The convective-reactive flash in Sakurai's object

Nucleosynthesis and hydrodynamics of nuclear combustion and implications for the evolution of the first generations of stars

Falk Herwig[1,2,‡], Paul Woodward[3], Marco Pignatari[1,2,4,‡], 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

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

e-mail: fherwig@uvic.ca

Nuclear combustion is encountered in quiescent (i.e. non-explosive) stellar evolution, for example, when unprocessed H-rich material is convectively mixed into a He-burning layer (either the He-core or He-shell). He-burning will have produced plenty of primary ^{12}C which vigorously reacts with H to eventually form the neutron source species ^{13}C: $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$. The **reaction time scale** at He-burning temperatures ($T>1.5*10^8K$) is minutes, and thus **comparable to the convective turn-over time scale**. We therefore expect that the instantaneous nuclear energy release in such a **convective-reactive episode** will significantly effect the **convective fluid-flow**. We then have to question if one-dimensional, spherically-symmetric stellar evolution models based on the mixing-length theory of convection can accurately describe the multi-dimensional hydrodynamic processes of nuclear combustion.

Such convective reactive events are common in stellar evolution, especially in the stars of very low metal content that formed in the Early Universe (e.g. Fujimoto etal. 2000 for AGB stars, or Ekström etal. 2008 for massive stars) as well as in **accreting compact objects** (e.g. Piro & Bildsten 2007 for X-ray bursts and Cassisi etal. 1998 for accreting white dwarfs).

We investigate the H-ingestion into the convective He-shell flash convection of the **very-late thermal pulse** (Herwig & Werner, 2006) in Sakurai's object (V4334 Sagittarii) which is a well observed ~$0.6M_{sun}$ pre-WD proto-type of this class of events. If we can **validate our simulations** against the multitude of observables available in this case we may improve the predictive power of simulations for the above mentioned applications.

