Hydrodynamic Simulations of He-shell Flash Convection

Falk Herwig, T-6; Bernd Freytag, T-6, MSU, Uppsala University; Robert M. Hueckstaedt, X-2; and Francis X. Timmes, T-DO

We have performed the first hydrodynamic, multidimensional simulations of He-shell flash convection [1]. This is an important nuclear production site in stars of low and intermediate mass. In particular the slow neutron capture process, which generates half of all trans-iron elements, is associated with this hot and turbulent He-burning environments. Current models of this stellar interior region exist only in one-dimensional (1-D) simulations that make averaging assumptions about the properties of convection. Here, we study this important nuclear astrophysics environment for the first time in multidimensional simulations. Our simulations are based on the hydrodynamics code RAGE.

We investigated the properties of shell convection at a time immediately before the He-luminosity peak during a He-shell flash of a stellar evolution track with initially two solar masses and half the solar metal content. We constructed the initial vertical stratification with a set of polytropes to resemble the stellar evolution structure. Convection is driven by a constant volume heating in a thin layer at the bottom of the unstable layer. We calculated a grid of 2-D simulations with different resolutions and heating rates. Our set of simulations includes one low-resolution 3-D run. The computational domain includes 11.4 pressure scale heights.

He-shell flash convection is dominated by large convective cells that are centered in the lower half of the convection zone (Fig. 1). Convective rolls have an almost circular appearance because focusing mechanisms exist in the form of the density stratification for downdrafts and the heating of localized eddies that generate upflows. Nevertheless, downdrafts appear to be somewhat more focused.

The He-shell flash convection generates a rich spectrum of gravity waves in both stable layers above and beneath the convective shell. An analysis of the oscillation modes shows that both g-modes and convective motions cross the formal convective boundaries, which leads to mixing across the boundaries (Fig. 2). Our resolution study shows consistent flow structures among the higher resolution runs, and we see indications for convergence of the vertical velocity profile inside the convection zone for the highest resolution simulations.

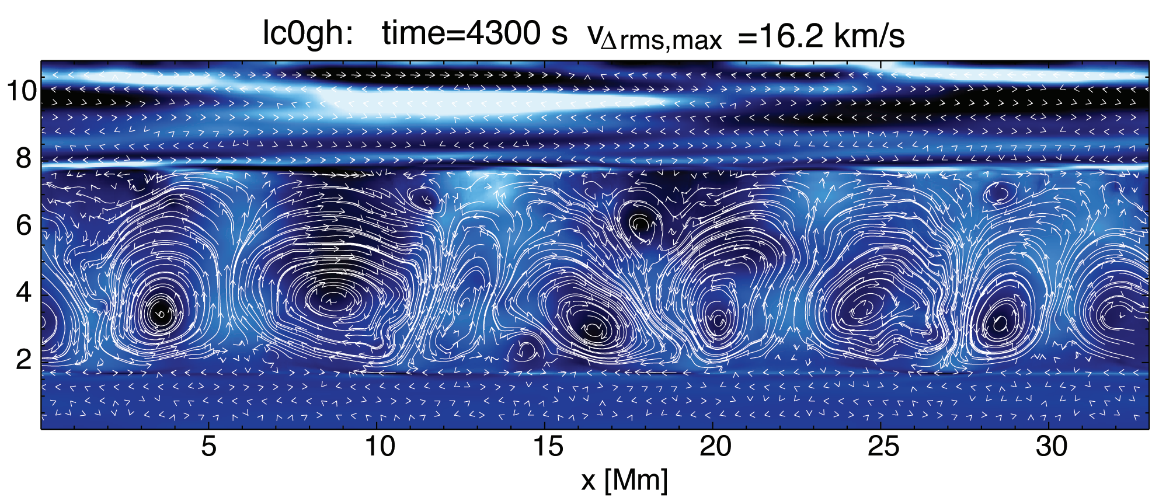

Fig. 1. *Snapshot of pressure fluctuations with pseudo-streamlines of fully developed convection in a high-resolution 2-D run. Darker areas have low pressure. The boundaries of the unstable at y = 1.7 Mm and y = 7.7 Mm are clearly marked in the flow field and the pressure inhomogeneities.*

