Classical novae: A laboratory for nuclear astrophysics

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Classical Novae: a Laboratory for Nuclear Astrophysics

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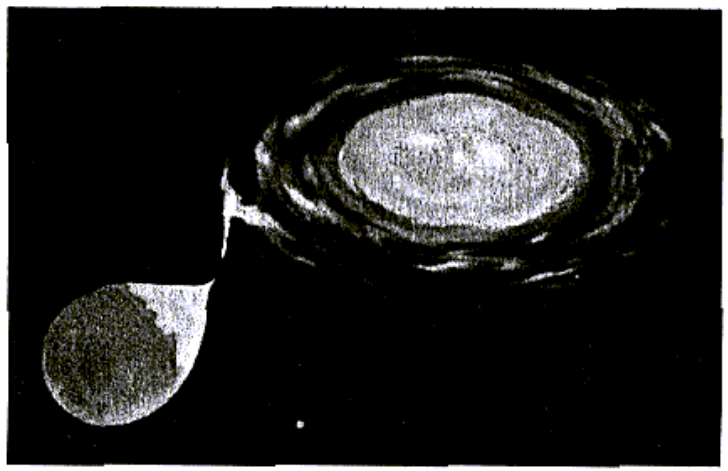
1. Introduction

- The TNR Model of Classical novae: Thermonuclear runaway in the white dwarf component of a close binary system (Starrfield et al. 1972; Prialnik, Shara & Shaviv 1978).

  The large, MS companion transfers matter through the inner L_1 Lagrangian point by Roche lobe overflow, building up an accretion disk. A fraction of this H-rich matter ends up on top of the WD, where it's compressed until conditions to drive a TNR are reached.



↓

* Interplay between nova outbursts and the Galactic chemical abundances
* Synthesis of γ-ray emitters

The nature of the binary system ➡ Outcome of the accreting WD

* Symbiotic systems (WD + RG star) ⟺ H-rich accretion
* Cataclysmic variables (WD + MS star)

* He-star companion ⟺ He-rich accretion
* Indirect He-accretion (ashes of H-burning)

* Double degenerate systems (WD + WD) ⟺ C/CO/ONe-rich accretion

Chemical composition

- Solar abundances (accreted): Anders & Grevesse (1989)
- Core composition (outermost shells):
  - CO WDs: Salaris et al. (1996)

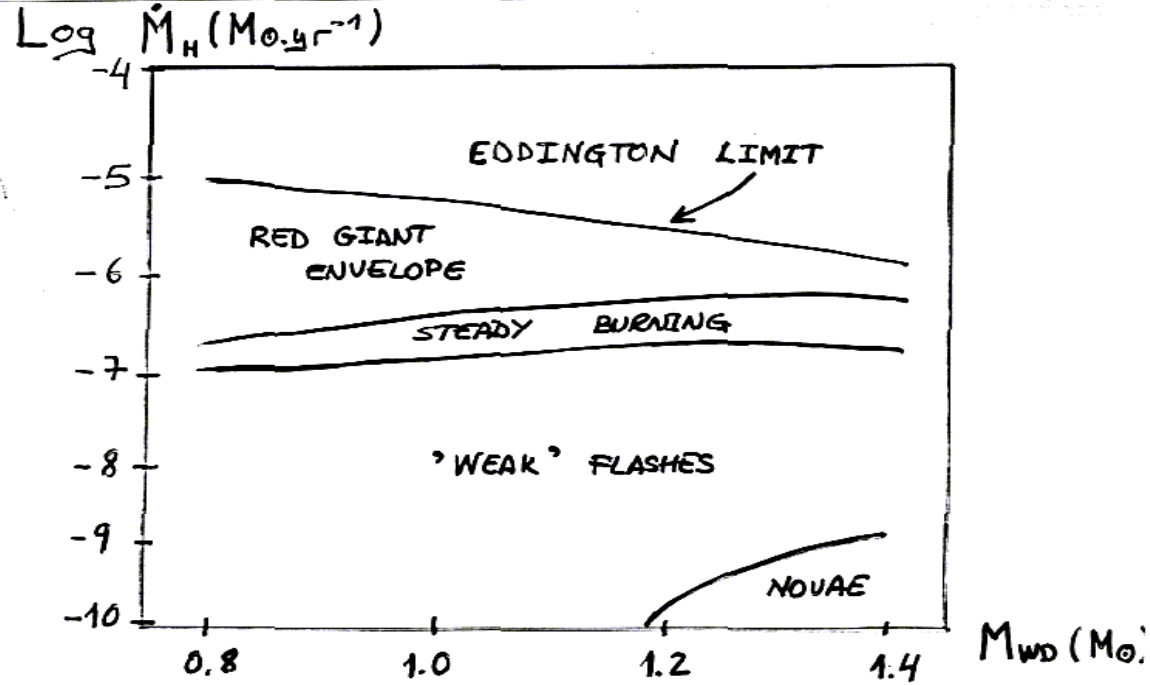
    $X(^{12}C)=X(^{16}O)=0.495$

    $X(^{22}Ne)=0.01$
  - ONe WDs: Ritossa, García-Berro & Iben (1996)

    $X(^{16}O) : X(^{20}Ne) : X(^{24}Mg)$

    10 : 6 : 1

    [1.5 : 2.5 : 1 Arnett & Truran 1969]



$$\dot{M}_{Edd}\,(M_\odot\,yr^{-1}) = 7.5\times10^{-6}\,(R/5\times10^{8}\,cm)$$

$$\dot{M}_{RG}\,(M_\odot\,yr^{-1}) = 8.5\times10^{-7}\,(M/M_\odot - 0.5)$$

(Paczyński 1970; Paczyński & Rudak 1980)

$$\dot{M}_{sb}\,(M_\odot\,yr^{-1}) = 0{,}4\,\dot{M}_{RG} = 3{,}3\times10^{-7}\,(M/M_\odot - 0.5)$$

(Livio, Prialnik & Regev 198[illegible])

$$\log \dot{M}_{nova}\,(M_\odot\,yr^{-1}) = -8{,}775 - 15{,}088\,(M/M_\odot - 1{,}459)^2$$

with $\log L_c\,(L_\odot) = -0{,}629 - 5{,}923\,(M/M_\odot - 1{,}766)^2$

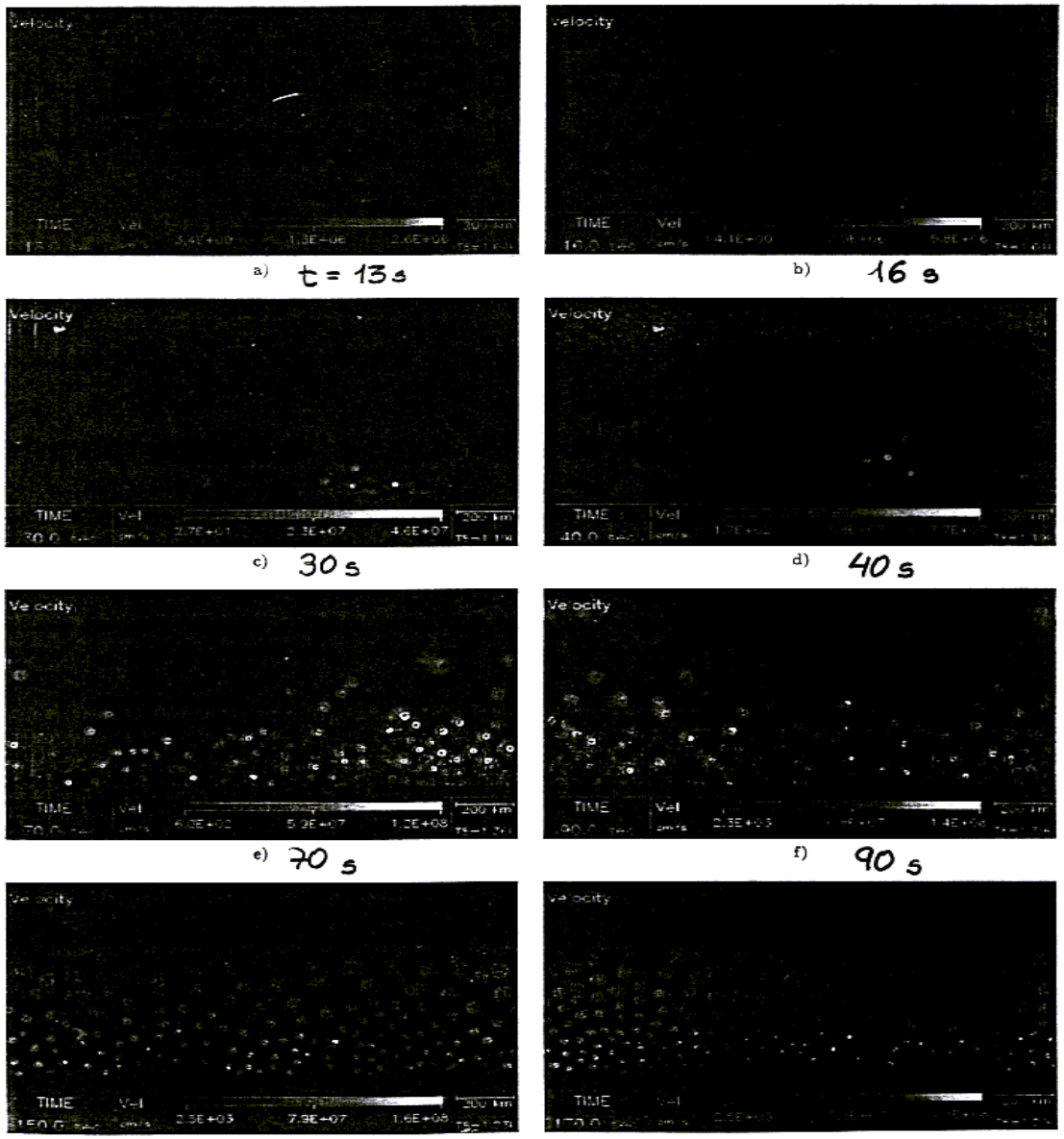
(MacDonald 1983)