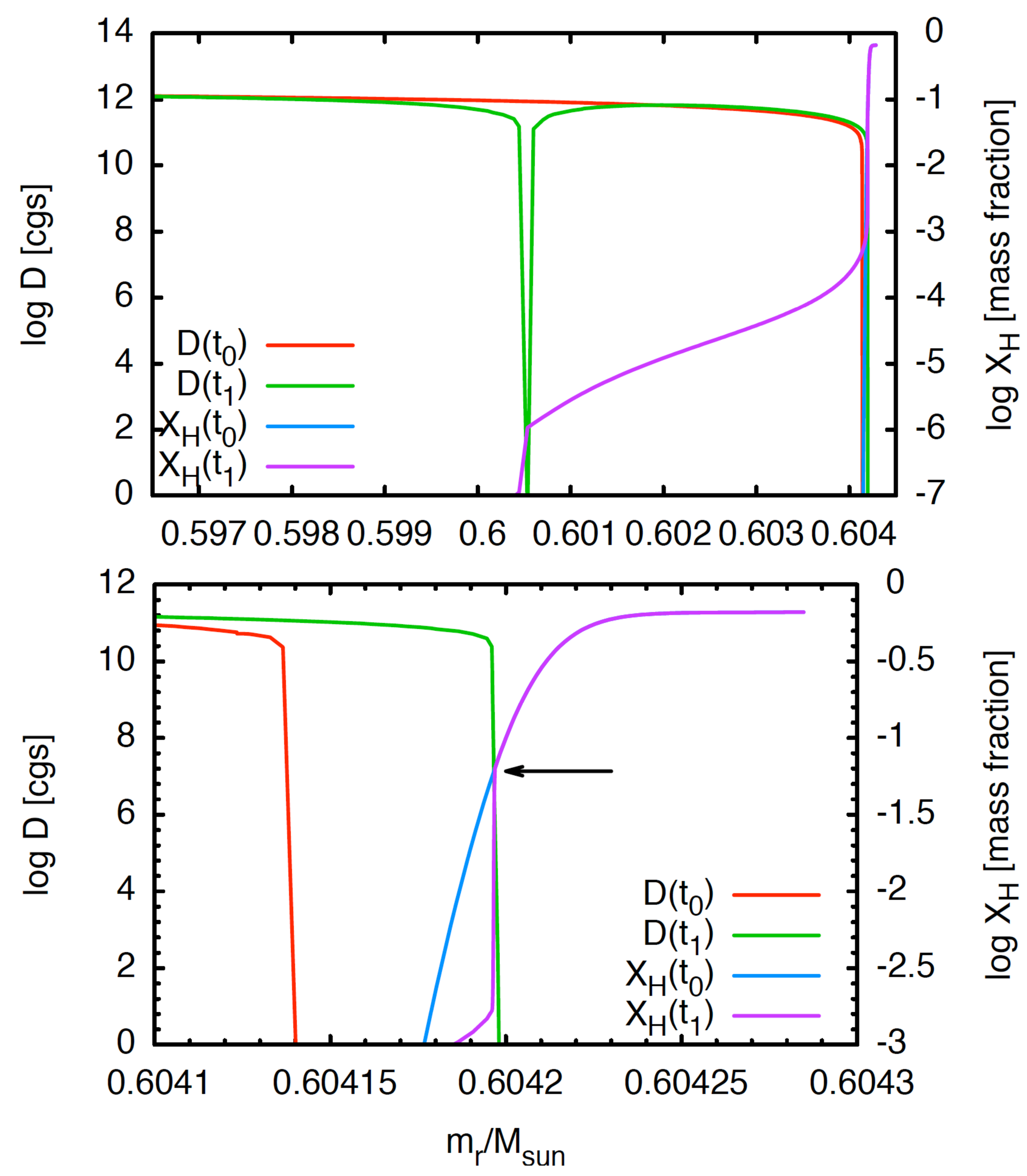

Fig. 1. Stellar evolution predictions for the nuclear combustion in Sakurai's object: Convective diffusion coefficient and H abundance profile at the beginning of the H-ingestion flash (t_0) and at the time when the split of the convection zone appears at $t_1=t_0 + 8.58*10^5$s. Top panel: the outer 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. The arrow indicates the H abundance at the position that has been reached by the convection zone at the time t_1. t_0 is at the time of the minimum of the H-burning luminosity at the onset of the H-ingestion event.

