PROCEEDINGS OF SCIENCE

AGB stars evolution and nucleosynthesis

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Asymptotic Giant Branch stars are the main nuclear production phase of low- and intermediate mass stars. The double-shell burning of He and H around the electron degenerate core drives a rich pattern of nucleosynthesis, including the slow neutron capture process, as well as the formation of neutron rich isotopes. This nucleosynthesis is now observationally accessible in extremely metal poor stars, in particular the carbon enhanced s- process rich stars in binaries. The most common approach to model AGB star evolution and nucleosynthesis is the one-dimensional, spherically symmetric stellar evolution approximation. The input physics (mass loss, convective and non-convective mixing, nucleosynthesis) and their uncertainties are discussed. More recently, hydrodynamic simulations of He-shell flash convection are becoming available, providing the means for a detailed analysis of some of the uncertain aspects of one-dimensional models. The differences between stellar interior convection and shallow surface convection is discussed. We also report on new studies that investigate the sensitivity of mixing and element production to nuclear reaction rates.

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1. Introduction

Asymptotic Giant Branch (AGB) stars are the advanced evolutionary representations of low and intermediate mass stars which have initial masses below about $10\,M_\odot$. A comprehensive review of many of the fundamental properties of AGB stars was presented by Iben & Renzini (1983). More recent reviews focussed on specific aspects, like the *s* process (Busso et al., 1999; Meyer, 1994), and the post-AGB stars and their observational implications for the *s* process (van Winckel, 2003). Overview articles on AGB stars in conference proceedings include Lattanzio & Boothroyd (1997) and Blöcker (1999). A textbook on AGB stars is now available and covers the interior evolution and the atmosphere, circumstellar and other observational properties (Habing & Olofsson, 2004). Another recent review (Herwig, 2005) covers current developements in more detail.

Several processes are characteristic and of great importance for AGB stars. AGB stars are fueled by two nuclear burning shells surrounding the inert electron-degenerate carbon/oxygen core, the hydrogen-burning shell and the helium-burning shell. The He-shell is only significantly activated during the recurrent thermoculcear runaways, with a mass dependent periodicity of a few 10000 to 10^5 yr. These thermal pulses, or He-shell flashes are a major nuclear production site in AGB stars because the highest temperatures for nucleosynthesis are reached in these events. Thermal pulses are followed by the third dredge-up mixing, at least for a core mass above approximately $0.58\,M_\odot$ (Marigo et al., 1999). This dredge-up is the mechanism in AGB stars that brings nuclear processed material from the He-shell flash burning to the stellar surface, where it is ejected through mass loss into the interstellar medium. Dredge-up is triggered by the He-shell flash. Previously stable layers of nuclear processed material just below the convective envelope becomes unstable as well, and are mixed to the stellar surface. Without dredge-up most nuclear burning products would remain eventually locked in the final white dwarf, and from a nucleosynthesis point of view AGB stars would be rather unimportant and boring objects without much consequence for the rest of us.

The super-massive AGB stars are evolving from stars with initial masses above about $8\,M_\odot$(at solar metallicity, lower at metal-poor composition) and ignite carbon burning (García-Berro & Iben, 1994; Gil-Pons et al., 2005). Some of these super-AGB stars may explode as supernova. However, poorly known details about envelope burning (hot-bottom burning, HBB), mass loss and dredge-up make the current predictions of the final outcome of this evolution and the supernova fraction uncertain.

Massive AGB stars with initial masses between 3.5 and $8\,M_\odot$ (depending on metallicity) are characterized by hot-bottom burning (HBB) during which the envelope is convectively connected with the H-burning shell (Blöcker & Schönberner, 1991; Forestini & Charbonnel, 1997; Denissenkov & Herwig, 2003; Ventura & D'Antona, 2005). This leads to large over-luminositities and CNO processing of the envelope material. The Ne-Na cycle and, to a lesser extent, the Mg-Al cycle are activated during HBB as well, which makes an accurate knowledge of the involved p-capture reaction rates necessary.

