Studying Convection with MESA

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1 Introduction

MESA (Modules for Experiments in Stellar Astrophysics) is a stellar evolution code with many features to model the complex evolution and dynamics of stars. Despite MESA being a 1-D code, it includes parameters and modules to incorporate convection. One of these is the use of Mixing Length Theory (MLT).

Mixing Length Theory (MLT) is a theory that characterizes convection in a fluid. It requires some approximations that don't exactly hold in stars. Nonetheless it has useful results and is at the very least a good phenomenological model according to Hansen, Kawaler, and Trimble (HKT).

One of the most important parts of MLT is the mixing length l. This is the characteristic size of the eddies/parcels which are convecting through the fluid. The theory does not predict this directly and so we have to approximate it's value in our stellar code. Typically it is determined by looking at the star we know most about, the Sun. Generally, we write the mixing length l as:

$$l = \alpha H_p \tag{1}$$

Where α is a dimensionless parameter and H_p is the pressure scale height of the system. α is typically given a global value of $1-2$ though more complex schemes may exist.

In this project, we investigate the differences in varying this α parameter in MLT for a $1M_\odot$ model and see how this impacts the evolution. Along with comparing Solar mass models, we look at the impact at much higher mass (around $15M_\odot$) on the main sequence.

2 Stellar Models

Each model started pre-main sequence in order to see how convection impacts the evolution to ZAMS. Then the models were simulated through the main sequence, with the $1M_\odot$ models continuing on through the giant phase. The $1M_\odot$ were run using the MESA Web[1] environment. The default parameters from the submission page were used with the exception of varying α. Only 2

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[1] http://www.astro.wisc.edu/ townsend/static.php?ref=mesa-web

of the runs finished to the white dwarf (WD) stage so that analysis was sadly limited.

The $15M_\odot$ stellar models were run locally on a laptop from pre-main sequence through the main sequence. These were not continued past the main sequence because the computation becomes much more expensive. These models were based off of the "tutorial-15M" example provided in the MESA source code. The only adaptions were to convection and mixing.

3 Pre-Main Sequence

The models all start prior to the main sequence which allows us to track the evolution as the star contracts until hydrogen fusion begins in the core. Zero Age Main Sequence (ZAMS) was defined when the luminosity from Hydrogen fusion was equivalent to the total luminosity given out by the star.

3.1 $1M_\odot$ Models: Hayashi Track

The different solar mass models diverge from each other almost immediately. An HR diagram for the pre-main sequence can be found in Figure 1. Interestingly, we can see that each model begins contracting and following the Hayashi track at a different temperature and luminosity. As we predicted in homework 7 problem 4, the Hayashi track shows a very strong dependence between luminosity and temperature. One of the assumptions in that problem was the protostar must be fully convective. Because of this, it makes sense that our models diverge here where convection is plays a major role in the evolution.

If we look at Table 1 we can see that the models with greater convection (higher α) reach the main sequence faster. This can be explained as more efficient convection will help the protostar emit energy more efficiently and thus quickly contract to a star.

α	Time to ZAMS (Myr)
1.0	48
1.5	45
2.0	43
4.0	38

Table 1: Time from the start of the simulation to Zero Age Main Sequence (ZAMS)

Each model will begin the main sequence at a different point on the HR diagram with the models with more convection (higher α) being hotter on the surface. In Section 4, we will look more closely at the evolution of these models from the main sequence onward.

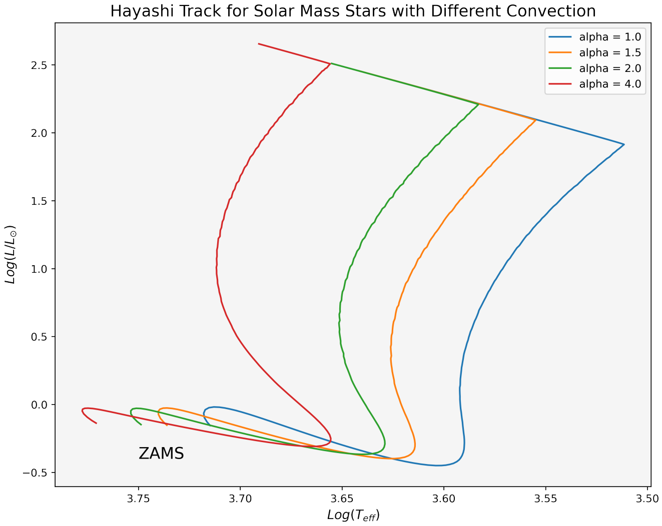

Figure 1: HR diagram for solar mass protostars

3.2 $15M_\odot$ Models

Prior to the Main Sequence, a $15M_\odot$ protostar also contracts similarly to the solar mass stars. However, there is a key difference in that the protostar does not follow the same Hayashi track because it is mainly radiative during this time. Because of this, we can see in Figure 2 that the models yield actually appear to converge to a similar region on the HR diagram at ZAMS. Again, we define ZAMS as the point where luminosity due to Hydrogen fusion is comparable to the total luminosity.

