The First Nova Explosions

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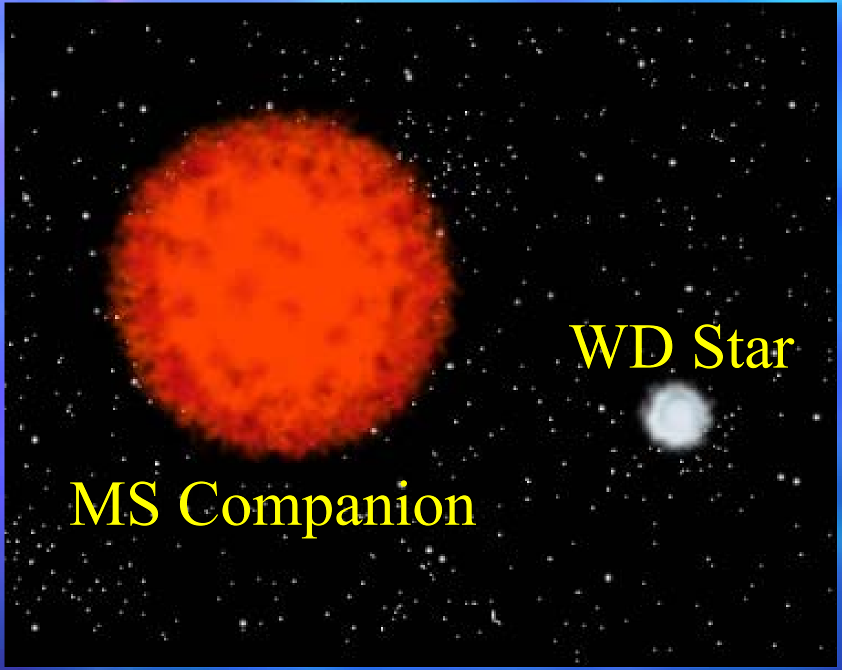
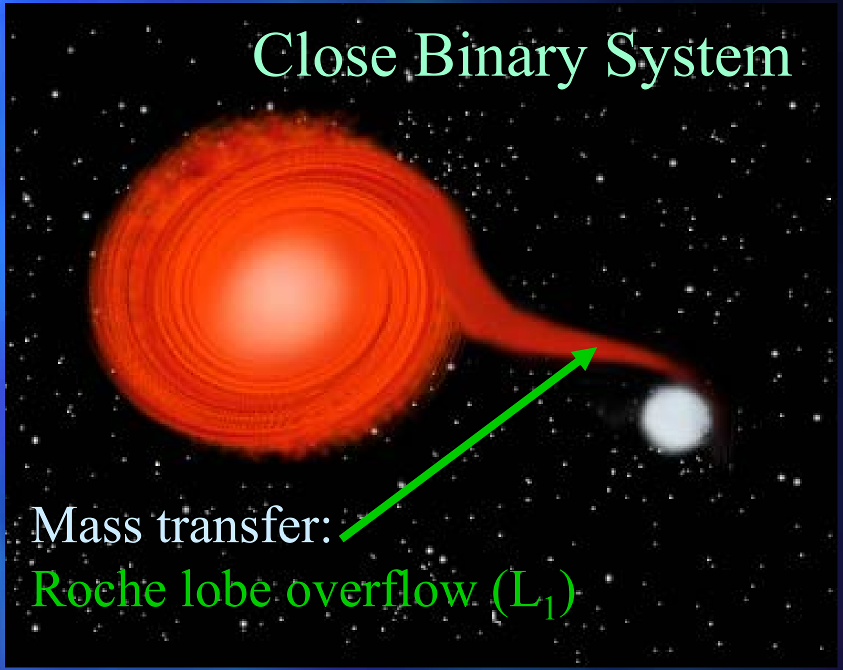
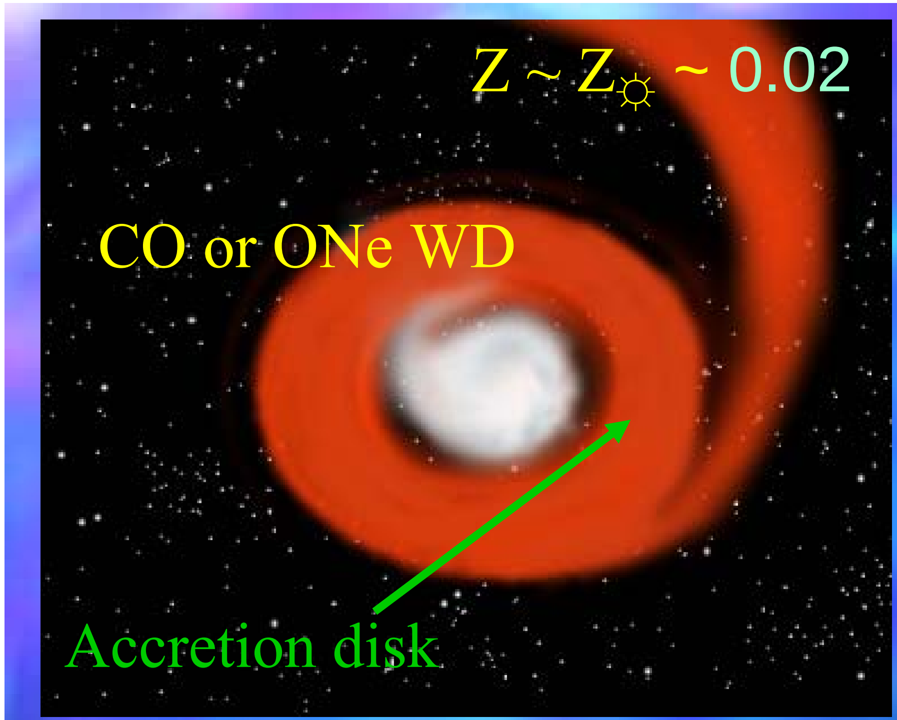
I. A *Primer* on Classical Nova Explosions





