Limits for one-dimensional stellar evolution

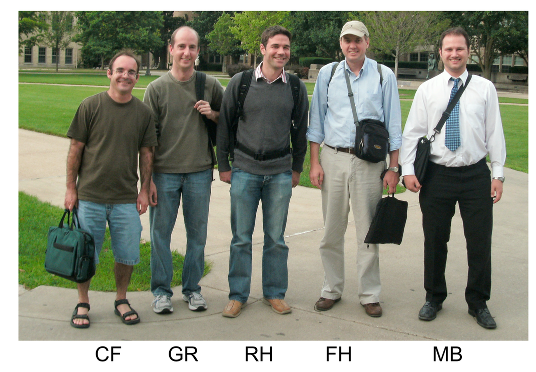
^{12}C-proton combustion in post-AGB stars and at very low metallicity

Falk Herwig[1,2,‡], Marco Pignatari[1,2,4,‡], Paul Woodward[3], Chris Fryer[5,‡], Gabriel Rockefeller[5,‡], David Porter[3], Michael Bennett[6,‡], and Raphael Hirschi[6,‡]

[1]Department of Physics and Astronomy, University of Victoria, Canada
[2]Joint Institute for Nuclear Astrophysics (JINA), University of Notre Dame, USA
[3]LCSE, University of Minnesota, USA
[4]TRIUMF, Vancouver, Canada

