Overshoot convective mixing in nova outbursts

Stella Novae – Cape Town - Feb. 2013

Ami Glasner; Eli Livne
The Hebrew University
Jim Truran
University of Chicago

Background (i)

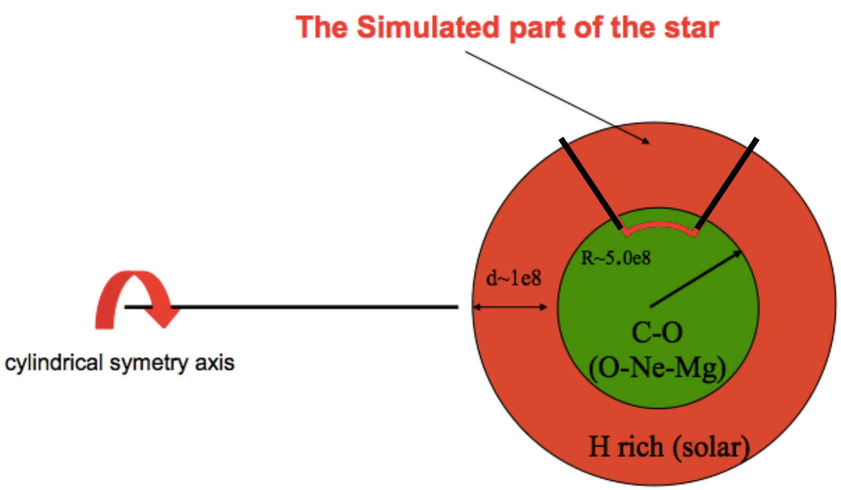
- Many classical and recurrent novae show enrichment, relative to solar composition, in heavy elements and/or helium.
- The source for such enrichment is dredge-up of matter from the underlying white dwarf to the accreted envelope*.

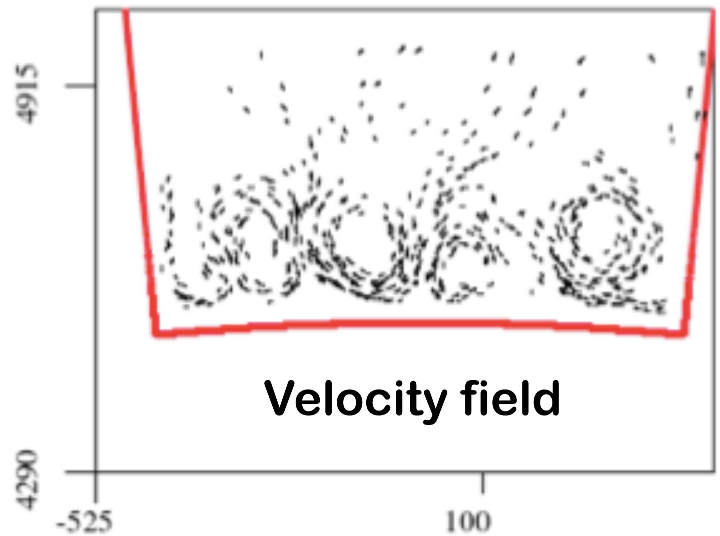
- A few mechanisms for such mixing were proposed:

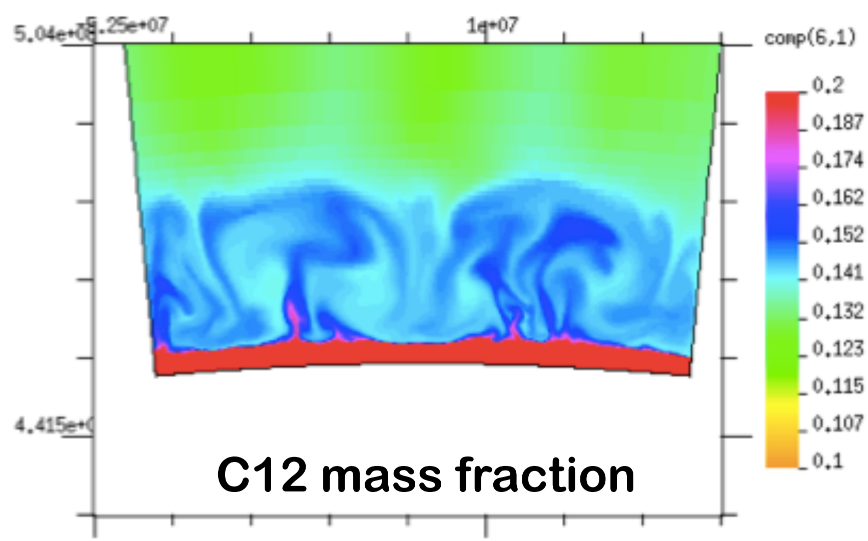
 - Mixing by a diffusion layer, for which diffusion during the accretion phase builds a layer of mixed abundances.
 - Mixing by shear instability induced by differential rotation.
 - Mixing by resonant interaction between large-scale shear flows in the accreted envelope and gravity waves in the white dwarf's core.
 - Mixing by overshoot of the convective flow during the runaway itself.

Background (ii)

Here we focus on the convective overshoot mechanisms that proved efficient for CO white dwarfs.

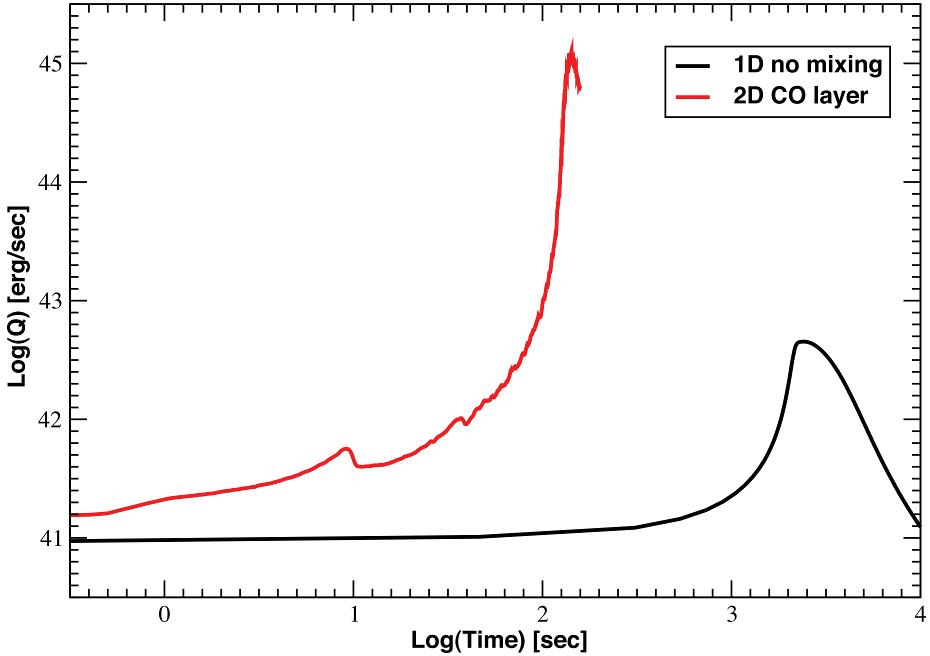




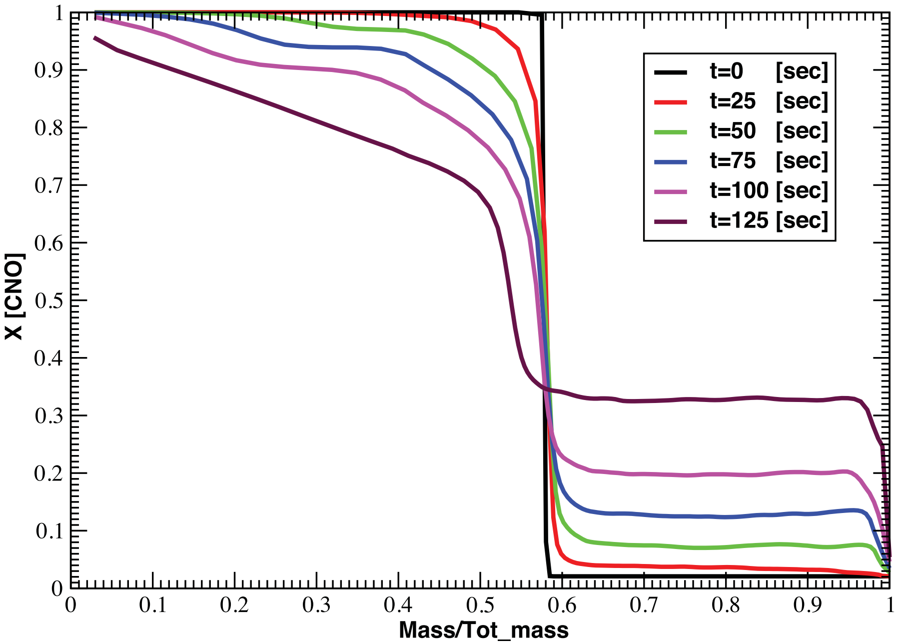


Background (iii)