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)



Build-up of an envelope in semi-degenerate conditions

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Thermonuclear runaway (TNR)

Strength of the explosion: $P_{base}(\Delta M_{env}, \text{gravity})$

→ More violent outbursts when: a) massive M_{wd}

b) larger ΔM_{env}

Triggering reaction: $^{12}C(p,\gamma)^{13}N$ → $^{13}N(\beta^{+})^{13}C(p,\gamma)^{14}N$ (*cold* CNO)
As T increases: $\tau_{(p,\gamma)}[^{13}N] < \tau_{(\beta+)}[^{13}N]$ → $^{13}N(p,\gamma)^{14}O$ (*hot* CNO)
$^{14}N(p,\gamma)^{15}O$
$^{16}O(p,\gamma)^{17}F$

The presence of intermediate-mass (CNO) elements in the envelope has remarkable consequences for the energy transport:

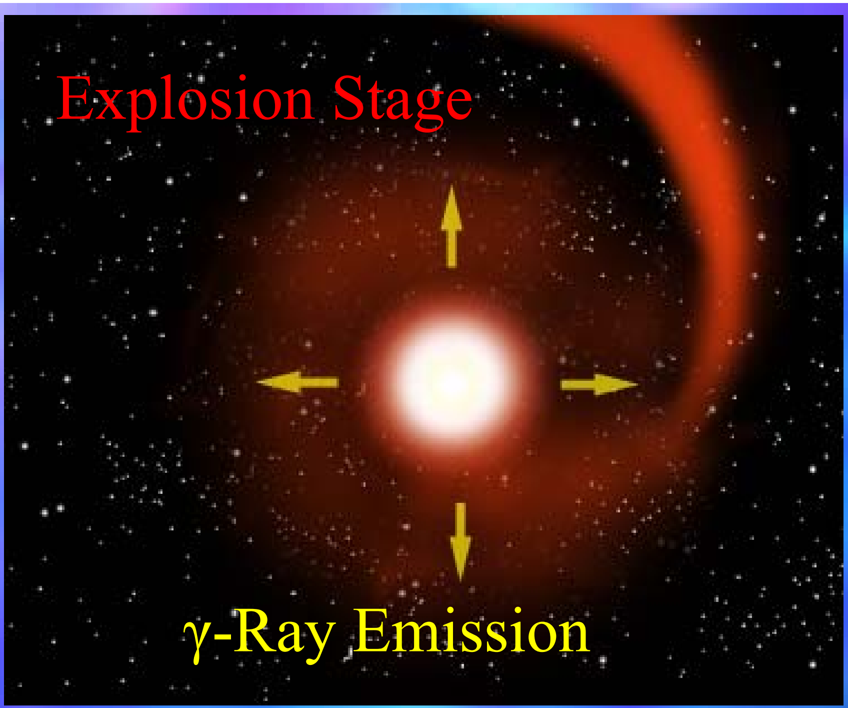
- * low Z regime → p-p chains → radiation
- * high Z regime → CNO-cycle → radiation + convection