NUCLEOSYNTHESIS: HISTORICAL BACKGROUND

- Observations (optical, UV, IR)
  → enrichments in CNO and often in Ne
- Models
  - Parametrized (one or two-zone) models
    - Wiescher et al. 1986: explosive H-nucleosynthesis
    - Boffin et al. 1993: ^{7}Be
    - Weiss & Truran 1990: ^{22}Na and ^{26}Al; Nofar et al. 1991: ^{26}Al
  - Fully convective hydrostatic models
    - MacDonald, 1983, Coc et al. 1995: effect of nuclear uncertainties in ^{22}Na and ^{26}Al Wanajo et al. 1999
  - Hydrodynamic models
    Global properties, including nucleosynthesis, but accretion phase not always followed
    - Starrfield et al. 1978 ...; Prialnik et al. 1978 ...
      → need of initial enrichment (core material) both to power the explosion and to synthesize some observed elements

Kercek, Hillebrandt & Truran (1998)

$1\ M_\odot$ CO



Mechanisms of mixing:

* **Diffusion Induced Convection** [Prialnik & Kovetz 1984; Kovetz & Prialnik 1985; Iben, Fujimoto & MacDonald 1991, 1992; Fujimoto & Iben 1992]
* **Shear mixing** [MacDonald 1983; Livio & Truran 1987]
* **Convective Oveshoot Induced Flame Propagation** [Woosley 1986]
* **Convection Induced Shear Mixing** [Kutter & Sparks 1989]
* **Multidimensional process** [Glasner, Livne & Truran 1997; Kercek & Hillebrandt 1998]

Usual assumption, → 50% solar-like material **(accreted)**
50% core material **(outermost shells)**

But! Degree of mixing becomes another free parameter of the model (to account for the wide spread in metallicity)

* Effect of the chemical composition : ONe vs CO white dwarf

$\dot{M} = 1.6 \times 10^{-10}\ M_\odot . yr^{-1}$

	Model 3	Model 6
$M_{wd}(M_\odot)$	1.15	1.15
Composition	50% solar 50% ONe	50% solar 50% CO
$\Delta M_{env}(M_\odot)$	$\boxed{3.18 \times 10^{-5}}$	$\boxed{1.81 \times 10^{-5}}$
t_{acc} (yr)	1.86×10^5	1.01×10^5
$P_{max}(\mathrm{dyn\,cm^{-2}})$	$\boxed{1.69 \times 10^{19}}$	$\boxed{1.20 \times 10^{19}}$
$\rho_{max}(\mathrm{g\,cm^{-3}})$	6.61×10^3	5.31×10^3
$T_{bs}(\mathrm{K})$	2.93×10^7	2.37×10^7
$\rho_{bs}(\mathrm{g\,cm^{-3}})$	4.97×10^3	4.21×10^3

Results of the hydrostatic evolution, at the end of the accretion phase.

	Model 3	Model 6
$M_{wd}(M_\odot)$	1.15	1.15
Composition	50% ONe, 50% Solar	50% CO, 50% Solar
$\Delta M_{env}(M_\odot)$	3.18×10^{-5}	1.81×10^{-5}
$t_{100}(\mathrm{s})$	1.26×10^7	7.18×10^5
$t_{max}(\mathrm{s})$	5.39×10^2	6.45×10^1
$T_{max}(\mathrm{K})$	$\boxed{2.19 \times 10^8}$	$\boxed{2.05 \times 10^8}$
$\varepsilon_{nuc,max}(\mathrm{erg\,g^{-1}\,s^{-1}})$	7.63×10^{15}	1.10×10^{16}
$\overline{v}_{ejec}(\mathrm{km\,s^{-1}})$	$\boxed{2498}$	$\boxed{2736}$
$K(\mathrm{erg})$	$\boxed{1.16 \times 10^{45}}$	$\boxed{9.75 \times 10^{44}}$
$\Delta M_{ejec}(M_\odot)$	$\boxed{1.87 \times 10^{-5}}$	$\boxed{1.31 \times 10^{-5}}$

Results of the hydrodynamic evolution.

- ΔM_{env} (ONe Model) $\sim$ 2 ΔM_{env} (CO Model)

$\downarrow$

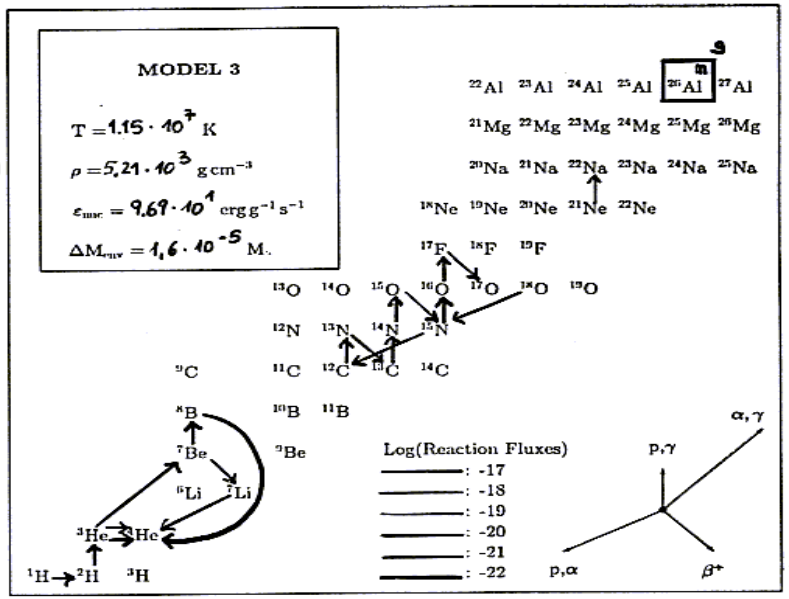
P_{max} (ONe Model) > P_{max} (CO Model)

A more violent outburst expected for the ONe Model.