Low-mass AGB stars with initial masses less than $3.5\,M_\odot$ are the dominant nuclear production site of the *s* process (Gallino et al., 1998). As in the more massive AGB stars these low-mass AGB stars experience the third dredge-up as well, but no HBB. These are the AGB stars that through dredge-up become C-rich (C/O>1) and are then classified as C-stars.

Currently the evolution of extremely metal-poor AGB stars is of great interest. Observationally the nuclear yields of these stars are accessible through the carbon-enhanced metal poor stars with s-process (CEMP-s) (Beers & Christlieb, 2005) that are mostly, if not entirely (Lucatello et al., 2005), binary stars. These CEMP-s stars are believed to be polluted by a former AGB companion, that is now orbiting as a white dwarf. As discussed below some CEMP-s stars show very good agreement with AGB stellar and nucleosynthesis models, while other observations pose serious problems for current models to explain (Johnson et al., 2006).

In this paper we will discuss - with the general audience of the NIC IX conference in mind - mixing and nucleosynthesis in the framework of one-dimensional calculations (Sect. 2) as well as new multi-dimensional simulations of the important thermal pulse flash convection triggered by the thermonuclear runaway of the He-shell (Sect. 3).

2. One-dimensional stellar structure and evolution models

By assuming spherical symmetry the entire life of stars can be simulated by a sequence of several ten or hundred thousand one-dimensional hydrostatic equilibrium models (under certain conditions it is useful to compute one-dimensional hydrodynamic models that add the inertia term to the equation of hydrostatic equilibrium). By design these models use a space- and time-averaged - and therefore simplified - approach to mixing and nuclear burning. This procedure works very well for many applications, in particular those where the nuclear, the thermal and the hydrodynamic time scales are very different. With this approach we can follow the entire stellar evolution from core H-burning on the main-sequence to the final stellar death as white dwarf or supernova, and it is therefore very useful for systematic nuclear reaction rate uncertainty studies. We can also study the global impact of specific models for mass loss or mixing, for example on the total integrated chemical yields.

2.1 Mass loss

Their stellar parameters - cool and luminous - make AGB stars very efficient mass losers. In the coolest AGB stars ($T_{\rm eff} < 4000\,$K) circumstellar dust can form out of the pulsationally driven gas and molecular ejecta. Observations at thermal infrared wavelengths allow mass loss to be measured (van Loon et al., 1999), and very recent observations indicate that especially at lower metallicity dust formation is more efficient for C-rich stars (Zijlstra et al., 2006). Radiation pressure will drive the dust away from the star dragging the gas along with it. This dust-driven mass loss can reach $10^{-4}\,{\rm M}_\odot/{\rm yr}$, and will prevent all AGB stars (with the exception of an uncertain fraction of the most massive super-AGB stars) from exploding as supernova. Although the star continuously grows due to nuclear shell burning of H and He, the mass loss is eventually larger than the rate of core growth and the AGB star evolves into a white dwarf. The ejected material however contains nuclear processed material, and AGB stars contribute to the galactic chemical evolution through these chemically enriched winds. The amount of nuclear processed material ejected with the winds depends sensitively on the exact amount of mass loss. The quantitative knowledge of mass loss, both due to observations and through hydrodynamic simulations of AGB star winds is currently greatly improving, and these results will soon be incorporated into stellar evolution computations (Sandin & Höfner, 2004; Wachter et al., 2002; van Loon et al., 2005; Schröder & Cuntz, 2005). The potential of detailed infrared studies of circumstellar structures around bright central sources