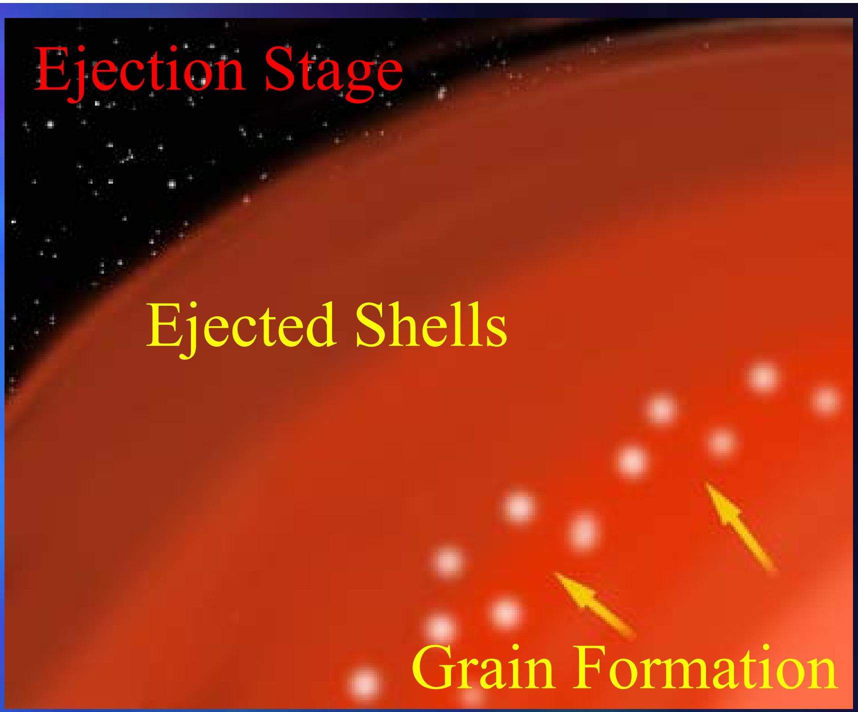
Critical role of convection: carrying the short-lived, β^{+}-unstable nuclei $^{14,\,15}O$, ^{17}F (^{13}N) to the outer, cooler layers of the envelope (escaping *deadly* p-capture reactions)

Sudden release of energy from these short-lived species powers the expansion and ejection stages [Starrfield et al.1972]:

^{15}N, ^{17}O (^{13}C)

→ Without convection, there's no nova outburst!





^{13}N, ^{18}F: Early γ-ray emission
at 511 keV plus continuum
^{7}Be, ^{22}Na, ^{26}Al: 478, 1275,
& 1809 keV lines

Comparison Models vs. Observations

a) Atomic abundances (spectra)

