The Evolution of a 1.5$M_\odot$ Star — The MESA Assignment

Bart J.H. Wolfs — S2413264 & **Catherine M. Slaughter** — S3238865
Course: Stellar Structure and Evolution
Place: Leiden
Professor: Prof. Dr. S. Viti
Date: July 10, 2023

1 Introduction

Stellar birth, evolution, and death are an often overlooked–but absolutely crucial–area of research in astronomy. Our understanding of the way(s) stars live and die is foundational to most other subfields, from solar astrophysics to cosmology. In recent years, computational advancements have allowed astronomers to more conveniently study stellar evolution through numerical simulations and modelling. One such stellar evolution code is Modules for Experiments in Stellar Astrophysics (MESA). MESA is one of a few industry standards and is used by astronomers across the globe. The original paper describing MESA (Paxton et al., 2011) has received several thousand citations. For this project, we will model the evolution of a 1.5 $M_\odot$ star with the use of MESA and analyse its convective properties at different stages.

1.1 Stellar Evolution

Throughout a given star's lifetime, every star goes through a number of different stages. All stars begin as clouds of gas and dust. Dense cores can form in these clouds due to instabilities, leading to collapse. The resulting protostars continue to grow via accretion from the remaining cloud. Once accretion stops, the star is called a pre-main sequence star. The pre-main-sequence star will contract due to gravity until the core becomes hot enough to ignite thermonuclear hydrogen fusion. If the star is not massive enough to ignite hydrogen fusion, it becomes a brown dwarf star. More massive stars, which can fuse hydrogen, are called main-sequence stars. Main sequence stars reach a state of hydrodynamic equilibrium, with the outward radiative pressure from the fusion balancing the inward gravitational pull. The main sequence is the longest evolutionary stage. Generally, the mass of a star has an inverse relationship with the amount of time that star stays on the main sequence–large stars burn fast. Once the hydrogen in the core is entirely used up, the next stage(s) depends on the stellar mass. Very massive stars will have cores hot enough to fuse heavier elements up until iron, at which point fusion becomes an endothermic process and cannot be used to further support the star. Depending on their mass, these stars will supernova or collapse into stellar-mass black holes. By comparison, lighter mass stars (such as our sun) will begin to fuse helium in their cores, causing them to expand to form red giants. Red giant stars will "pulse," ejecting their outer layers to form a planetary nebula. The remaining core collapses into a white dwarf star, held up by electron degeneracy pressure (Pols, 2011). This final product of low-mass stellar evolution will slowly cool down as it radiates the energy away and becomes less bright.

2 Methods

As a star evolves it will undergo changes in its internal properties at certain stages throughout its lifetime. We will use the MESA numerical simulation software to get better insight in the internal properties of a 1.5 $M_\odot$ star during these different stages of the stellar evolution. By producing figures that best display these changes we aim to provide a better understanding in how the internal properties evolve and characterise the evolution of a low-mass star. In the first figure we will plot the core density against the core temperature in logarithmic scale over the lifetime of the star. We include the theoretical evolutionary track of a 1.5 $M_\odot$ star from the literature (Pols, 2011) to compare this with the MESA results. For the theoretical track we can use the fact that the evolution of a star up to after the main-sequence stage can be approximated as a slowly contracting star in hydrostatic equilibrium consisting an ideal gas: $\rho_c = T_c^3 \left(\frac{R}{CG\mu M^2}\right)^3$. Therefore, we can use a $\frac{1}{3}$ power law to best describe this stage of the core's evolution. After the star leaves the main sequence we can use the following equation to calculate the core density, which is constant for temperature: $\rho_c = \left(\frac{CG}{K_{NR}}\right)^3 \mu_e^2 M^2$. Where we use the ideal gas constant R= 8.314×10^7 ergs mole^{-1} K^{-1}; The gravitational constant G= 6.674×10^{-8} dyne cm^2 g^{-2}; K_{NR}= 1.0036×10^{13} is the non-relativistic electron gas pressure constant; A constant C= 0.41; The mean molecular weight μ= 0.61 and μ_e= 1.17 are similar to the values of the sun, since we are dealing with a solar like star. We use $T_{c,\odot}$= 1.57×10^7 Kelvin and $\rho_{c,\odot}$ = 140 g cm^{-3} as the parameters to visualise the current solar position in this figure. In the second figure we present the evolution of the effective temperature and the bolometric luminosity in a Hertzsprung–Russell diagram. We will use the last two figures to analyse the differences in the convective regions in the pre-main-sequence and the main-sequence stage by looking at the adiabatic and radiative temperature gradients at certain timesteps.