Mixing of carbon from the underlying layer significantly enhances the hydrogen burning rate. The enhanced burning rate drives higher convective fluxes, inducing more mixing. Therefore, the fact that the underlying layer is rich in C12 is a critical feature of all the overshoot convective models that have been analyzed up to this work.



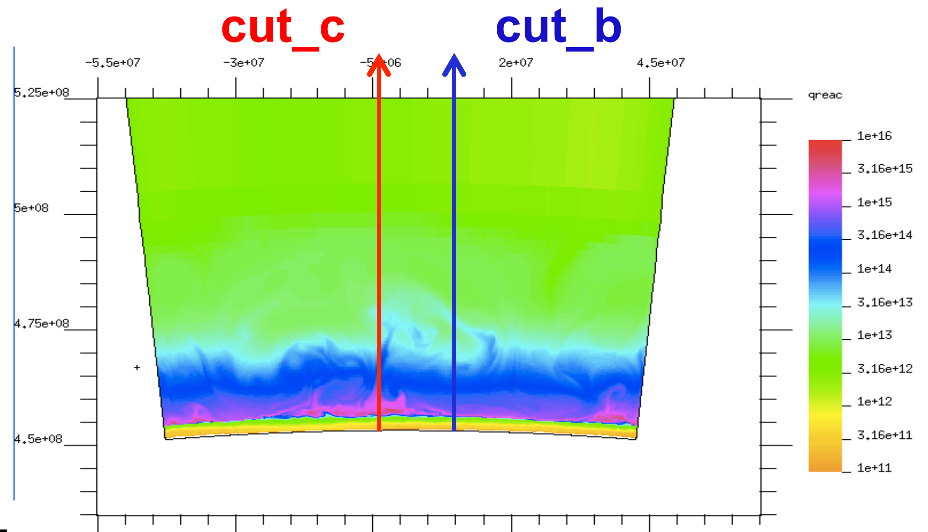
Integrated burning rate as function of time 1D (no-mix) vs. 2D

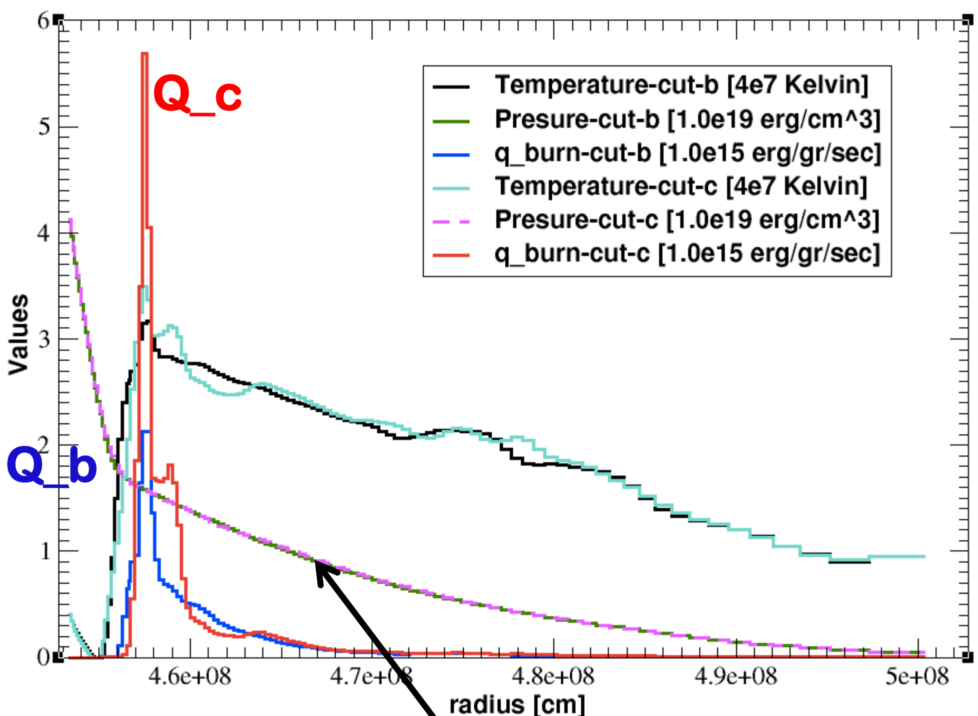


Radial profiles of the transverse average total CNO abundance at several times.

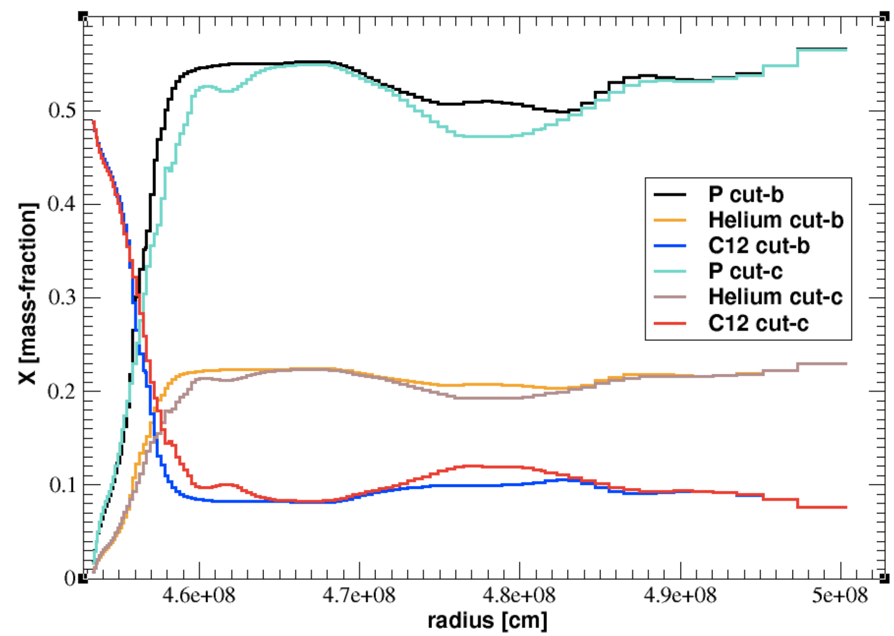
Background (iv)

The convective flow is subsonic (almost hydrostatic). Fluctuations in the convective flow change the local temperature distribution.





Identical pressure profiles



abundances

Motivation (i)

All of the proposed mechanisms find it hard to identify a unique observational prediction that will single out one of them. Its hard to rule out the possibility that they are all contributing to the abundance enrichment and the question is what is the exact amount that each mechanism contributes.

⬇

Possible finger prints of the mixing mechanisms are needed.

Motivation (ii)

- According to the theory of stellar evolution, we expect the composition of the underlying white dwarf to be CO for masses in the range ~ 0.5-1.1 solar masses and ONe(Mg) for more massive white dwarfs*.
- Observations show enrichment in helium, CNO, Ne, Mg and heavier elements.
- For recurrent novae, helium abundances can achieve levels of 40-50%. High helium abundances can simply be explained as the ashes of hydrogen burning during the runaway, but one can not exclude the possibility that the source of He enrichment is dredge up from an underlying helium layer.

