From early convective phases to ignition: the convective Urca process

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Motivation

- Big surveys SNFactory, SNLS, SNAP ...
- Pskovsky-Phillips relations $\Rightarrow$ Cosmology
- **Links**: host galaxy $\Leftrightarrow$ **progenitors** $\Leftrightarrow$ ignition **conditions** $\Leftrightarrow$ explosion models $\Leftrightarrow$ light curves and spectra

The computation loop is now closed
Path to the supernova: initial conditions

*Single Degenerate Channel:*

- a C/O White Dwarf of mass $M_{WD}$ is born as the warm heart of an AGB star
- it has a metallicity $Z$, so has its companion
- the companion Roche-Lobe overflows at time $T$ which corresponds to the Main sequence life time of its mass; it also determines the WD cooling time
- the WD accretes C/O at a rate $f(M_{WD})$ given by the Hachisu (1996) wind model and the efficiency of conversion $H \to$ He $\to$ C/O
Path to the supernova:
accretion phase

Neutrino cooling time : $t_v$
Convective turnover time : $t_c$
Carbon fusion time : $t_f$

- $t_c < t_v < t_f$  **C burns mildly** ; neutrino cooling gets rid of energy generation

- $t_c < t_f < t_v$  **C flash** : convection sets in ; convective core grows fast due to temperature sensitivity of fusion and electron degeneracy

- $t_f < t_c < t_v$  **C ignition** : a flame front builds up
Stellar evolution code: FLASH_THE_TORTOISE

- **STAR** (Eggleton 1971) with a new moving mesh algorithm (Dorfi & Drury 1986)

- A **staggered mesh** for small steps **stability**

- Special treatment of **Chemical fluxes** for extremely low gradients: allows **physical mixing**

- A **front tracking** algorithm for the interfaces between radiative and convective regions: allows to compute the **ultimate phases** 0.01 s before ignition
Initial $M_{\text{WD}}$ effect

Lesaffre, Han, Tout, Podsiadlowski, Martin (2006) MNRAS

- **Higher $M_{\text{WD}}$** start with higher density and lead to higher ignition density
- **Small $M_{\text{WD}}$**: thermal diffusion is faster than accretion, all have the **same evolution**
- **High density**: electron screening effects in the burning rates **fix ignition density**

$M_{\text{WD}} = 0.7$ to $1.2 \, M_\odot$ for $T=0.4$ Gyr
Age effect


- Younger systems start at higher temperature and ignite at smaller density
- For old age and high initial mass, Coulomb screening effects yield same ignition density

\[ M_{\text{WD}} = 1 \, M_\odot \text{ for } T = 0.1, 0.2, 0.4 \text{ and } 0.8 \, \text{Gyr.} \]
Ignition conditions: Central Density

- A range of ignition density
- The minimum density corresponds to the global thermal equilibrium
- The maximum density corresponds to screening effects on the ignition curve
- Note: these high densities require the treatment of electron captures (cf. Urca process, not yet included)

Diamonds, triangles, squares and crosses correspond to ages $T = 0.1, 0.2, 0.4$ and $0.8$ Gyr.
Ignition conditions
Distributions

- Population synthesis by Z.Han
- Bimodal distribution
- Young systems ignite at higher density
- Density $\leftrightarrow$ Luminosity?

**Solid:** $T > 0.8$ Gyr
**Dotted:** $0.4$ Gyr $< T < 0.8$ Gyr
**Dashed:** $T < 0.4$ Gyr
Luminosity
Observed Distributions

- Suggests that \textit{density increases luminosity}?
- \textbf{But} quantitatively incorrect:
  - ages ratio incorrect
  - number ratio inverted
  - bimodal distribution shows up at intermediate ages
- Work in progress...

