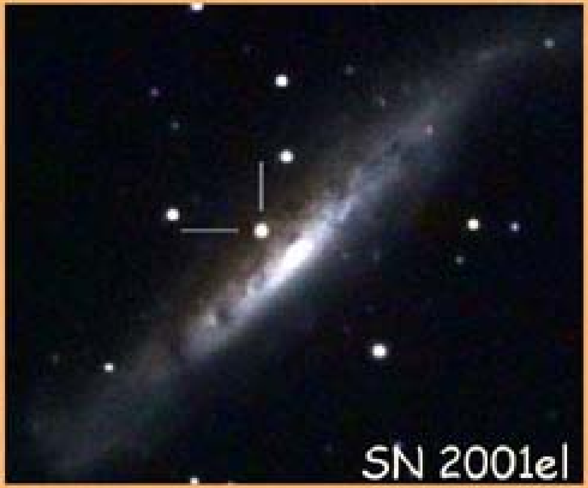
Type Ia Supernovae:





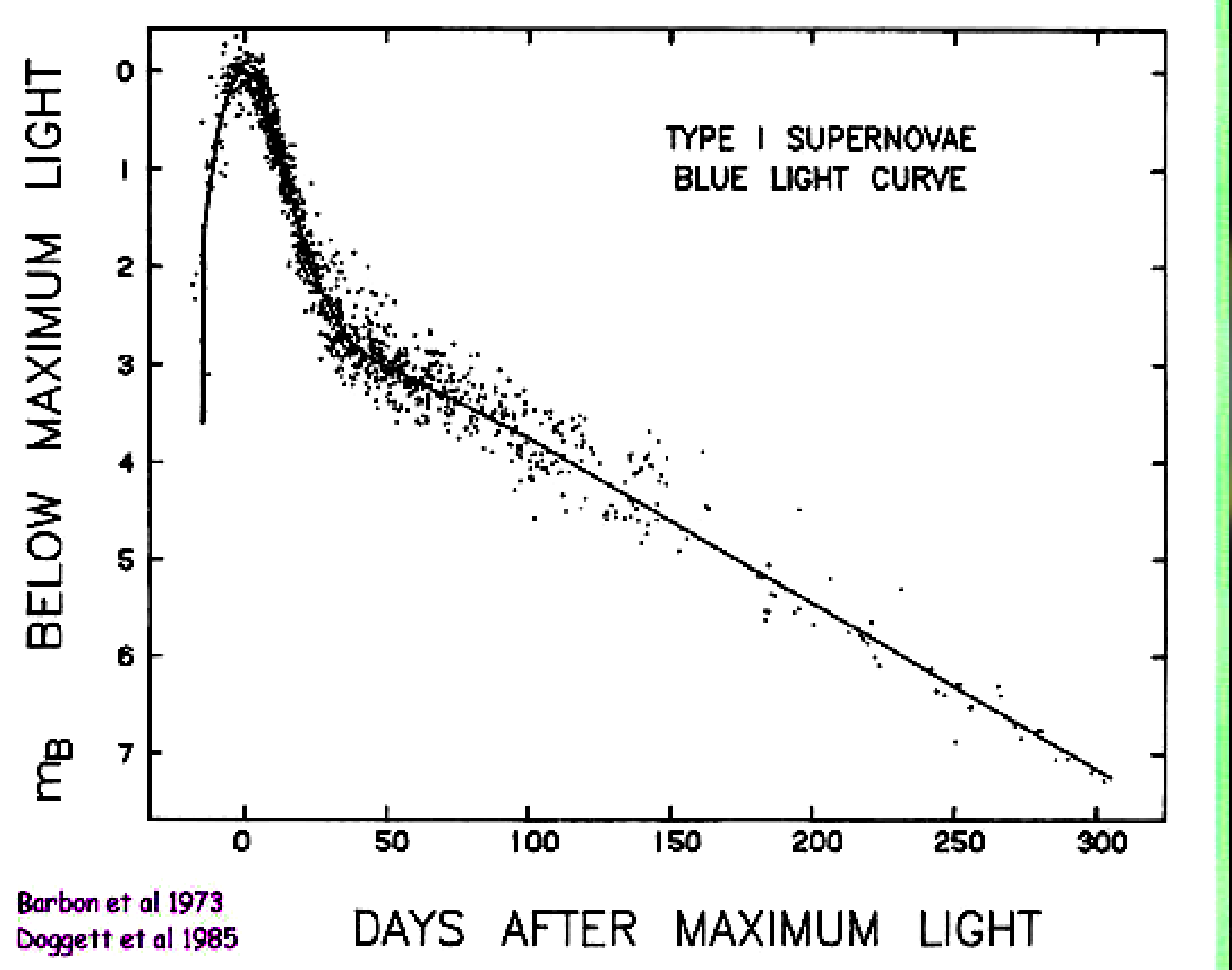
Our goal is to understand (and identify) the progenitors of thermonuclear supernovae.

Type Ia SN are among the brightest explosions in the universe.

They are important producers of the iron peak elements.

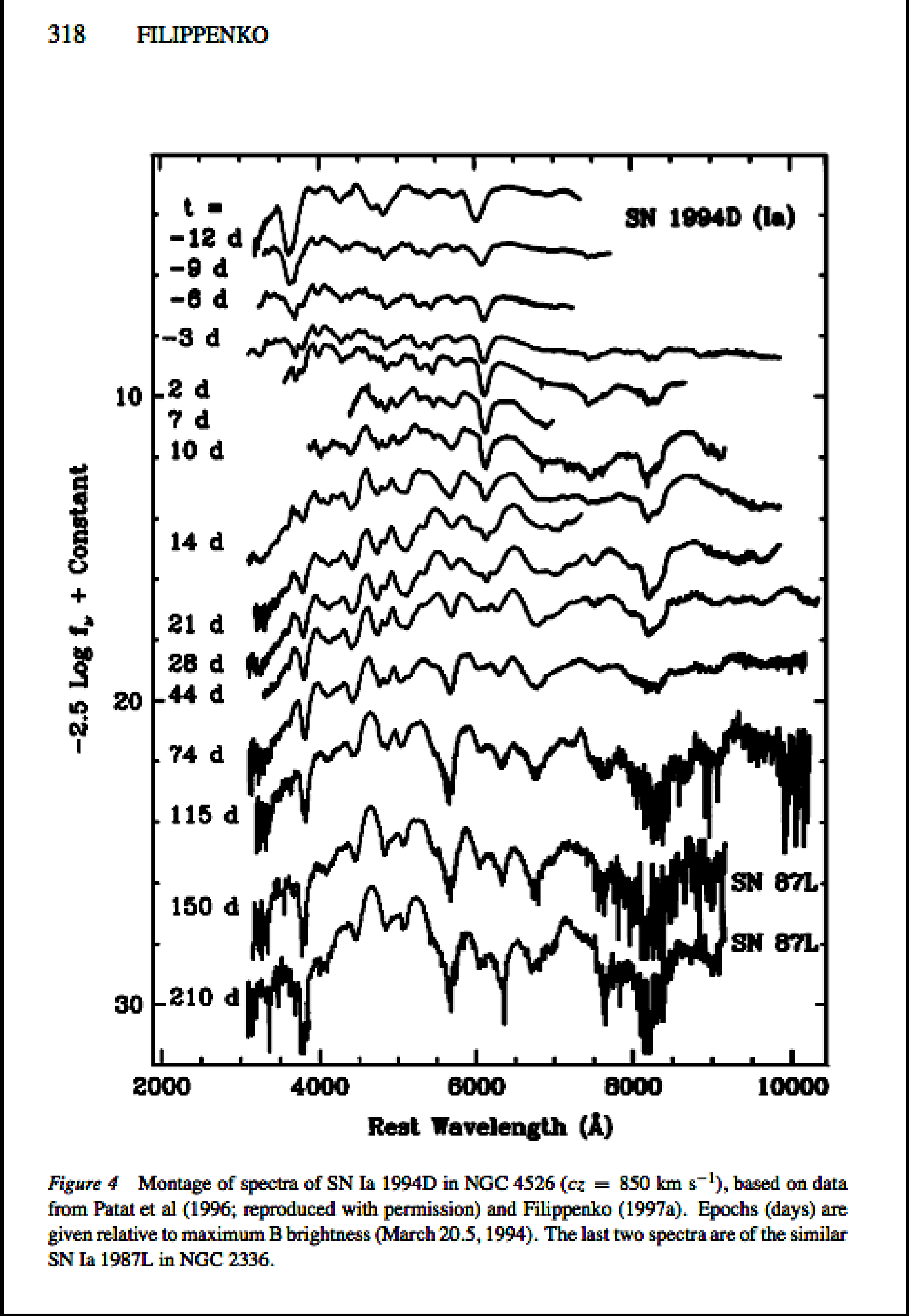
They are also a vital tool for exploration of the fate of our universe.

The Light Curves of Type Ia Supernovae show Remarkable Similarity



No

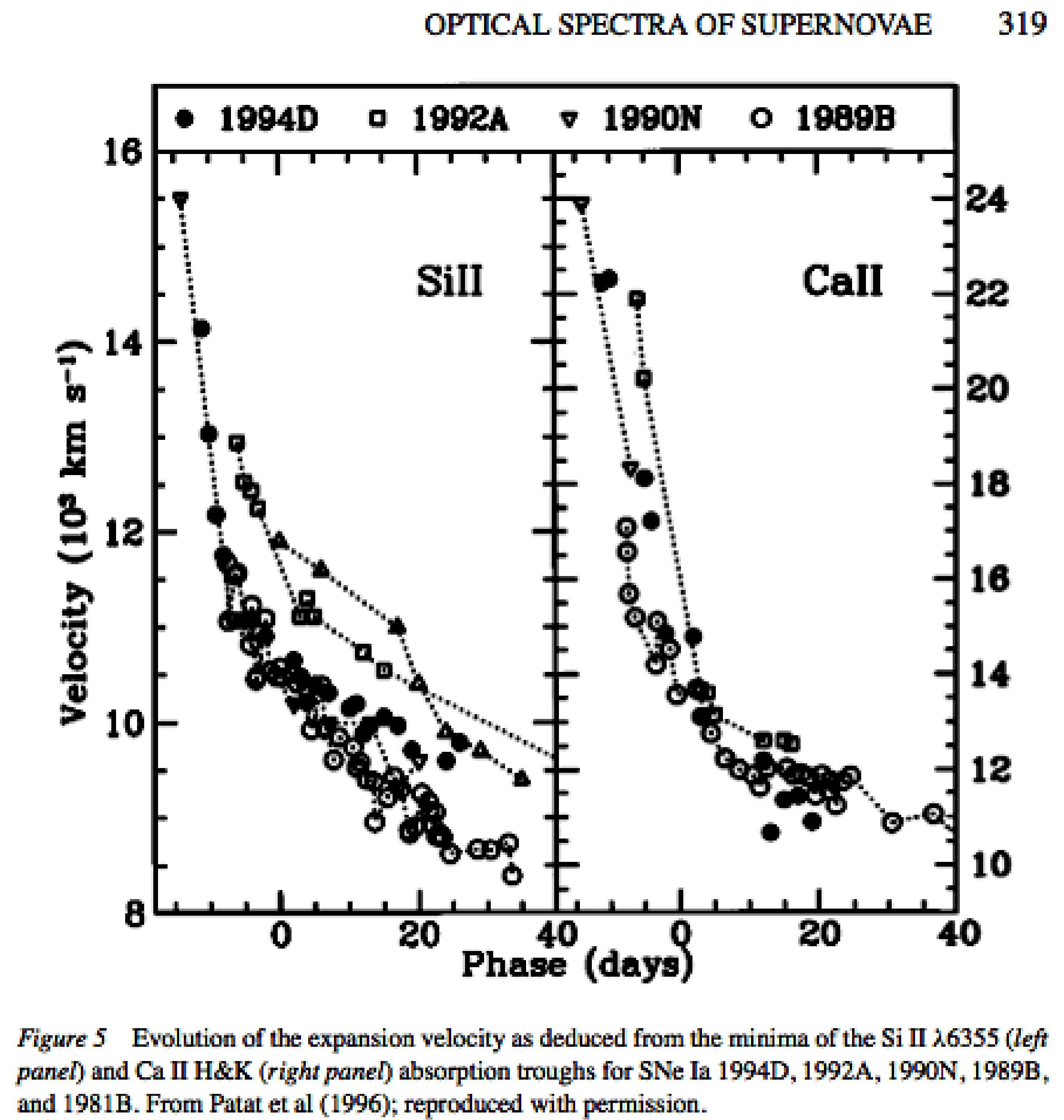
H or He
is present
in the
spectrum
at any
time
during the
evolution



