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Multidimensional hydrodynamic simulations of the core helium flash

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Abstract. Using an initial model, which is obtained from the evolution of a 1.25 $M_{\odot}$ star with a metallicity of 0.02 computed with the Garching stellar evolution code, we investigate the hydrodynamics of the core helium flash near its peak. Past research concerned with the dynamics of the core helium flash is inconclusive. Its results range from a confirmation of the standard picture, where the star remains in hydrostatic equilibrium during the flash (Deupree 1996), up to a disruption of the star (Edwards 1969). However, the most recent multidimensional hydrodynamic study (Dearborn et al. 2006) suggests a quiescent behavior during the flash and seems to rule out an explosive scenario. Here we present the first results of a new comprehensive study of the core helium flash, which seem to confirm this qualitative behavior.

Key words. Stars: evolution – Stars: convection – Stars: hydrodynamics

1. Introduction

The most violent event in the life of a star with an initial mass between $0.7 M_{\odot}$ and $2.2 M_{\odot}$ is the core helium flash (Sweigart & Gross 1978, Schwarzschild et al. 1962). The electron degeneracy in the core leads to a thermonuclear runaway at the ignition of helium on the tip of the red giant branch. This does not seem to be catastrophic affair, although simulations of the flash have a confusing past predicting either severe explosions (Edwards 1969) or just calm evolution (Deupree 1996, Dearborn et al. 2006). Rather quiescent behavior of the core helium flash is favored by recent 3D simulations (Dearborn et al. 2006) in which the energy transport due to convection, heat conduction and radiation seems to be always able to deliver most of the flash energy quiescently from the stellar interior to the upper layers. The conceptual problems associated with the helium flash arise from the extremely short timescales involved. While pre-flash evolution proceeds on the nuclear time-scale of $\sim 10^{8}$ years, typical e-folding times for the energy release from helium burning become as low as hours at the peak of the flash. Such short time scales are comparable to the time scales related to the rising and sinking of convective elements in the core.

Here we study the core helium flash with a new version of the hydrodynamic code HERAKLES (Kifonidis et al. 2003, Kifonidis et al. 2006) which is itself a descendant of the code PROMETHEUS developed by Bruce Fryxell and Ewald Müller (Müller et al. 1991, Fryxell et al. 1991). The basic code has been extended to handle thermal transport and nuclear burning.

Table 1. Properties of the initial model: total mass M, stellar population, metal content Z, mass M_{He} and radius R_{He} of the helium core, nuclear energy production in the helium core L_{He}, maximum temperature T_{max}, radius r_{max} and density ρ_{max}at the location of the temperature maximum.

Model	M $[M_\odot]$	Pop.	Z	M_{He} $[M_\odot]$	R_{He} [10^9 cm]	L_{He} [$10^8 L_\odot$]	T_{max} [10^8 K]	r_{max} [10^8 cm]	ρ_{max} [10^5 g cm^{-3}]
M	1.25	I	0.02	0.45	2.1	9.78	1.73	4.7	3.33

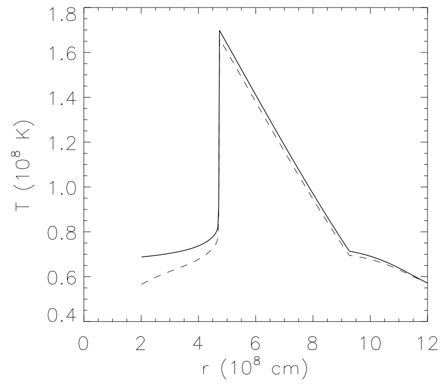

Fig. 1. Temperature distribution as a function of radius. The solid line gives the distribution obtained from stellar evolutionary calculations with the GARSTEC code, while the dashed line shows the slightly modified distribution used as initial condition in the hydrodynamic simulations.

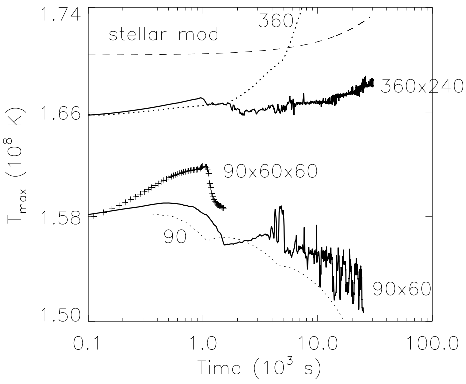

Fig. 2. Temporal evolution of the temperature maximum in our hydrodynamic simulations. The different curves correspond to models with different grid resolution.