↓

Study nova outbursts for the whole range of possible composition of the underlying WD

Preliminary comments

(longer version available at the end of the talk)

- Numerical hydro codes

  vs.

  Micro-physics of mixing.

- 2D ⇔ 3D

The calculated models

- We study here the runaway of the accreted hydrogen layer on top of a WD, changing only its composition. Having a fixed mass and radius, we can compare the time-scales, convective flow, energetics and dredge up in the different cases.
- A more comprehensive study which varies the white dwarf's mass with compositions is left to future work (CO, ONe(Mg) or He rich)*.

  - Core mass = 1.15 solar.
  - Envelope mass accreted with solar composition= 3.4e-5 solar.
  - Default:

    Mapping from 1D to 2D once the temperature at the base of the accreted envelope is 9e7 kelvin. Exceptions from these default are marked along the way.

The Helium underlying layer (i)

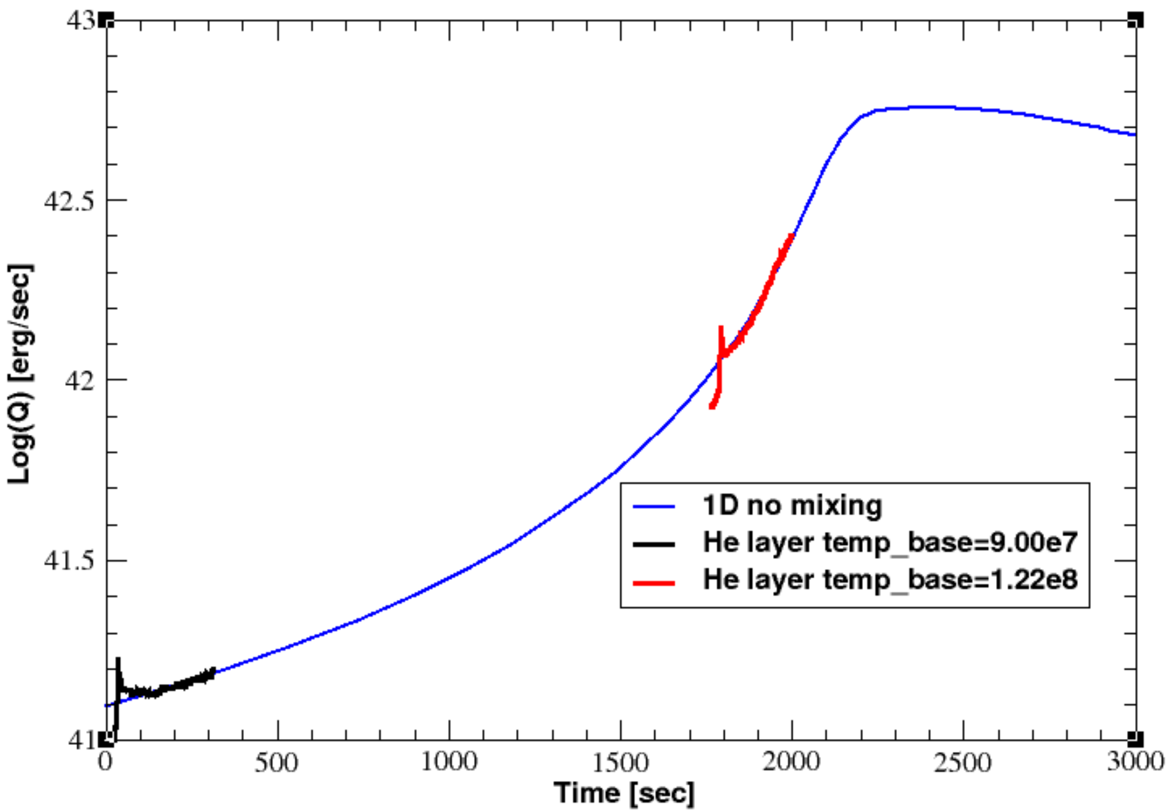
Can the convective overshoot mechanism lead to the observed helium enrichment in recurrent nova ?

***Burning rates**: for the densities and temperatures prevailing in nova outbursts, helium is an inert isotope. Therefore, it does not play any role in the enhancement of the runaway* ➔

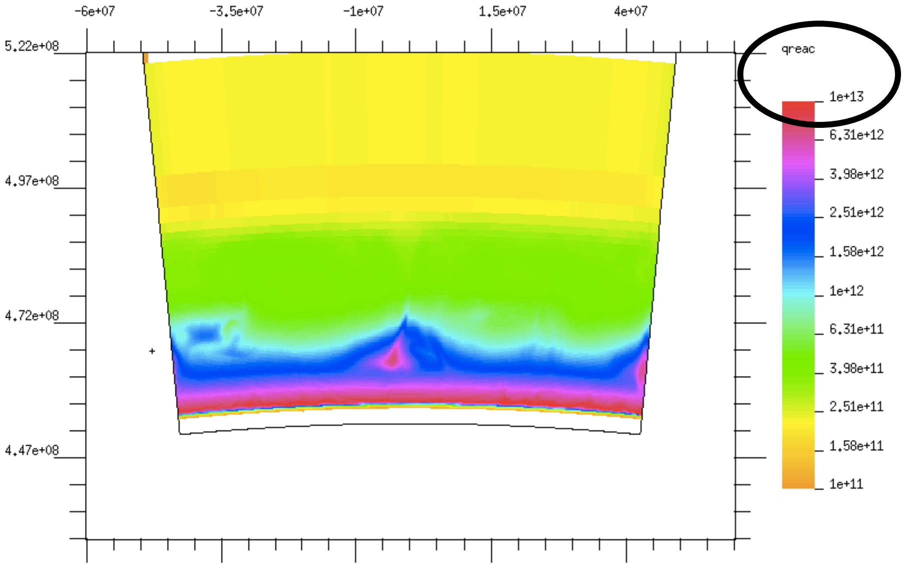
2D resemble 1D

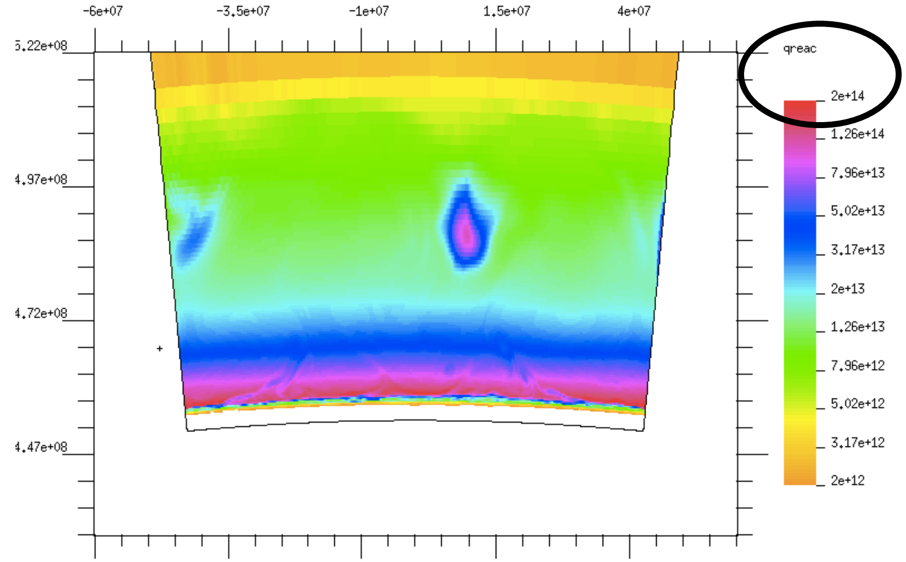
(mild burning rates, long runaway time). ➔

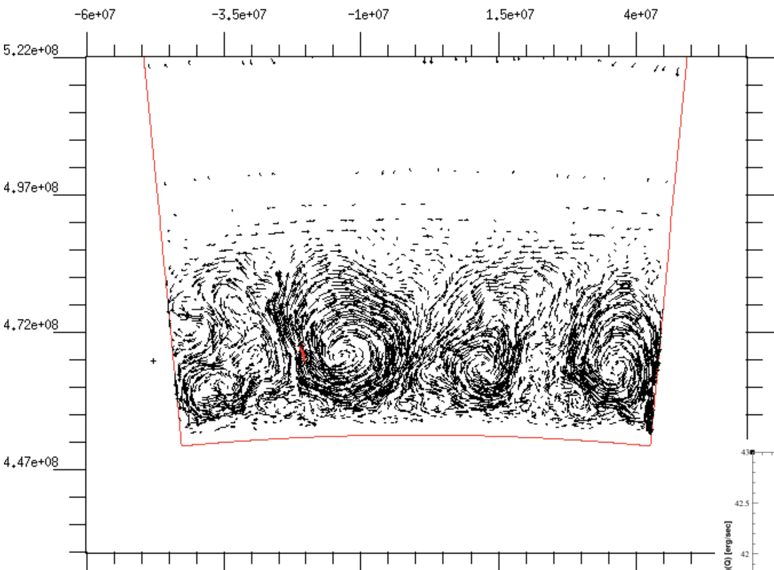
Two 2D models (black and red) at different epochs of the 1D model.