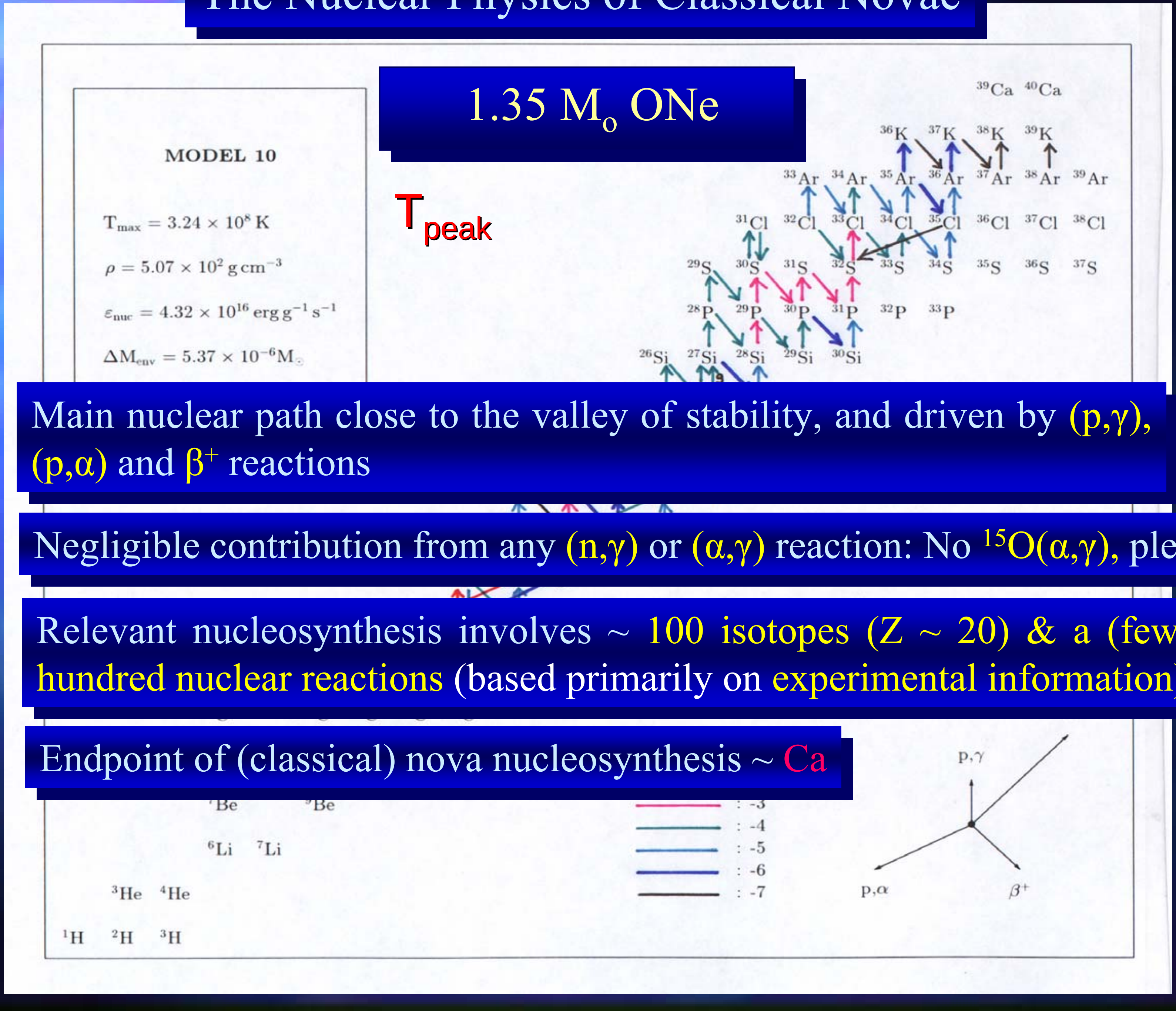
b) Isotopic abundance ratios (grains)

Composition of the ejecta:

a) $Z_\odot \rightarrow Z \sim 0.50$ (up to 0.86, for V1370 Aql 1982)? Limited $T_{peak} \rightarrow$ CNO-breakout unlikely! → Mixing at the core-envelope interface

b) Depends on the nature of the WD (cf., CO vs. ONe): M_{WD} & X_i

The Nuclear Physics of Classical Novae



1.35 M_o ONe

T_{peak}

Main nuclear path close to the valley of stability, and driven by (p,γ), (p,α) and β^+ reactions

Negligible contribution from any (n,γ) or (α,γ) reaction: No ^{15}O(α,γ), please!

Relevant nucleosynthesis involves ~ 100 isotopes (Z ~ 20) & a (few) hundred nuclear reactions (based primarily on experimental information)

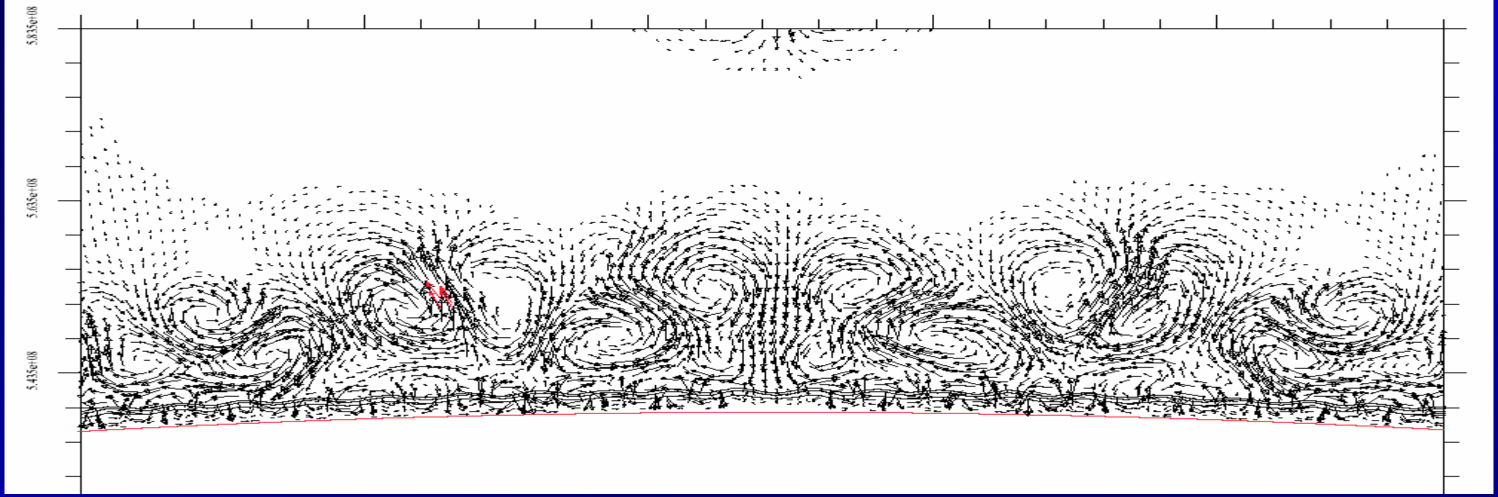
Endpoint of (classical) nova nucleosynthesis ~ Ca