318 FILIPPENKO

Figure 4 Montage of spectra of SN Ia 1994D in NGC 4526 (cz = 850 km s^{-1}), based on data from Patat et al (1996; reproduced with permission) and Filippenko (1997a). Epochs (days) are given relative to maximum B brightness (March 20.5, 1994). The last two spectra are of the similar SN Ia 1987L in NGC 2336.

There is
high velocity
Calcium,
Silicon,
and
Magnesium
observed
early in
the spectral
evolution.



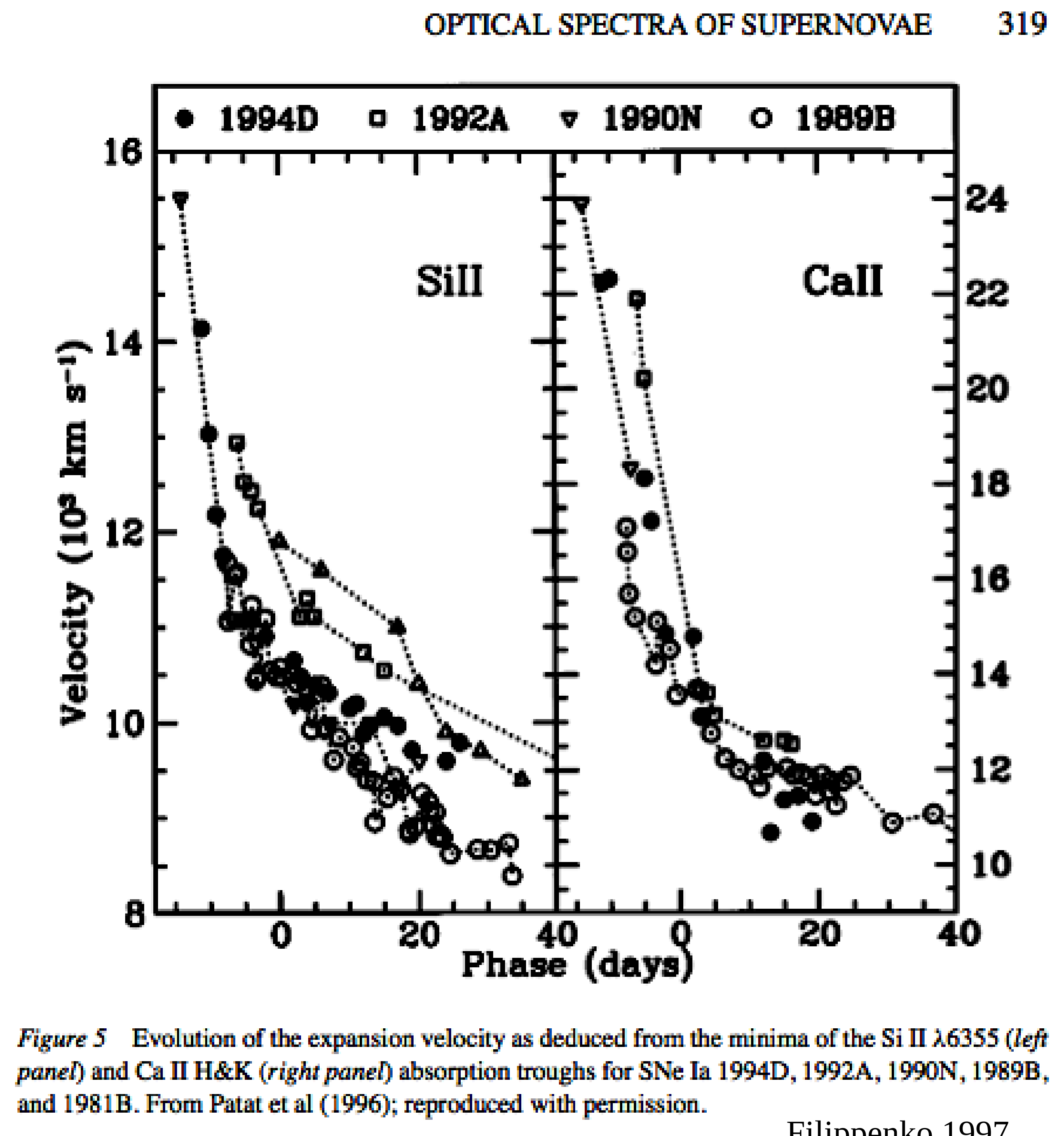
OPTICAL SPECTRA OF SUPERNOVAE 319

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

There is
high velocity
Calcium,
Silicon,
and
Magnesium
observed
early in
the spectral
evolution.

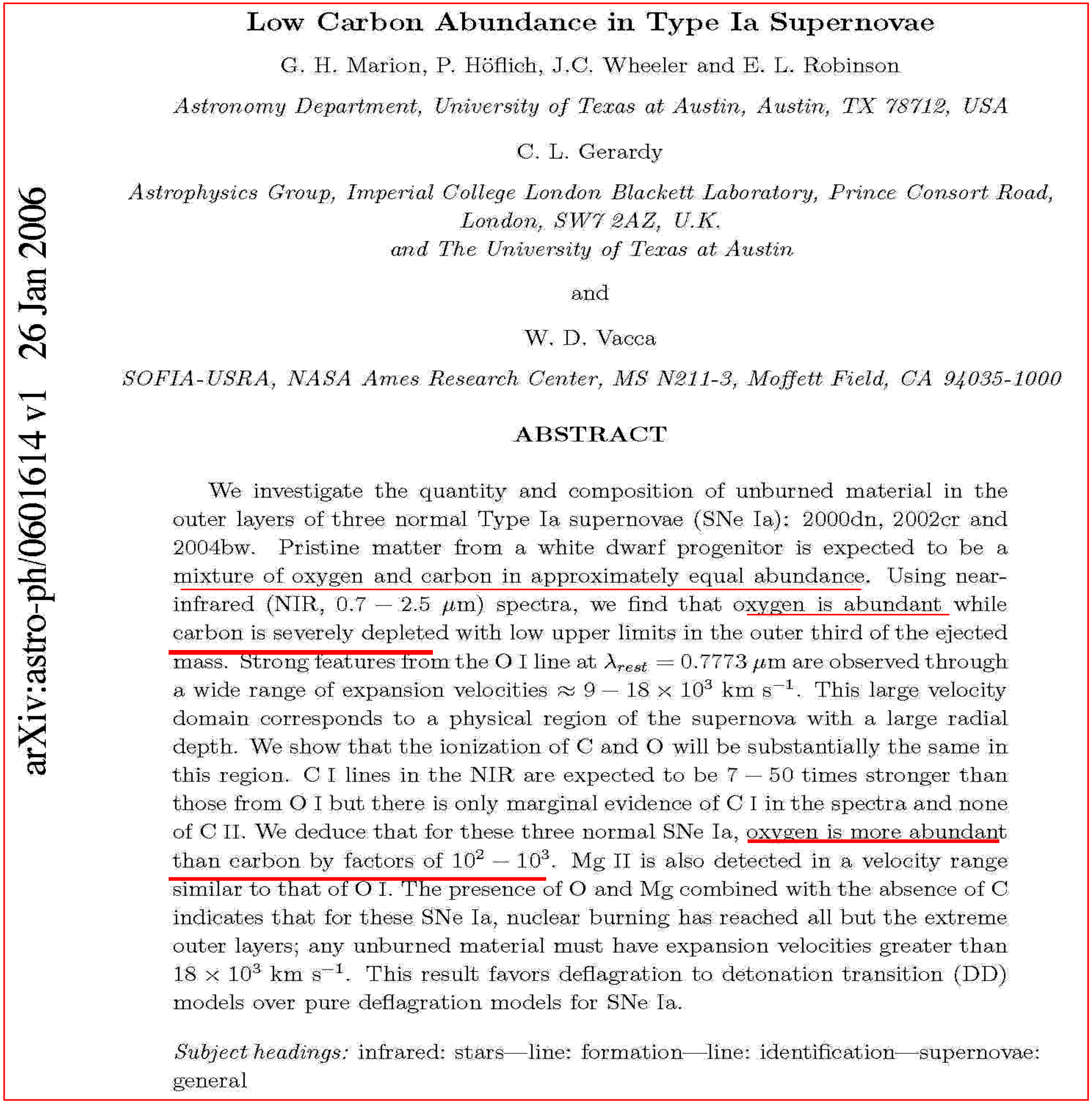
Is it already present in the outer layers or produced by the shock?