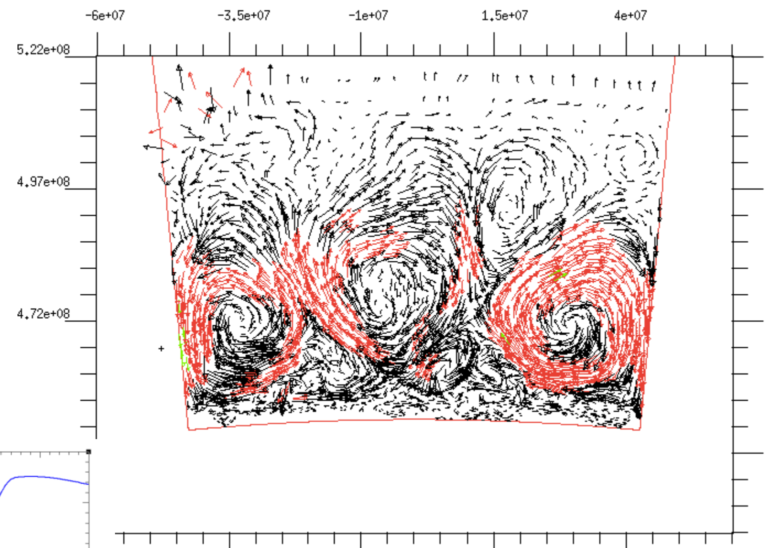


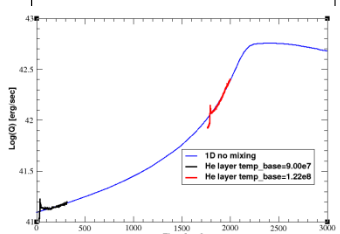
The Helium underlying layer (ii)









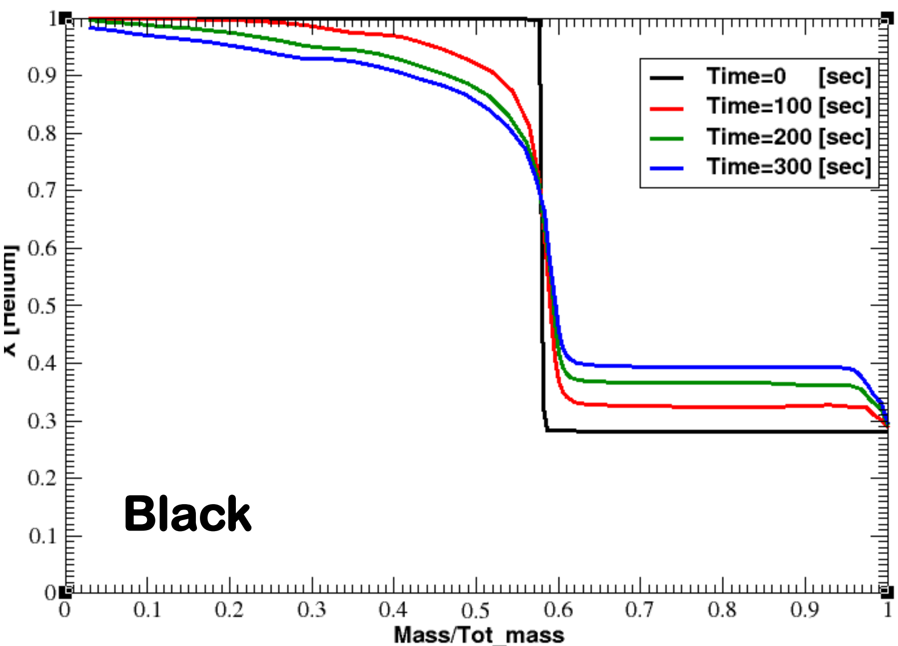


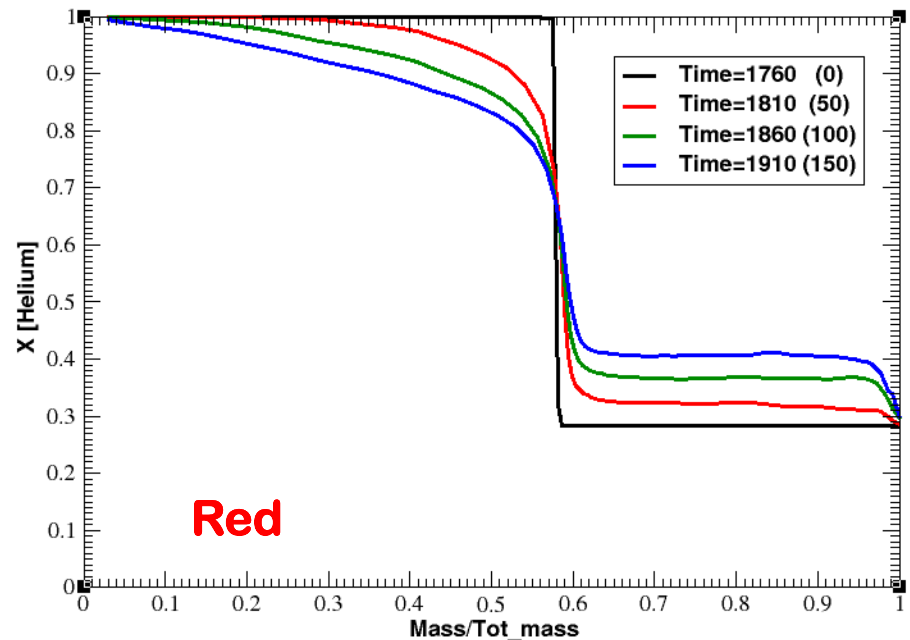
Black t~250

Red t~2000

The Helium underlying layer (iii)

Convective overshoot mixing: *once the bottom of the envelope is convective, the flow induces substantial amounts of mixing with the underlying helium.*

