Hydrodynamics of stellar convection

Fig. 7.— Fully developed convection in a high-resolution 2D run with standard heating rate. The flow field is represented by 25x75 pseudo-streamlines, integrated over 100 s for the constant velocity field of this single snapshot of evolved convection during the lc0gh run. The color indicates the corresponding pressure inhomogeneities. The pressure itself does not deviate much from the initial values. Therefore, to make the fluctuations visible, the horizontal average of the pressure has been subtracted from the pressure value of every grid point. Bright means over-pressure (prominently where a “mushroom” approaches the upper boundary of the unstable region: compare with Fig. 8). Dark color indicates low-pressure (in the “eyes” of the vortices). The boundaries of the unstable layer (the entropy plateau in Fig. 6) at $y=1.7 \text{ Mm}$ and $y=7.7 \text{ Mm}$ are clearly marked in the flow field and the pressure inhomogeneities.

Fig. 8.— Entropy inhomogeneities for the same model of the lc0gh sequence as in Fig. 7. Again, the horizontal average of the entropy has been subtracted to render the small fluctuations visible. A bright color indicates material with higher entropy (and in fact higher temperature – due to the near pressure-equilibrium). Dark means low entropy (or temperature). The boundaries of the entropy plateau at $y=1.7 \text{ Mm}$ and $y=7.7 \text{ Mm}$ are again clearly visible in the change of the patterns. The subtraction of the horizontal mean causes bright features to be accompanied by dark horizontal stripes. These are pure artifacts of the visualization procedure and do not exist in the simulation data itself.

References:

2D plane parallel, entropy fluctuations (2400x800), realistic heating rate, courant time scale at this resolution: $\sim3E-3\text{ sec} \rightarrow 1.6\text{ M cycles}$, RAGE simulation
Fig. 24.— Comparison of vertical velocities derived from a hydrodynamics model (continuous lines: lc0gg) and mixing-length velocities from stellar evolution calculations (dashed line: model 70238).

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Comparison 3D vs. 1D
entainment at top boundary of convection

Fig. 3.— Hydrodynamic picture of H-entainment into He-shell flash convection near the luminosity peak of the flash. The setup is based on a stellar evolution model corresponding to the situation shortly after time $t_0$ shown in Fig. 2, when the top of the convection zone is just making contact with the H-rich stable layer. Colors indicate abundance of proton-rich material that is originally only in the stable layer above the convection zone that is entrained into the convection zone. Volume fractions of about $\sim 1\%$ are shown as blue, while concentrations that are close to one are transparent. The lowest concentration yellow blobs that are mixed deep into the convection zone correspond to $\sim 0.01\%$. Abundance levels below approximately $5 \times 10^{-5}$ have been made transparent as well. The left panel shows a snapshot from a $384^3$ grid while the right panel image is from a run on a $576^3$ grid. Slightly different times are shown and similar but not identical color maps have been used. The PPM simulation is described in more detail in Sect. 4.1, and the simulation code is described in Sect. A.2.

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Fig. 5.— Comparison of entrainment of material from the stable layer above the convection zone into the $^{12}\text{C}$-rich layer as it is represented in the one-dimensional stellar evolution model with mixing treated as diffusion in the mixing-length picture and in the 3D simulations discussed in this paper. The 3D profile (green line) shows the same data, radially averaged, as in Fig. 3, right panel. The 1D line (blue) is the line labeled $t_0$ in Fig. 2. The mass coordinates have been set to zero in both cases near the top of the convection zone.
Intermediate mass stellar evolution

- core-mass evolution: the third dredge-up
- Luminosity evolution: recurrent peaks in He-shell burning and quiescent H-burning during the interpulse phase

**Figure 23.** Properties of a $M_i = 2.0 M_\odot$ star from MESA star as it approaches the end of the AGB. Top: the boundaries of the C/O core and the He layer. Middle: luminosities from hydrogen and helium burning. Bottom: central temperature evolution.

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Figure 3  Thermal pulse 14, the subsequent interpulse phase and thermal pulse 15 of $2\,M_\odot$, $Z = 0.01$ sequence ET2 of Herwig & Austin (2004). The timescale is different in each panel. The red solid line indicates the mass coordinate of the H-free core. The dotted green line shows the boundaries of convection; each dot corresponds to one model in time. Convection zones are light green. The shown section of the evolution comprises 12,000 time steps. The colors indicating convection zones, layers with H-shell ashes and the region of the $^{13}$C pocket match those in Figure 5.
Fig. 26.— The C/O number ratio (top panel) and stellar mass, $M$ (bottom panel) as a function of time from EVOL (solid black line) and MESA star (thick grey line). Time has been set to zero for both tracks at the onset of the third dredge-up.

- repeated 3DUP events lead to the formation of C-stars
- effective mass loss leads to the ejection of nucleosynthetically processed material
- when all mass is lost the AGB evolution is terminated
Evolution of thermal pulses and the final departure from the AGB
Structural profiles of the AGB stars

Figure 4  Structural profile of stellar model 46000 of sequence ET2 ($2 \, M_\odot$, $Z = 0.01$) of Herwig & Austin (2004), corresponding to $t = 76000$ yr in Figure 3.

thermal pulses during the advanced AGB phase. Increasing mass loss leads to the ejection of the envelope. This promotes the post-AGB evolution and finally the central star of planetary nebulae and white dwarf evolution phases.

AGB stars have a unique structural makeup (Figure 4). The core is basically a preformed C/O white dwarf with a mass of $\sim 0.5 \ldots 1.0 \, M_\odot$. More massive white dwarfs are known observationally (Należyty & Madej 2004) in significant numbers. According to stellar-evolution models their internal composition is O, Ne, and Mg, and their progenitors are the super-AGB stars (García-Berro & Iben 1994). Larger samples of white dwarfs will show if single stars with initially $8 \ldots 10 \, M_\odot$ are the dominant evolutionary channel for these objects. Apart from Section 5 this review deals exclusively with C/O-core AGB stars.

The tiny core is surrounded by an extended giant envelope filling the stellar radius of several hundred $R_\odot$.

Nuclear processing of hydrogen and helium takes place in two spherical shells on top of the core (Figures 3 and 5). The final phase of AGB evolution is characterized by recurrent thermal pulses. These thermonuclear flashes of burning shells on degenerate cores are in fact quite common, and are also known, for example, to occur in the form of X-ray bursts in accreting neutron stars (Woosley et al. 2004). The instability is caused by a combination of the thin-shell instability and partial degeneracy (Kippenhahn & Weigert 1990; Yoon, Langer 2005).
Abundance profiles of the AGB stars

Figure 5  Chemical profile (H, He, C, N, O) of stellar model 46000 of sequence ET2 (2 $M_\odot$, $Z = 0.01$) of Herwig & Austin (2004), corresponding to $t = 76000$ yr in Figure 3.