OPTICAL SPECTRA OF SUPERNOVAE 319

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



Low Carbon Abundance in Type Ia Supernovae

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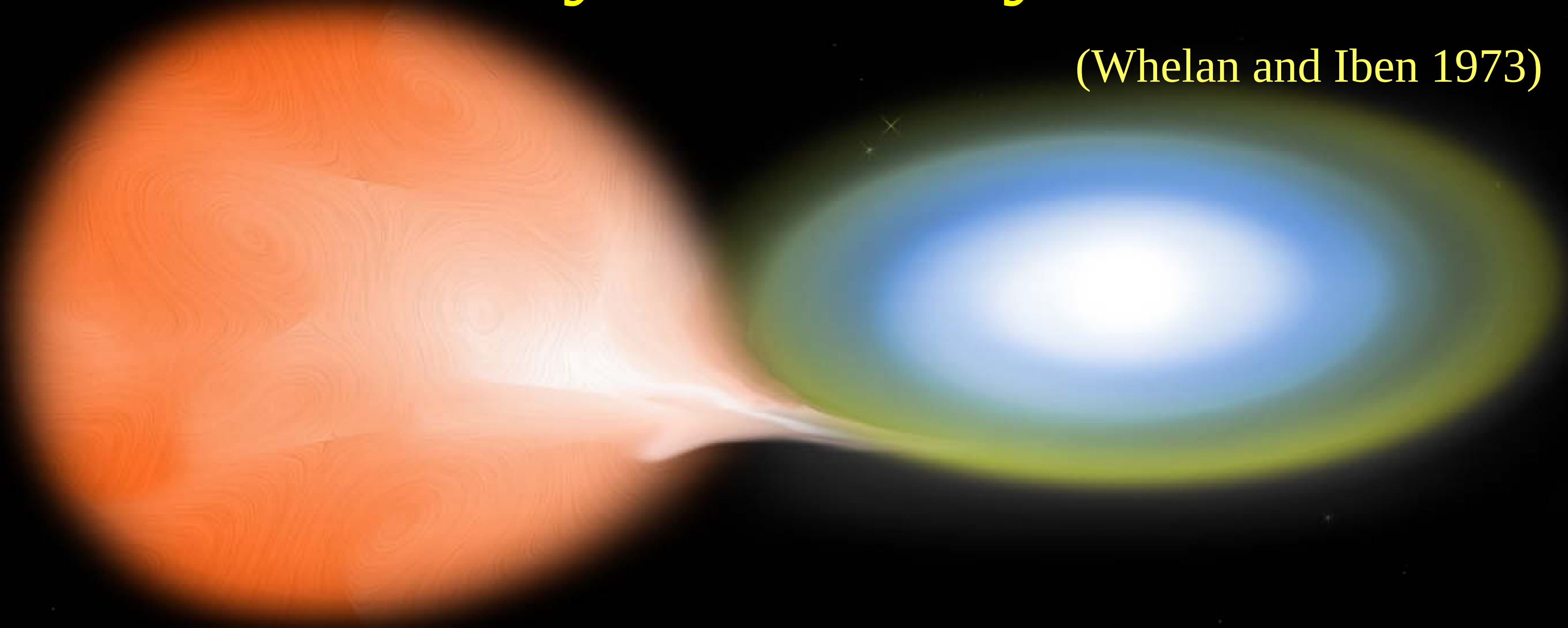
ABSTRACT

We investigate the quantity and composition of unburned material in the outer layers of three normal Type Ia supernovae (SNe Ia): 2000dn, 2002cr and 2004bw. Pristine matter from a white dwarf progenitor is expected to be a mixture of oxygen and carbon in approximately equal abundance. Using near-infrared (NIR, $0.7 - 2.5$ μm) spectra, we find that oxygen is abundant while carbon is severely depleted with low upper limits in the outer third of the ejected mass. Strong features from the O I line at $\lambda_{rest} = 0.7773$ μm are observed through a wide range of expansion velocities $\approx 9 - 18 \times 10^3$ km s^{-1}. This large velocity domain corresponds to a physical region of the supernova with a large radial depth. We show that the ionization of C and O will be substantially the same in this region. C I lines in the NIR are expected to be $7 - 50$ times stronger than those from O I but there is only marginal evidence of C I in the spectra and none of C II. We deduce that for these three normal SNe Ia, oxygen is more abundant than carbon by factors of $10^2 - 10^3$. Mg II is also detected in a velocity range similar to that of O I. The presence of O and Mg combined with the absence of C indicates that for these SNe Ia, nuclear burning has reached all but the extreme outer layers; any unburned material must have expansion velocities greater than 18×10^3 km s^{-1}. This result favors deflagration to detonation transition (DD) models over pure deflagration models for SNe Ia.

Subject headings: infrared: stars—line: formation—line: identification—supernovae: general

SN Ia are Thought to Occur on the White Dwarf 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 Thermonuclear Runaway in a ~1.4$M_\odot$ Carbon-Oxygen White Dwarf (WD) can match the explosion observations.

Need accretion from a binary companion to grow a WD to the Chandrasekhar mass (~1.4$M_\odot$).

Unless the secondary has a strange composition (double degenerate systems, for example) it is transferring H and He.

As Important as they are, we still do not
know what type of star
explodes as a SN Ia.

BUT there is **NO** evidence for
Hydrogen or Helium
in the ejected gases.
This is extremely unusual because
H and He are the
most abundant elements in the Universe.

Suggested:

Classical Novae: But more mass is ejected than accreted -- the White Dwarf mass is decreasing.

Dwarf Novae: Mass Accretion rates are low will take too long.

Recurrent Novae: Either too much hydrogen or helium

In ALL cases there is too much hydrogen and helium present in the system.

Are they the SN Ia progenitors: probably not!

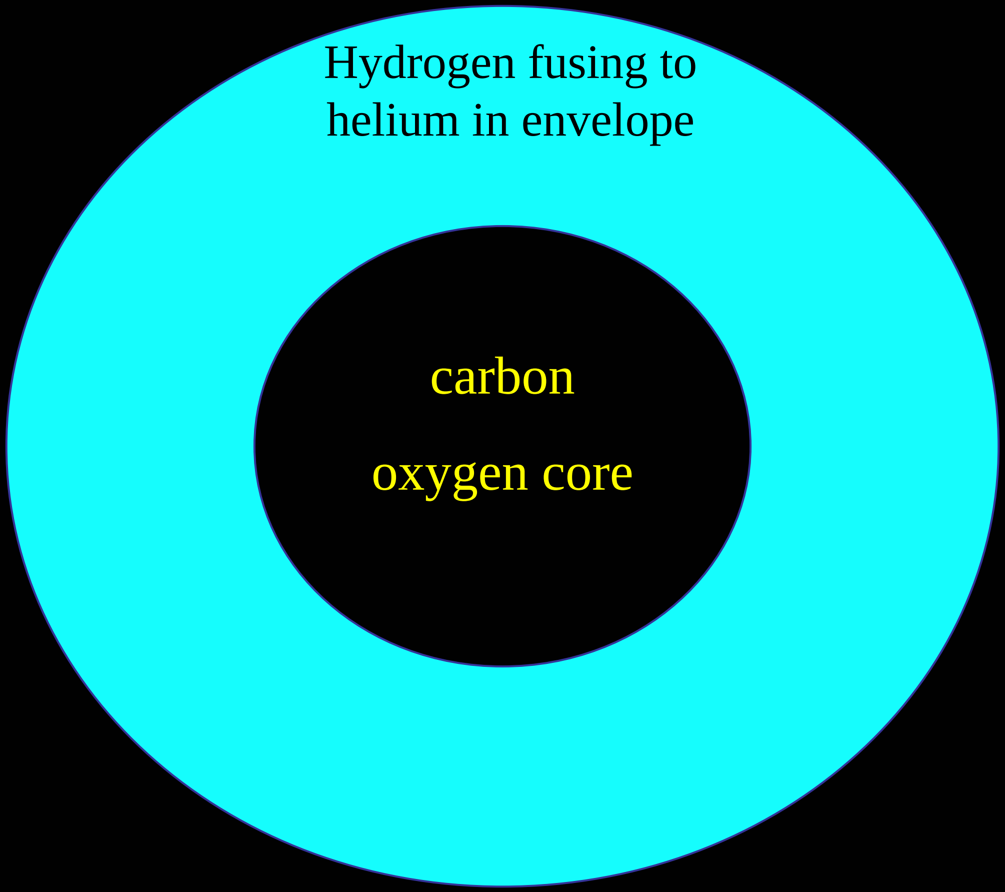
HOW DO WE GET RID OF THE H and He?

[PROPOSAL (van den Heuvel et al. 1992):

The Super Soft X-ray Binary Sources (SSS: Cal 83; Cal 87)]

- By thermonuclear burning in the surface layers while they are accreting material.
- Stable Burning: H burns to He as fast as it accretes
- But Stable Burning only works for “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.)
- Stable burning was not tested with evolution codes until now.

“Stable” Burning White Dwarf Composition:

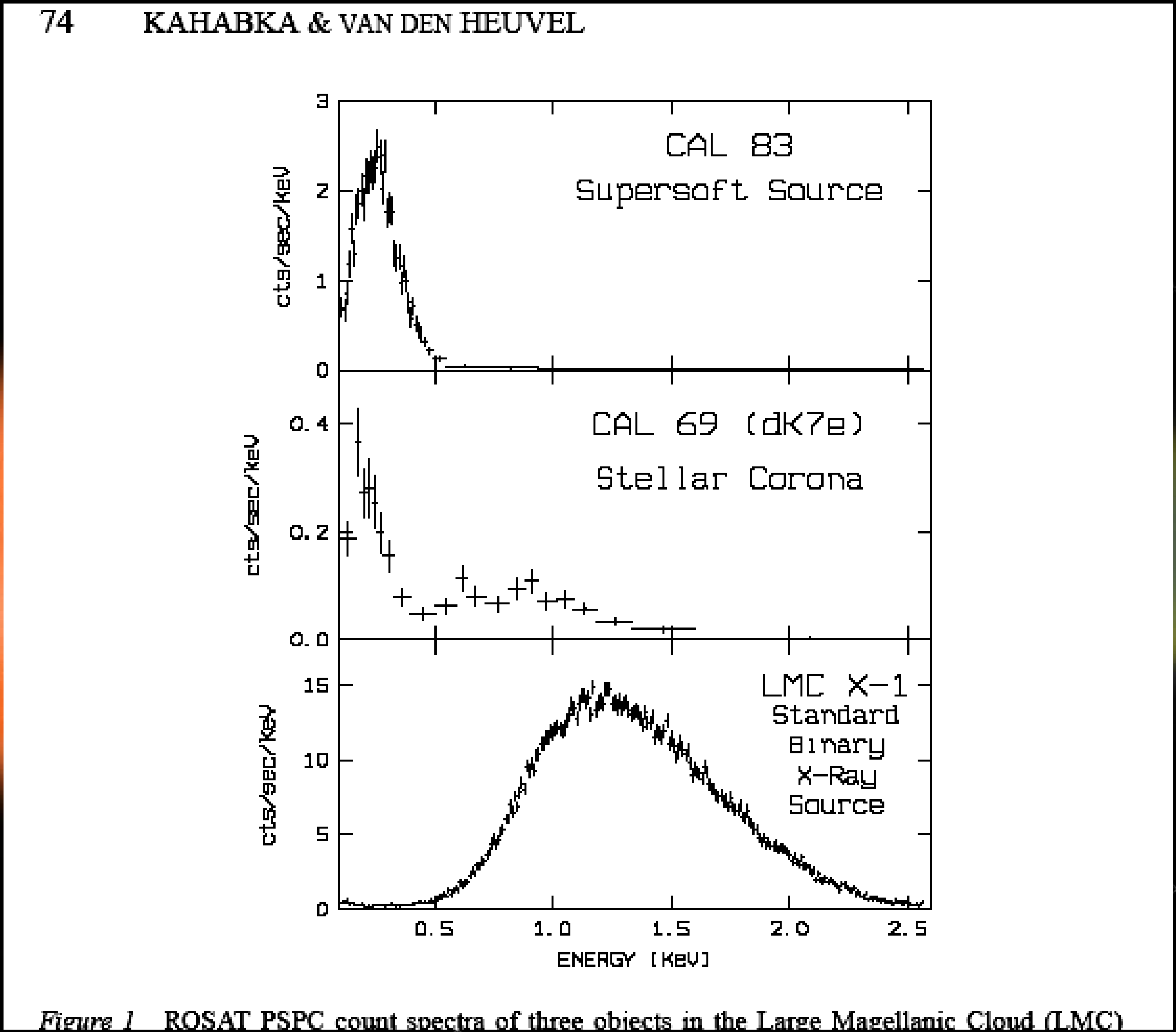


Hydrogen fusing to helium in envelope

carbon

oxygen core

Works for mass accretion rates: ~3 x 10^{-7} $M_{\odot}$ /yr at $1.35M_{\odot}$



74 KAHABKA & VAN DEN HEUVEL

Figure 1 ROSAT PSPC count spectra of three objects in the Large Magellanic Cloud (LMC)

