3D hydrodynamic simulations of C ingestion into a convective O shell

Robert Andrassy

In collaboration with: Falk Herwig, Paul Woodward, Christian Ritter, Sam Jones

University of Victoria, B.C., Canada
CITA fellow, JINA

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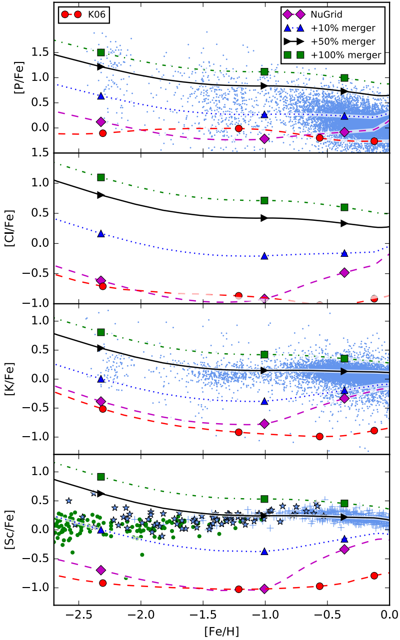
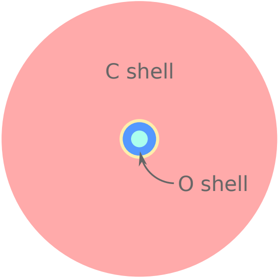
Shell mergers in evolved massive stars

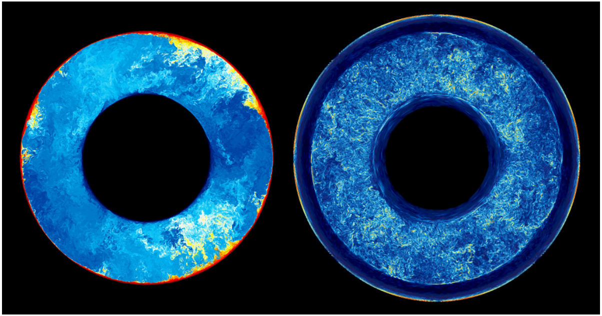
- **production of odd-Z elements:**
  - O-C shell mergers – production sites of P, Cl, K, Sc (Ritter+17, arXiv)?
  - production factors depend on $\dot{M}$ and $D(r)$ in 1D
  - convective-reactive nucleosynthesis $\Rightarrow$ 3D treatment needeed
- **SN progenitor structure:**
  - shell interactions depend on CBM and influence the structure at collapse (Davis+17, in preparation, Alex Heger's talk)
  - mergers as source of large, aspherical fluctuations at collapse?
- **pre-SN outbursts**:
  - mass ejections via wave-driven energy transport into the envelope (Quataert&Shiode12, Fuller17)?



O shell set-up

- MESA: 25 $M_\odot$ star 11 days before core collapse
- $\dot{M}$ at the top of the O shell (Jones+17) large enough to reach the C shell
- Paul Woodward's PPMStar code
- convection zone between two stable layers
- 2 fluids, ideal gas, no neutrino cooling
- upper stable layer assumed to have $X_{\mathrm{C12}} = 5\, X_{\mathrm{C12,MESA}} = 0.13$

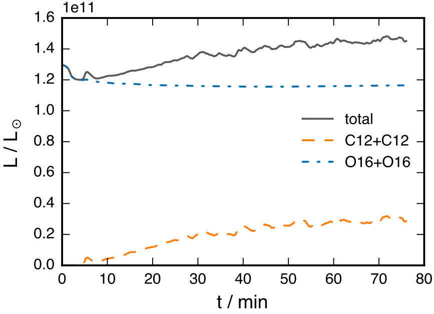


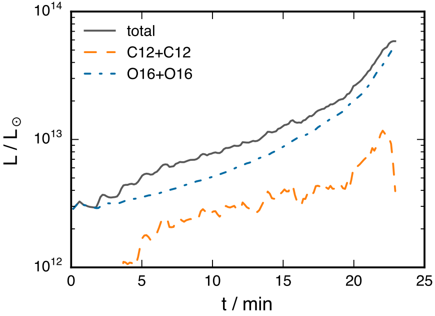


Movies: Flow structure & C burning at 768^3

Luminosity evolution with reaction network (1)