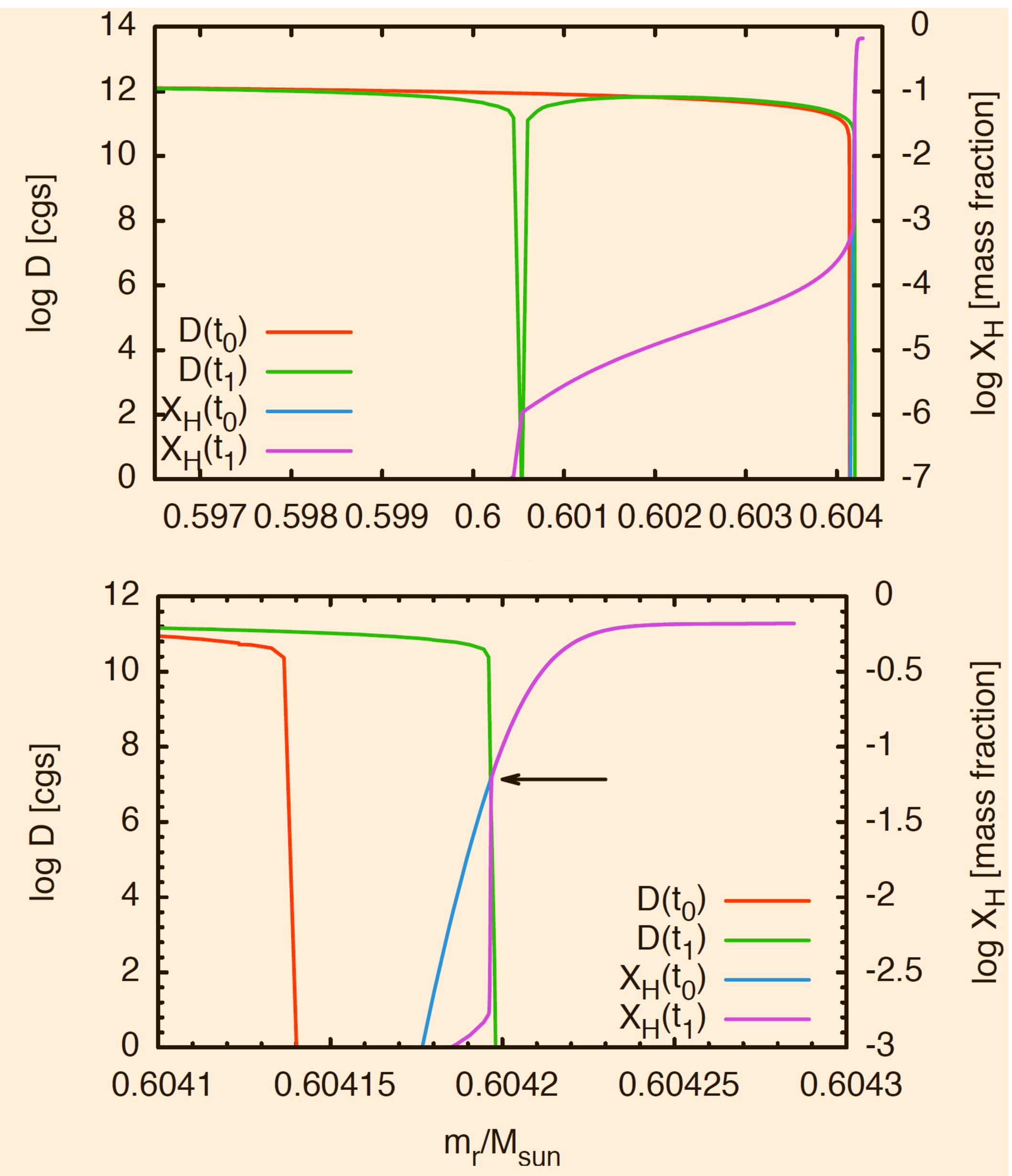
e-mail: fherwig@uvic.ca

[5]CCS Division, Los Alamos National Laboratory, USA
[6]Keele University, UK
‡NuGrid collaboration

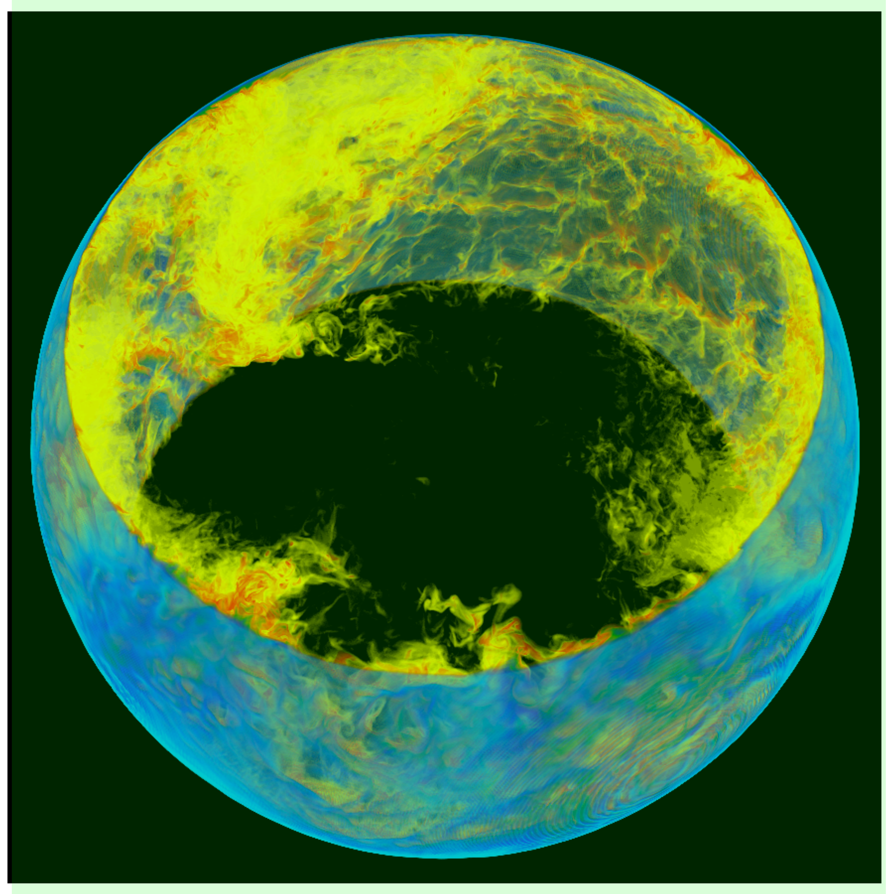


Nuclear combustion is encountered when the **reaction time scale** (for example ^{12}C(p,γ)^{13}N(β$^+$)^{13}C reaction at He-burning temperatures T>1.5*10^{8}K) is **the same as the hydrodynamic fluid flow time scale of convection**. This occurs when unprocessed H-rich material is convectively mixed into a He-burning layer (either the He-core or He-shell), as for example in **first generations star models of very low metallicity** (e.g. Fujimoto etal. 2000 for AGB stars) as well as in **accreting compact objects** (e.g. Piro & Bildsten 2007 for X-ray bursts and C1Dassisi etal. 1998 for accreting white dwarfs).