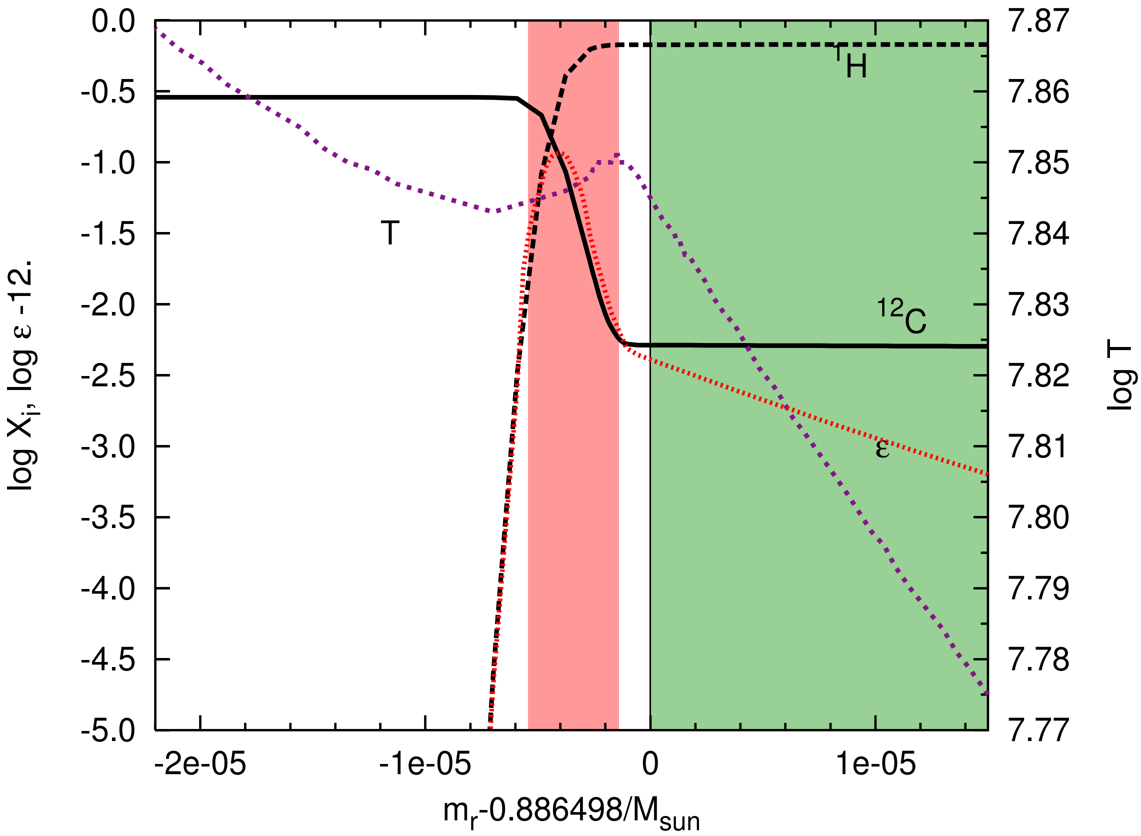

Figure 1: Conditions at the bottom of the convective envelope in a $5\,M_{\odot}$ stellar model with metallicity Z=0.0001 during the dredge-up phase after a thermal pulse (Herwig, 2004). The green area is the lowest layer of the convective envelope. Shown are the H and ^{12}C abundances, the energy generation ε due to H-burning and the temperature T. The red shaded layer below the convection zone exhibits vigorous H-burning fueled by H brought below the convection zone by mild, assumed convective overshooting.

was recently demonstrated by the first detection of the stellar-wind bow shock interaction for an AGB star (Ueta et al., 2006).

2.2 Convective and non-convective mixing

The most important mixing processes in stars is convective mixing, driven by a need for more efficeint energy transport than possible through radiation alone. Convection can be caused by efficient cooling on the stellar surface, or by nuclear burning and heating, as for example in the case of the He-shell flash convection zone. Unfortunately the treatment of convection in one-dimensional models of stars is still an important source of uncertainty. Within the mixing-length theory model for convection the efficiency is calibrated through fitting a mixing-length parameter $\alpha_{\rm MLT}$ in a solar model to the solar parameters. This mixing length parameter is then used unchanged throughout all other phases of stellar evolution, and for stars of very different mass than the sun. However, Ludwig et al. (1999) have shown through a differential study based on two-dimensional radiation-hydrodynamics models that even within a temperature range of $\pm 1000\,$K $\alpha_{\rm MLT}$ varies within $\pm 5\%$. It has also been shown by Boothroyd & Sackmann (1988) and several later studies