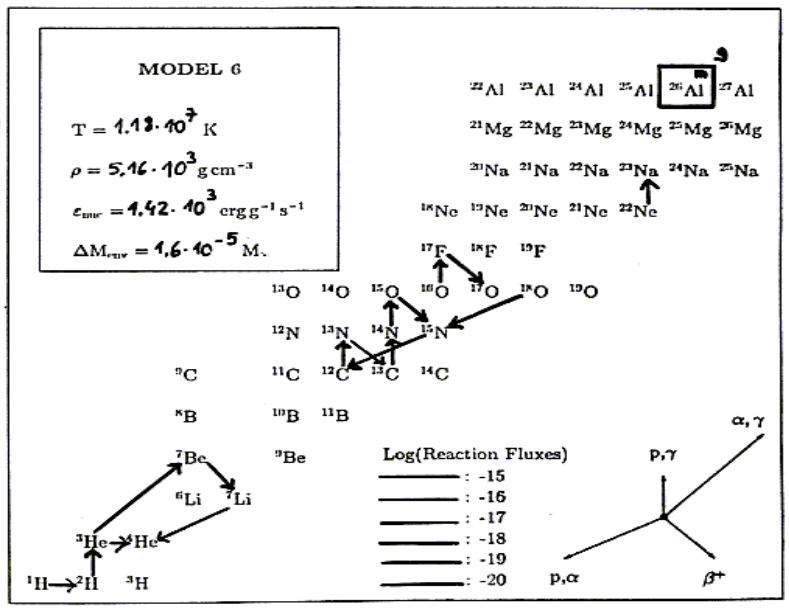
(T_{max}, K, ΔM_{ejec} $\uparrow$)

(José 1996

1.15 $M_\odot$
ONe WD
[$1.6 \times 10^{-10} M_\odot yr^{-1}$]



1.15 $M_\odot$
CO WD
[$1.6 \times 10^{-10} M_\odot yr^{-1}$]



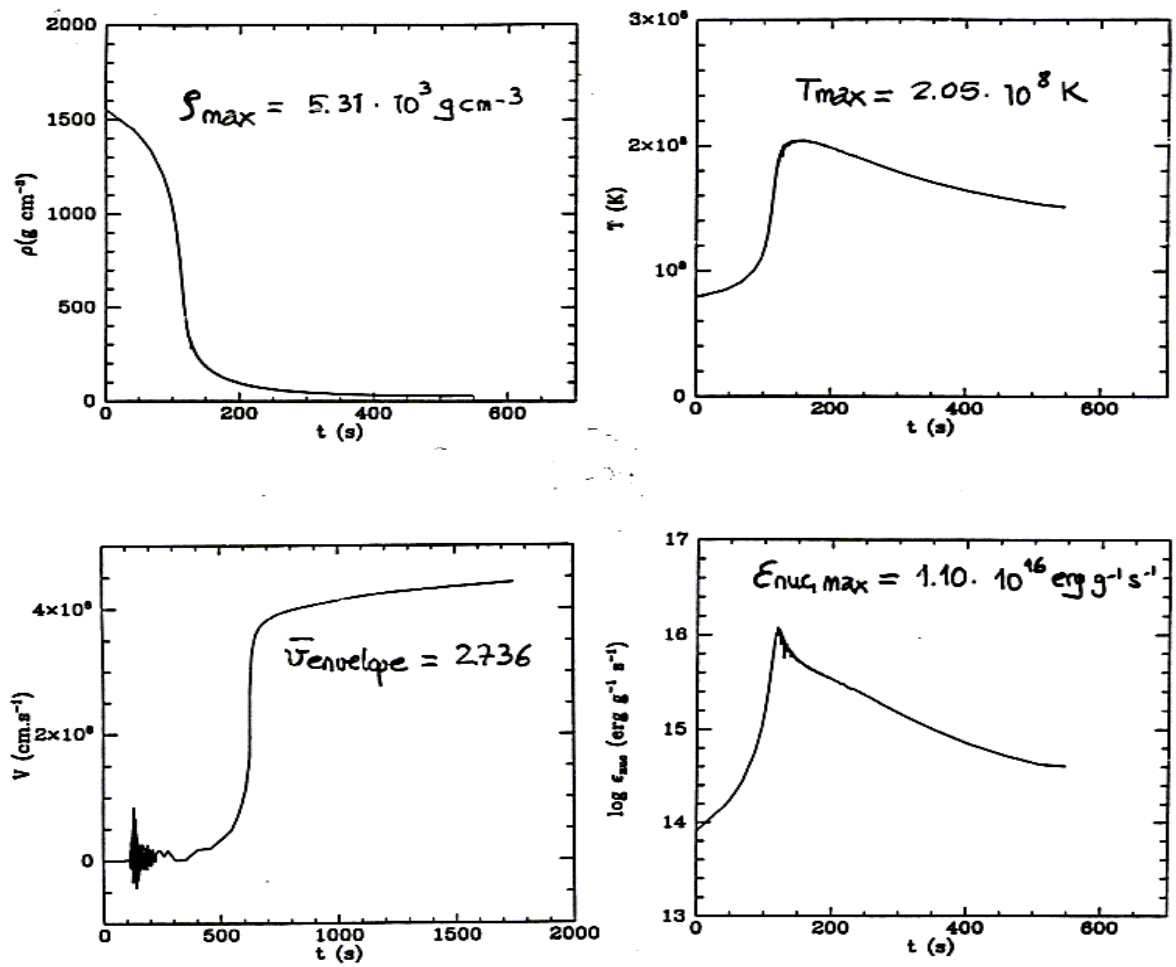


Fig. 3.14. Evolution of density, temperature, pressure and rate of nuclear energy generation at the burning shell for Model 6 (1.15 CO white dwarf, with $\dot{M} = 1.6 \times 10^{-10}\,M_\odot\,yr^{-1}$), as a function of time. The origin of the time coordinate is arbitrarily chosen as the moment when $T_H = 8 \times 10^7$ K, in order to display the different physical magnitudes around the peak of the TNR.