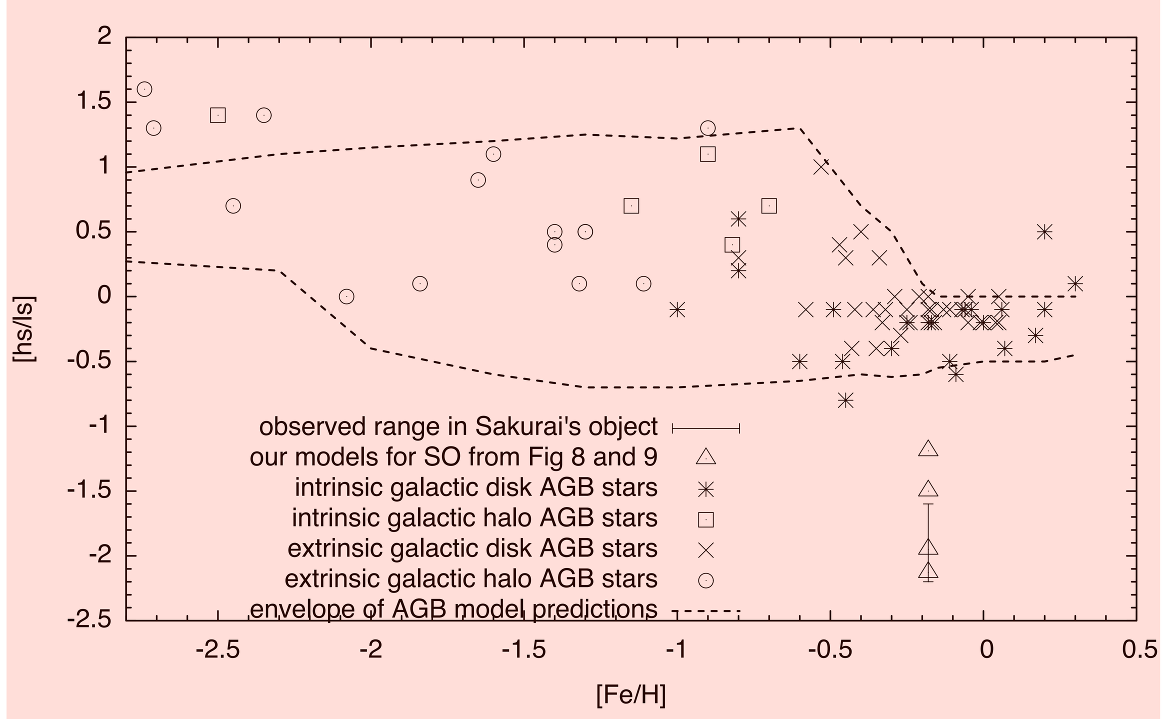
Here we investigate the physics of this important regime through stellar evolution calculations, complete multi-zone nucleosynthesis simulations as well as 4π 3D hydroydynamic simulations of the **very-late He-shell flash** (Herwig & Werner, 2006) that occured in Sakurai's object (V4334 Sagittarii) a ~0.6M_{sun} pre-WD post-AGB star. We can **validate our simulations** against the multitude of observables available in this case, in particular 20 spectroscopic elemental abundances from Asplund etal. (1999). Full details can be found in Herwig etal. (2010, **arXiv:1002.2241v1**).



Stellar evolution predictions for the nuclear combustion in Sakurai's object: Convective diffusion coefficient and H abundance profile at the beginning of the H-ingestion flash (t_0) and at the time when the split of the convection zone appears at $t_1=t_0$ + 8.58*10^{5}s. In 1D models mixing through this split is not possible. Top panel: the outer section of the convection zone showing the location of the split as a deep dip in D; bottom panel: just the interface of the outer boundary of the convection zone.

