Clés, outcome of the comparisons and future plans

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Current status of the code comparisons

Previous comparisons between sequences computed with our evolution code Clés and other codes (CESAM and ASTEC) already taught us that the more similar was the physics of the codes the closer were the results, though the codes have very different numerical implementations.

During this workshop, we were given the opportunity to discuss a few problems of stellar physics and to compare the solutions adopted in different codes. As far as Clés is concerned, we were particularly attentive to the different ways to implement a good description of the limits of convective zones. Another point which was the object of fruitful discussions was the necessity of implementing semi-convection not only for main-sequence stars with masses between 1.2 and 1.5 $M_\odot$ but also for the Sun, as situations where semi-convection could develop may be encountered just below the convective zone, precisely in a region where the larger discrepancies have been noticed between the computed sound speed and the one deduced from helioseismology.

In the following sections we describe the work done during this workshop and the achieved results.

The effect of the temperature gradient in the overshooting zone

In the absence of a definitive theory of the convection, there are uncertainties on the extent and structure of the overshooting zone surrounding the convective core of large and intermediate mass stars. The extent of the overshooting zone is described by an overshooting parameter which must be adjusted to fit the observations. The usual range adopted is 0 to 0.2. As to the temperature gradient, it can be safely stated that its value must be between the radiative and the adiabatic gradients. Whereas CESAM uses the adiabatic gradient, the radiative gradient has been adopted in the standard version of Clés. In order to allow the comparison for a 2 $M_\odot$ star with initial X=0.72 and Z=0.02 and an overshooting parameter of 0.15 (task 1.5), the possibility to choose between the two gradients has been implemented in Clés. Figure 1 shows that the evolution tracks computed by Clés and CESAM are very close in the HR diagram, when the same temperature gradient is used.

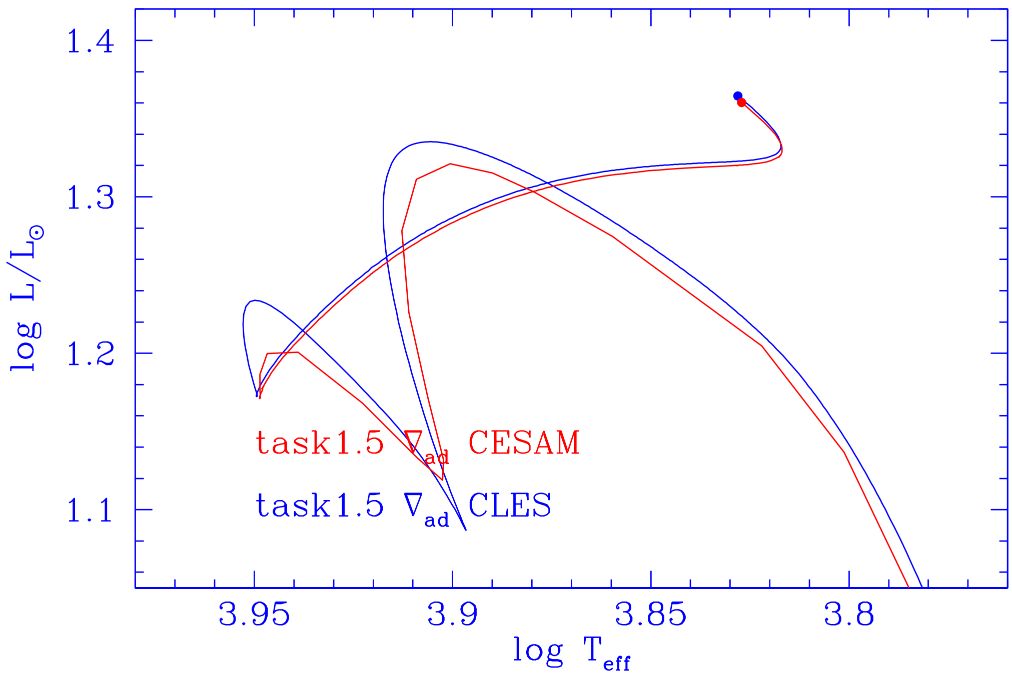

Figure 1: Evolutionary tracks for task 1.5, computed by CESAM and Clés.