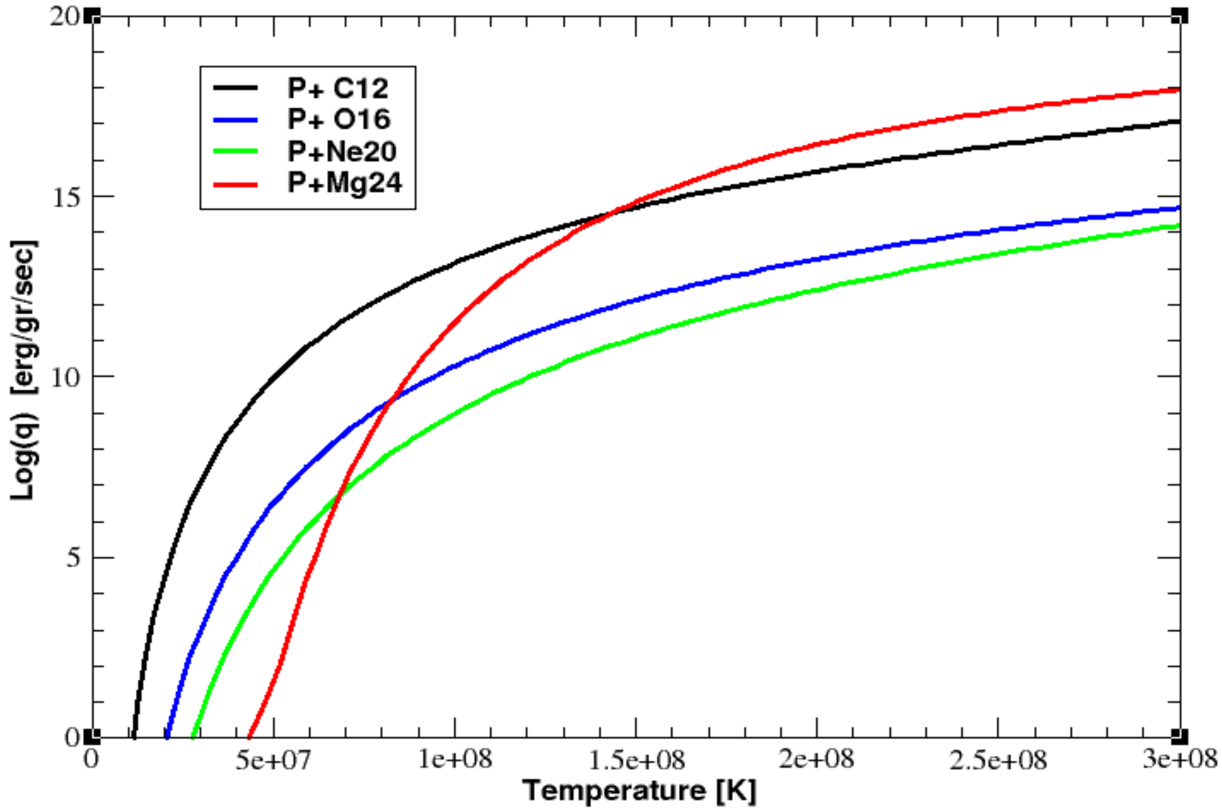




Helium mass abundance is increased by mixing from Xhe=0.28 to Xhe>0.4

WD's with O Ne (Mg) cores (i)

Burning rates issues – *candidates for rate enhancement.*



In absence of the enhancement by C12, the overshoot mixing mechanism can generate such energetic outbursts by mixing the solar abundance accreted matter with the underlying ONe(Mg) core. Examination of the energy generation rate of proton capture reactions on O16, Ne20 and Mg24 make it evident that only Mg24 can compete with C12 in the range of temperatures relevant to nova runaways.

WD's with O Ne (Mg) cores (ii)

The need to increase the number of elements for burning reaction net in the multi-D models

- *Old net 15 elements:*

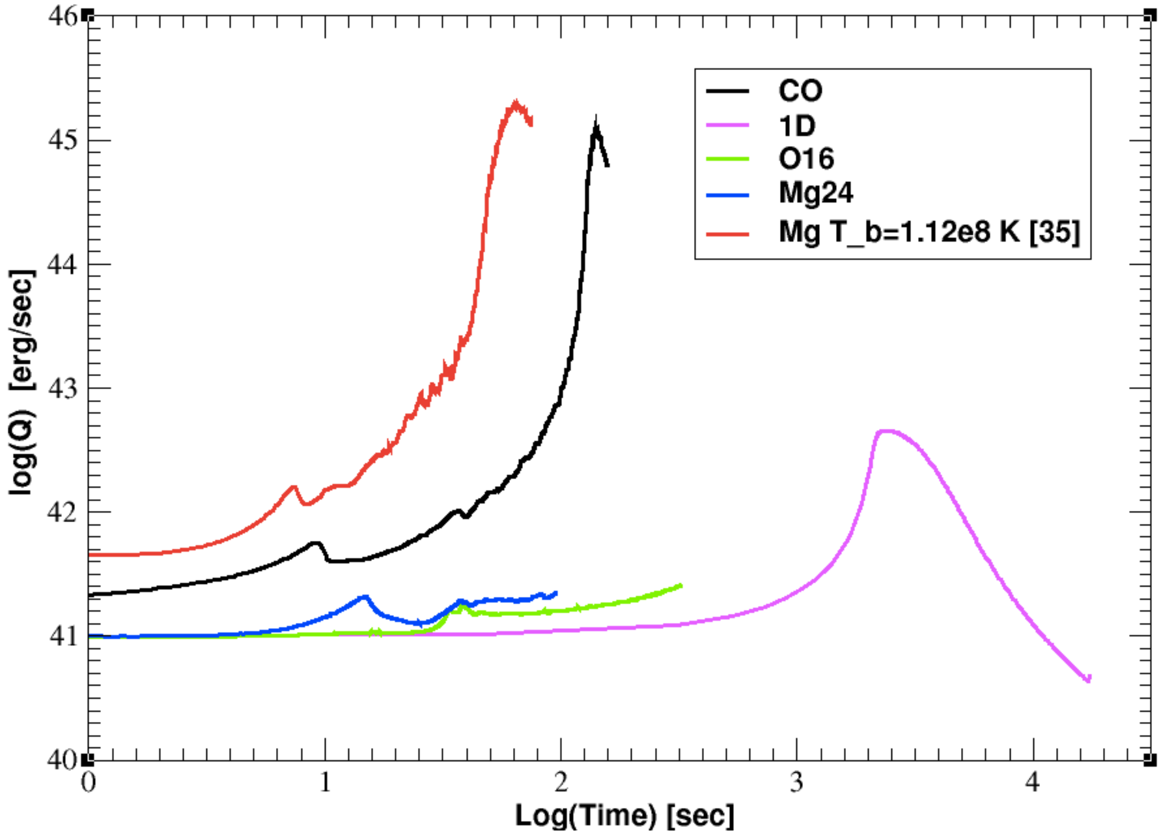
1H, 3He, 4He, 7Be, 8B
12C, 13C, 13N, 14N, 15N
14O, 15O, 16O, 17O and 17F.

- *New net 35 elements:*

n, 1H, 2H, 3He, 4He
7Be, 8B, 12C, 13C, 13N
14N, 15N, 14O, 15O, 16O
17O, 18O, 17F, 18F, 19F
19Ne, 20Ne, 21Ne, 22Ne, 20Na
21Na, 22Na, 23Na, 23Mg, 24Mg
25Mg, 26Mg, 25Al, 26Al, 27Al

WD's with O Ne (Mg) cores (iii)