PSPC = Position Sensitive Proportional Counter

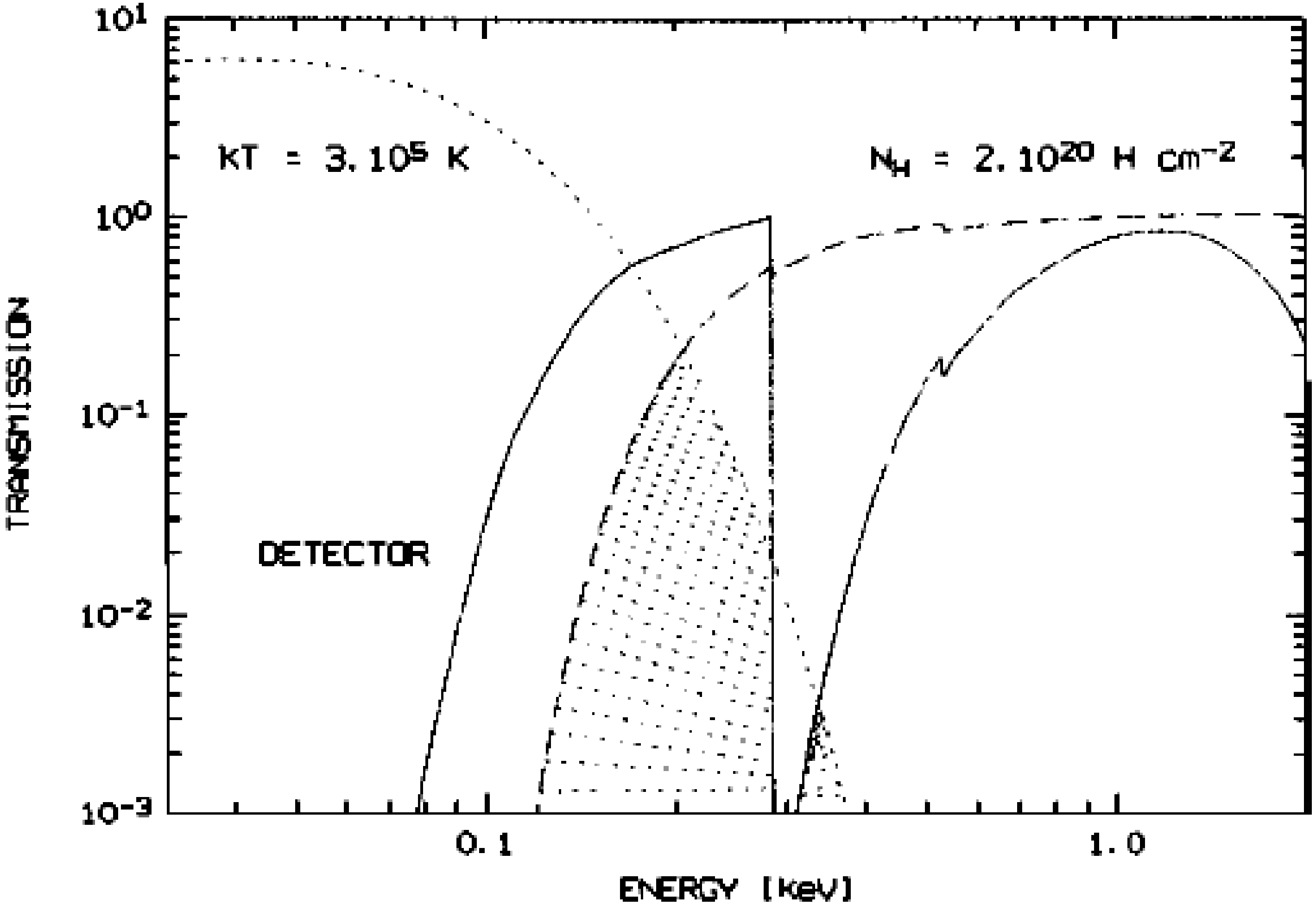
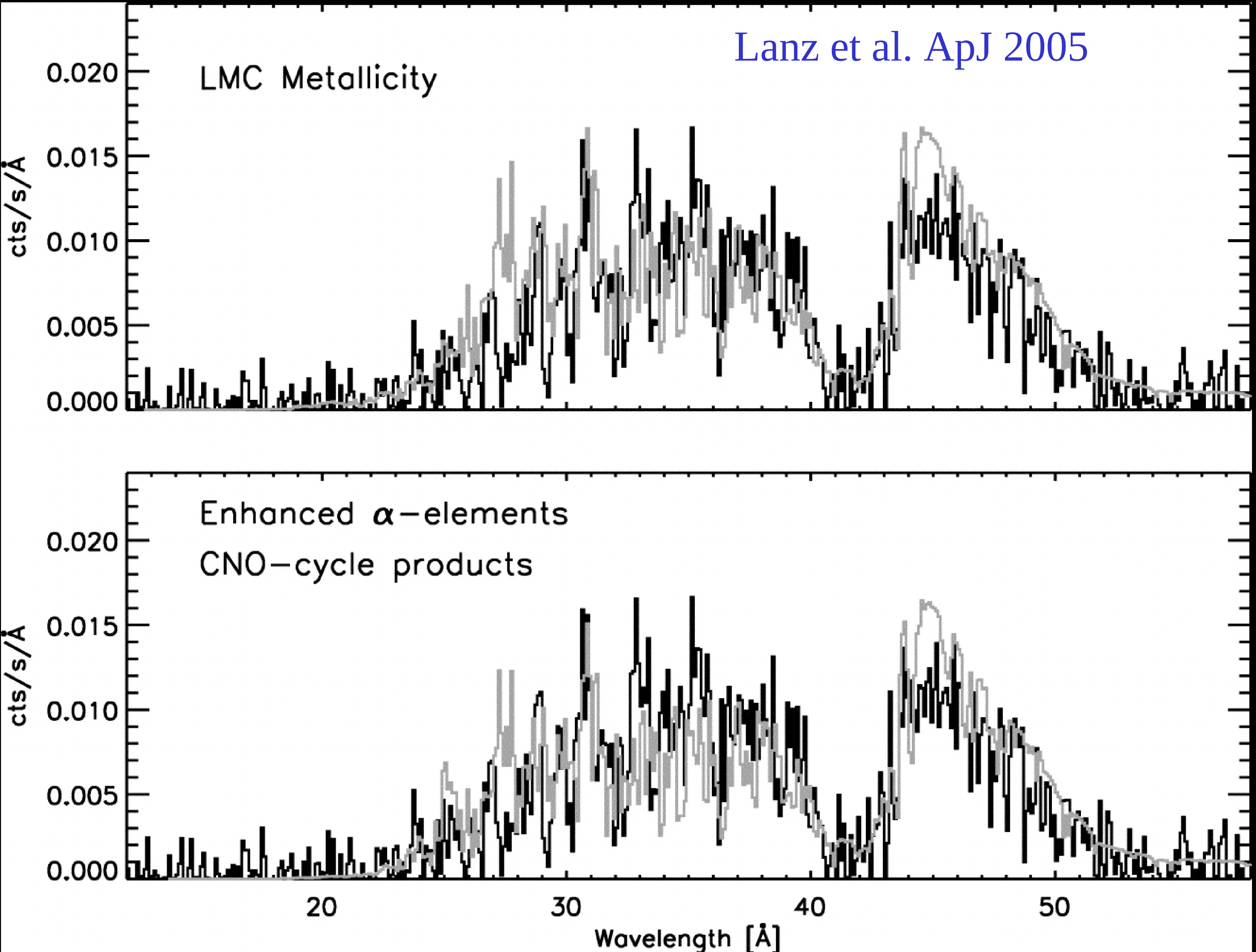
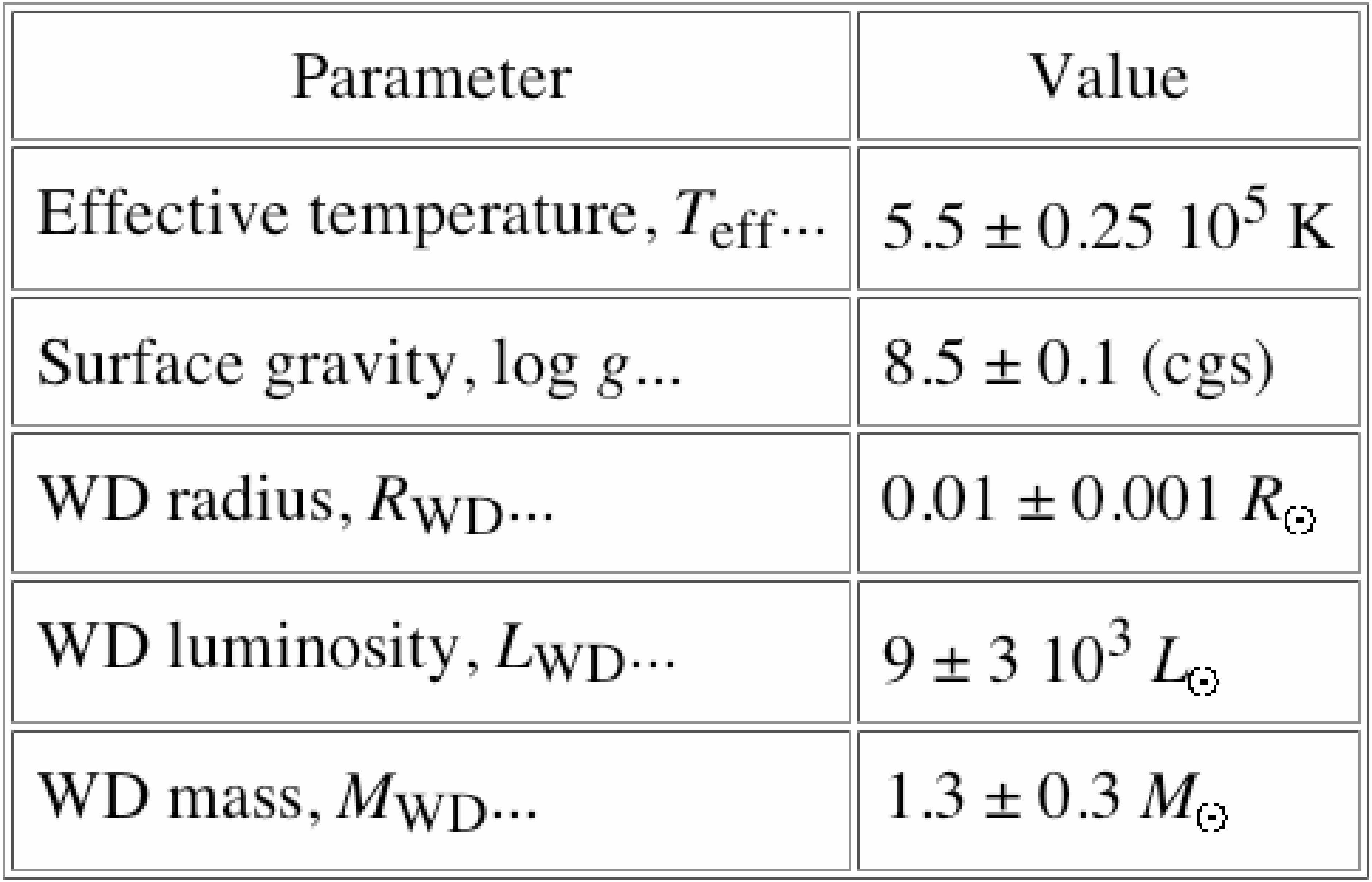


Figure 2 ROSAT PSPC efficiency (*solid curve*), transmission of ISM for hydrogen column of 2.10^{20} H atoms cm^{-2} (*dashed line*), distribution of a 3.10^5-K blackbody spectrum (*dotted line*) and folded (observed) distribution (*hatch marks*) (SA Rappaport, private communication).