3 Results

Running the MESA code and analysing the data we present the evolution of the properties of a 1.5 $M_\odot$ star in the following figures. Figure 1 shows the evolutionary track of the stellar core in the $\log T_c - \log \rho_c$ plane. Figure 2 displays the Hertzsprung-Russell Diagram. Figures 3 and 4 present the radii in which convection governs the main energy transport in the pre-Main Sequence and in the Main Sequence phase respectively.

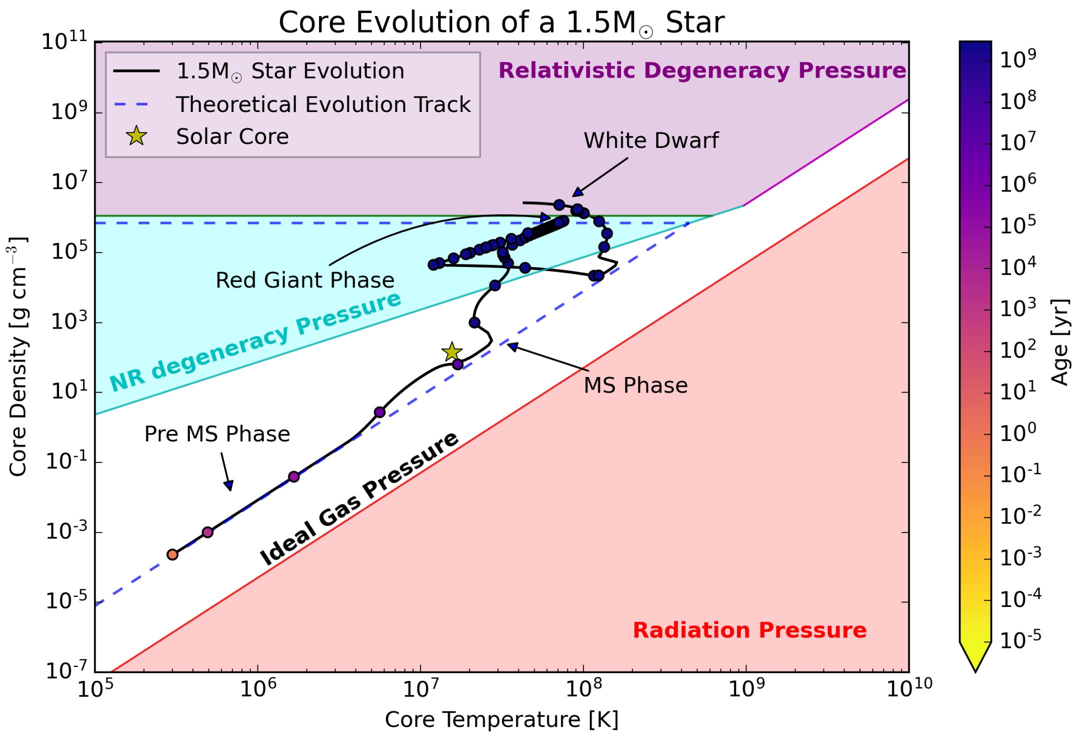

Figure 1: The core density vs. the core temperature in logarithmic scale of a 1.5 $M_\odot$ star. The figure visualises the different pressure regimes by the colored areas and the current position of the sun is indicated by the yellow star. The theoretical evolutionary track is represented by the dashed line. The evolutionary timescales are indicated by the colored points along the evolutionary track of the star and the color bar. In addition, the different evolutionary stages are portrayed by the included annotations.