Results for test models with single core element



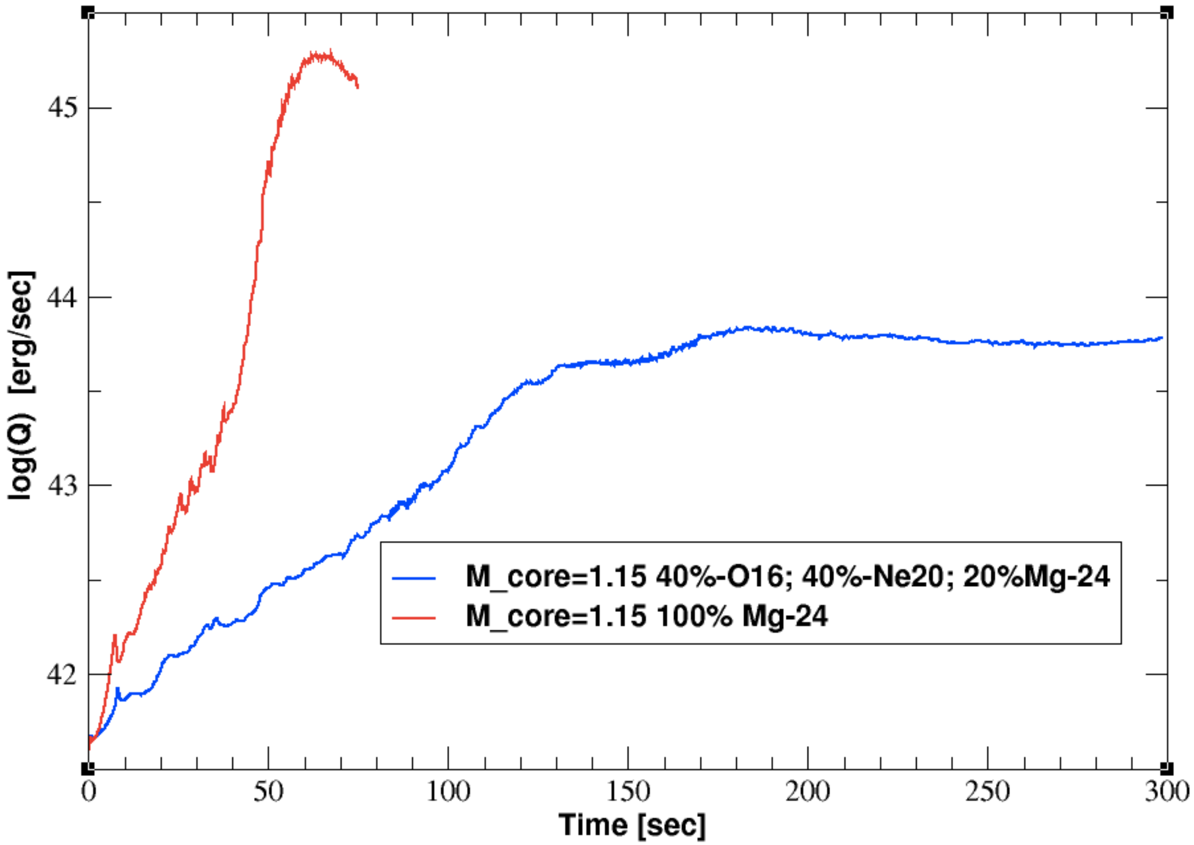
All models mapped from 1D to 2D at base temperature 9e7 kelvin follow the expected trend. Mixing enhances the burning according to the hierarchy:

Q(C12)> Q(Mg24)>Q(O16)

The Mg24 model mapped at base temperature 1.125e8 kelvin indeed proves: Q(Mg24)>Q(C12) (for temperatures above 1.3e8 Kelvin).

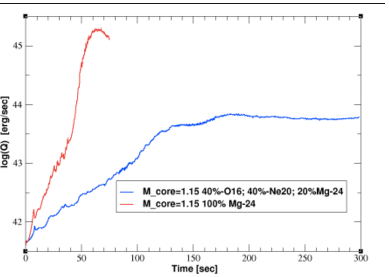
WD's with O Ne (Mg) cores (iv)

Mg24 abundance ?



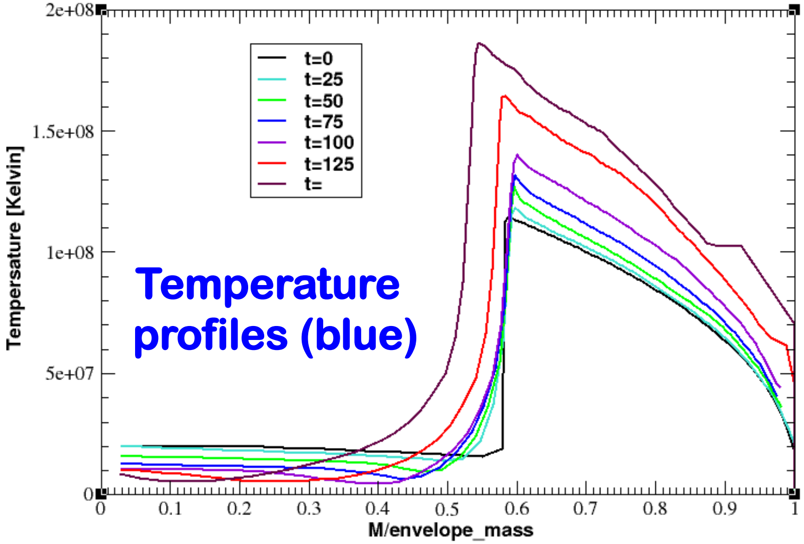
According to modern stellar evolution models Mg24 in the entire core sums up to only a few per cent (Gil-Pons & Garcia Berro 2001; Siess 2006).

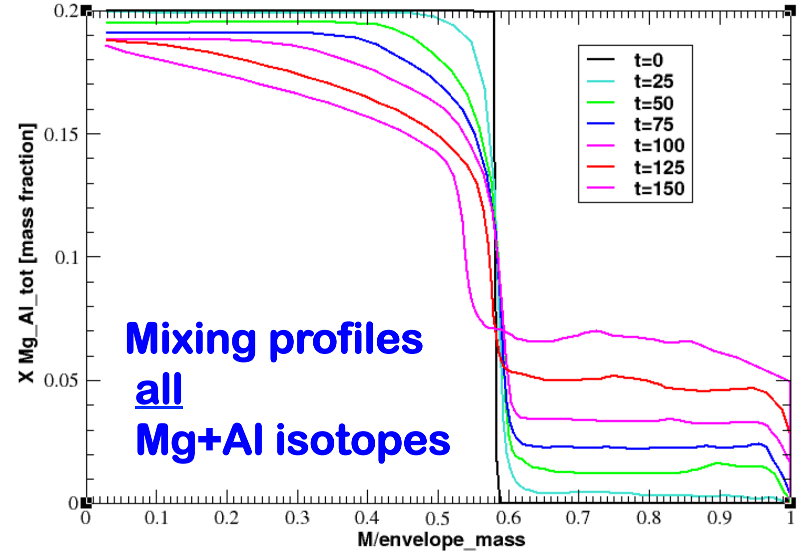
Previous studies show that in the outer parts of the core, the parts important for our study, 24Mg is more abundant and can represent up to about 25% (Garcia-Berro & Iben 1994).

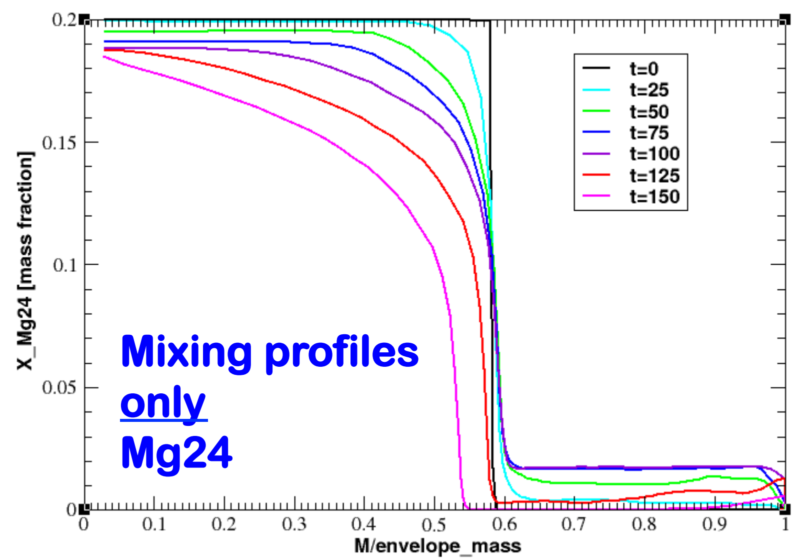


WD's with O Ne (Mg) cores (v)

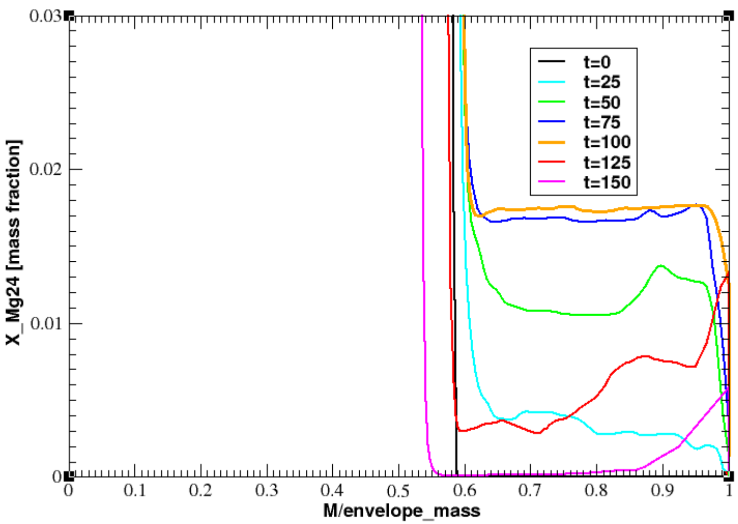
What's the difference ? (red(100%) vs. blue(20%))







zoom



Conclusions

We present here detailed 2D modeling of nova eruptions for a range of possible compositions of the underlying WD.