This affirms what we expect, that the models will only differ during periods where convection plays an important role in the evolution. Otherwise, these models should yield very similar results.

4 Main Sequence and Beyond

Once the star contracts to ZAMS, the main sequence is relatively easy to compute. It is not until we move off the main sequence that again the computations become more intensive. This is due to the switch to shell burning and Helium burning and in this case a core that is at least partially degenerate.

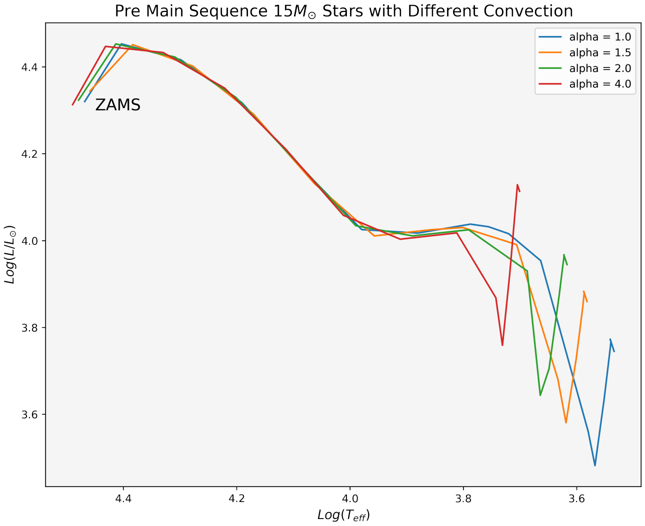

Figure 2:

4.1 $1M_\odot$ Models: Main Sequence and Giant Phas

Looking at the HR diagram in Figure 3, we can first recognize the impact of each model starting at a different temperature. The general evolution of each model is offset by that difference in temperature. During the main sequence, the evolution is relatively similar as can be seen in the main sequence life time differing by about $\sim 1\%$ (see Table 2). It is not until the models leave the main sequence that the trajectories appear to differ more significantly.

α	Main Sequence Lifetime (Gyr)
1.0	9.10
1.5	8.98
2.0	8.90
4.0	8.66

Table 2: Time on the Main Sequence

The $\alpha = 2.0$ model most accurately reflects the Sun. It is the only model that comes closest to running through the Sun's current state on the HR diagram (indicated by the purple plus in Figure 3). Although there are other parameters that could be tuned, for this set of reasonable parameters, a mixing length that is about twice the pressure scale height gives a good result.

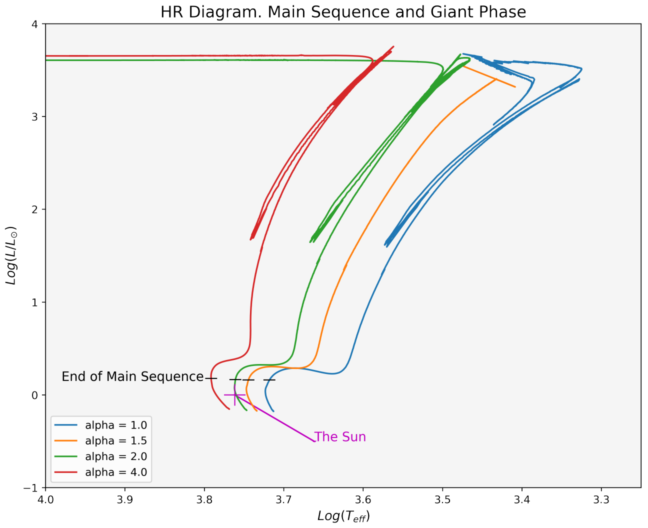

Figure 3: HR diagram of four solar mass models from ZAMS through giant phase. Purple plus indicates the Sun's current position on HR diagram. Black dashes indicate the end of Hydrogen fusion in the center

4.2 $1M_\odot$ Models: White Dwarfs

Only two of the solar mass models continued all the way to the white dwarf stage. These were the $\alpha = 2.0$ and $\alpha = 4.0$ models. In Figure 4, we can see the final composition of the models are relatively similar as the dashed and dotted lines only differ by a small amount, mostly near the surface. This indicates that the different levels of convection do not have a large impact in the final remnant, despite influences on the earlier evolution. Looking at Table 3 we can see that there was about 1.45% difference in final mass. This again indicates that the difference in convection had a fairly small affect on the resulting white dwarf.

Unfortunately we could not investigate the $\alpha = 1$ or 1.5 because those simulations stopped too soon. Nonetheless it is quite interesting that after initial differences the solar mass models converged to similar white dwarfs in mass and composition.