1.15 $M_\odot$, CO WD with 1.6×10^{-10} $M_\odot\,yr^{-1}$

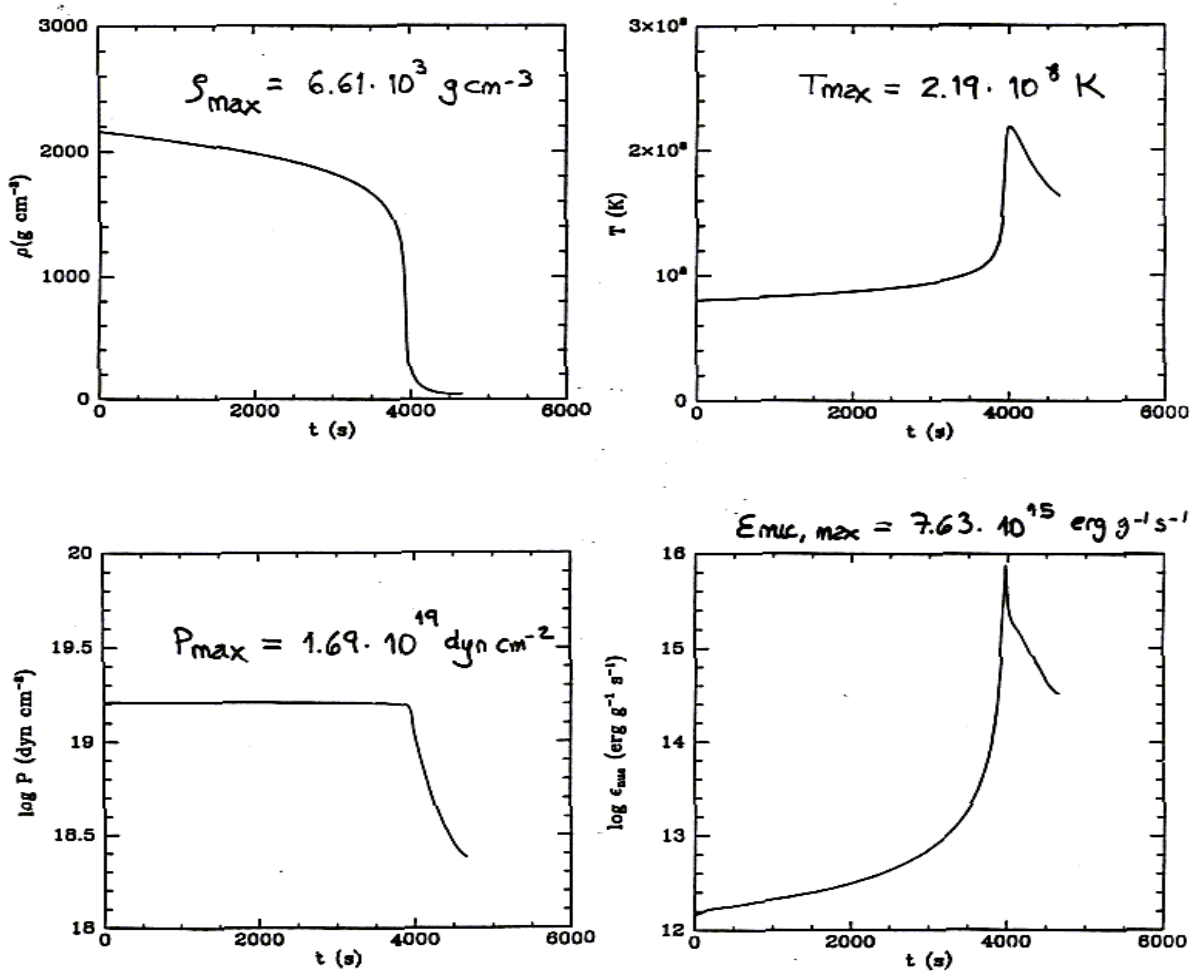
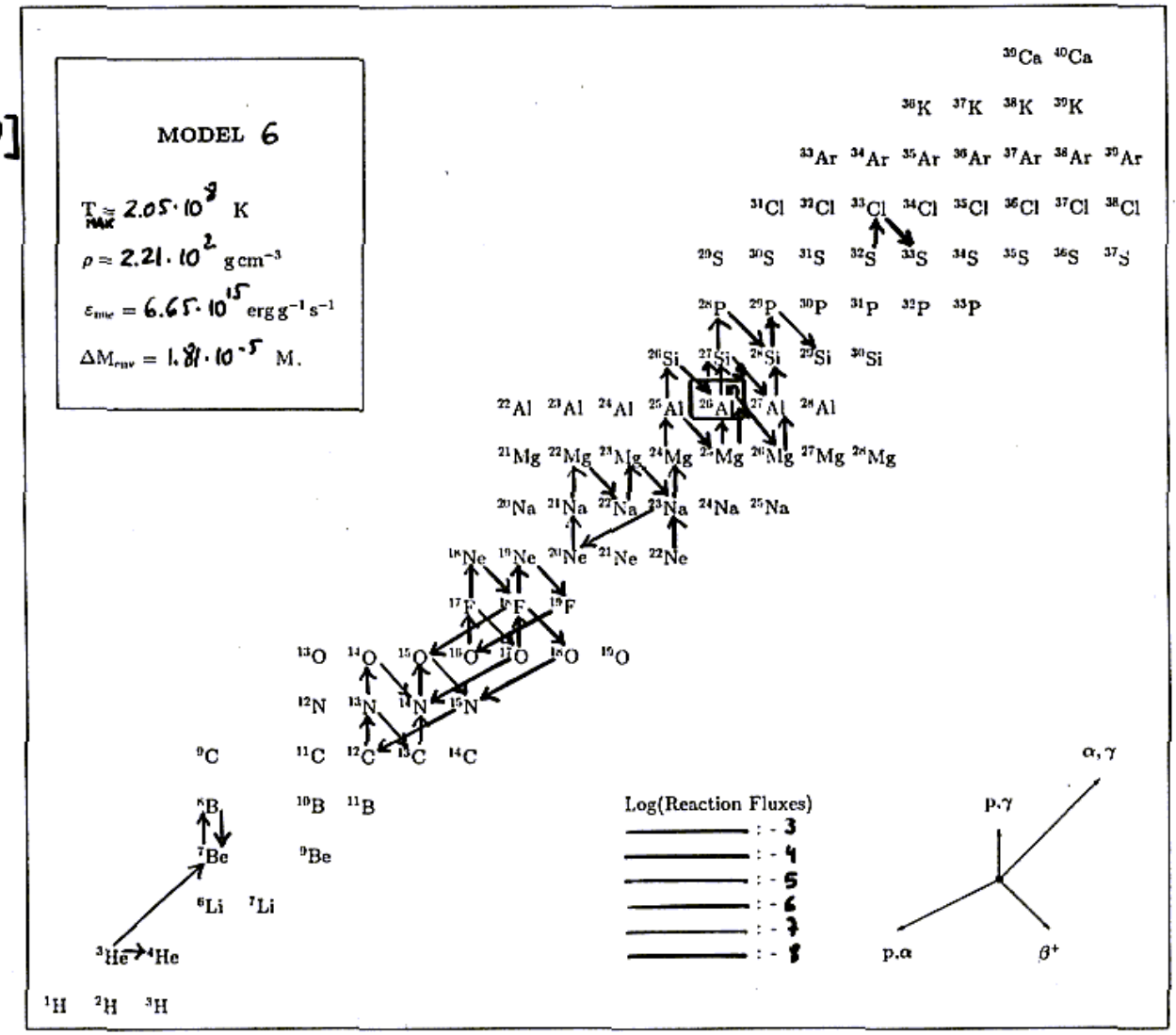


Fig. 3.9. Evolution of density, temperature, pressure and rate of nuclear energy generation at the burning shell for Model 3 (1.15 ONe white dwarf, with $\dot{M} = 1.6 \times 10^{-10}\,M_\odot\,yr^{-1}$), as a function of time. The origin of the time coordinate is arbitrarily chosen as the moment when $T_H = 8 \times 10^7$ K, in order to display the different physical magnitudes around the peak of the TNR.

1.15 $M_\odot$, ONe WD with 1.6×10^{-10} $M_\odot yr^{-1}$

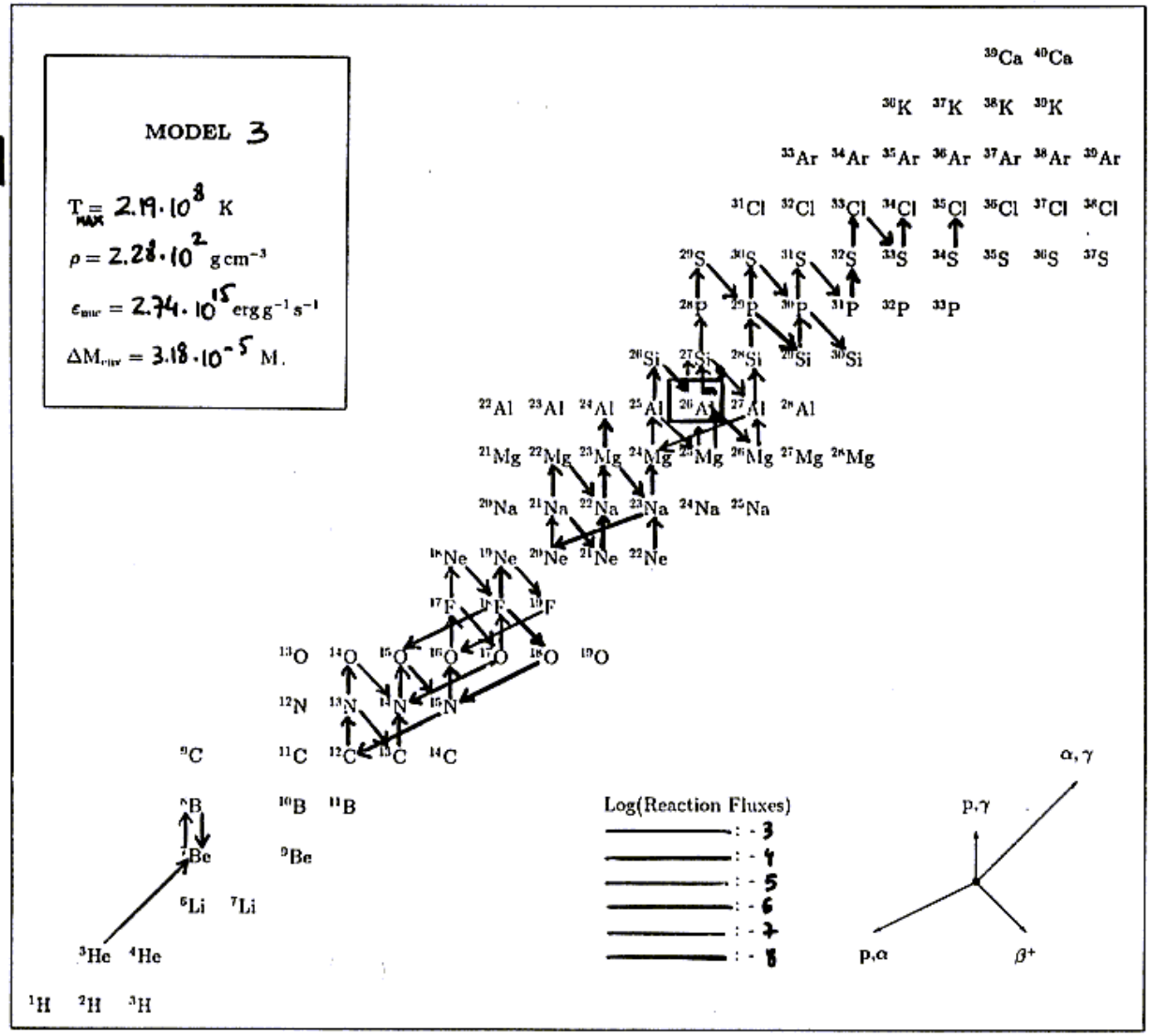
1.15 $M_\odot$
CO WD
[$1.6 \times 10^{-10} M_\odot yr^{-1}$]