The main conclusion are:

- ✓ *Significant enrichment (~30%) of the ejected layer, by the overshoot convective mechanism, is a common feature of the entire set of models, regardless of the composition of the accreting WD.*
- ✓ *The burning rates and therefore, the time-scales of the runaway, depend strongly on the composition of the underlying layers.*
- ✓ *There is a one-to-one correlation between the burning rate, the velocities in the convective flow and the amount of temporal mixing.*

end

Preliminary comments

- *A significant shortcoming of all of the multi dimensional models is the lack of a capability to describe the micro-physics of mixing at abundance discontinuities in a realistic manner. The main difficulties arise from the complicated coupling between hydrodynamics and combustion, which demands high accuracy on many different scales. It is a problem to distinguish between numerical mixing, that arises from the advection terms in the Euler equations (and has the scale of the minimal zone), and the physical mixing which occurs on microscopic scales due to dissipative processes, like diffusion or turbulence.*

- *Despite these concerns, we can learn much about the physics of the process an predict the overall evolution from 2D and 3D simulations on coarse grids. This overall strategy is common to simulations done for novae, SNe Type II and SNe Type Ia.*

- *The present study is limited to 2D axially symmetric configurations. The well known differences between 2D and 3D unstable flows can yield uncertainties of few percents on our results, but can not change the general trends, as previous studies showed reasonable agreement between 2D and 3D simulations with regard to integral quantities, although larger differences persist in the local structure (Casanova et al. 2011). We therefore regard our present results as a good starting point to more elaborated 3D simulations.*

Background (i)

- **Almost all classical and recurrent novae for which reliable abundance determinations exist show enrichment (relative to solar composition) in heavy elements and/or helium** (Starrfield, Sparks & Truran 1986; Gehrz et al. 1998, 2008; Iliadis et al. 2002). **It is now widely accepted that the source for such enrichment is dredge-up of matter from the underlying white dwarf to the accreted envelope.**

A few mechanisms for such mixing were proposed:

- **Mixing by a diffusion layer, for which diffusion during the accretion phase builds a layer of mixed abundances.** (Prialnik & Kovetz 1984; Kovetz & Prialnik 1985; Iben, Fujimoto & MacDonald 1991, 1992; Fujimoto & Iben 1992)
- **Mixing by shear instability induced by differential rotation.** (Durisen 1977; Kippenhahn & Thomas 1978; MacDonald 1983; Kutter & Sparks 1987, 1989; Livio & Truran 1987; Sparks & Kutter 1987; Fujimoto 1988
- **Mixing by resonant interaction between large-scale shear flows in the accreted envelope and gravity waves in the white dwarf's core.** (Rosner et al. 2001; Alexakis, Young & Rosner 2002; Calder et al. 2002; Alexakis et al. 2004)
- **Mixing by overshoot of the convective flow during the runaway itself.** (Woosley 1986; Shankar, Arnett & Fryxell 1992; Shankar & Arnett 1994; Glasner & Livne 1995; Glasner, Livne & Truran 1997; Kercek, Hillebrandt & Truran 1998, 1999; Glasner, Livne & Truran 2007; Casanova et al. 2010, 2011a,b)

CNO Breakout under extreme conditions - motivation

- *There is a population of CV's below the gap that accretes at very low rates*

  $10^{-10} – 10^{-11}$ M_o/Yr
- *The "steady state" central temperature of an accreting WD for those rates is quite low 4-5 times 10^6 deg. Kelvin (Townsley&Bildsten Ap.J,600,390,2004).*
- *The maximal temperature at runaway increases as:*

a) M_{wd} increases

b) Tc decreases

c) M_{dot} decreases

Accreted mass vs. Tc

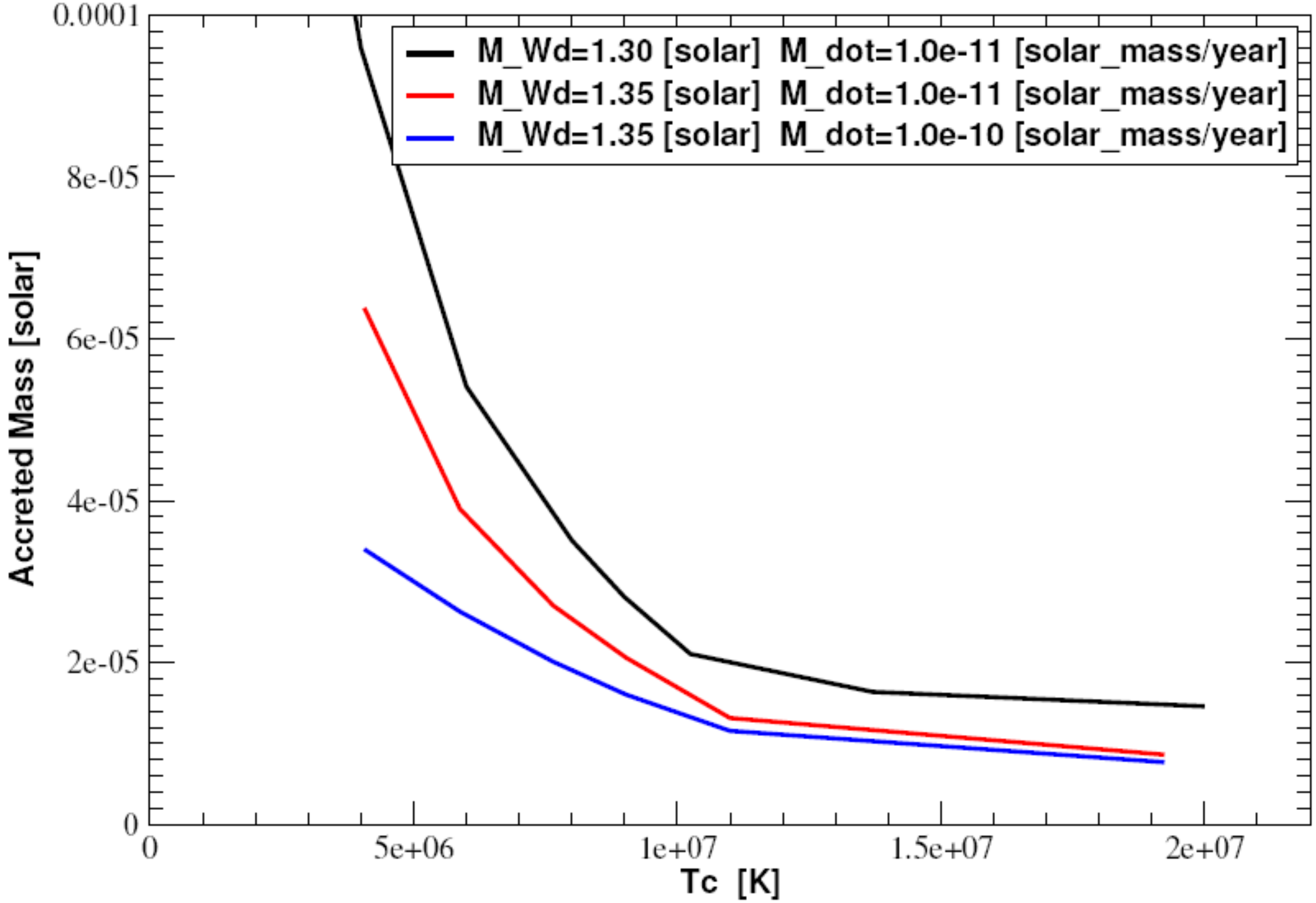


FIG. 3.— The accreted mass at ignition as a function of the central temperature T_c of the white dwarf.