Lanz et al. ApJ 2005

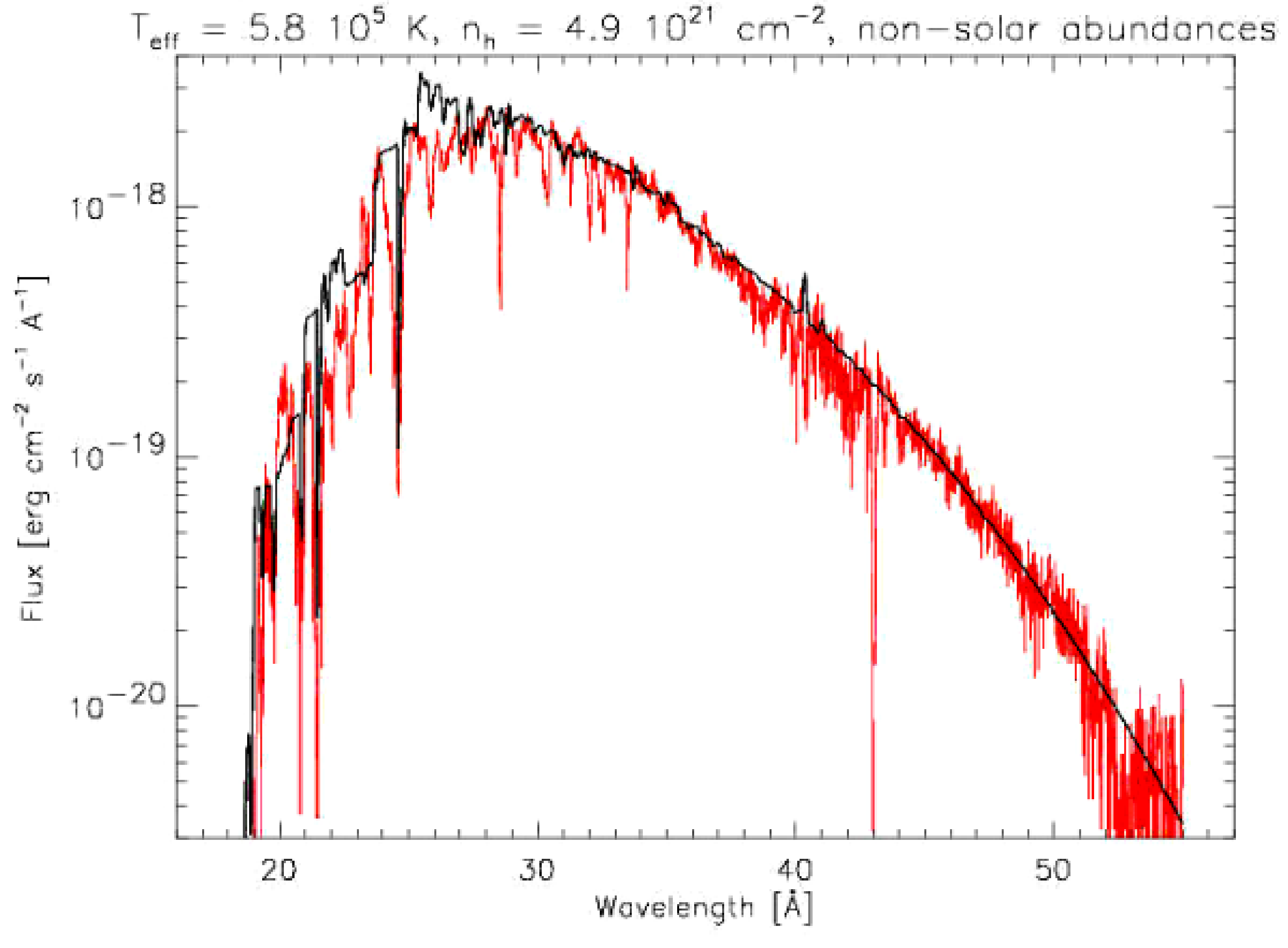


Lanz et al. ApJ 2005:

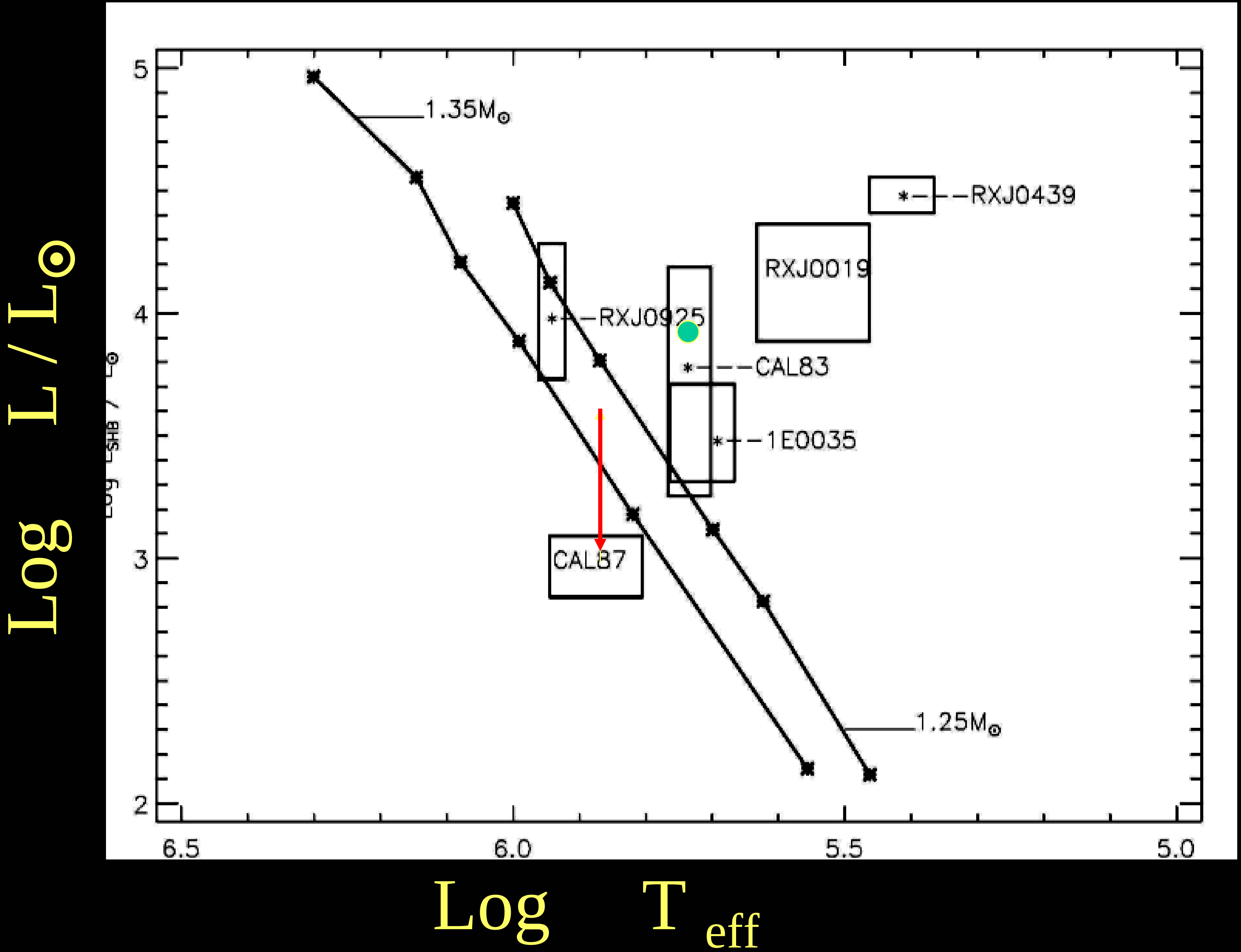


Parameter	Value
Effective temperature, T_{eff}…	$5.5 \pm 0.25\ 10^5$ K
Surface gravity, log g…	8.5 ± 0.1 (cgs)
WD radius, R_{WD}…	$0.01 \pm 0.001\ R_\odot$
WD luminosity, L_{WD}…	$9 \pm 3\ 10^3\ L_\odot$
WD mass, M_{WD}…	$1.3 \pm 0.3\ M_\odot$

Stellar Atmosphere fit to X-ray Spectrum:



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



Log L / L⊙
Log L_SHB / L⊙
5
4
3
2
1.35M⊙
1.25M⊙
RXJ0439
RXJ0019
RXJ0925
CAL83
1E0035
CAL87
6.5
6.0
5.5
5.0
Log T eff

THE NOVA CODE:

- Lagrangian, fully implicit, 1-D hydrodynamics
- Radiation transport by diffusion
- OPAL opacities
- EOS: Timmes
- Time dependent, mixing-length, convection
- Elements mixed by diffusion in convective region
- 34 nuclei reaction network from Timmes
- New Network from Hix and Thielemann (1999)
- Iliadis reaction rate libraries + pep reaction
- Accretion via a fast rezoning algorithm
- Boundary layer heating

The Initial Models:

1) Start with a Classical Nova Simulation go through an outburst and remove ejected material

2) Allow white dwarf to cool after explosion until luminosity is 30 $L_\odot$ (~3 years after outburst: Nova Cyg 92).