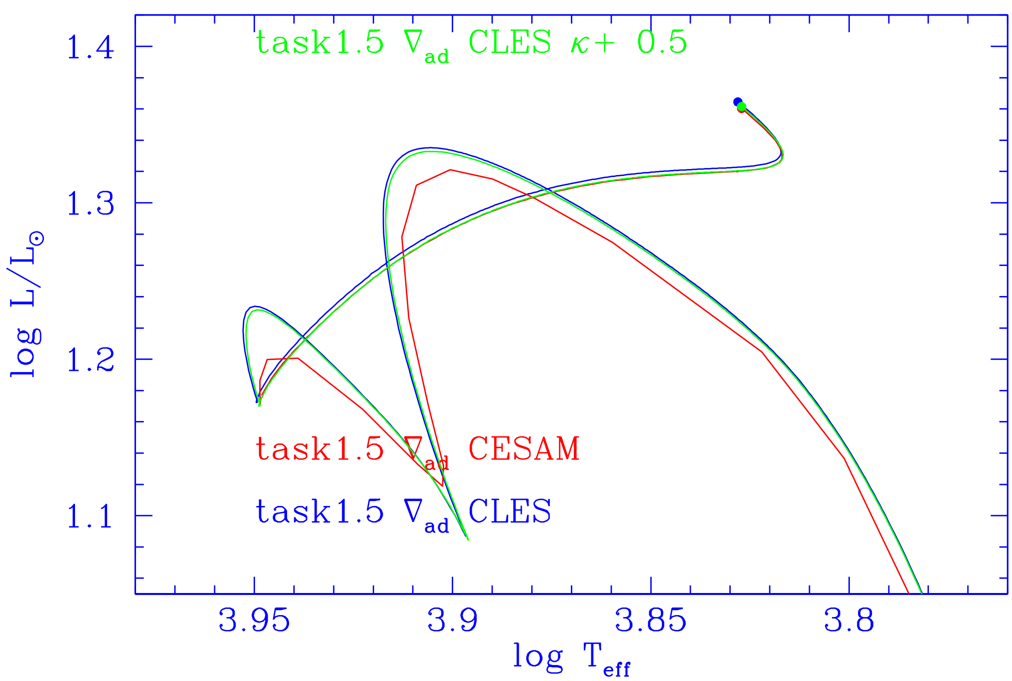

Figure 2: Evolutionary tracks for task 1.5, computed by CESAM and Clés with original opacities and with increased opacities.