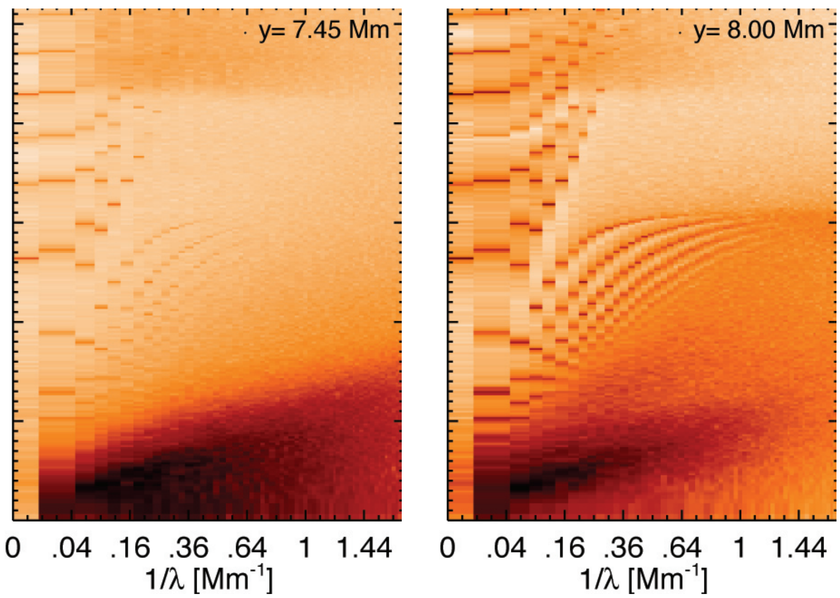

Fig.2.
k-ω diagrams for a vertical position just below and above the top convection boundary. This diagram reveals the properties of the oscillations that are excited in the simulation. The dark blob in the lower left area represents the convective motions. Ridge systems of signals above correspond to gravity and pressure modes. The comparison of these two diagrams allows a quantitiative analysis of how effectively convective motions, which induce mixing, can cross the convective boundary.

The magnitude of the convective velocities from our 1-D stellar evolution theory model and the rms-averaged vertical velocities from the hydrodynamic model are consistent within a factor of a few (Fig. 3). However, the velocity profile in the hydrodynamic simulation is more asymmetric, and decays exponentially inside the convection zone.

For more information contact Falk Herwig at fherwig@lanl.gov.

[1] F. Herwig, et al., Los Alamos National Laboratory report LA-UR-05-8084 (2005); submitted to *Astrophys. J.*, 2005.

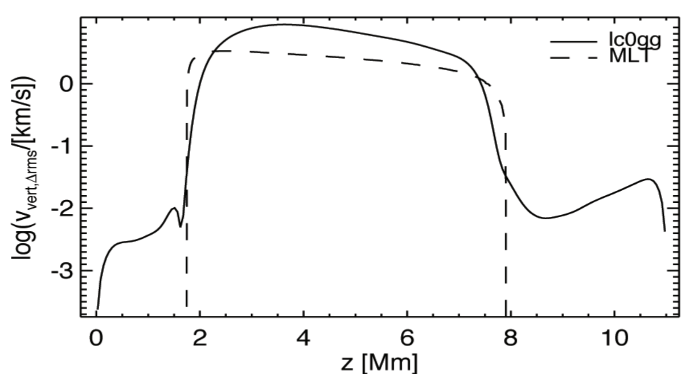

Fig. 3.
Comparison of vertical velocities derived from a hydrodynamics model (continuous line) and 1-D stellar evolution model (dashed line).