3) Start accreting and assume no mixing with core (accreting gas has either solar or LMC metallicity)

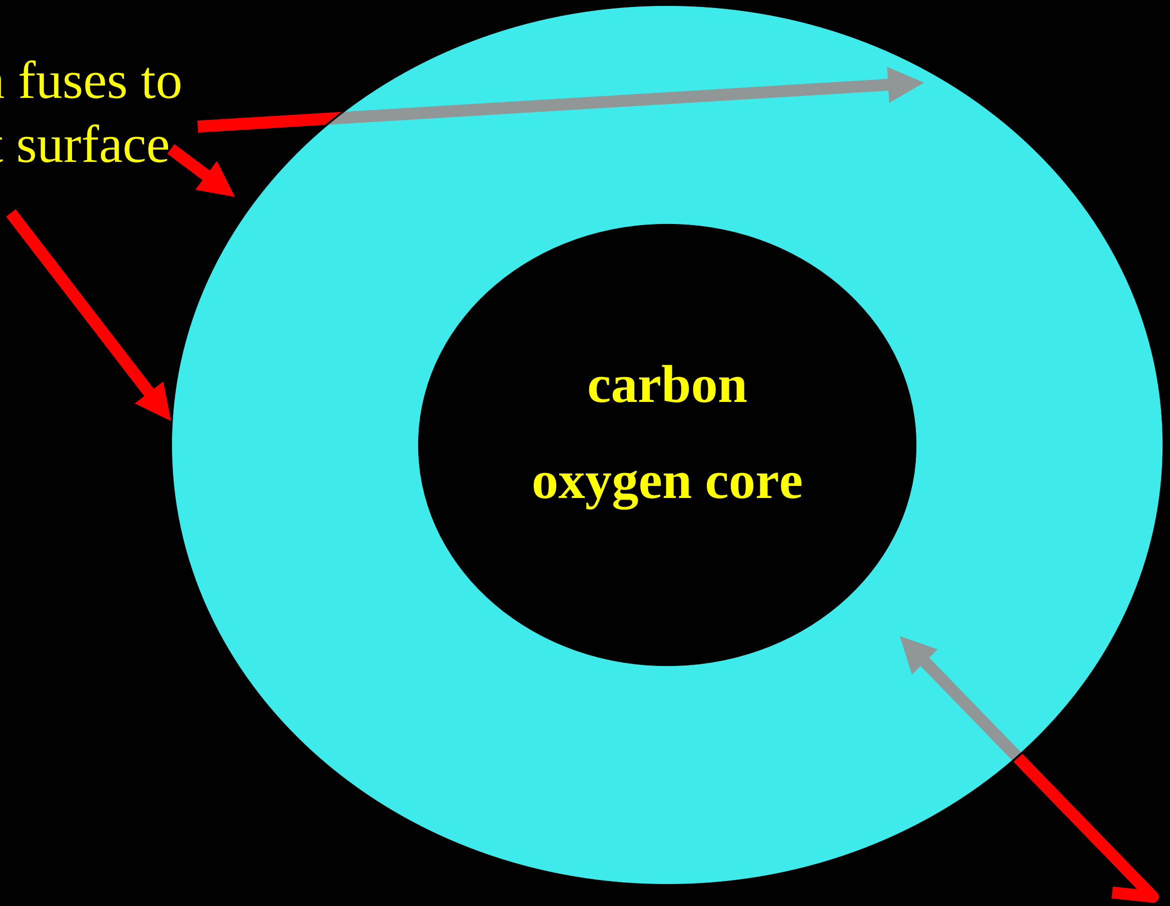
4) Include all necessary physics (I don’t have to say this anymore)

5) Evolve 1.25$M_\odot$ and 1.35$M_\odot$ HOT WDs

6) Vary the mass accretion rates

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: Hot $1.35M_\odot$ 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
$\delta M_{acc}(M_\odot)$	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 $M_{WD}=1.35M_\odot$, $L_{WD}=30L_\odot$, $T_{eff}=2.3 \times 10^5$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 Carbon Oxygen core
- For surface zone (sz) mass ~ $10^{-7}M_\odot$
- After 15 yrs of evolution, $T_{sz} = 3 \times 10^8$K
- H burns to He in the upper 10^{-6} Solar masses
- He mass fraction declines to zero somewhat deeper into WD
- Have accreted ~ $3 \times 10^{-2}M_\odot$ and WD mass reached $1.38M_\odot$
- Stopped evolution because at Chandrasekhar Mass
- Carbon/Oxygen ratio depends on mass accretion rate
- Carbon completely depleted at highest mass accretion rate

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

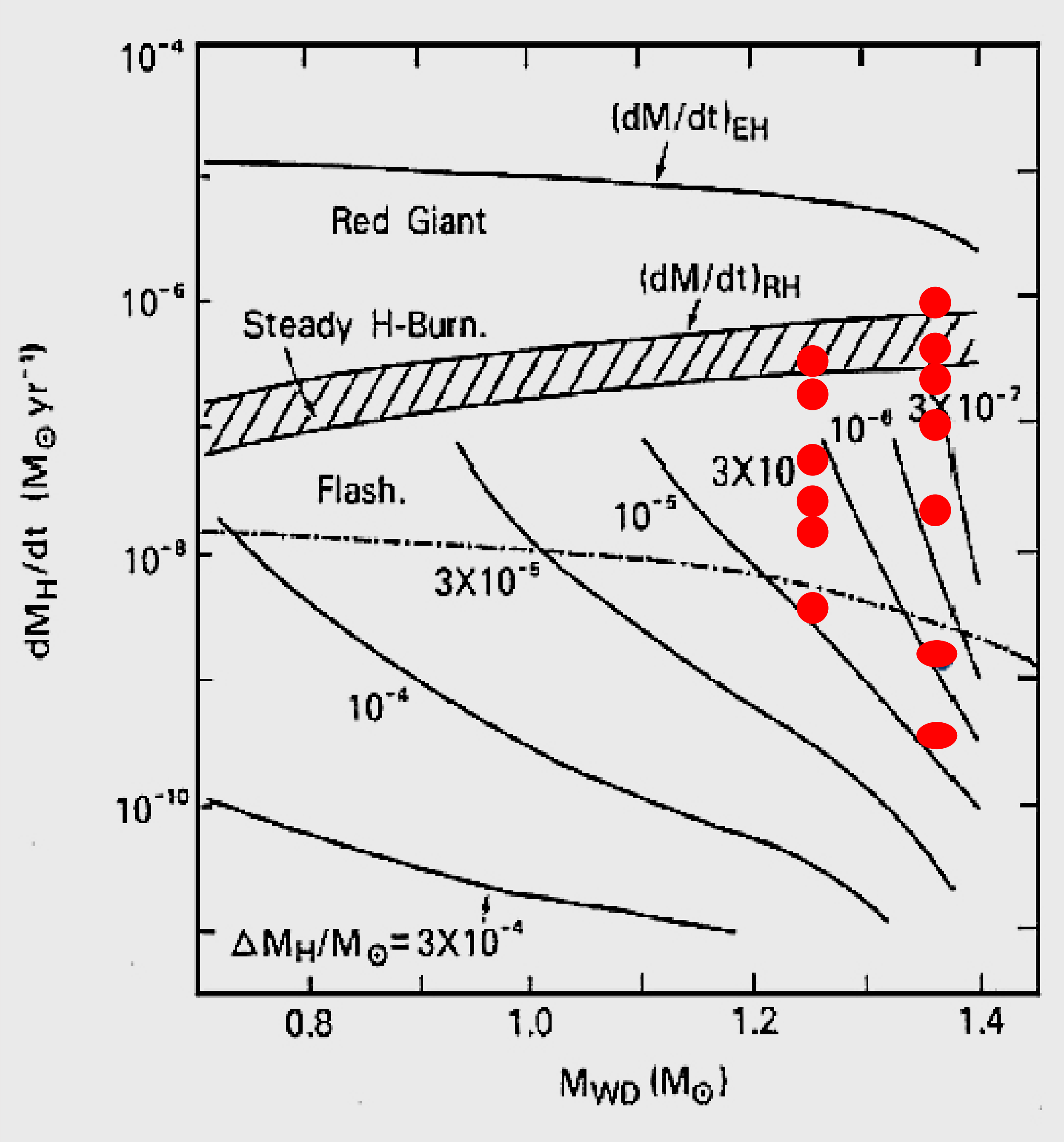


Table 1: Results of the Hot 1.25$M_\odot$ White Dwarf Evolutionary Sequences

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_{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}
τ_{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
$\delta M_{acc}(M_\odot)$	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}
$T_{SHB}(10^6K)$	79	102	114	156	182	190	169	230
ϵ_{nuc}(SHB:) 10^8erg $gm^{-1}s^{-1}$)	.2	.8	1.6	7.8	15.6	29.6	78.	~30.
L_{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_{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_{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_{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	

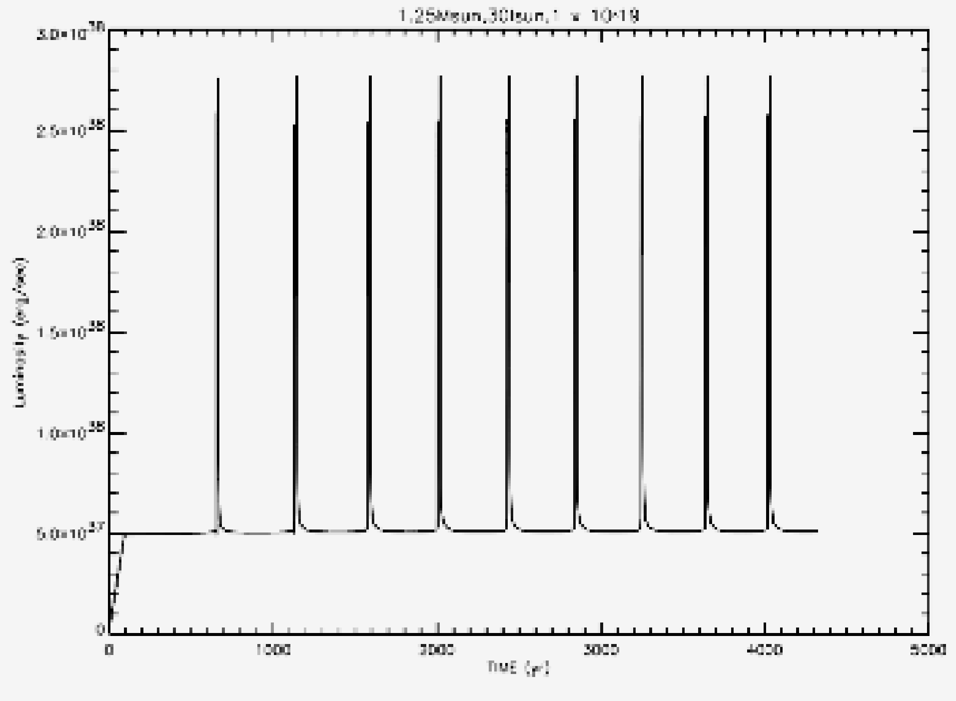
† Sequences 2,3, and 7 underwent helium runaways at the evolution time listed in the table. Only a small fraction of accreted material ($\sim 10^{-5} M_\odot$) was ejected.