1.15 $M_\odot$

ONe WD

[$1.6 \times 10^{-10} M_\odot yr^{-1}$]



* Influence of the white dwarf mass

$\dot{M} = 1.6 \times 10^{-10}\ M_\odot\, yr^{-1}$

ONe Models

	Model 3	Model 9	Model 10
$M_{wd}(M_\odot)$	1.15	1.25	1.35
$\Delta M_{env}(M_\odot)$	$\boxed{3.18 \times 10^{-5}}$	$\boxed{2.21 \times 10^{-5}}$	$\boxed{5.38 \times 10^{-6}}$
t_{acc} (yr)	1.86×10^5	1.27×10^5	3.05×10^4
$P_{max}(\mathrm{dyn\,cm^{-2}})$	$\boxed{1.69 \times 10^{19}}$	$\boxed{2.43 \times 10^{19}}$	$\boxed{5.65 \times 10^{19}}$
$\rho_{max}(\mathrm{g\,cm^{-3}})$	6.61×10^3	8.47×10^3	1.48×10^4
$T_{bs}(\mathrm{K})$	2.93×10^7	2.77×10^7	2.69×10^7
$\rho_{bs}(\mathrm{g\,cm^{-3}})$	4.97×10^3	6.85×10^3	1.32×10^4

Results of the hydrostatic evolution, at the end of the accretion stage.

	Model 3	Model 9	Model 10
$M_{wd}(M_\odot)$	1.15	1.25	1.35
$\Delta M_{env}(M_\odot)$	3.18×10^{-5}	2.21×10^{-5}	5.38×10^{-6}
$t_{100}(\mathrm{s})$	1.26×10^7	6.80×10^6	2.47×10^6
$t_{max}(\mathrm{s})$	5.39×10^2	3.84×10^2	1.52×10^2
$T_{max}(\mathrm{K})$	$\boxed{2.19 \times 10^8}$	$\boxed{2.44 \times 10^8}$	$\boxed{3.24 \times 10^8}$
$\varepsilon_{nuc,max}(\mathrm{erg\,g^{-1}\,s^{-1}})$	7.63×10^{15}	2.14×10^{16}	1.87×10^{17}
$\overline{v}_{ejec}(\mathrm{km\,s^{-1}})$	$\boxed{2498}$	$\boxed{3160}$	$\boxed{4808}$
$K(\mathrm{erg})$	1.16×10^{45}	1.43×10^{45}	1.00×10^{45}
$\Delta M_{ejec}(M_\odot)$	$\boxed{1.87 \times 10^{-5}}$	$\boxed{1.44 \times 10^{-5}}$	$\boxed{4.35 \times 10^{-6}}$

Results of the hydrodynamic evolution.

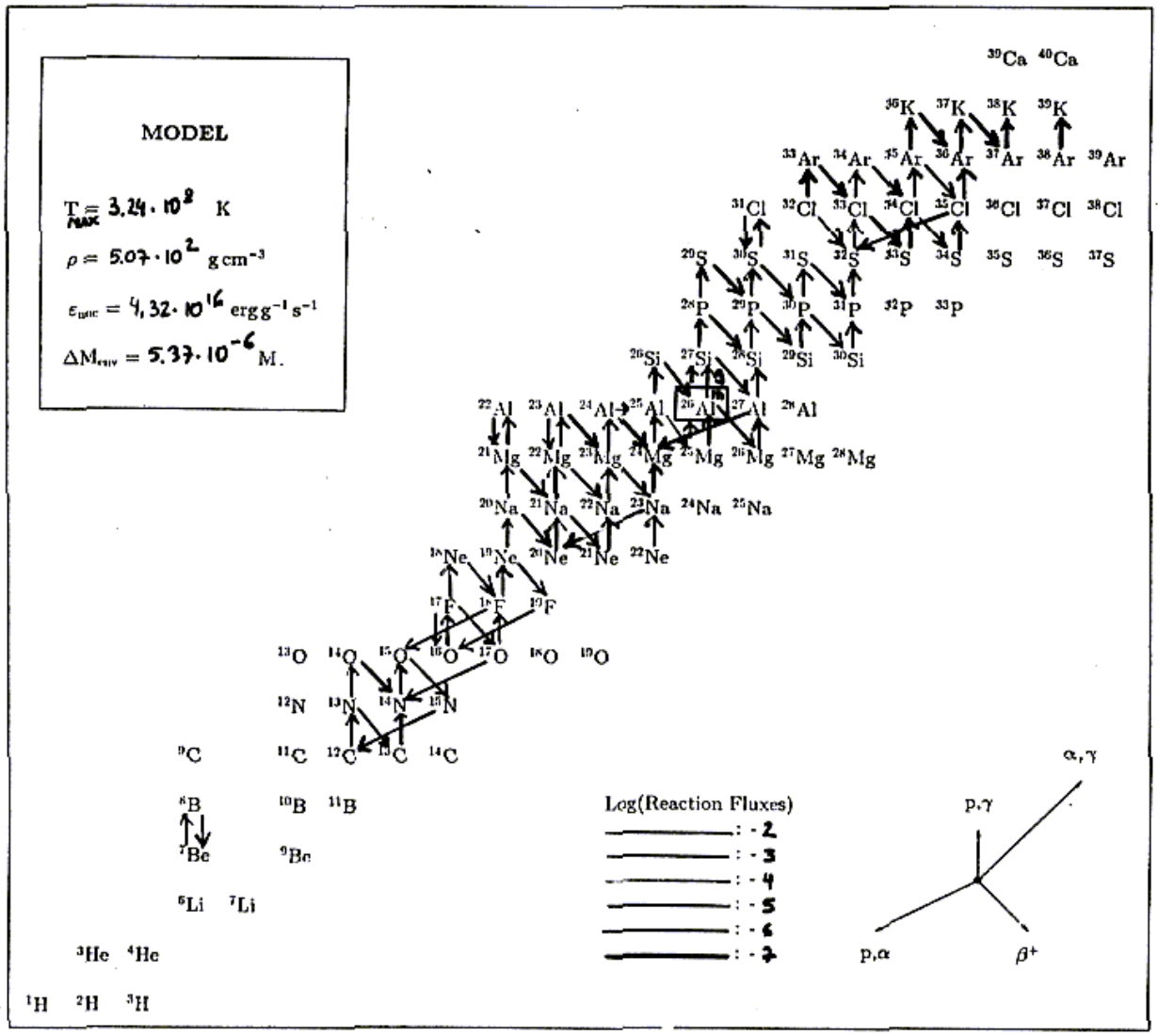
Most relevant feature : when $M_{WD} \uparrow \longrightarrow \begin{cases} \Delta M_{env} \downarrow \\ P_{max} \uparrow \end{cases}$

$\longrightarrow$ More violent outbursts when $M_{WD} \uparrow$

($T_{max} \uparrow$: a moderate leakage from the CNO cycle for 1.25 & 1.35 $M_\odot$ Models)

($\overline{v}_{ejec} \uparrow$, $\Delta M_{ejec} \downarrow$)

1.35 $M_\odot$
ONe WD
$1.6 \times 10^{-10}\ M_\odot yr^{-1}$]



* Effect of the degree of mixing with the white dwarf core.