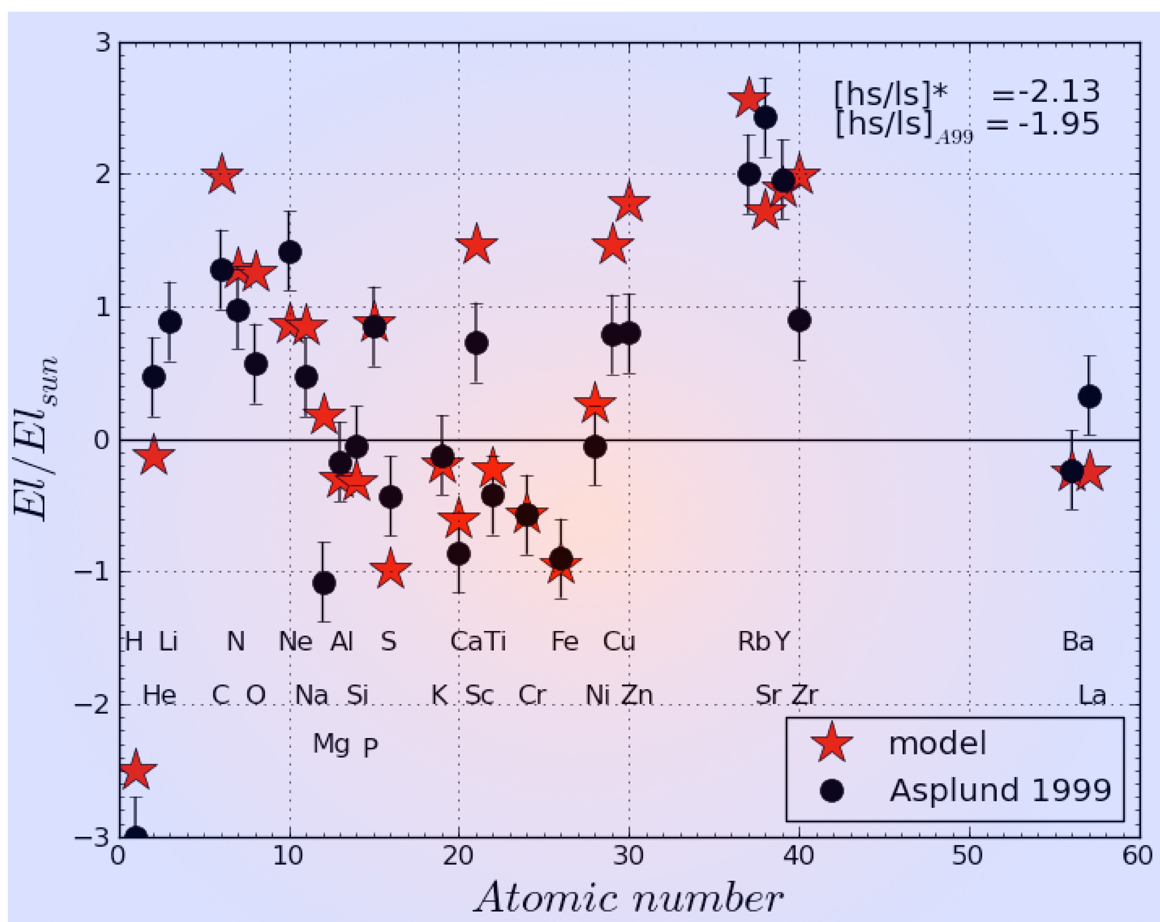


Hydrodynamic picture of H-entrainment into He-shell flash convection: Snapshot of **PPM simulation** on uniform Cartesian grids of 576^3 cells of flash convection in full 4π, representing stellar evolution situation for time t_1. Colors indicate abundance of material in the stable layer above the convection zone that has been entrained into the convection zone (no H-burning is included in this run). Volume fractions of about 1%: blue, concentrations close to one: transparent, lowest concentration 0.01%: yellow, below approximately $5 \cdot 10^{-5}$ and above 1%: transparent. (More infromation and movie animations on the LCSE web site at http://www.lcse.umn.edu.)