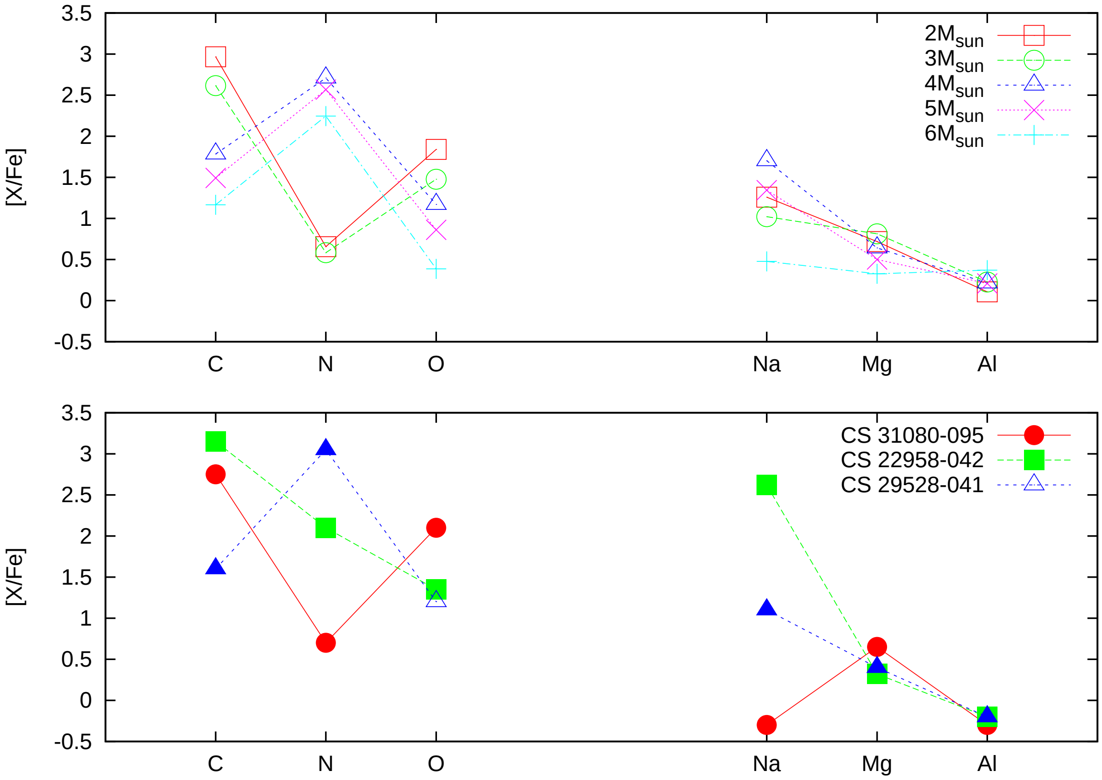

Figure 2: Top panel: overabundances of total AGB wind ejecta for Z=0.0001 (Herwig, 2004); bottom: overabundances in three carbon-enriched metal poor stars that very likely have been poluted by former AGB companions (Sivarani et al., 2006).

that the third dredge-up is sensitive to the value of $\alpha_{\rm MLT}$. Realistic 3D simulations of AGB envelope convection can remove this uncertainty (Porter & Woodward, 2000). It may be that the results of these simualtions will be implanted back into stellar evolution models in more sophisticated ways, like the full-spectrum turbulence convection theory (Mazzitelli et al., 1999).

In addition to transport of energy and material inside the unstable zone, convection induces mixing accross the convective boundary and in the nearby, stable layers. The nature and properties of specific convection boundaries can be studied using multi-dimensional hydrodynamic simulations (see Sect. 3). The effect of such mixing on the overall, global evolution is investigated by adding parameterized mixing algorithms to mixing-length based stellar evolution calculations (see for example Herwig et al., 1997; Mowlavi, 1999, and Cristallo, this volume).