The mixing mechanism: the *Holy Grail* of nova modeling

* 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 1995; Glasner, Livne & Truran 1997, 2005; Rosner et al. 2002; Alexakis et al. 2004]

Glasner & Livne 1995; Glasner, Livne, & Truran 1997, 2005

→ Multi-dimensional simulations agree with 1-D's , but!:



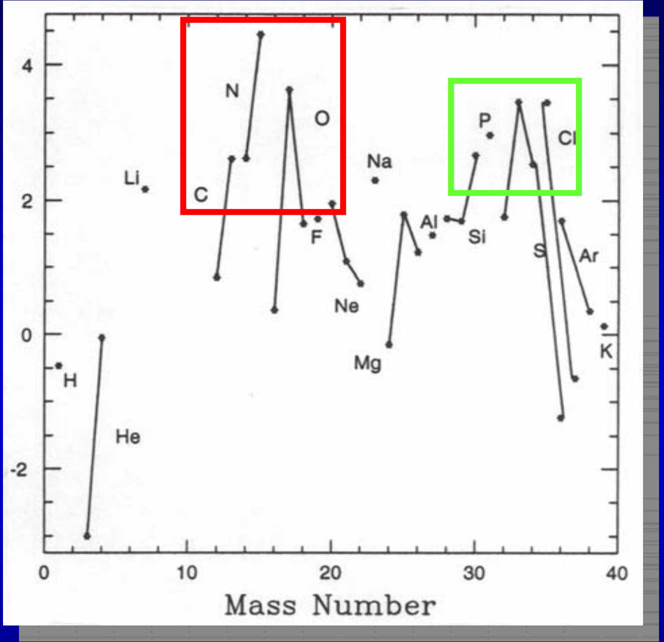
The build-up of convective eddies at the envelope's base causes shear flow at the core/envelope interface [Kelvin-Helmholtz instability]: pure "solar-like" accreted material can be enriched at the late stages of the TNR by some sort of *convective overshoot* (Woosley 1986), leading to a powerful nova event!

Convection: a) Transport of short-lived species (ejection phase)
b) Mixing at the core-envelope interface

Nucleosynthesis vs. Galactic Abundances

Galactic nova rate: ~ 30 events.yr^{-1}
Galaxy’s lifetime: ~ 10^{10} yr
Mean ejected mass per outburst: ~ 2×10^{-5} M_o

~ 6×10^{6} M_o (~ 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, $f = X_i / X_{i,\odot} > 1000$

Classical novae are likely sites for the synthesis of a significant fraction of the Galactic ^{13}C, ^{15}N & ^{17}O (José & Hernanz 1998), and contribute to the Galactic content of other species like ^{7}Li, or ^{26}Al [Hernanz et al.’s poster; Ruiz et al.’s talk]

These are quantitative estimates only, since they are based on poorly known quantities.

Reasons to believe that, *a priori*, contemporary (classical) novae are not the same sort of objects than the most “primitive” novae:

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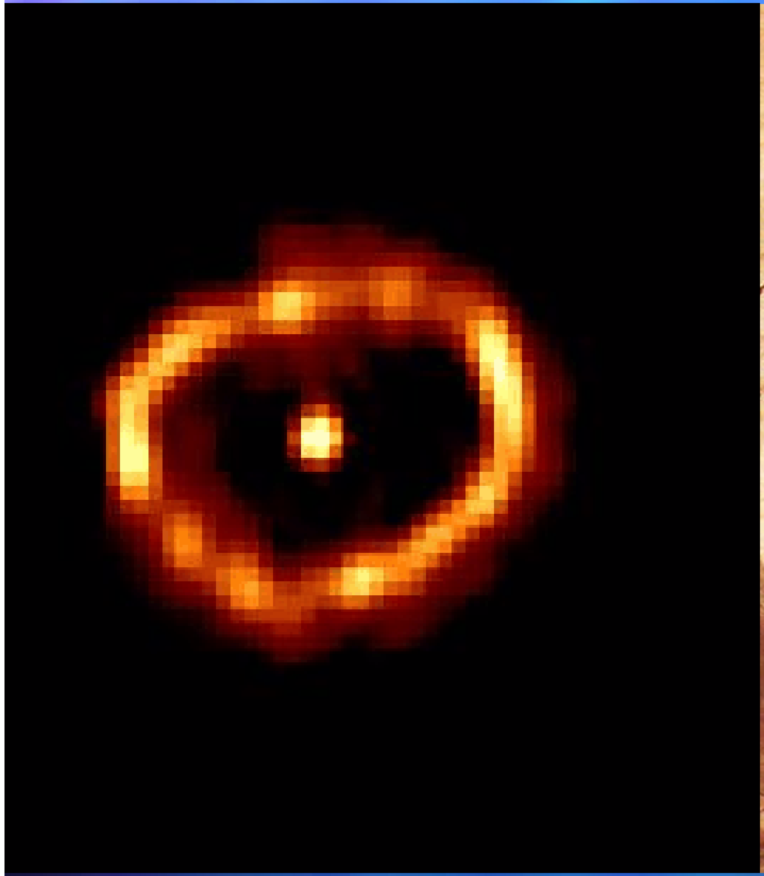
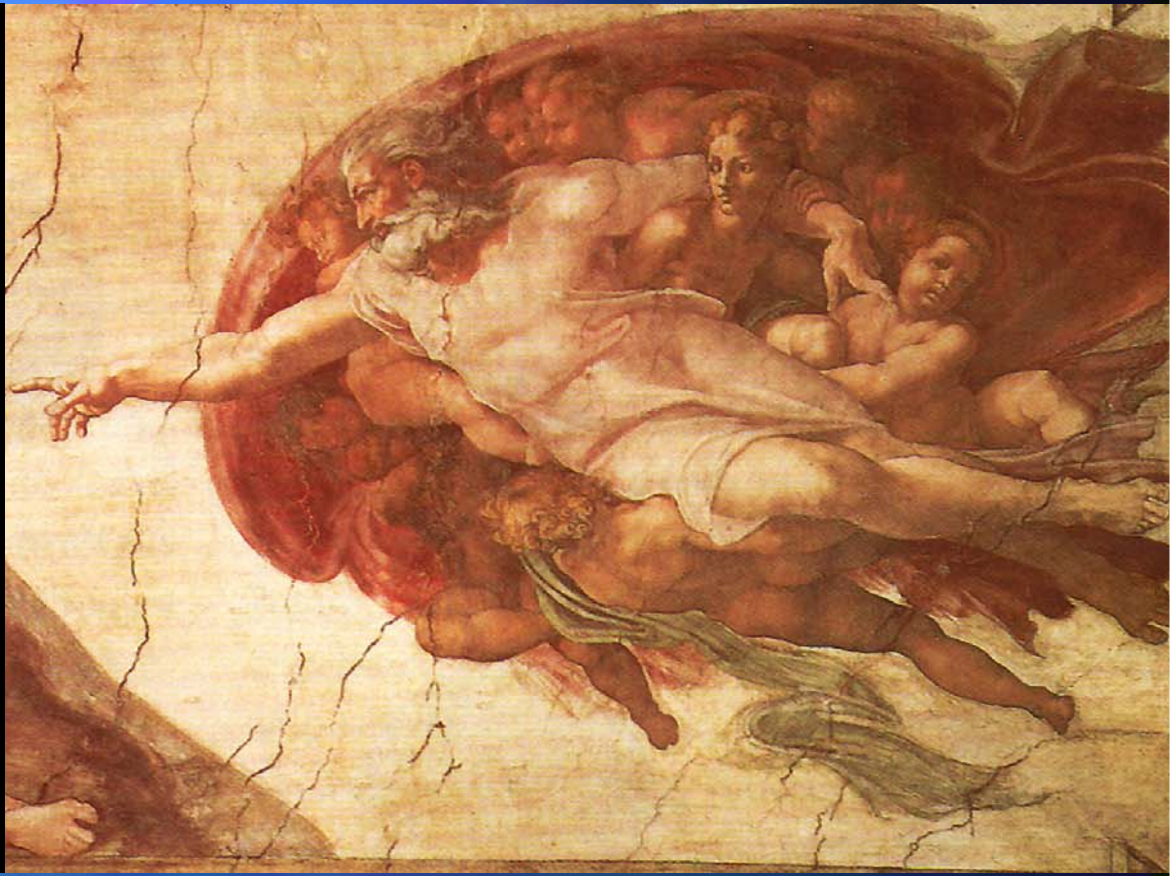
*Do novae eject today the same amount of mass than in the past?
*Is the chemical abundance pattern of the ejecta the same?
*How has the nova frequency changed in the last 10^{10} yr?