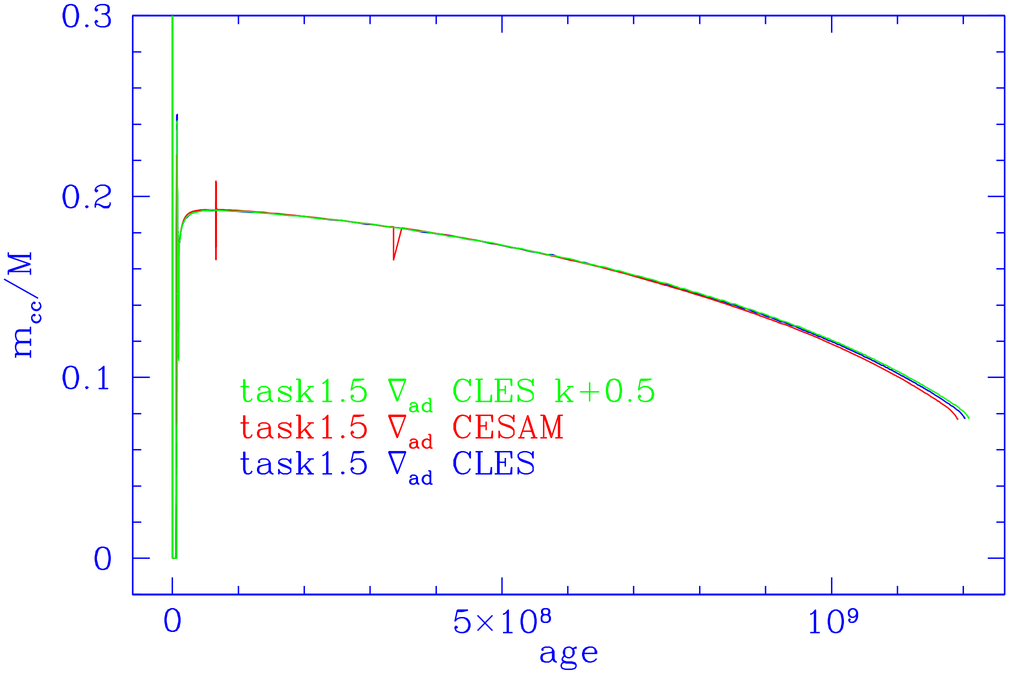

Figure 3: Convective core evolution for task 1.5, computed by CESAM and Clés with original opacities and with increased opacities.

The small remaining discrepancy is due to an unexplained difference in the opacities. If the opacities in Clés are increased by 0.5 %, we obtain an excellent agreement (figure 2). In figure 3 we show the evolution of the convective core for the three different task 1.5 models, and in figure 4 the relative differences in the structure of task 1.5 model computed by CESAM and by CLES with opacity increased by 0.5%.

The effect of changing the time step and the spatial mesh

We have computed several task 1.5 and task 1.3 models, doubling the number of time steps and/or mesh points. In figures 5 and 6 we show the relative differences, computed at the same m/M in both codes, for luminosity (L), hydrogen abundance (X), sound speed (c) and adiabatic index (Γ_1).

For task 1.5 (2 $M_\odot$) the main differences are located at the boundary of the convective core, and close to the surface. Task 1.3 models (1.2 $M_\odot$ in post-main sequence), however, show much larger differences for the sound speed in the convective envelope. Similar behavior has been found in the corresponding computations made by using the ASTEC code.