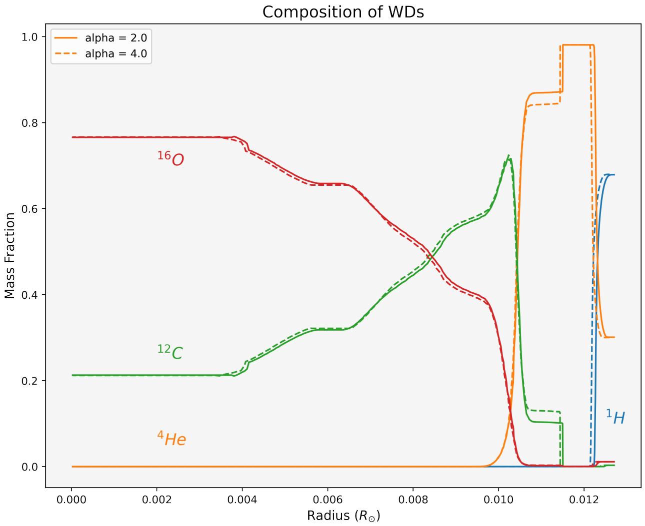

Figure 4: Mass fractions of four main species in each White Dwarf (Hydrogen, Helium, Carbon and Oxygen). The solid lines represent the $\alpha = 2$ model and the dashed lines represent the $\alpha = 4$ model.

α	Age (Gyr)	Mass ($M_\odot$)
2.0	24.6	0.563
4.0	22.9	0.571

Table 3: White Dwarf properties

4.3 $15M_\odot$ Models: Main Sequence

The $15M_\odot$ models were not evolved past the main sequence phase, but we can still see some interesting results from the evolution from ZAMS to the end of core hydrogen burning. Figure 5 shows that the differences in convection do not play an out-sized role in the evolution. This is similar to the pre-main sequence stage, each of the models remain relatively close to each other on the HR diagram with only small variations. In a high mass star like this, we would expect a convective core due to the CNO process generating a large temperature gradient, with a radiative envelope surrounding the core. The lack of significant differences in the evolution along the HR diagram suggests that the convective core is not playing as substantial a role as we might have initially thought. At the very least, our varying of α has not made a sizeable impact on these models.

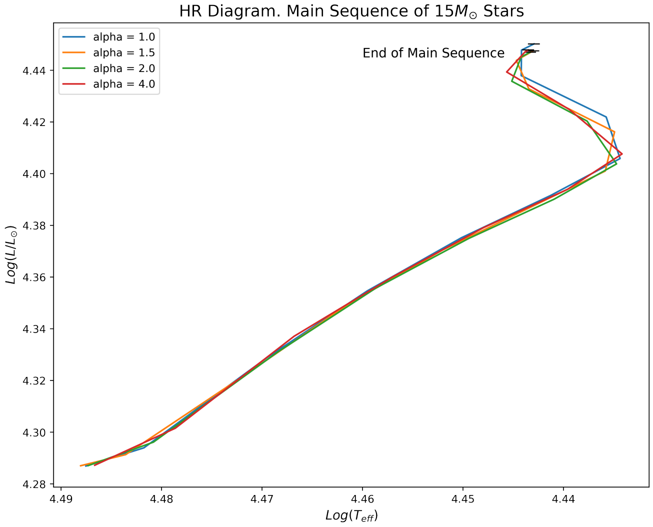

Figure 5: Main Sequence evolution of $15M_\odot$ models

5 Conclusion

The main goal of this project was to investigate how varying parameters in convection would impact a stellar simulation. The most deeply investigated models were the $1M_\odot$ stars. These were run using MESA Web and resulted in four simulations that ran from pre-main sequence to the giant phase, with two of the four continuing on to white dwarfs. These showed that starting from the initial collapse to a main sequence star, the differences in convection led the models to diverge and end up reaching the main sequence at temperatures that varied by $\sim 10\%$ (see Figure 1. Each model continued to take a different track as they moved off the main sequence into the giant phase. Here, differences in the shape of their trajectories through the HR diagram (see Figure 3) could be due to the ranging levels of convection. Only two of the simulations were able to complete the giant phase and descend the HR diagram to become cooling white dwarfs. Analyzing these white dwarfs in Figure 4 and Table 3, we found that there were only small differences on the order of $\sim 1\%$ in final mass. The composition of each white dwarf was very similar and it did not appear that differences in convection made a significant impact in that respect.

A secondary goal of this project was to simply gain experience in using MESA. A set of $15M_\odot$ stellar models were run locally following examples in MESA's source code. These simulations showed a significantly different result in the pre-main sequence stage. Unlike in the solar models, these $15M_\odot$ models all converged to a similar spot on the HR diagram when they hit ZAMS. Continuing the simulations through the main sequence, the models remained tightly clustered on the HR diagram (see Figure 5). These simulations were not continued further due to the computational costs but this does point to the different roles convection plays in high mass and solar mass stars.

6 Acknowledgements

This project could not have been possible without MESA and MESA Web which was used to create these different models. Additionally *Stellar Interiors: Physical Principles, Structure and Evolution* by Hansen, Kawaler, and Trimble was vital for information about Mixing Length Theory and stars in general. And then of course Stars Fall 2021 course taught by Dr. Michael Zingale, thank you for a wonderful semester.