ONe Models

	Model 2	Model 3	Model 4
$M_{wd}(\mathrm{M}_\odot)$	1.15	1.15	1.15
Composition	25% Solar 75% ONe	50% Solar 50% ONe	75% Solar 25% ONe
$\Delta M_{env}(\mathrm{M}_\odot)$	$\boxed{3.48 \times 10^{-5}}$	$\boxed{3.18 \times 10^{-5}}$	$\boxed{3.16 \times 10^{-5}}$
t_{acc} (yr)	2.05×10^5	1.86×10^5	1.85×10^5
$P_{max}(\mathrm{dyn\,cm^{-2}})$	2.32×10^{19}	1.69×10^{19}	1.68×10^{19}
$\rho_{max}(\mathrm{g\,cm^{-3}})$	9.87×10^3	6.61×10^3	5.56×10^3
$T_{bs}(\mathrm{K})$	2.89×10^7	2.93×10^7	3.54×10^7
$\rho_{bs}(\mathrm{g\,cm^{-3}})$	8.09×10^3	4.97×10^3	3.60×10^3

Results of the hydrostatic evolution, at the end of the accretion stage

M_{wd} $(\mathrm{M}_\odot)$	25% Solar 75% ONe	50% Solar 50% ONe	75% Solar 25% ONe
1.00	8.09×10^{-5}	7.39×10^{-5}	7.23×10^{-5}
1.15	3.48×10^{-5}	3.18×10^{-5}	3.16×10^{-5}
1.25	2.57×10^{-5}	2.29×10^{-5}	2.27×10^{-5}
1.35	5.68×10^{-6}	4.95×10^{-6}	4.94×10^{-6}

Dominant reactions: $^1H(p, e^+\nu)\,^2D$

$^3He\,(^3He, 2\,^1H)\,^4He$

$^{12}C\,(p,\gamma)\,^{13}N\,(\beta^+)\,^{13}C$

Its influence turns out to be very small on ΔM_{env}, compared with the effect of other parameters.

II. Nucleosynthesis vs. Galactic Abundances

Hydrodynamic nova models → Mass ejection ($\sim 2 \times 10^{-5}\ M_o$)

Since $T_{peak} \sim (2 - 3) \times 10^8$ K → Nuclear processed material in the ejecta

Which is the role of nova outbursts in the Galactic chemical puzzle?

Assuming, Galactic nova rate: ~ 30 events.yr^{-1}
Galaxy's lifetime: $\sim 10^{10}$ yr
Mean ejected mass per outburst: $\sim 2 \times 10^{-5}\ M_o$

$\sim 6 \times 10^6\ M_o$ ($\sim$ 1/3000 of the Galactic disk's gas & dust component)

→ **Novae** scarcely contribute **to the Galactic abundances, but they can be likely sites for the synthesis of individual nuclei with** overproduction factors, $f = X_i / X_{i,\ solar} > 1000$

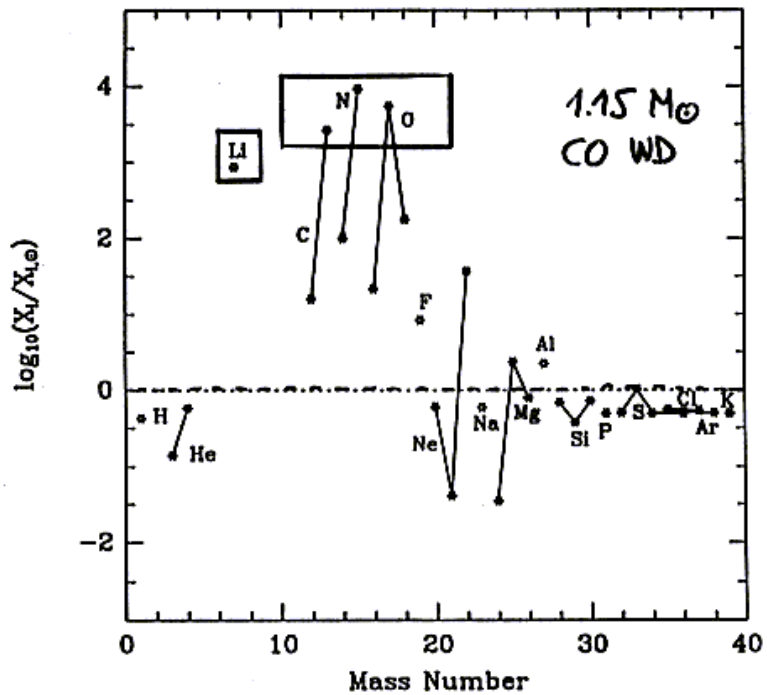


FIG. 1.—Overproduction factors relative to solar abundances vs. mass number for model CO5 ($M_\odot$ CO white dwarf with 50% mixing).

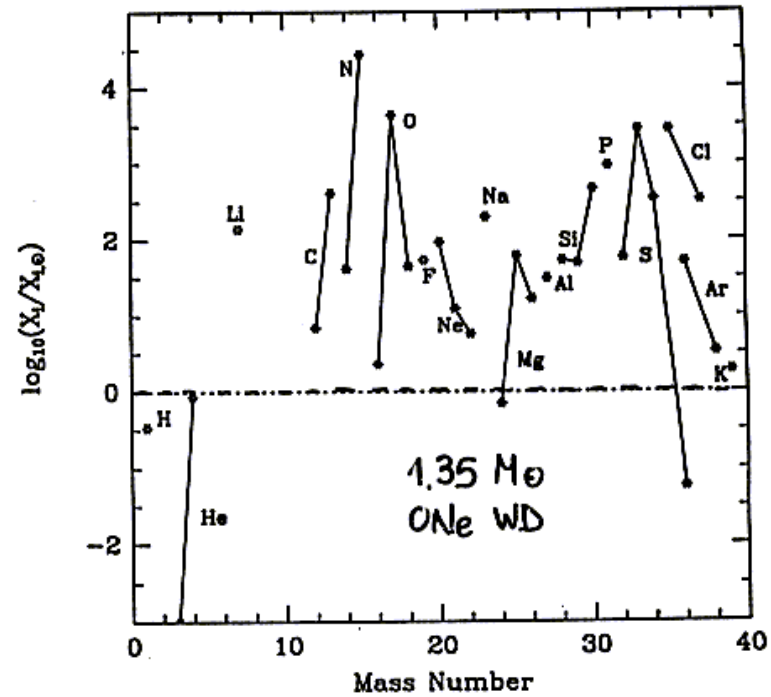


FIG. 3.—Same as Fig. 1, but for model ONe6 (1.35 $M_\odot$ ONe white dwarf with 50% mixing).

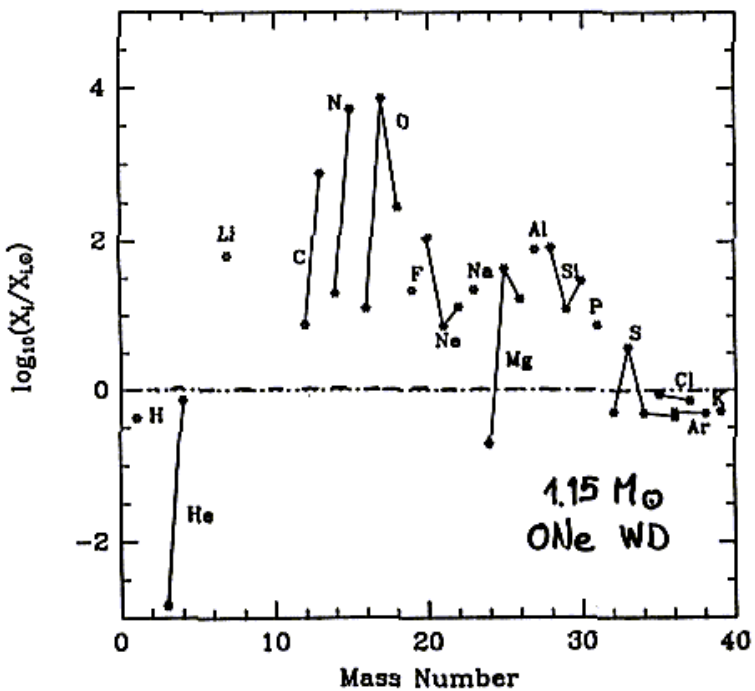


FIG. 2.—Same as Fig. 1, but for model ONe3 (1.15 $M_\odot$ ONe white dwarf with 50% mixing).