Maximal temperature vs. Tc

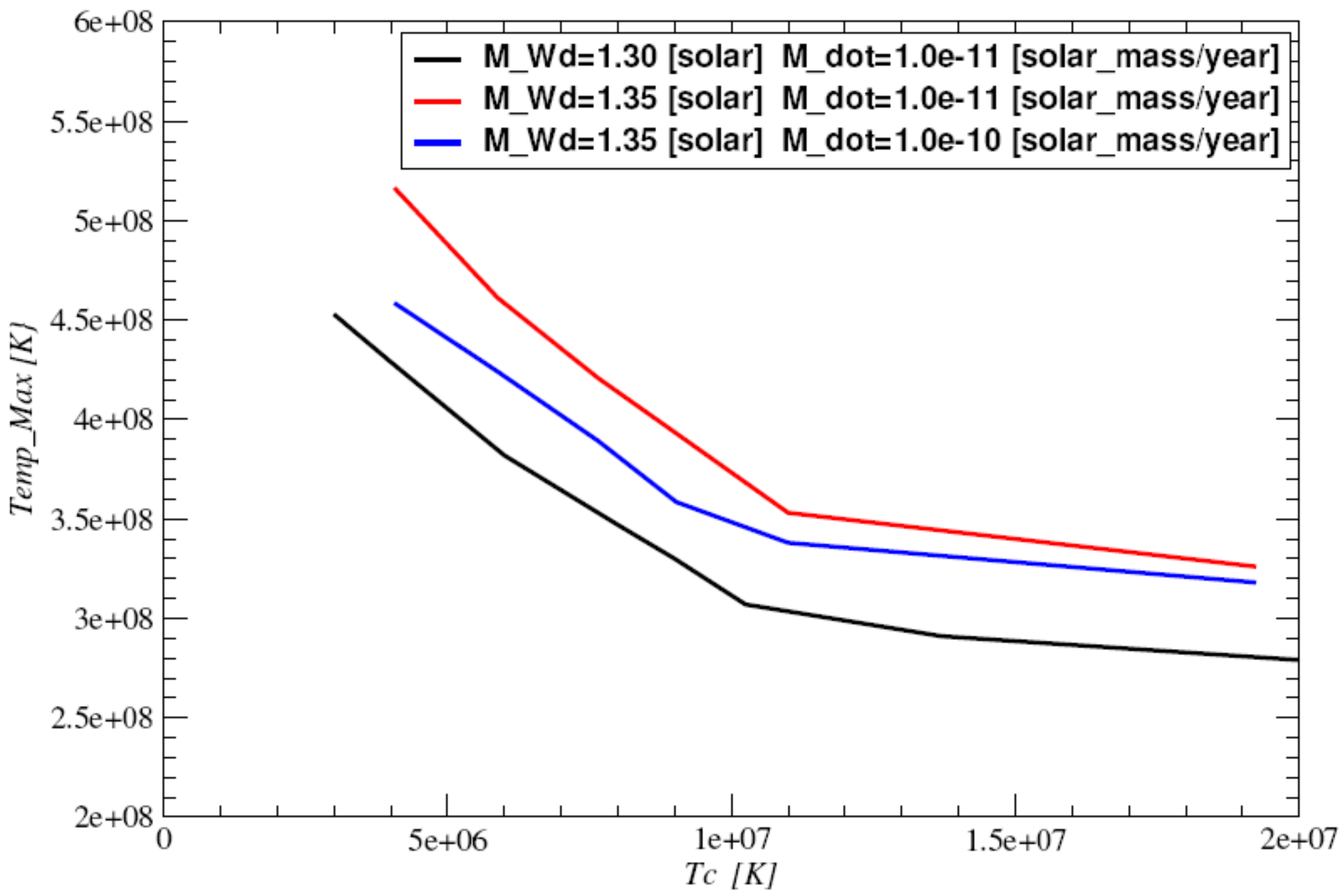


FIG. 2.— The maximum temperature achieved in the runaway as a function of the central temperature T_c of the white dwarf.

Abundances vs. solar (m=1.35)

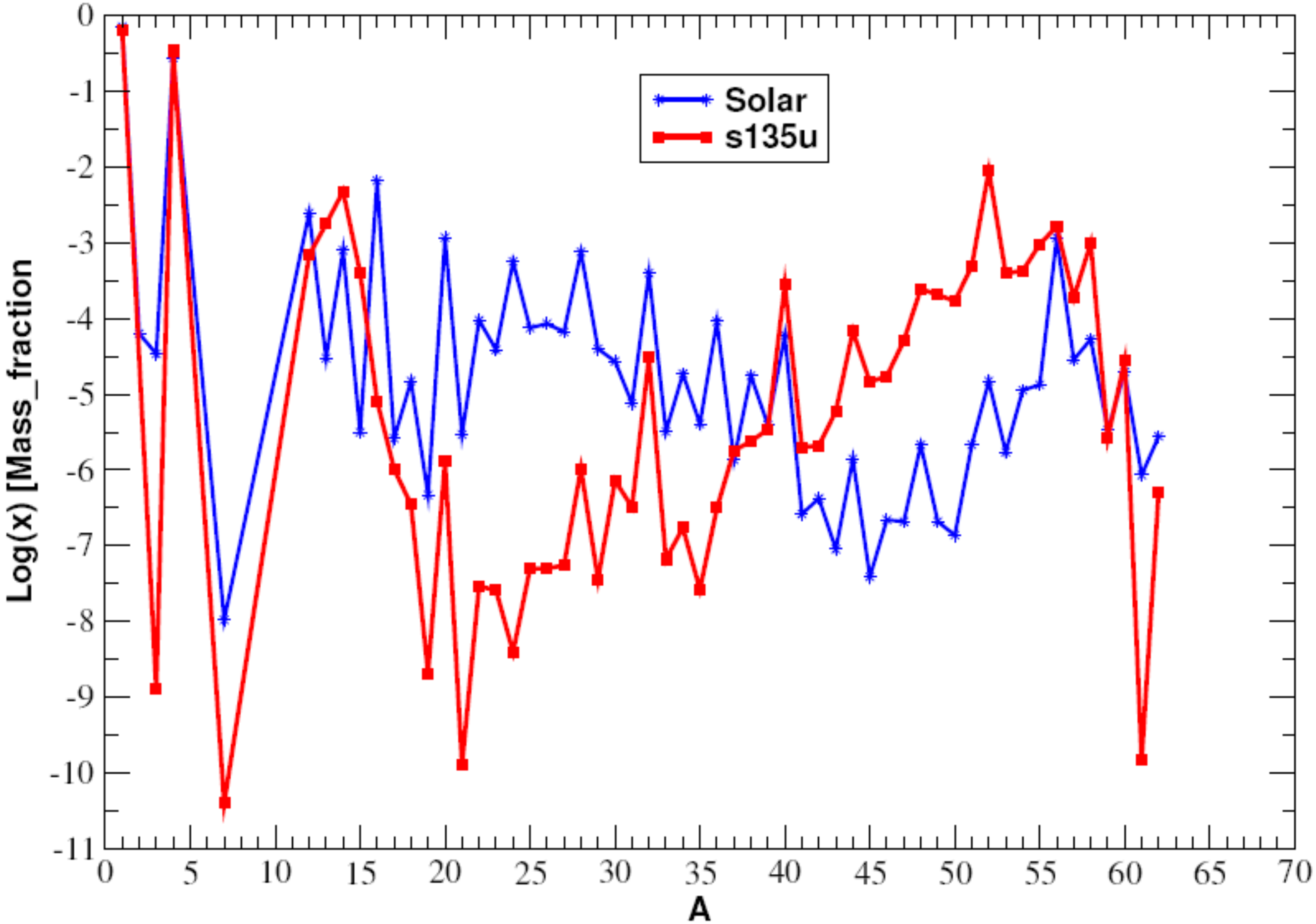


FIG. 4.— The abundances of the elements in the reaction network as a function of the mass number A. Presented are both the (solar) abundances and the 'final' abundances when the maximum temperature has fallen below T_{crit} (Model s135ui, M=1.35 $M_{\odot}$).

end