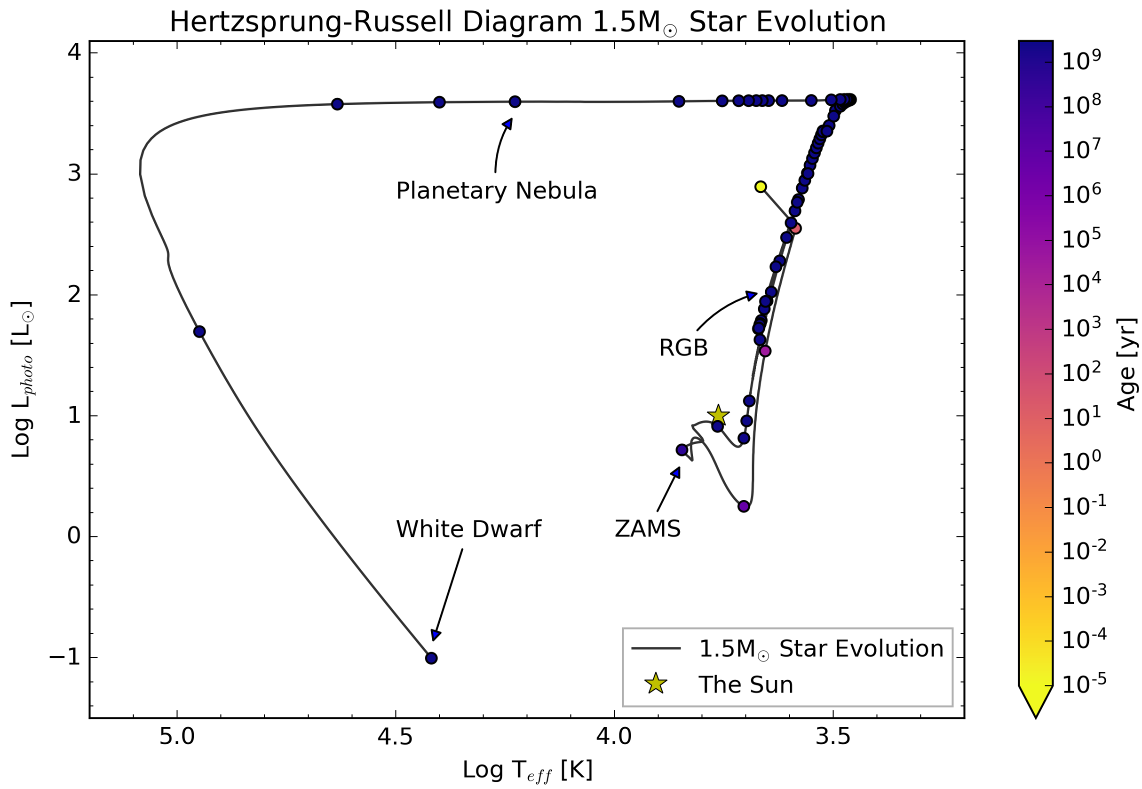

Figure 2: The Hertzsprung–Russell diagram concerning the evolutionary track of a 1.5 $M_\odot$ star. The position of the sun is indicated by the yellow star. The evolutionary timescales are indicated by the colored points along the evolutionary track of the star and the color-bar. In addition, the different evolutionary stages are portrayed by the included annotations.

4 Discussion

4.1 Pre-Main Sequence

A pre-main sequence star is one that is no longer actively accreting but has yet to begin thermonuclear fusion in its core. In this stage, convection is the dominant form of energy transfer throughout the star. This is reflected in Figure 3, where the convective energy transport zone covers nearly the whole radius of the star. This makes sense, as the primary driver of radiative transfer in stars comes from the photons generated in thermonuclear fusion, and there is no fusion yet. As a result, the radiative temperature gradient is dominant. Figure 1 clearly shows that the core of the pre-main sequence star evolves almost exactly along the theoretical evolution track. We can also tell the core is held by ideal gas pressure. As expected, we also see the core temperature and density increase with time, as the star contracts. On the HR diagram (Figure 2), we see that the effective temperature (color) of the stellar exterior changes significantly less than the core, a result of the convective transport dominating. We also see the star slowly growing less luminous with time, only for the luminosity to suddenly increase leading up to the zero-age main sequence (ZAMS) point. The data point colour scale in Figure 1 and Figure 2 shows us that the 1.5 $M_\odot$ star stays in the pre-main sequence phase for $\sim 10^8$ years before hydrogen fusion begins, a relatively short amount of time, compared to the stellar lifetime.

4.2 Main Sequence

The main sequence phase occurs when a star begins hydrogen fusion in its core and is the longest evolutionary stage. In Figure 1cwe see the core evolution begin to diverge from the theoretical track during the main sequence, though the general evolution trends (increased temperature, increased density), remain the same between the two. We also observe that the core continues to be supported by ideal gas pressure in this phase. Figure 2 shows