3.2.2. *Synthesis of the* CNO-*Group Nuclei*

The dominant nuclear reaction at the beginning of the TNR in a nova outburst is typically $^{12}C(p, \gamma)^{13}N$, which is followed by a combination of β^+ decay, or (p, γ) and (p, α) reactions, as a function of the local temperature. As pointed out by Starrfield et al. (1972), some of the most overabundant species at peak temperature, except hydrogen and helium, are the short-lived β^+-unstable nuclei ^{13}N, ^{14}O, ^{15}O, and ^{17}F, which decay releasing enough energy to account for the ejection of a fraction of the envelope. Therefore, their daughter nuclei ^{13}C, $^{14,15}N$, and ^{17}O are among the main products in the ejecta of classical novae. Models presented in this paper show large overproduction factors of ^{13}C, ^{15}N, and ^{17}O with respect to solar abundances (see Figs. 1–3).

The synthesis of ^{13}C is initiated by $^{12}C(p, \gamma)^{13}N$. Its evolution follows a competition between destruction through $^{13}C(p, \gamma)^{14}N$ near the burning shell and production by means of $^{13}N(\beta^+)^{13}C$ in the outer envelope, where a fraction of ^{13}N has been carried out by convection. Our computations show that the synthesis of ^{13}C is favored in CO novae because of the higher initial content of ^{12}C. Hence, its final amount increases when higher degrees of mixing with the underlying core are adopted. Overproduction factors for the different CO models computed lay in the range ~900–5200, with a maximum abundance of $X(^{13}C) \sim 0.2$

* Classical novae are likely sites for the synthesis of most (all) of the Galactic ^{13}C, ^{17}O (and maybe ^{15}N?) (José & Hernanz 1998)

Trend ⟶ ratios O/N, C/N decrease when M_{wd} increases
(Observational clue for massive WDs)

* Mg isotopes are destroyed

* P, S, Cl: are significantly produced in classical novae with massive WDs (may reveal the presence of a massive WD!)

* Isotopic ratios $^{12}C/^{13}C$, $^{14}N/^{15}N$ plus $\delta^{29,30}Si/^{28}Si$ are comparable with recent measurements in presolar grains.

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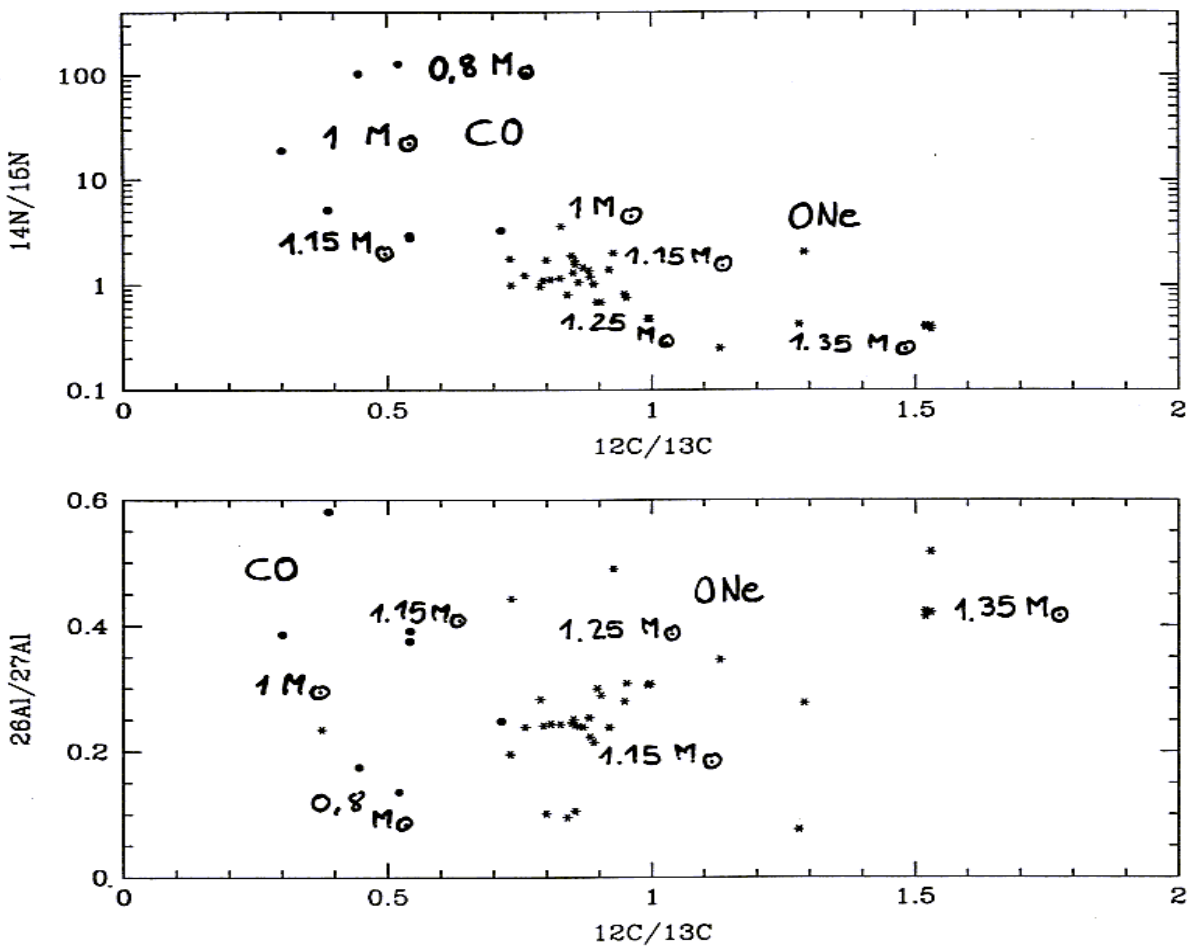
NiC 2000 #5.4 José, Hernanz, Amari & Zinner



José, Hernanz, Amari & Zinner (2000)

Posters → 5.4 ; 5.1
NiC 2000

José & Hernanz (ApJ 1998)

TABLE 5

MODELS VERSUS OBSERVATIONS OF SOME CLASSICAL NOVA SYSTEMS

Model	Element							
	H	He	C	N	O	Ne	Na–Fe	Z
V693 CrA 1981								
Vanlandingham et al. 1997	0.25	0.43	0.025	0.055	0.068	0.17	0.058	0.32
Model ONe3	0.30	0.20	0.051	0.045	0.15	0.18	0.065	0.50
Andreä et al. 1994	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66
Model ONe4	0.12	0.13	0.049	0.051	0.28	0.26	0.10	0.75
Williams et al. 1985	0.29	0.32	0.0046	0.080	0.12	0.17	0.016	0.39
Model ONe5	0.28	0.22	0.060	0.074	0.11	0.18	0.071	0.50
V1370 Aql 1982								
Andreä et al. 1994	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86
Model ONe7	0.073	0.17	0.051	0.18	0.14	0.24	0.14	0.76
Snijders et al. 1987	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86
Model ONe7	0.073	0.17	0.051	0.18	0.14	0.24	0.14	0.76
QU Vul 1984								
Austin et al. 1996	0.36	0.19	...	0.071	0.19	0.18	0.0014	0.44
Model ONe1	0.32	0.18	0.030	0.034	0.20	0.18	0.062	0.50
Saizar et al. 1992	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10
Model ONe2	0.47	0.28	0.041	0.047	0.037	0.090	0.0035	0.25
PW Vul 1984								
Andreä et al. 1994	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30
Model CO4	0.47	0.25	0.073	0.094	0.10	0.0036	0.0017	0.28
V1688 Cyg 1978								
Andreä et al. 1994	0.45	0.22	0.070	0.14	0.12	...	...	0.33
Model CO4	0.47	0.25	0.073	0.094	0.10	0.0036	0.0017	0.28
Stickland et al. 1981	0.45	0.23	0.047	0.14	0.13	0.0068	...	0.32
Model CO1	0.51	0.21	0.048	0.096	0.13	0.0038	0.0015	0.28