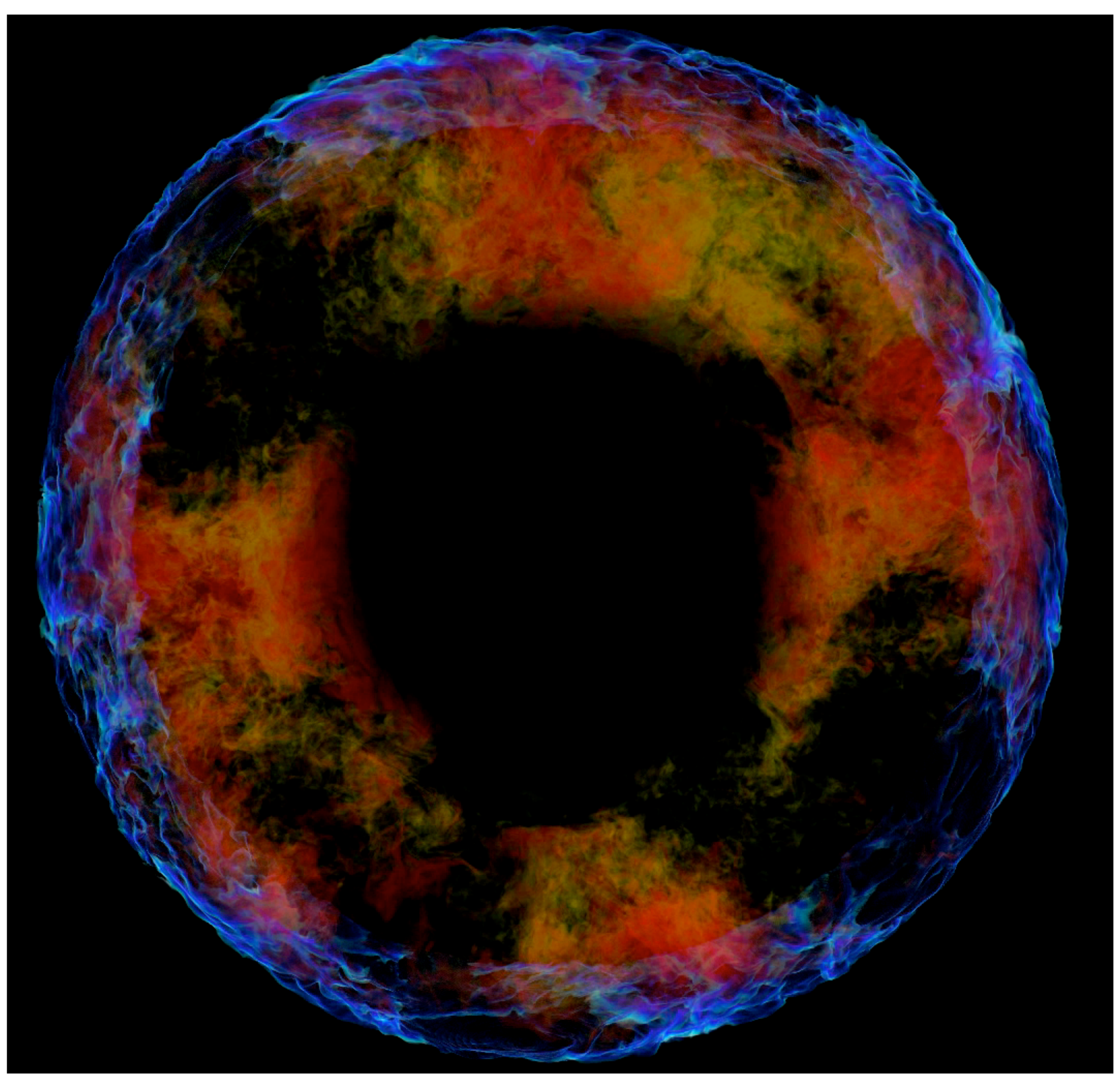

Fig. 2. Hydrodynamic picture of H-entrainment into He-shell flash convection: Snapshot of a hemisphere of the AGB star's interior taken from a preliminary **PPM simulation** on uniform Cartesian grids of 512^3 cells. The setup reflects the conditions near the peak of the He-shell flash, and is based on a stellar evolution model similar to the one shown in Fig.1 for time t_0. Colors indicate abundance of material in the stable layer above the convection zone that has been entrained into the convection zone. The convection zone is approximately 5000km thick. Concentrations of H-rich entrained fluid from above the convection zone that are near but not quite equal to unity are blue, while red and yellow correspond to concentrations of around 1% and 0.1 to 0.01%. The hemisphere facing in and out of the page have been cut away and the visualised part of the star is really a thick slice of the star. In this exploratory simulation the He-luminosity has been increased by a factor 62 and the reaction of entrained H-rich material with the ^{12}C in the He-shell flash zone has not yet been included. (More images and movie animations that are accessible from the 'MOVIES' link on the main LCSE web site at http://www.lcse.umn.edu.)

Stellar evolution simulations (Fig.1) predict that H-burning induced energy release will split the convection zone at an early stage of the H-ingestion, when only a few $10^{-7}M_{sun}$ of H have been burned. An entropy barrier develops which prevents any further mixing between the upper H-burning driven convection zone and the lower He-flash convection zone.

Powerful **observational constraints** come from spectroscopic observations of heavy elements 2yrs after the flash by Asplund etal. (1999): the ratio of heavy (hs = <Ba,La>) to light s-process elements (ls = <Rb,Sr,Y,Zr>) is very low [hs/ls]<-2, which is entirely due to a very large ls production: [ls/Fe]>2. 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 neutrons would be released in the early-split convection scenario predicted from stellar evolution (Fig.1).