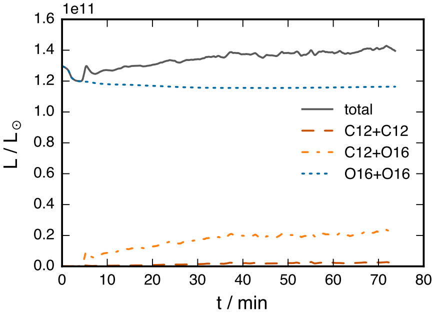
- Net 1: ^{12}C(^{12}C, α)^{20}Ne & ^{16}O(α, γ)^{20}Ne
- all but one run reach a quasi-stationary state
- contribution of $L_{\mathrm{C12+C12}}$ to L_{tot} increases with L_{tot} from $\sim$ 17% to $\sim$ 35%

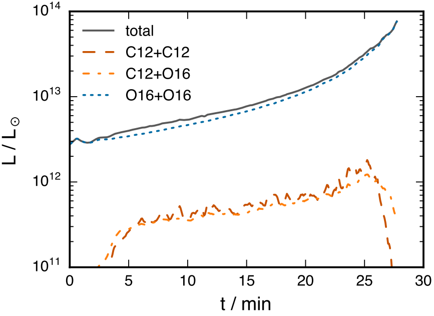




Luminosity evolution with reaction network (2)

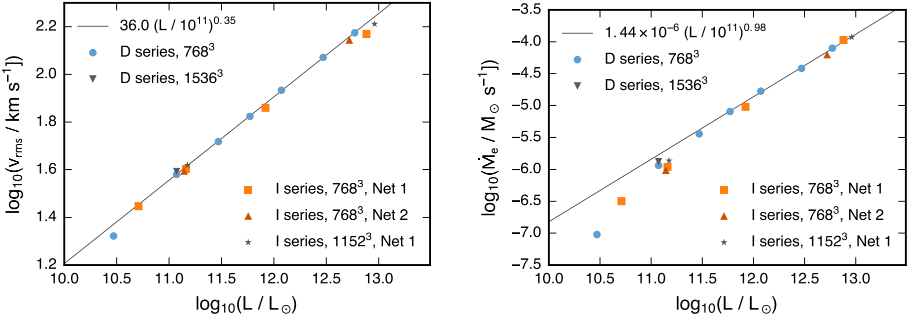
- Net 2: all branches of ^{12}C+^{12}C & ^{16}O+^{12}C with subseqent reactions induced by n, p, α neglected
- both runs reach a quasi-stationary state
- contribution of L_{C12} to $L_{\mathrm{tot}} \sim 17\%$ and $\sim 14\%$
- Marco Pignatari: possibly interesting neutron density? nucleosynthesis will depend on the uncertain branching ratios





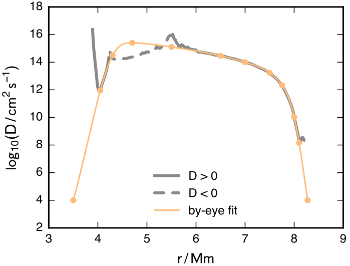
Scaling relations

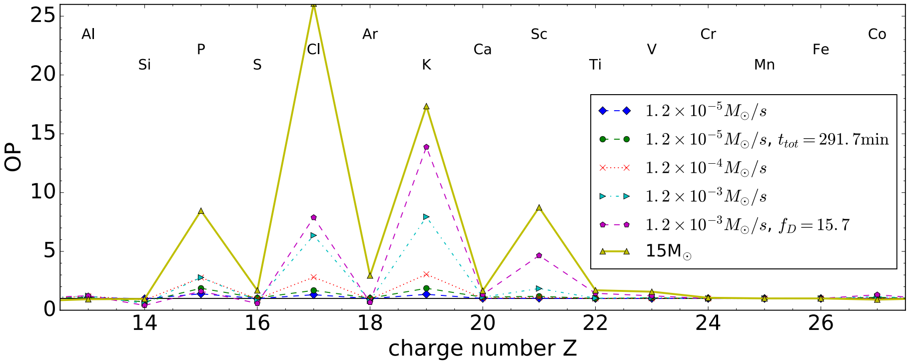
- exact shape of heat source does not matter much
- both sets of C-burning reactions give the same scalings
- numerical issues at low *L*



3D hydro ⟶ 1D nucleosynthesis

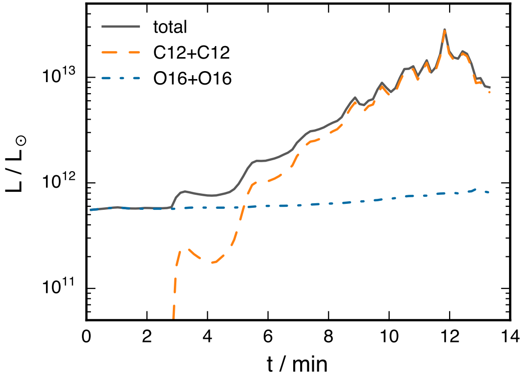
- diffusion coefficient $D(r)$ derived from a low-luminosity run
- 1D nucleosynthesis using MPPNP
- significant production of P, Cl, K, Sc at large entrainment rates and high mixing speeds