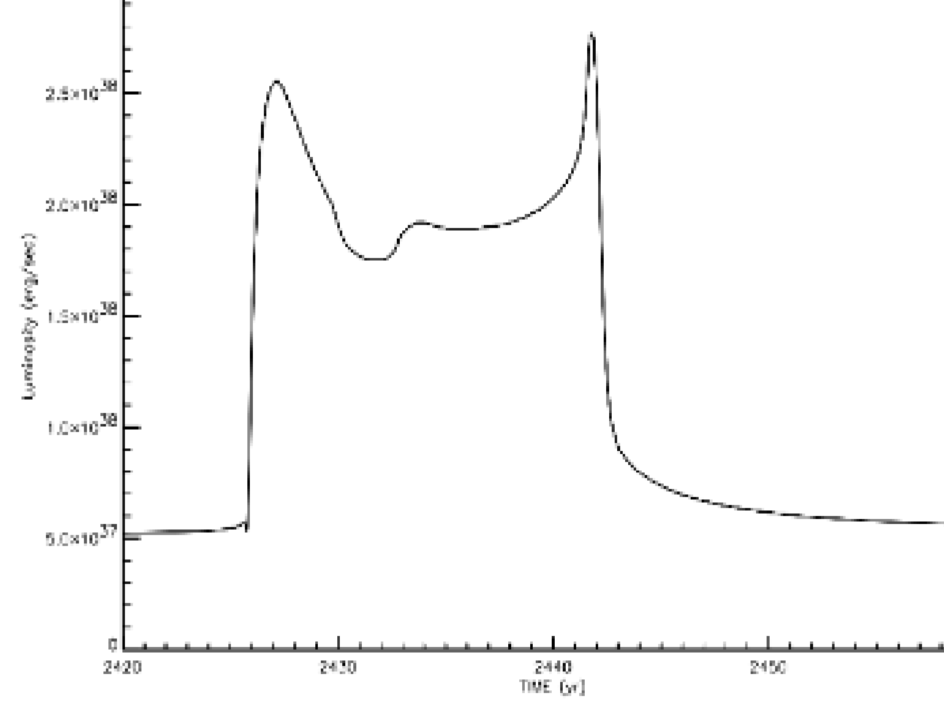
$^\#$ Canonical theory predicts that Steady Burning occurs at this mass only for $\dot{M} \sim 3 \times 10^{-7} M_\odot$ yr^{-1}.

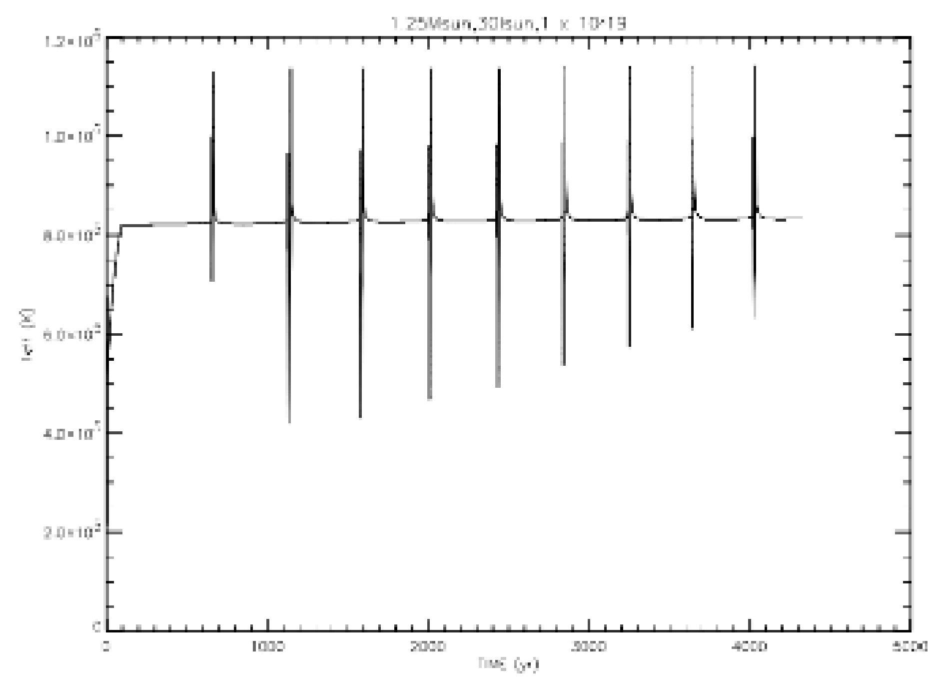
$^\%$ This sequence expanded to large radii after 25 yr of evolution.

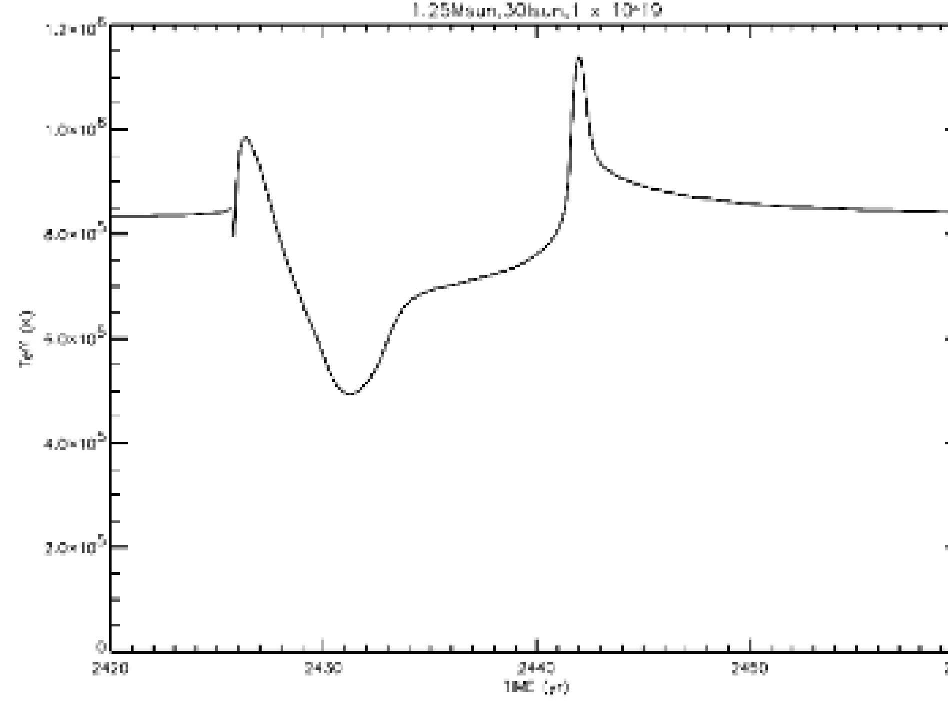
^{a} CI = Composition Interface: All abundances are mass fractions.

^{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)


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
1.2×10^5
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
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)

Our Results Justify the Neglect of Hydrogen and Helium in the Study of Accretion onto White Dwarfs by Nomoto (1982)

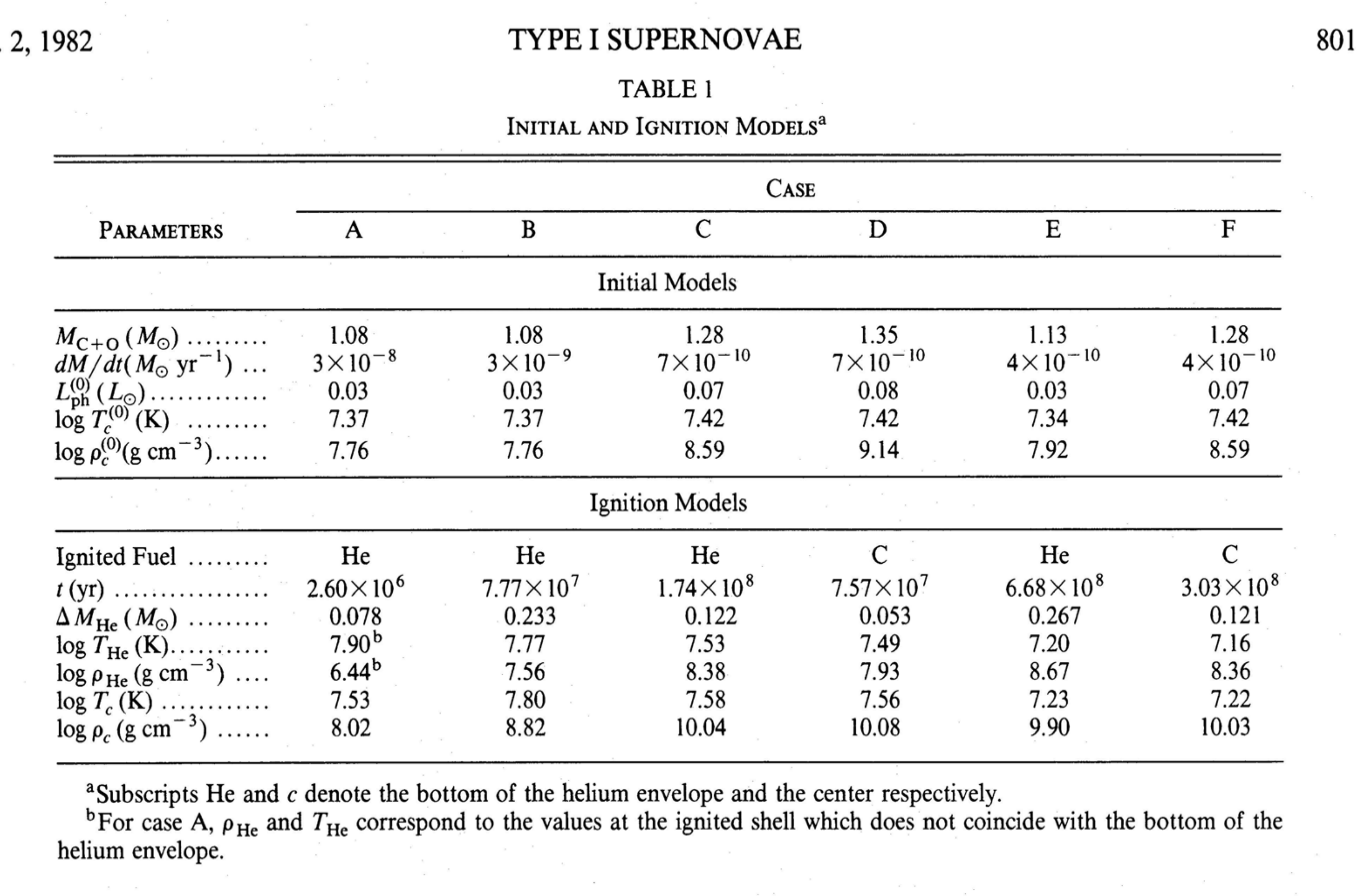


TABLE 1

INITIAL AND IGNITION MODELS[a]

PARAMETERS	CASE A	CASE B	CASE C	CASE D	CASE E	CASE F
	Initial Models					
$M_{C+O}\,(M_\odot)$	1.08	1.08	1.28	1.35	1.13	1.28
$dM/dt(M_\odot\ \mathrm{yr}^{-1})$ ...	3×10^{-8}	3×10^{-9}	7×10^{-10}	7×10^{-10}	4×10^{-10}	4×10^{-10}
$L_{ph}^{(0)}\,(L_\odot)$	0.03	0.03	0.07	0.08	0.03	0.07
$\log T_c^{(0)}$ (K)	7.37	7.37	7.42	7.42	7.34	7.42
$\log \rho_c^{(0)}(\mathrm{g\ cm}^{-3})$......	7.76	7.76	8.59	9.14	7.92	8.59
	Ignition Models					
Ignited Fuel	He	He	He	C	He	C
t (yr)	2.60×10^{6}	7.77×10^{7}	1.74×10^{8}	7.57×10^{7}	6.68×10^{8}	3.03×10^{8}
$\Delta M_{He}\,(M_\odot)$	0.078	0.233	0.122	0.053	0.267	0.121
$\log T_{He}$ (K)...........	7.90[b]	7.77	7.53	7.49	7.20	7.16
$\log \rho_{He}\,(\mathrm{g\ cm}^{-3})$	6.44[b]	7.56	8.38	7.93	8.67	8.36
$\log T_c$ (K)	7.53	7.80	7.58	7.56	7.23	7.22
$\log \rho_c\,(\mathrm{g\ cm}^{-3})$	8.02	8.82	10.04	10.08	9.90	10.03

[a] Subscripts He and c denote the bottom of the helium envelope and the center respectively.