2. Initial stellar model

The initial model was computed with the GARSTEC code (Weiss & Schlattl 2000). Its properties are summarized in Tab.1. A key feature of the model is the temperature stratification (Fig.1) characterized by an "off center" temperature maximum followed by a superadiabatic temperature gradient driving the convection. Due to differences between the physics included in our code and the GARSTEC, a small modification of the temperature distribution is necessary in order to keep the star in hydrostatic equilibrium after the model is mapped to the hydrodynamic code.

3. Simulations

Almost all our 1D simulations end up with a hydrodynamic event which could eventually disrupt the star. However, none of our 2D and 3D simulations have confirmed this (Fig.2). Contrary to 1D, convective flows in the 2D and 3D runs arise spontaneously. The gas heated by nuclear burning rises in the form of hot bubbles to the upper stellar layers where it cools and sinks back to the center so that it controls the dynamics of the thermonuclear flash.

The onset of the convection is characterized by the appearance of hot bubbles (Fig.3) rising from the region where the helium burns in a thin shell. They are typically about 0.15% hotter than their surroundings and are rising with velocities $\sim 2 \cdot 10^6$ cm/s. Later, a stable convective pattern appears (Fig.3), with 2 dominant upstreams of hot gas and 5 vortices (diameter $\sim 5 \cdot 10^8$ cm, typical velocities $\sim 2 \cdot 10^6$ cm/s). The size of the convective eddies is fully determined by the height of the convection zone.

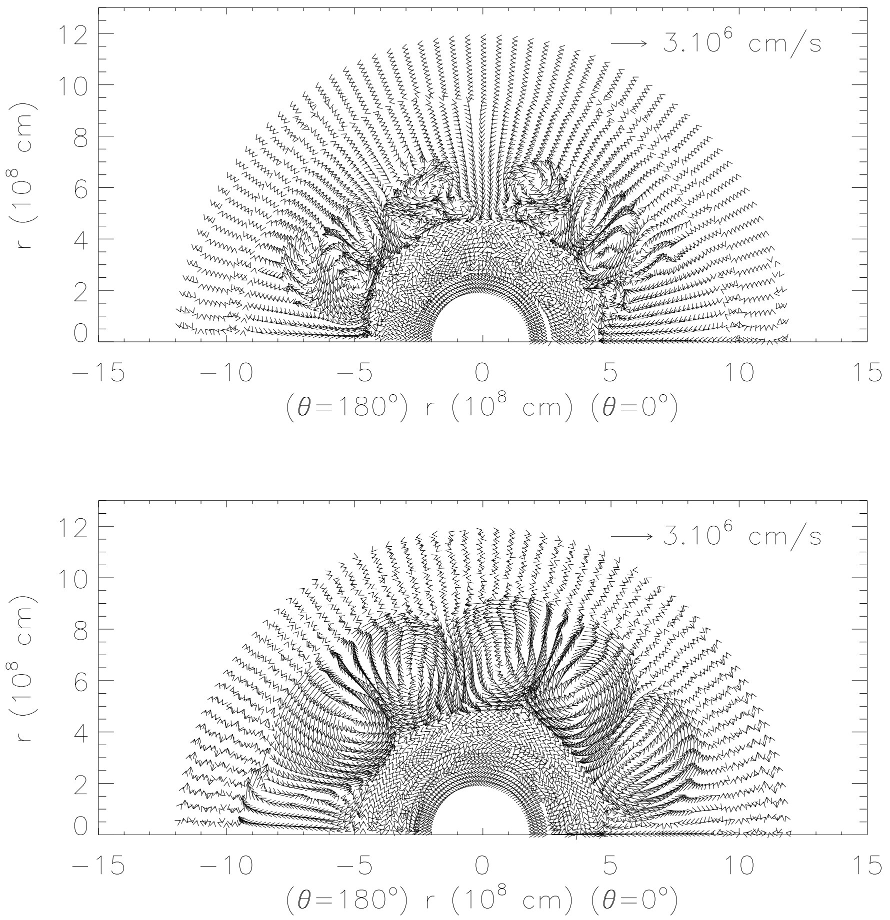

Fig. 3. Snapshots of the convective flow pattern in the 2D simulation (grid 360 × 240) at $t = 1\,232$ s, and 6 822 s (from top to bottom), respectively. The symmetry axis coincides with the horizontal axis.

4. Conclusions

We find that the core helium flash neither rips the star apart nor significantly alters its structure. The convection plays a crucial role in keeping the star in hydrostatic equlibrium. Our hydrodynamic simulations support results of stellar evolution calculations. Previous research which predicted an explosive scenario cannot be confirmed. In the future we plan to extend our study to 3D high resolution models.

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