Mixing accross the convective boundary and into the stable layer can have important consequences, in particular when nuclear burning is involved as well. One example concerns the evolution of extremely metal-poor intermediate mass stars. Herwig (2004) found that models of such stars with assumed mild exponential overshoot (Herwig, 2000) display vigorous H-burning below the bottom of the convection zone during the third dredge-up phase (Fig. 1). Within the one-dimensional framework H is mixed into the hot ^{12}C-rich layer just below the convection zone, and causing a corrosive, flame-like burning that can deepen the third dredge-up (hot third dredge-up). The overshoot mixing assumed in this model is about ten times less efficient compared to the

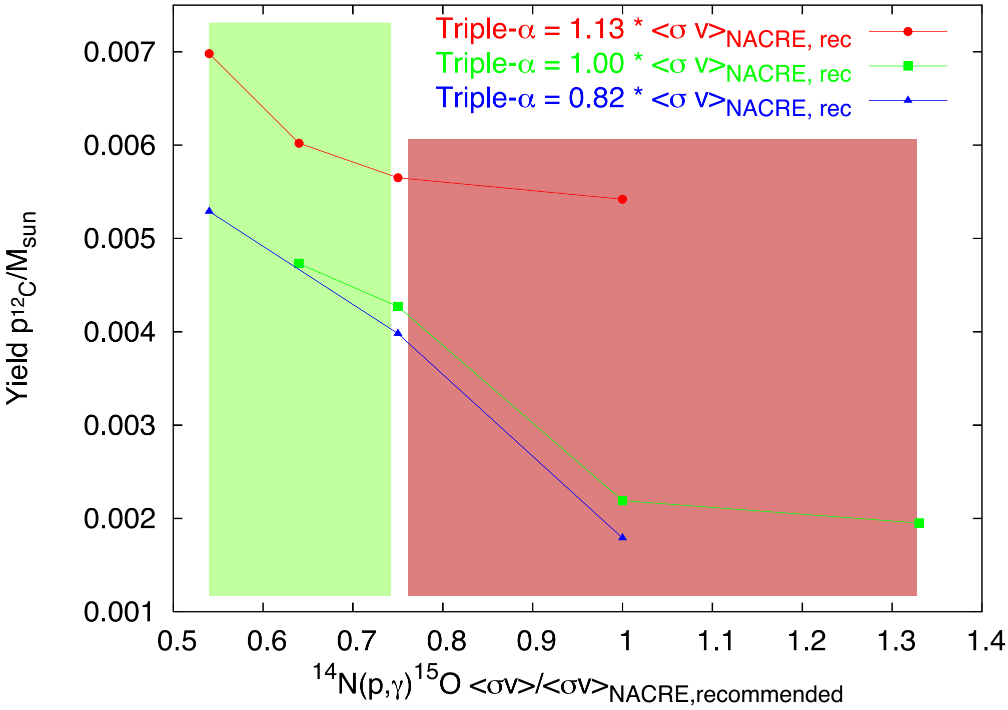

Figure 3: Total ^{12}C yield as a function of nuclear reaction rate, corresponding to what one $2\,M_\odot$ star of $0.5Z_\odot$ ejects into the interstellar medium. The red shaded region indicates the NACRE uncertainty range. The green area covers the updated range for the ^{14}N$(p,\gamma)^{15}$O reaction, as discussed in Herwig & Austin (2004).

overshoot mixing that would be required to drive a proper ^{13}C-pocket for the *s* process in low-mass AGB stars (Lugaro et al., 2003). If the same overshoot parameter were applied in both cases models would either not show the observed *s*-process overabundances in low-mass stars or intermediate mass AGB stars at very low metallicities would evolve very differently than currently assumed, burning-up and loosing their H-rich envelope in maybe only a single violent hot-dredge up flame. In one case, CS 29528-041, good agreement between models with small overshooting and only mild H-burning during dredge-up and observations can be reported (Fig. 2).