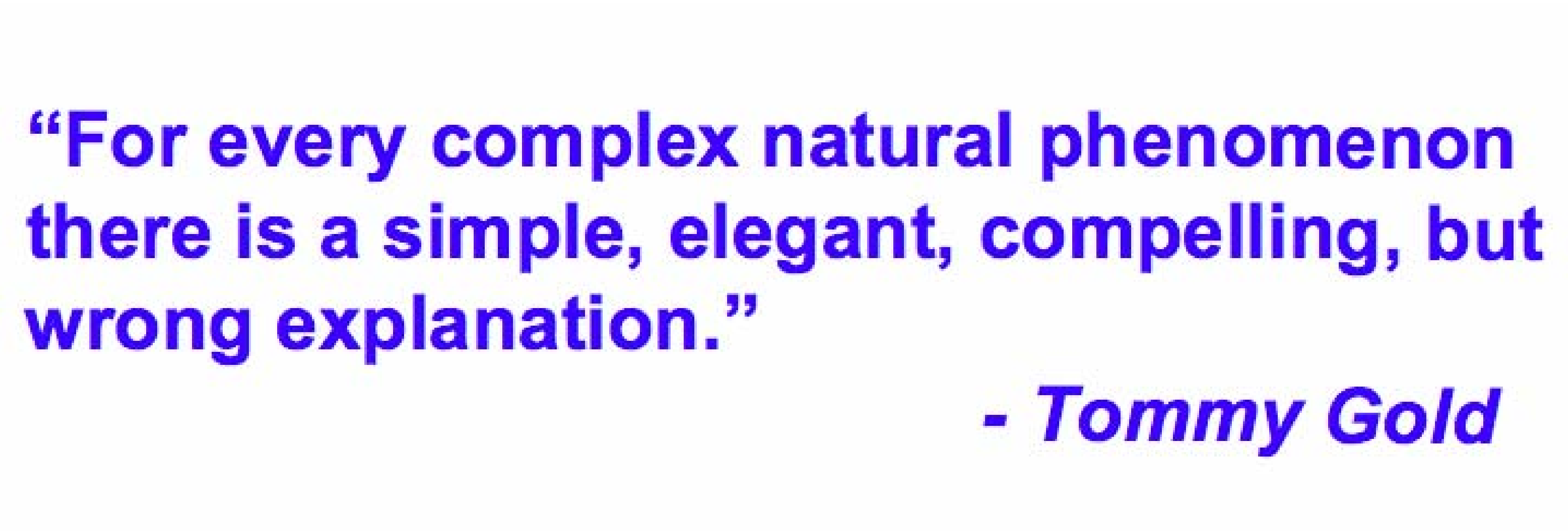
[b] For case A, ρ_{He} and T_{He} correspond to the values at the ignited shell which does not coincide with the bottom of the helium envelope.

STABLE:

1.not likely to fall or give way, as a structure, support, foundation, etc.; firm; steady.
2.able or likely to continue or last; firmly established; enduring or permanent: *a stable government.*
3.resistant to sudden change or deterioration: *A stable economy is the aim of every government.*
4.steadfast; not wavering or changeable, as in character or purpose
5.not subject to emotional instability or illness; sane; mentally sound
6.*Physics*. to react to a disturbing force by maintaining or reestablishing position, form, etc.

7. a building for the lodging and feeding of horses, cattle, etc.
8. such a building with stalls.
9. a collection of animals housed in such a building.

Stable Burning:



> “For every complex natural phenomenon there is a simple, elegant, compelling, but wrong explanation.”
>
> *- Tommy Gold*

Accretion of Solar Material onto LOW Luminosity White Dwarfs (Preliminary)

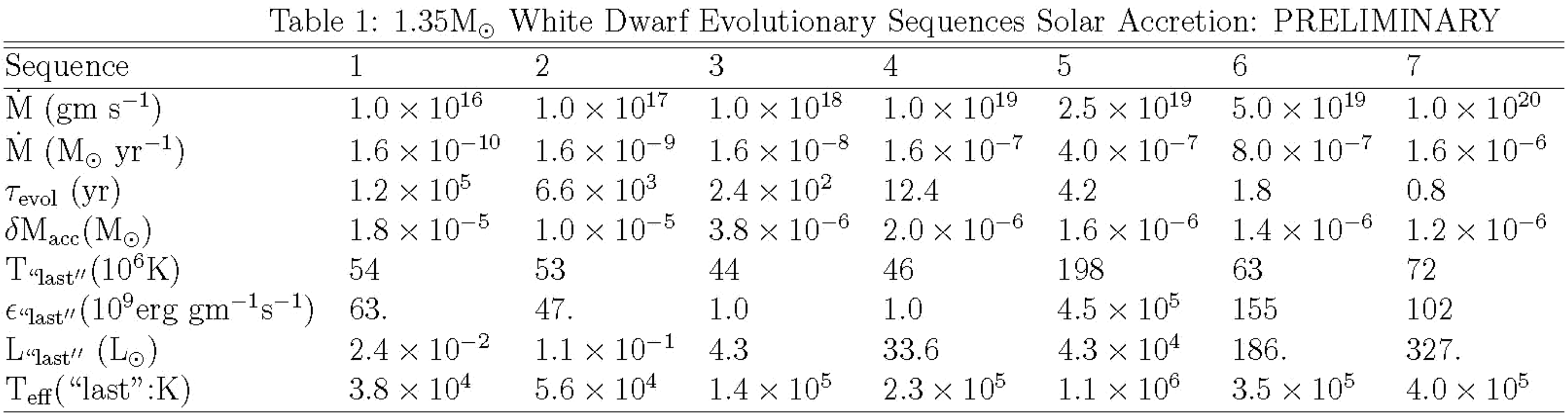


Table 1: $1.35 M_\odot$ White Dwarf Evolutionary Sequences Solar Accretion: PRELIMINARY

Sequence	1	2	3	4	5	6	7
$\dot{M}$ (gm s^{-1})	1.0×10^{16}	1.0×10^{17}	1.0×10^{18}	1.0×10^{19}	2.5×10^{19}	5.0×10^{19}	1.0×10^{20}
$\dot{M}$ ($M_\odot$ yr^{-1})	1.6×10^{-10}	1.6×10^{-9}	1.6×10^{-8}	1.6×10^{-7}	4.0×10^{-7}	8.0×10^{-7}	1.6×10^{-6}
τ_{evol} (yr)	1.2×10^{5}	6.6×10^{3}	2.4×10^{2}	12.4	4.2	1.8	0.8
$\delta M_{acc} (M_\odot)$	1.8×10^{-5}	1.0×10^{-5}	3.8×10^{-6}	2.0×10^{-6}	1.6×10^{-6}	1.4×10^{-6}	1.2×10^{-6}
$T_{\text{“last”}} (10^6 K)$	54	53	44	46	198	63	72
$\epsilon_{\text{“last”}} (10^9 \text{erg gm}^{-1} s^{-1})$	63.	47.	1.0	1.0	4.5×10^{5}	155	102
$L_{\text{“last”}}$ ($L_\odot$)	2.4×10^{-2}	1.1×10^{-1}	4.3	33.6	4.3×10^{4}	186.	327.
T_{eff}(“last”:K)	3.8×10^{4}	5.6×10^{4}	1.4×10^{5}	2.3×10^{5}	1.1×10^{6}	3.5×10^{5}	4.0×10^{5}

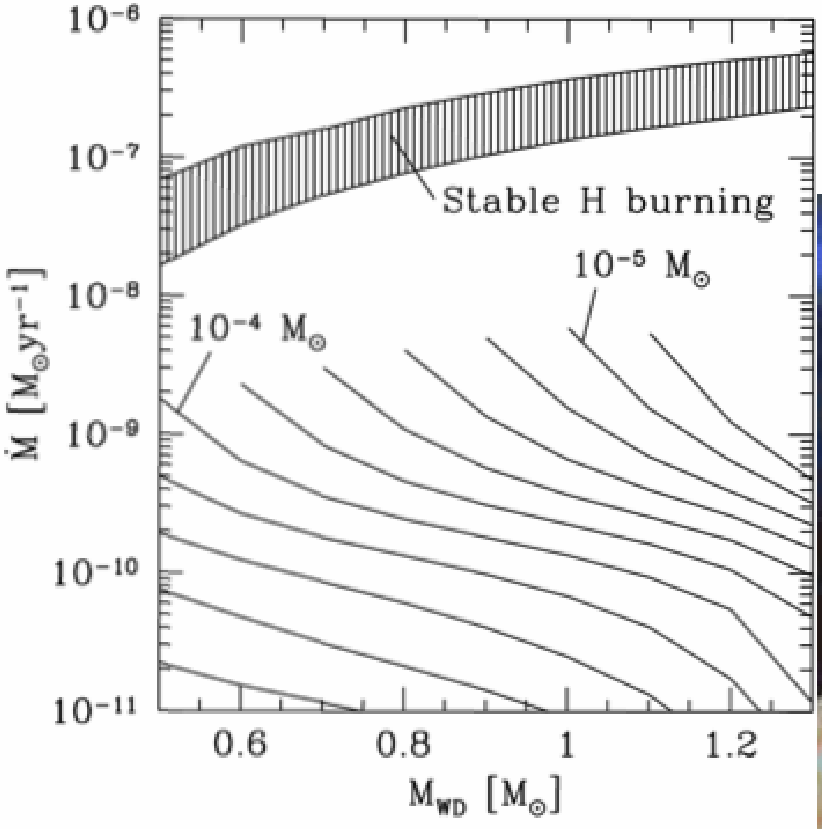
L (initial) $= 9.2 \times 10^{-3} L_{sun}$

Teff (initial) $= 3 \times 10^4$ K

R(initial) = 2494 km

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 Stable Burning.
5) However, the luminosity and effective temperature can remain constant for thousands of years (at 1.35 $M_{\odot}$).
6) We call it "Surface Hydrogen Burning (SHB)."
7) The range of mass accretion rates onto HOT WDs at which SHB occurs is much larger than the "single" value assumed for Steady Burning.
8) We do not find Stable Burning for Low Luminosity WDs



(Nomoto et al. ‘06; Townsley & Bildsten ‘0