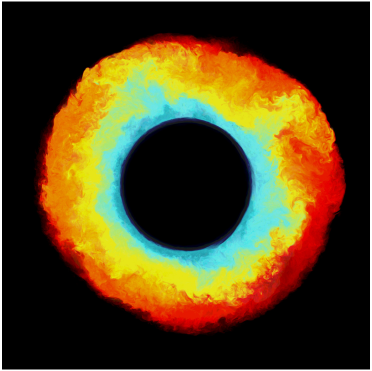




An extreme case

- numerical experiment: Q value of C burning increased by a factor of 10
- global instability
- possible explanation: 1.1 MeV required to entrain 1 amu of fuel, but 1 amu of fuel releases 3.9 MeV ($10\times$Net 1)
- softer boundary $\Rightarrow$ less energy to entrain 1 amu of fuel $\Rightarrow$ easier to reach instability



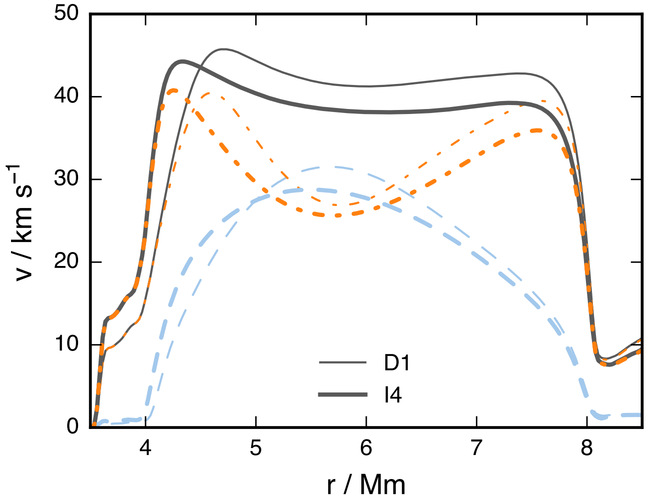


Summary

- stationary convective-reactive regime is reached
- $v_{\rm conv} \propto L^{1/3}$
- $\dot{M} \propto L$; constant of proportionality depends on the stiffness of the boundary
- significant production of odd-Z elements P, Cl, K, Sc at high $\dot{M}$ and $v_{\rm conv}$
- global instability might occur if the boundary is very soft or due to the interaction with a convective C-burning shell
- if a merger becomes violent:
  - source of large fluctuations
  - pre-SN outbursts?
- our team (w/ Paul Woodward) is already working towards:
  - 3D nucleosynthesis post-processing
  - full-blown merger of two convective shells in 3D

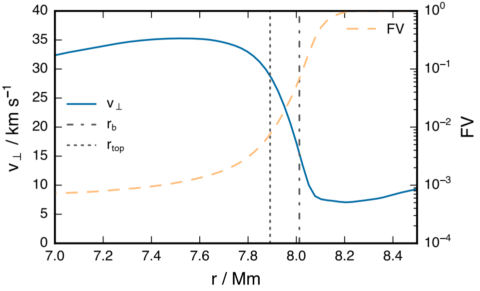
RMS velocity profiles

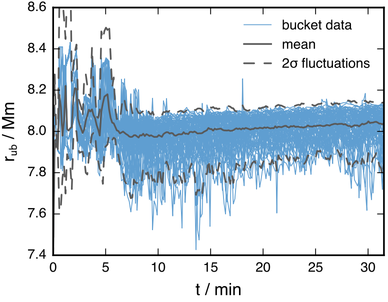
- similar to those of Jones+17
- heat source a bit deeper



Velocity-based boundary definition

- no obvious and unique definition of a convective boundary in 3D
- our definition: $r_{\rm b}$ is where $\partial v_{\perp}/\partial r$ is the steepest
- alternatives: use $\partial FV/\partial r$, or $FV = FV_0$, or?





Entrainment rates

$$\left(\begin{array}{c}\text{mass entrained into}\\ \text{convection zone}\end{array}\right) = \left(\begin{array}{c}\text{mass present in}\\ \text{convection zone}\end{array}\right) + \left(\begin{array}{c}\text{mass burnt in}\\ \text{convection zone}\end{array}\right)$$