Enrico Cappellaro
Ignition Conditions
Partial summary

• Age and WD mass determine $\rho$
• All parameters at ignition (but Z, C/O) are correlated to $\rho$
• => Two independent parameters:
  − central density $\rho$ at ignition ($1^{st}$ ?)
  − metallicity Z of the progenitor stars ($2^{nd}$ ? cf. Mazzali & Podsiadlowski 2006)
• Distribution of $\rho$ $\iff$ luminosity function of SNIa?
The convective Urca process

- At high densities, **electron captures** enter into play.
- The **neutrino losses** associated to them plays a complex rôle as we shall see.
The convective Urca process through the literature
Convection
Two-streams formalism

(Lesaffre, Podsiadlowski, Tout, 2005)

**Inputs:**
- spherical RHD
- no viscosity
- an MLT model for horizontal exchanges

**Outputs:**
- Correct Energy and Chemical budget
- Differential reactivity
- Ledoux criterion and convective velocities depend on chemistry
- Time-dependent model
- Handles convective velocity asymetries, hence potentially overshooting
- Handles interactions with mean flow
To the 1-stream limit: a Self-consistent MLT

Energy equation:
\[ \frac{Dc}{Dt} + p \frac{D}{Dt} \left( \frac{1}{\rho} \right) = \epsilon - \frac{\partial L_{\text{tot}}}{\partial m} + W_{\text{conv}} \]

Chemistry equation:
\[ \frac{DN}{Dt} = R - \frac{\partial}{\partial m} F_{\text{tot}} \]

with
\[ W_{\text{conv}} = -\frac{u^3}{\lambda}, \]
\[ L_{\text{tot}} = L_{\text{rad}} + \frac{1}{2} S \rho u [\frac{u}{u + u_0} (\nabla - \nabla_0) - \mu . \nabla N] \]

and
\[ F_{\text{tot}} = F_{\text{diff}} - S \rho u \mu . \nabla N \]

where the convective velocity:
\[ u \simeq c_s \sqrt{\delta (\nabla - \nabla_0) - \mu'' . \nabla N}. \]

Additional features (to MLT):
- Convective work
- Chemical dependence of the convective luminosity
- Chemical dependence of the convective velocity

**However**, numerical difficulties are extreme...
Buoyancy Forces

- Ice cubes sink in classical stellar evolution codes...
- **Density** is what matters
- In *degenerate matter*, density depends little on T and a lot on electron fraction
  => Urca reactions slow down convective motions (Lesaffre, Podsiadlowski, Tout 2005)
- a rough estimate shows that C burning wins over electron captures when: \[ \frac{\delta R_C}{R_U} \gtrsim 1 \]
1D simulations

- Regions where the Ledoux criterion is nearly zero want to form when approaching the Urca shell
- Newton-Raphson has a hard time...

2 snapshots of a 1D simulation by FLASH_THE_TORTOISE
Ledoux (solid) and Schwarzschild (dotted) gradients

![Graph showing Ledoux and Schwarzschild gradients](image)
2D simulations

Stein & Wheeler (2006)  
Code DWARF

- **Code Features:**
  - 2D *implicit-pressure* scheme
  - Chemical *rates rescaled*

- **Results:**
  - Urca reactions *slow down convective motions*
  - Convective core confined yields *higher rate of increase for the entropy*

- C burning rates eventually should win?
A simple model & Cosmological implications

Podsiadlowski, Mazzali, Lesaffre, Wolf, Förster (astro-ph/0608324)

• **Budget of electron captures** on the path to explosion
  - **H burning:** the CNO cycle converts C,N and O to $^{14}\text{N}$ via $(\beta^+)$
  - **He burning:** $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$
  - **C burning:** $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}(p,\gamma)^{24}\text{Mg}(p,\gamma)^{25}\text{Al}(\beta^+)^{25}\text{Mg}(p,\gamma)^{26}\text{Al}(\beta^+)^{26}\text{Mg}$
  - **total:** from 2 to 4 captures depending on the convective Urca efficiency and completeness of $^{22}\text{Ne}$ burning (Förster confirms)

• I then deduce the neutron excess at ignition = $f(Z)$

• Assuming fast combustion as in Timmes, Brown & Truran (2003), I deduce from explosive nucleosynthesis $X(^{56}\text{Ni}) = f(Z)$

• We finally use the simple light curve models from Mazzali & Podsiadlowski 2006 to deduce the drift of luminosity-width relations with respect to the metallicity $Z$. 
Conclusions

- Urca processes yield complex interactions between convection and chemistry
- A simple model illustrates the potential sensitivity of cosmological measures
- The convective Urca process must be included in our models...
- *End of the loop*: explosion models, nucleosynthesis, light curves
Prospects

- Models **FLASH** with electron captures (F. Förster)
- **2D-3D Explosions** (Iapichino, Röpke)
- Nucleosynthesis (C. Travaglio)
- **Light curves** (S. Blinnikov)