Several non-convective mixing processes play an important role in AGB stellar evolution. Internal gravity waves (Press, 1981) are excited by convection (Sect. 3). Denissenkov & Tout (2003) have shown that internal gravity waves may play an important role to provide mixing for the formation of the ^{13}C pocket of the *s*-process. Internal gravity waves may also play an as yet unexplored role at the boundaries of other convective boundaries. Future multi-dimensional simulations of the stellar interior will allow us to validate the one-dimensional model of internal gravity wave mixing. AGB stellar models including rotation (Langer et al., 1999) seem to miss additional means of angular momentum transport. The resulting AGB cores, the white dwarfs to be, are rotating faster

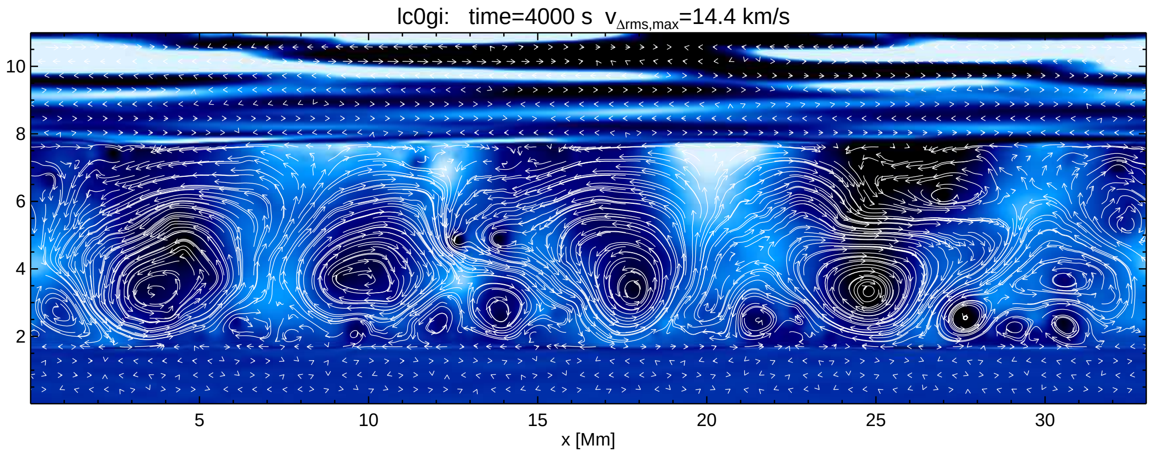

Figure 4: Pressure fluctuations and pseudo-stream lines of a 2D He-shell flash convection run with 2400x800 grid.

than what is observed using asterioseismology (Kawaler, 2003). In addition, mixing through too much differential rotation at the core-envelope interface during the interpulse phase seems to shut down the radiative *s*-process fueled by the ^{13}C pocket through admixture of the neutron poison ^{14}N (Herwig, 2003). Magnetic fields may provide the missing angular momentum transport, as seems to be the case in massive stars (Heger et al., 2005). However, for AGB stars detailed studies of the effect of magnetic fields are not yet available.

2.3 Nuclear reaction rates and nucleosynthesis

Nuclear production in AGB stars depends sensitively on a number of reactions, including the $^{14}\mathrm{N}(\mathrm{p},\gamma)$ and the triple-α reactions (Fig. 3). These two reactions affect the structural evolution of thermal pulses (Herwig et al., 2006). A lower $^{14}\mathrm{N}(\mathrm{p},\gamma)$ as well as a larger triple-α rate lead to stronger He-shell flashes with the result of more efficient and deeper third dredge-up. This in turn then leads to larger yields of ^{12}C and all other elements dredged up into the envelope.