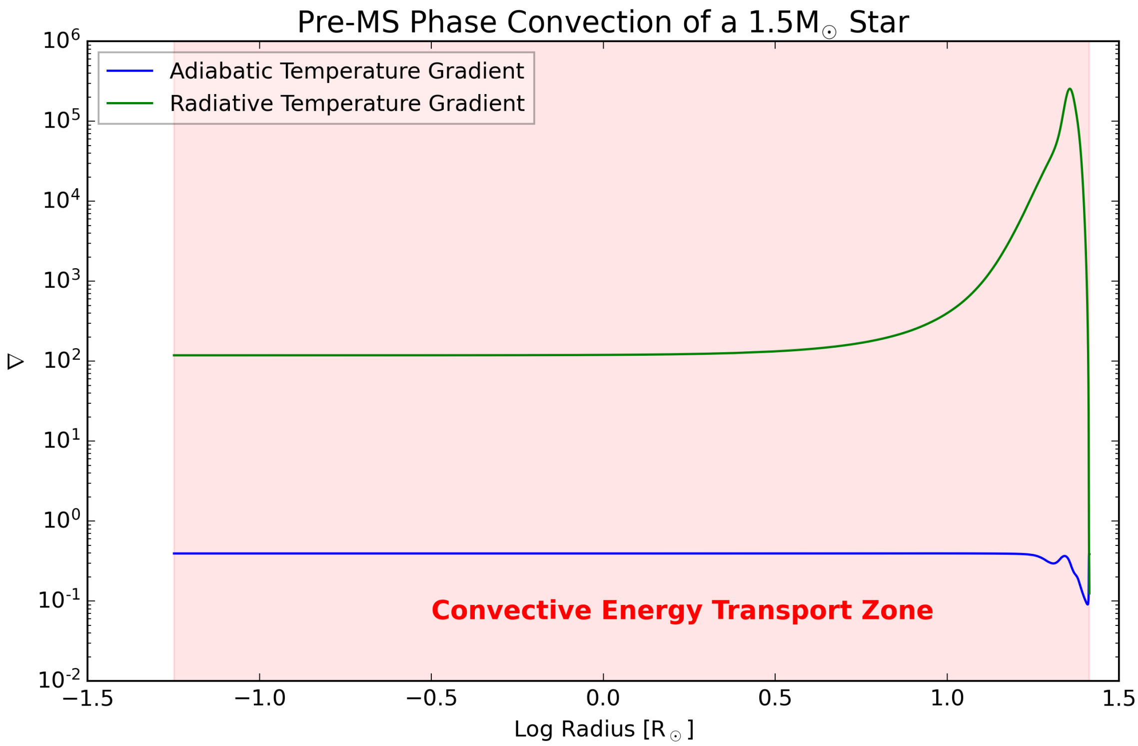

Figure 3: A 1D radial snapshot of the pre-main sequence phase of a 1.5 $M_\odot$ star. The figure shows the adiabatic and radiative temperature gradients vs. the logarithmic radius of the star in units of the solar radius. The radii where convection dominates the energy transport in the star are indicated by the red area.