II. *Primordial Novae*: the First Nova Explosions





Primordial Novae = Nova-like, stellar explosions on white dwarfs evolved in a cataclysmic primordial binary ($Z_{zams} = 0$).

The nature of a cataclysmic primordial binary ($Z_{zams} = 0$)

a) WD cores evolved from $Z_{zams}=0$ or $Z_{zams}=0.02$ share a similar composition (Gil-Pons et al. 2006)

b) But the companion stars are quite different!: the older star, the lower its overall metallicity (down to $Z=0$?)

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Stellar evolution of the close binary system (common-envelope phase?) may induce chemical contamination in the outer layers of the companion star (the exact value of Z_{min} is not well constrained...)

Nucleosynthesis in Primordial Novae

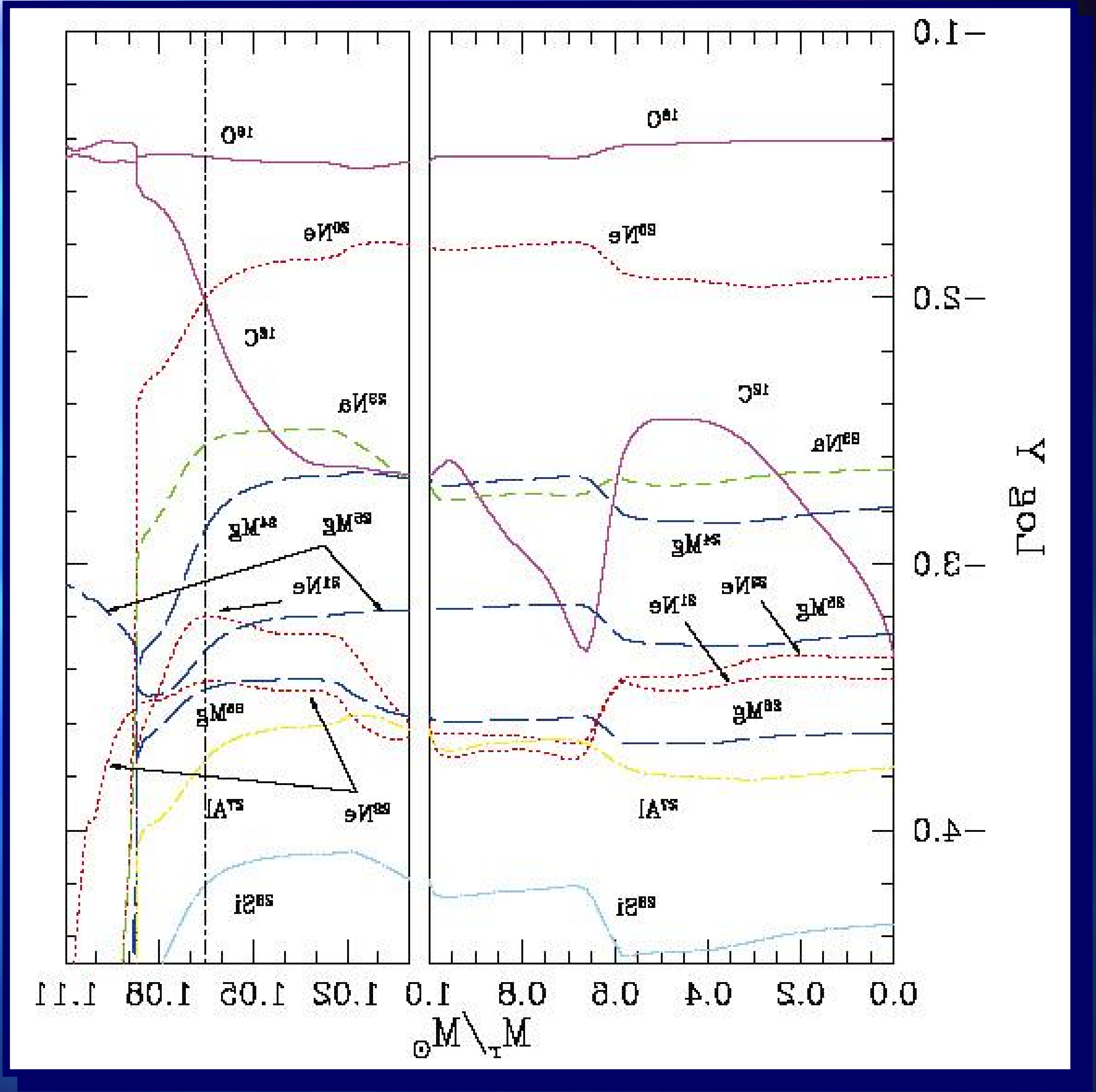
1.35 $M_{\odot}$ Models **WORK IN PROGRESS!!!**