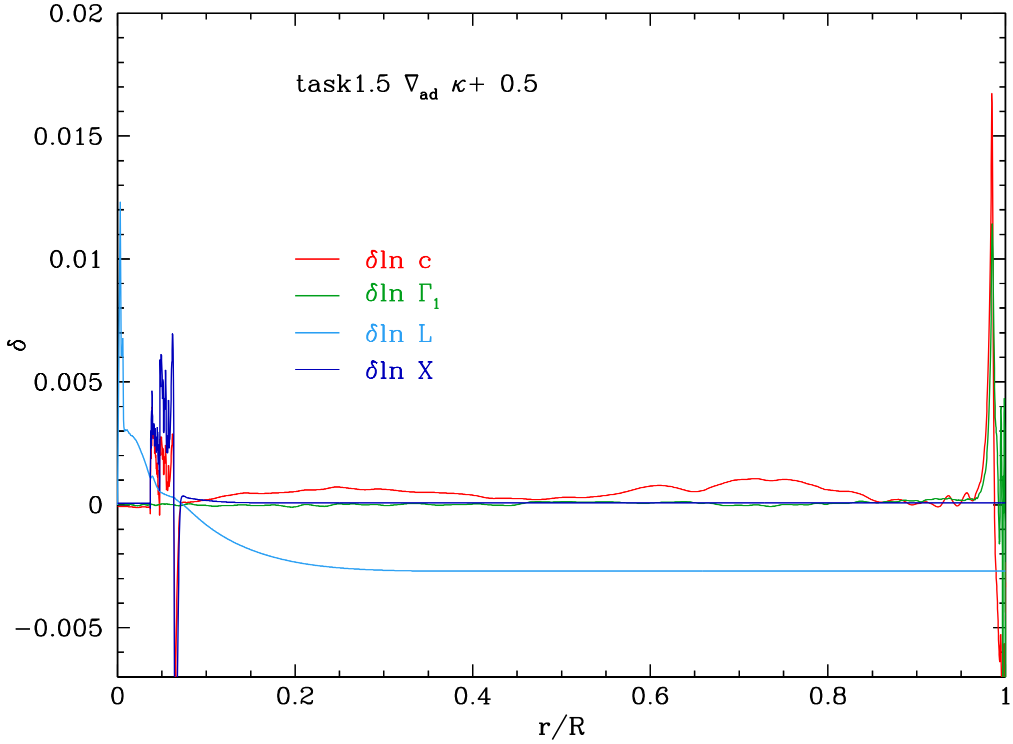

Figure 4: Relative differences (at the same m/M) between the task 1.5 model computed by CESAM, and the one computed by CLES with increased opacities.

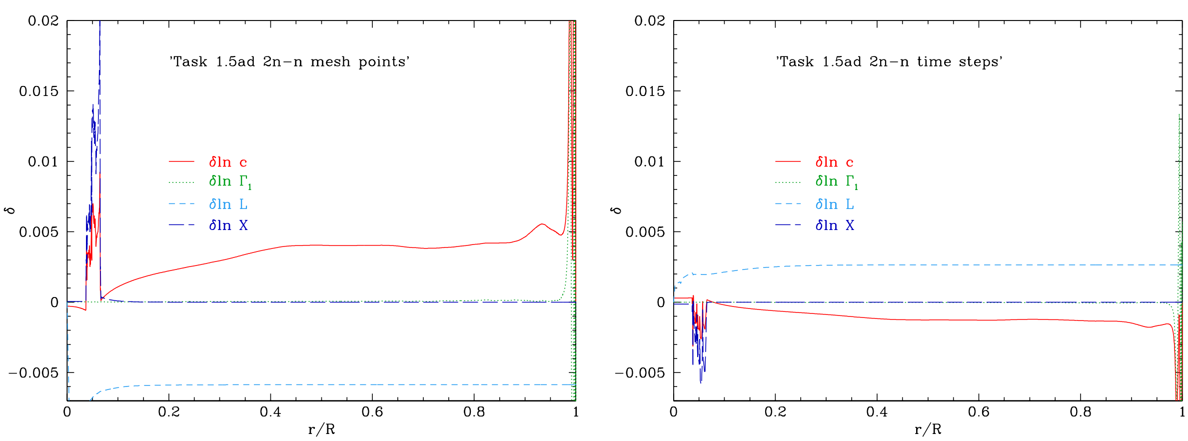

Figure 5: Relative differences between the task 1.5 models computed by doubling the number of mesh points (left panel), and between models computed by dividing by 2 the time step (right panel).