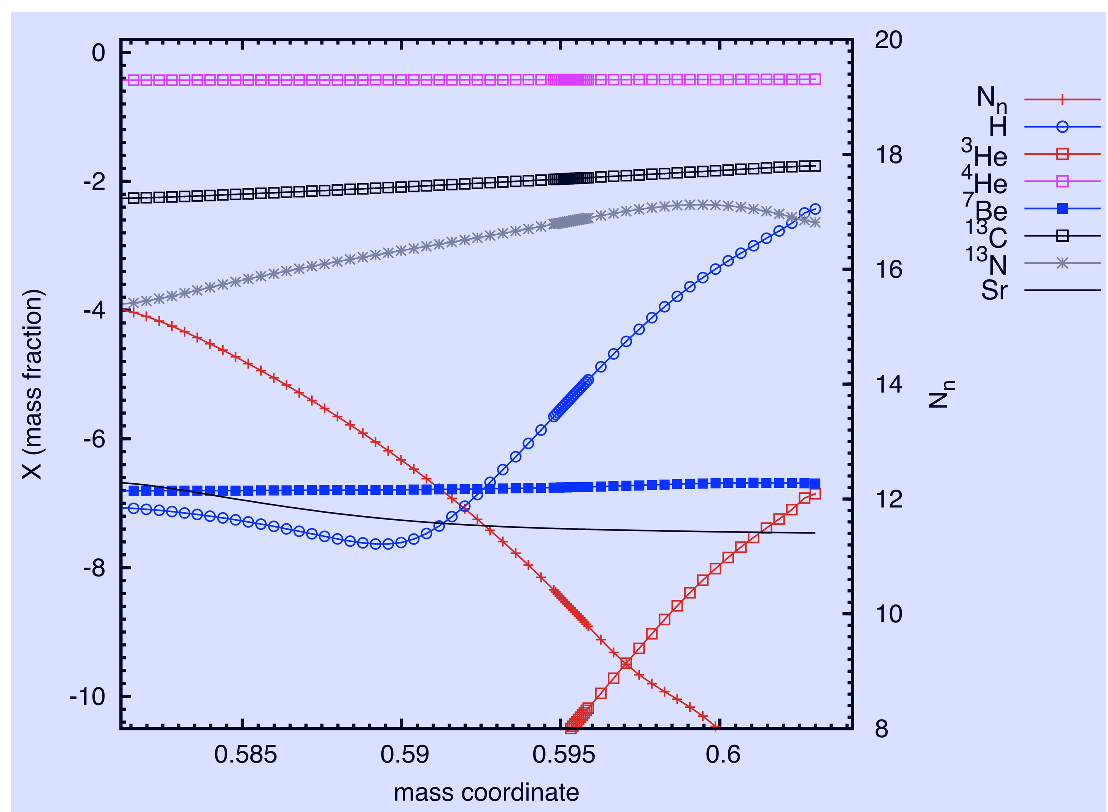


Observational constraints: Ratio of heavy (hs = <Ba,La>) to light s-process elements (ls = <Rb,Sr,Y,Zr>) is very low (Asplund etal. 1999). Other observed abundances (e.g. Li, P, Cu, Zn up and S, Ti, Cr and Fe down) are also **anomalous in a way that can not be reconciled with any known s-process production site during the progenitor AGB evolution** (Busso etal. 2001). In particular, no or very few neutrons would be released in the early-split convection scenario predicted from stellar evolution.

Hydrodynamic simulations suggest that the entrainment is inhomogeneous, possibly causing a much more distributed burn layer than found in stellar evolution. Mixing may be possible much longer than predicted by stellar evolution. We tested that scenario with nucleosynthesis simulations and indeed find only with this enhanced hydrodynamic mixing across the burn layer a good match with observations.



Comparison of nucleosynthesis simulation of H-ingestion episode and observations by Asplund etal (1999).



Nucleosynthesis simulation of H-ingestion episode in 1D using the **multi-zone NuGrid MPPN code**. In order to reproduce observations, in particular **[hs/ls] large neutron densities** are needed. This is obtained only if mixing can proceed longer between the upper layers where ^{13}C forms and deep, hotter layers where ^{13}C(α,n)^{16}O releases **large amounts of neutrons.**

We interpret our results as a failure of 1D stellar evolution to accurately describe mixing for nuclear combustion (or convective-reactive) phases of stellar evolution. This has important consequences for the nucleosynthesis predictions of the first generations of stars. At extremely low or even zero metallicity combustion events are frequently encountered in both massive (e.g. Ekström etal. 2008) and low-/intermediate-mass stars and yield predictions from present 1D stellar evolution simulations may suffer similar difficulty in accurately predicting mixing, just as demonstrated here for the case of combustion in Sakurai's object.

The next goal of this research program is to improve the hydrodynamic simulations to fully include the nuclear reactions for combustion and to quantify mixing in the different regimes of this event. This will eliminate some of the free parameters in the nucleosynthesis simulations, and will eventually lead to mixing models that can be incorporated into 1D stellar evolution simulations for the evolution and yields of the first generations of stars.

References:

Asplund, M., Lambert, D. L., Kipper, T., Pollacco, D., & Shetrone, M. D. 1999, A&A, 343, 507

Busso, M., Gallino, R., Lambert, D. L., Travaglio, C., & Smith, V. V. 2001, ApJ, 557, 802

Cassisi, S., Iben, I. J., & Tornambe, A. 1998, ApJ, 496, 376

Ekström S., Meynet, G., Chiappini, C., Hirschi, R., & Maeder, A. 2008, A&A, 489, 685

Fujimoto, M. Y., Ikeda, Y., & Iben, I., J. 2000, ApJ Lett., 529, L25

Piro, A. L. & Bildsten, L. 2007, ApJ, 663, 1252

Herwig, F. & Werner, K., 2006, PASP 118, 138

Rep. No. LA-UR 10-00630