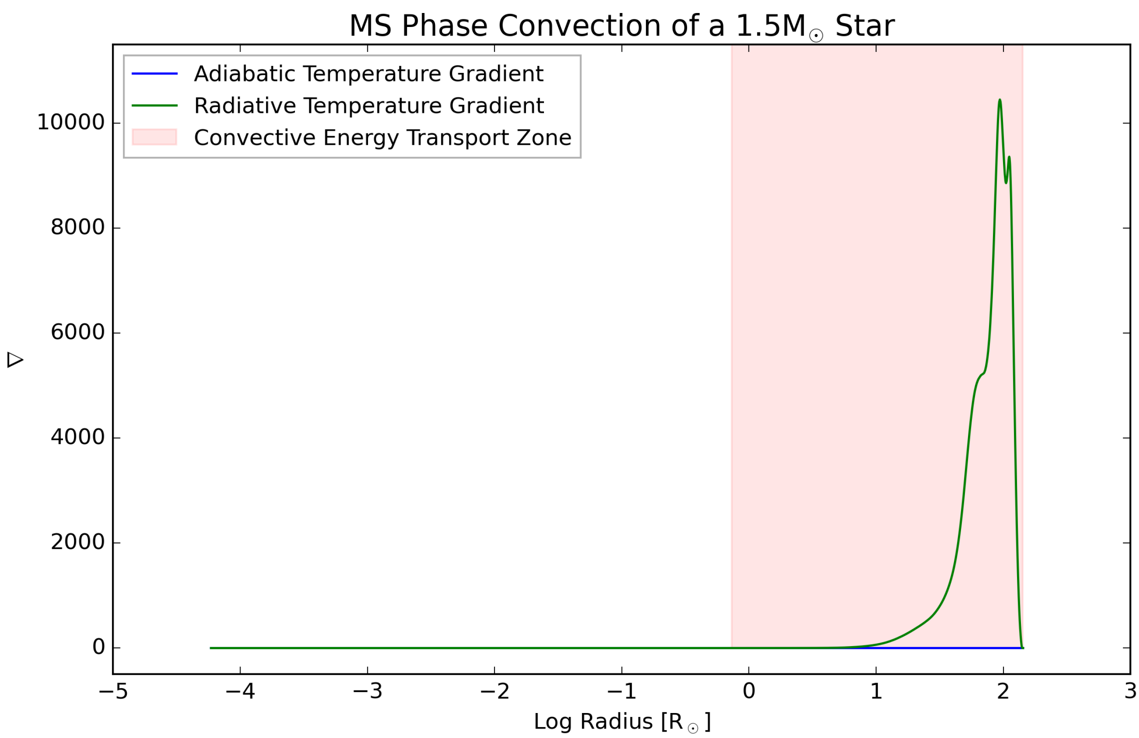

Figure 4: A 1D radial snapshot of the main sequence phase of a 1.5 $M_\odot$ star. The figure shows the adiabatic and radiative temperature gradients vs. the logarithmic radius of the star in units of the solar radius. The radii where convection dominates the energy transport in the star are indicated by the red area.

us that there is relatively little change in the outer layers of the star. The effective temperature of the star decreases and the luminosity varies. The convection zone plot (Figure 3 shows us that, during the main sequence phase, the core is radiative, while the very outermost parts of the star are convective. A more massive ($<\sim 2M_{\odot}$) star would have a hotter core (and a higher temperature gradient near the core), creating the reversed situation with a convective core and a radiative envelope. For a 1.5 $M_{\odot}$ star, however, it is more than reasonable to see a convective envelope. In this case, the convective envelope is expected to be relatively small compared to other MS stars of lower mass.

4.3 Red Giant

The lack of convection near the core during the main sequence reduces the amount of helium created for fusion in the red giant phase. When hydrogen fusion in the core stops, the star falls out of equilibrium and begins to contract again. In Figure 1, we see a sharp increase in both the density and temperature in the core as a result of this contraction. This causes the core of the star to reach a degeneracy pressure regime for some time. Soon after, helium fusion begins in the core, temporarily changing back to the ideal gas regime. As is seen in Figure 2, the sudden energy input from helium fusion causes the whole star to expand, decreasing its effective temperature. The luminosity of the star also greatly increases, as it begins up the red giant branch on the HR diagram.

4.3.1 Planetary Nebula

In Figure 2, we see that after the red giant phase, the star takes a horizontal path across the HR diagram. This is representative of the creation of the planetary nebula. During this time, the outermost layers of the star get "shed" off, meaning the "surface" of the star becomes closer to the core, and the effective temperature of the star increases. However, the shedding process does not change anything about the helium fusion in the core, so the star's luminosity remains constant.

4.4 White Dwarf

Finally, once the helium in the stellar core is used up, what remains of the star once again begins to collapse. At 1.5 $M_{\odot}$, the star is not large enough to fuse any heavier elements than helium, so no further radiative pressure can maintain hydrostatic equilibrium. Instead, the star collapses until it reaches the white dwarf phase. In this phase, electron degeneracy pressure counteracts gravity for the star to maintain equilibrium. In the core of the star (Figure 1), the electrons move at relativistic speeds. As seen in Figure 2, the lack of thermonuclear fusion corresponds with a rapid decrease in luminosity. However, the high density of a white dwarf means a high effective temperature.

5 Conclusion

MESA and similar codes are a convenient, simple way for astronomers to study stellar structure and evolution with ease, as compared to strictly observational methods. We successfully model the evolution of a 1.5 $M_{\odot}$ star using MESA. We are able to track the star through its main evolutionary stages: pre-main sequence, main sequence, red giant (with planetary nebula), and a white dwarf. In doing so, we are able to analyse the changing structure of the star over time. This includes tracking the star along with an HR diagram (Figure 2), looking at the pressure regime of the stellar core (Figure 1), and the relative locations of the convective and radiative zones within the star's layers (Figure 3 and Figure 4) at different evolutionary stages.

References

Bill Paxton, Lars Bildsten, Aaron Dotter, Falk Herwig, Pierre Lesaffre, and Frank Timmes. Modules for Experiments in Stellar Astrophysics (MESA). , 192(1):3, January 2011. doi:10.1088/0067-0049/192/1/3.

O.R. Pols. Stellar structure and evolution. Astronomical Institute Utrecht, Utrecht, sep 2011.