III. Synthesis of γ-ray emitters: ^{7}Li, ^{22}Na, ^{26}Al, et al.

Isotope	Lifetime	Disintegration channel	Nova type
^{17}F	93 sec	β^{+}-decay	CO & ONe
^{14}O	102 sec	β^{+}-decay	CO & ONe
^{15}O	176 sec	β^{+}-decay	CO & ONe
^{13}N	862 sec	β^{+}-decay	CO & ONe
^{18}F	158 min	β^{+}-decay	CO & ONe
^{7}Be	77 day	e^{-}-capture	CO
^{22}Na	3.75 year	β^{+}-decay	ONe
^{26}Al	10^{6} year	β^{+}-decay	ONe

Main radioactive species synthesized during nova outbursts

* $^{14, 15}O$, ^{17}F (^{13}N): Expansion and ejection stages
* ^{13}N, ^{18}F: Early gamma-ray emission (511 keV plus continuum)
* ^{7}Be, ^{22}Na, ^{26}Al: Gamma-ray lines

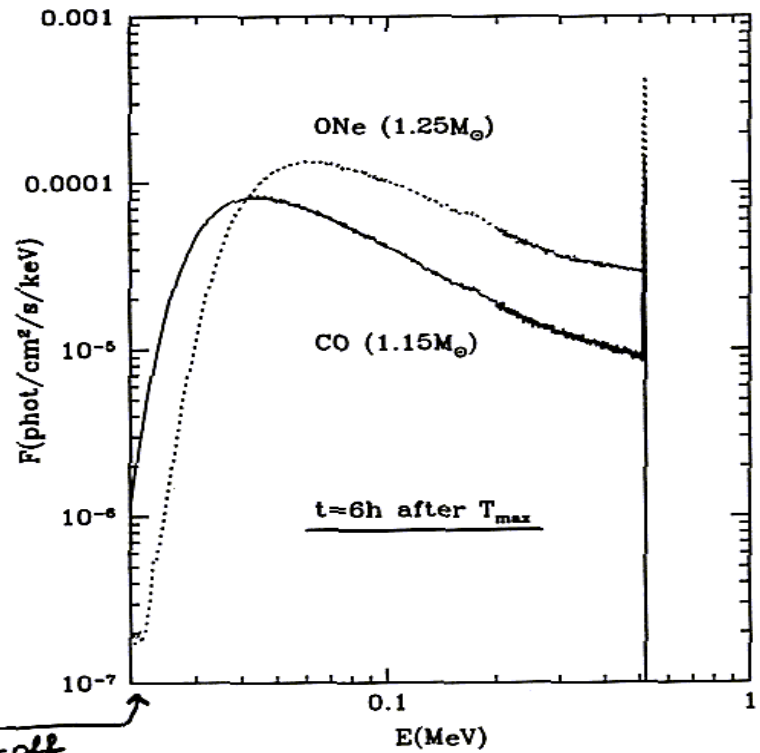
γ-ray emission: lines + continuum

- Early phase: optically thick envelope
  $\longrightarrow$ Comptonization of 511 keV γ (continuum)

- Later phase: optically thin envelope
  $\longrightarrow$ absorption & comptonization negligible
  . Intensity of the lines $= f(\underbrace{M(^7Be)}_{CO}, \underbrace{M(^{22}Na)}_{ONe})$

^{13}N, ^{18}F decay $\longrightarrow$ e^--e^+ annihilation at 511 keV line
(direct e^--e^+ annih. + positronium emission in singlet state
+
continuum (511 $\rightarrow$ 20~30 keV)
(positronium continuum - triplet state - +
comptonization of γ emitted in the 511 keV line)

CO vs. ONe (early) spectra



lines + continuum

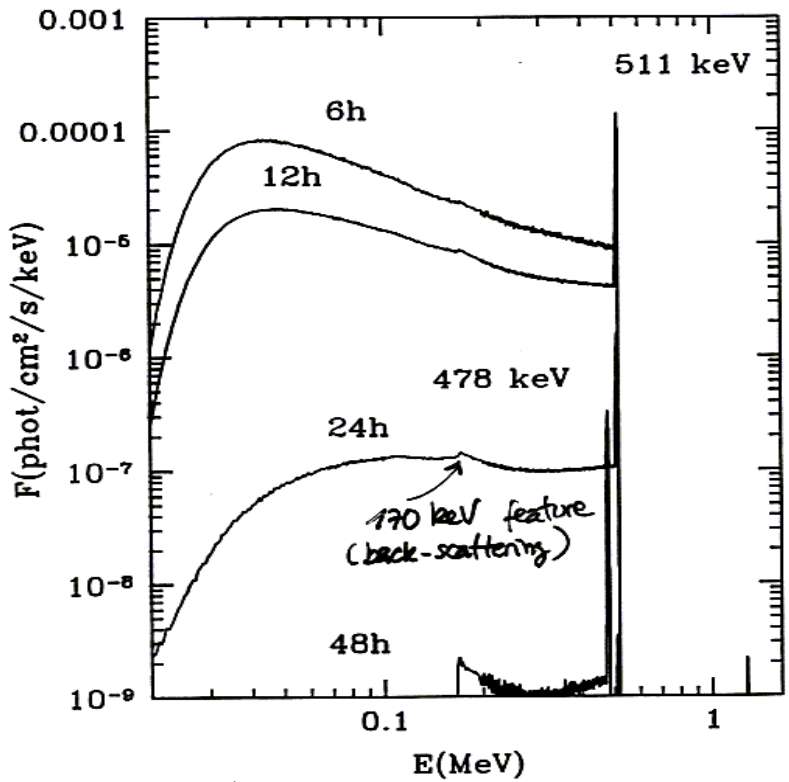
d ≈ 1 kpc

cut-off (~ 20-30 keV) photoelectric absorption

- $F_{ONe} > F_{CO}$
- At larger times, 478 keV line (CO novae)
  1275 keV line (ONe novae)

Gómez-Gomar, Hernant, José, Isern (MNRAS, 1998)
Hernant, José, Coc, Gómez-Gomar, Isern (ApJ, 1999)

1.15 $M_\odot$ CO

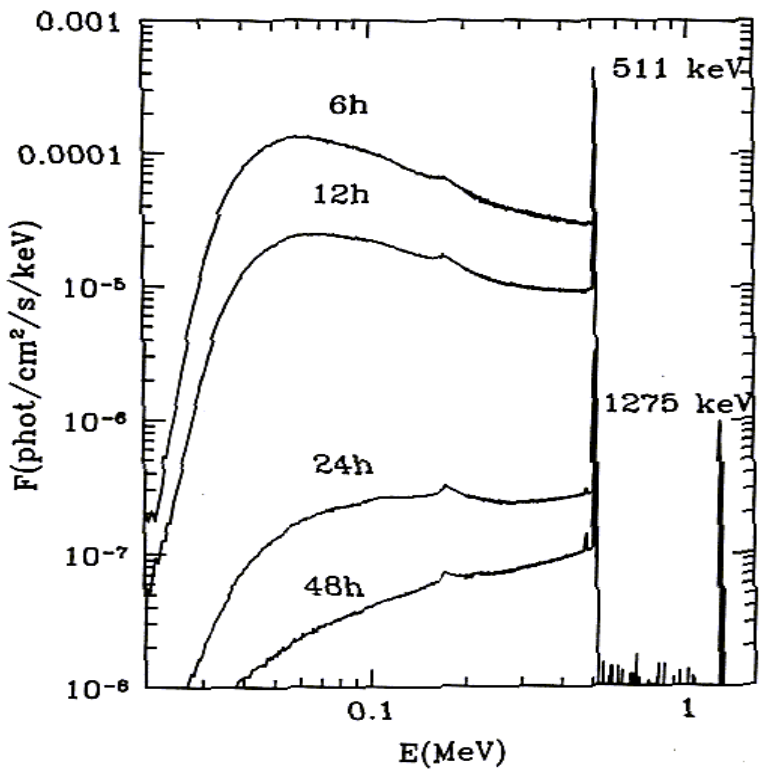


d = 1 kpc

478 keV line : ^{7}Be

511 keV line + continuum : ^{13}N + ^{18}F

1.25 $M_\odot$ ONe



d = 1 kpc

1275 keV line : ^{22}Na

511 keV line + continuum : ^{13}N, ^{18}F

→ Most intense emission : $E \leq 511$ keV

but ! it's very short (before optical detection)

↳ wide FOV instruments

BATSE, TGRS ...