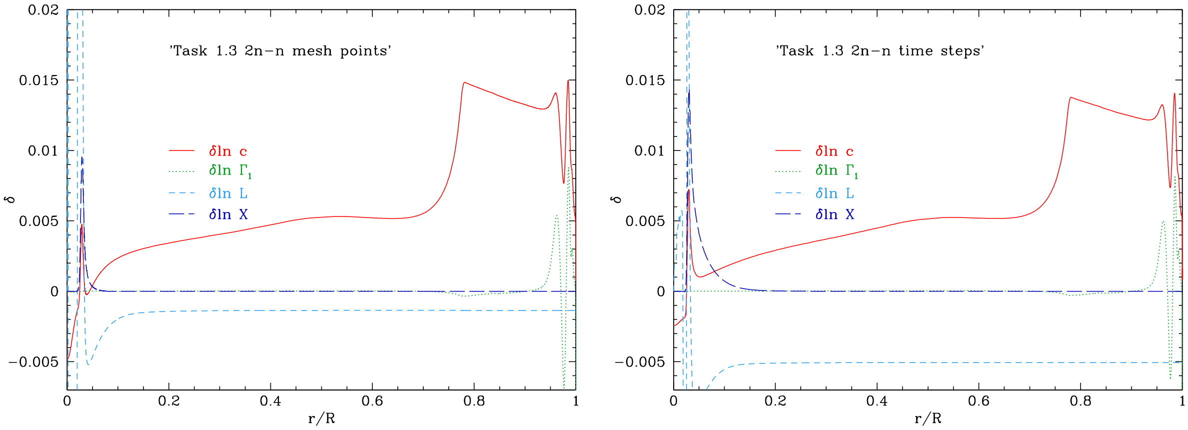

Figure 6: As in fig. 5 for task 1.3 models

Refinement of the mesh and semi-convection

We have modified Clés in order to refine the mesh in the neighbourhood of the limits of the convective core, increasing the number of points by a factor ten in this region. We have then studied how the limit of the convective core was affected during the main sequence for a model of 1.2 $M_\odot$, with initial X=0.73, Z=0.01 and no overshooting (task 1.3). We were particularly interested in this case because the standard version of Clés gives results rather different from ASTEC. As can be seen in figure 7, the discrepancy is not reduced. In fact, it is a case where a semi-convective zone develops at the edge of the convective core. But the ability to describe semi-convection lacks in both Clés and ASTEC and the positions of the limit of the convective core assigned by the codes are not physical and depend on the details of the numerical implementation. The refinement of the mesh size is by no means a solution to this problem.

Future plans

A number of improvements of our evolution code are currently in progress, such as adding a better treatment of the diffusion and other nuclear reaction rates (NACRE tables). The OPAL equation of state will soon be updated with the new available tables. We do not consider an increase of the number of points at the limit of the convective zones as an optimal solution and we plan to put a double point at each zone boundary to describe the discontinuity.

More difficult problems have been pointed out during this workshop and should be addressed, such as semi-convection and rotational mixing. Owing to the difficulty of the task, their implementation cannot be expected in a very near future.

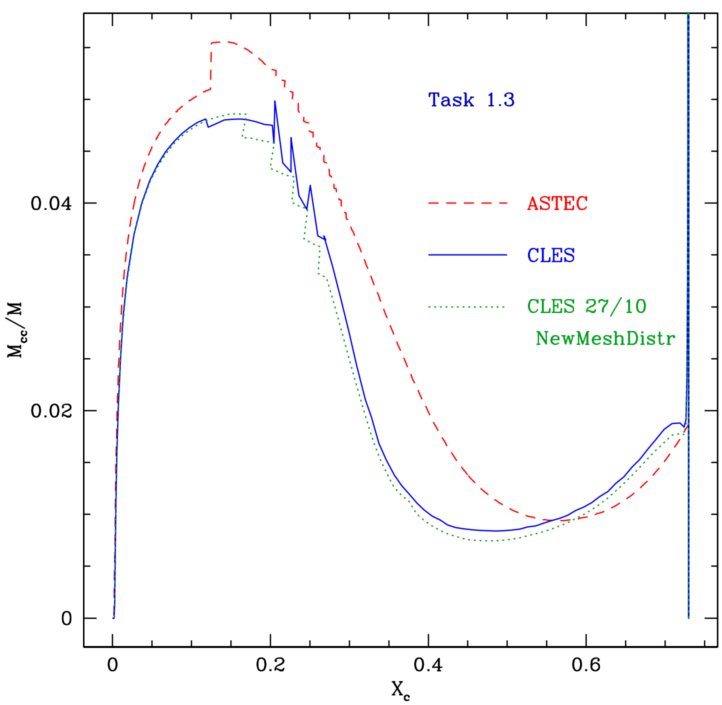

Figure 7: Evolution of the limit of the convective core (from right to left)