$Z_{envelope}$	12C, ini	Δm_{env} (M_o)	t_{acc} (yr)
$Z_{\odot}$ (solar)	$3.03 \cdot 10^{-3}$	$6.61 \cdot 10^{-6}$	$3.82 \cdot 10^{4}$
$Z_{\odot}/2 \cdot 10^{5}$	$1.12 \cdot 10^{-8}$	$1.67 \cdot 10^{-5}$	$1.01 \cdot 10^{5}$
0 (BBN)	0	$5.23 \cdot 10^{-5}$	$3.24 \cdot 10^{5}$
50% ONe, 50% Solar	$6 \cdot 10^{-3}$	$5.33 \cdot 10^{-6}$	$3.33 \cdot 10^{4}$

[Fe/H] in EMP Stars: -5.4 (Frebel et al., 2005), -5.3 (Christlieb et al., 2002)

Nuclear reaction networks:

- Classical: 100 nuclei (^{40}Ca), 300 reactions
- Primordial: 480 nuclei (^{108}Te), 2640 reactions → ^{75}As



Structure of the WD core below the CO-buffer

García-Berro, Rittosa & Iben, ApJ, 1997

* The amount of mass accreted (envelope) decreases with time (as Z increases): more violent outbursts ($T_{peak,}$ Δm_{ejec}) likely happened in the past → Nucleosynthetic endpoint?

* Δm_{env} for solar-like accretion is very similar to that for pre-enriched models [50% solar, 50% ONe]

⟹ pre-enriched models (Starrfield et al.; José et al.) mimik reasonably well the dynamics of the explosion → explains their success in reproducing the abundance patterns

1.35 $M_\odot$ Models

$Z_{envelope}$	Tpeak (K)	t_{rise} $3 \cdot 10^7 \rightarrow 10^8$ K	t_{peak} 10^8 K → Tpeak	t_{eject} Tpeak → $R = 10^{12}$ cm
$Z_\odot$ (solar)	$3.07 \cdot 10^8$	1.13 yr	3 948 sec	8 175 sec
$Z_\odot / 2 \cdot 10^5$	$3.77 \cdot 10^8$	$2.28 \cdot 10^4$ yr	3.83 yr	2.85 days
0 (BBN)	$4.98 \cdot 10^8$	$2.46 \cdot 10^5$ yr	7.30 yr	10.5 hr

Preliminary results:

* Is there a minimum ^{12}C abundance to power a nova-like explosion?

All these models (1.35 $M_\odot$) lead to mass ejection (nova-like events)
→ min $^{12}C = 0$!

But 1.15 $M_\odot$ with Z=0 does not eject! Mild TNR (H → He)
→ likely outcome?

Strange features associated with these low Z models:

- Weird nucleosynthesis (Z=0: endpoint ~ ^{73}Ge)
- Mild rp-process: 3α, ^{15}O(α,γ), ^{20}Na(p,γ)...
- Radioactivities:
- Implications for meteorites: Ti-excesses
- Higher ejected masses but only minor CNO breakout.

Causes for these strange features: Higher T_{peak} but mainly a much larger τ_{TNR} because of lack of fuel.

But! Following Glasner et al., we expect shear flows when the envelope is convective: mixing at the core-envelope

1.35 $M_{\odot}$ Models:

*$Z_{\odot}$: $T_{base}=2.2\cdot10^{7}$ K
*$Z_{\odot}/2\cdot10^{5}$: $T_{base}=7.3\cdot10^{7}$ K
*$Z=0$: $T_{base}=1\cdot10^{8}$ K

•If mixing is fast → peculiar features will be deeply smoothed
•If mixing is slow → these features can show up in the ejecta

Calculations with different τ_{mix} are underway: at $t=t_{conv}$, but also at $t<t_{conv}$ (rotational mixing, diffusion...)

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Nuclei in the Cosmos IX, CERN, Geneva, Switzerland. June 26-30, 2006

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