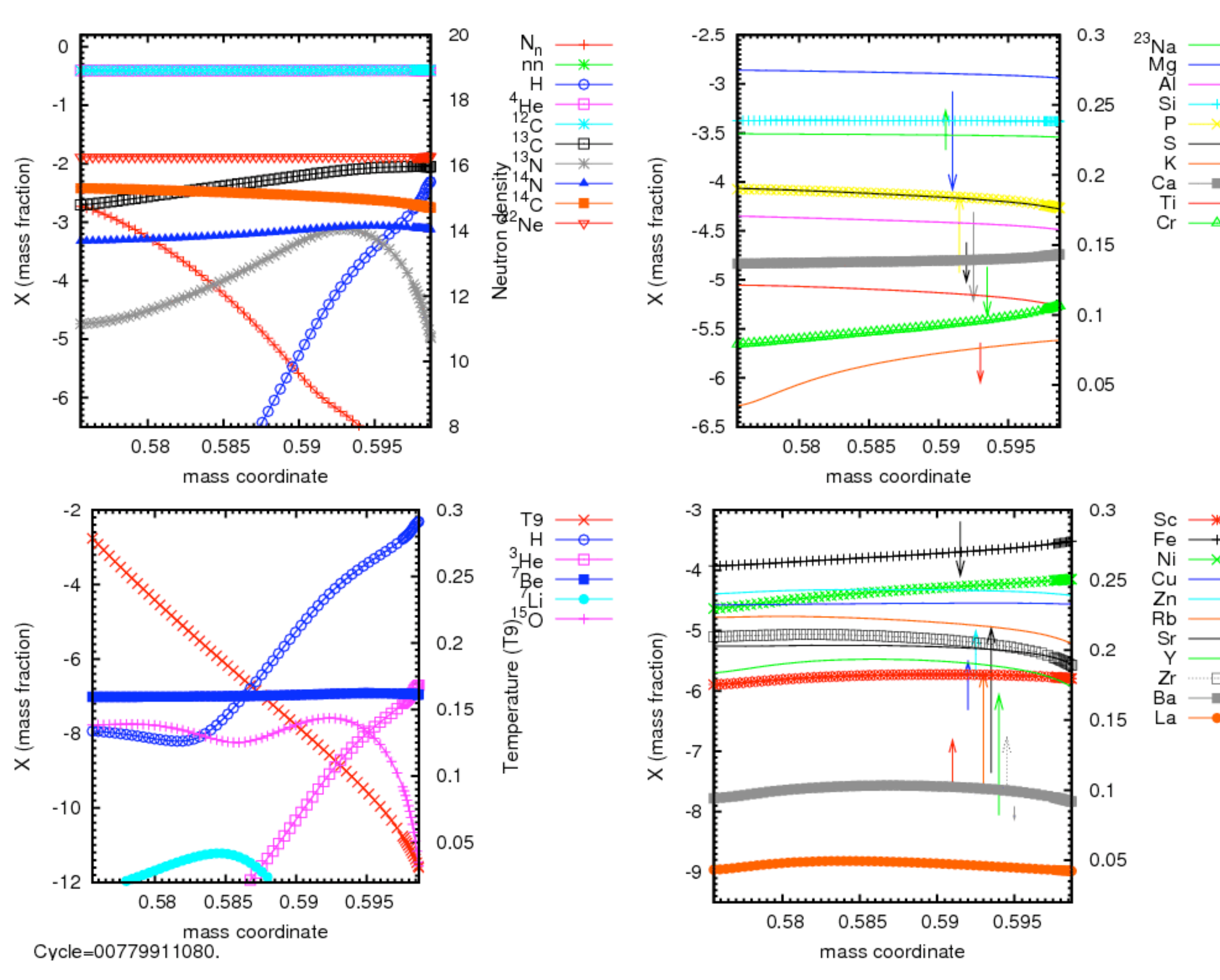

Fig. 3. Nucleosynthesis simulation of H-ingestion episode in one-D using the **multi-zone NuGrid MPPN code** at 1080min. The stratification is a peak-flash model like t_0 in Fig.1 just before the split occurs. It is assumed that mixing can proceed between the upper layers where ^{13}C forms and deep, hotter layers where the 13C(α,n)^{16}O reaction can release **large amounts of neutrons.** Arrows in the right panels indicate solar abundance (arrow base) to observed abundance (arrow heads) changes for the respective elements.

Hydrodynamic simulations (Fig.2) 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. ^{13}C, that forms in the upper layers, may then reach the hot, deep layers and cause very high n-densities N_n (top-left panel, Fig.3). Indeed, **comprehensive nuclesynthesis simulations** show that many of the observed abundance signatures can be accomodated in this scenario. **Fig.3 shows the nucleosynthesis** already at a late time when even Ba starts to be produced. This is not observed, and the conclusion is that eventually mixing between the two layers is shut down, due to the continued build up of a positive entropy gradient from convective-reactive burning of ingested H.

Summary: Our nucleosynthesis simulations show that 1D stellar evolution codes can not provide reliable models of situations involving nuclear combustion. Hydrodynamic simulations are starting to shed light on the process of entrainment, and support our conclusions. Once completed this multi-physics investigation of convective-reactive nuclear combustion will yield a better understanding of the physics of stars from the early Universe, as well as accreting compact objects.

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