The recent reevaluation and improvement of the $^{14}\mathrm{N}(\mathrm{p},\gamma)$ rate (A. M. Mukhamedzhanov *et al.*, 2003; A. Formicola, *et al*, 2004; Runkle et al., 2005) leads to significant accuracy improvement of AGB wind yields. Still, the combined effect of the uncertainty of this rate and the triple-α rate is source of a more than a ±20% uncertainty in the total yield of AGB stars. Other nuclear reaction rate uncertainties effect the HBB processing (Izzard et al. , this volume) and the *s* process. In order to investigate the interplay of rotation, magnetic fields and possibly internal gravity waves for the radiative *s* process in the ^{13}C pocket, accurate rates for the $^{13}\mathrm{C}(\alpha,\mathrm{n})$ and $^{14}\mathrm{N}(\mathrm{n},\mathrm{p})$ reactions will be indispensible.

3. Multi-dimensional hydrodynamics simulations of He-shell flash convection

It is likely that with high-fidelity, multi-dimensional simulations of the stellar interior we will be able to improve many aspects of modelling mixing and burning in one-dimensional stellar evolution calculations. As an example we describe the He-shell flash convection simulations by Herwig et al. (2006). There are several goals to such an investigation: (1) what is the morphology of He-shell flash convection? (2) what is the velocity distribution for short-lived T-dependent *s*-process branchings (e.g. ^{128}I, Reifarth et al., 2004)? (3) how large is entrainement, mixing accross the convective boundaries?

The calculations were done with the explicit, Eularian, compressible grid code RAGE. The initial conditions was a piecewise polytropic stratification with gravity that closely resembles the actual conditions in a specific one-dimensional $2\,M_\odot$, Z=0.01 thermal pulse model. Both 2D and 3D simulations have been run out to between $3 \cdot 10^3$s and up to $2 \cdot 10^4$s. This is many times the convective turn-over timescale of 600s. All runs reached a convective steady-state.

The simulations reveal the large-scale behaviour of He-shell flash convection (Fig. 4). Convective systems span the entire vertical extent of the convection zone, and are centered in its lower half. The rms-vertical velocities are within a small factor consistent with the MLT estimate, however, local gusts can reach much higher velocities.

There are important differences between these interior He-shell flash convection simulations and those of shallow surface convection, as for example presented by Freytag et al. (1996). He-shell flash convection has very stiff convective boundaries. Coherent convective motions do not cross into the stable layers. Internal gravity waves are excited through the interactions of convective motions with the rather stiff convective boundaries. These waves populate the stable layers both above and below the convection zone. Surface convection behaves opposite in all these aspects: no gravity waves are excited, and convective systems overshoot a large distance into the stable layers because the convective boundaries are rather soft.

Parameterized investigations of exponential overshoot have already indicated that the decay of the convective velocity field must be much more rapid in He-shell flash convection than what was found in the simulations of shallow surface convection of A-type stars. The new He-shell flash convection simulations are consistent with that finding (Freytag & Herwig, in prep).

In the multi-dimensional simulations of He-shell flash convection mixing accross the convective boundaries is quantitatively detected. The mixing mechanism is more complicated than the simple and rather straight forward overshooting seen in the shallow surface convection simulations. The boundaries of He-shell flash convection experience a complicated interaction between the convectively perturbed, rather stiff boundary and vigorous periodic vertical flows associated with the internal gravity waves. It is thus prudent to refer to cross-boundary mixing in He-shell flash convection as convection induced extra mixing, rather than overshooting.

4. Conclusions

AGB stellar evolution and nucleosynthesis is possibly about to enter a new phase where some of the well known road blocks for progress can be finally overcome through advances in simulation. Recent years have seen an enourmouse increase in availability and accesibility of multi-dimensional simulation methods for a range of problems in astrophysics. This trend is now adopted in stellar evolution as well. These advances match those in better nuclear physics data as well as new observational data with new constraints for models.

An better quantitative modeling capability of AGB stars is needed for a number of applications of great general astrophysical interest. One example is the use of AGB stellar yields in chemical evolution models (e.g. Venn et al., 2004; Font et al., 2006) of satellite galaxies. This approach can be used for accurate dating of poppulations and thereby reveal important properties of the hierachical formation of our own galaxy.

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