Stellar Models for Hydrodynamic Simulations

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The motivation for this project was to design a fast and user-friendly way of exploring the properties of a large range of stars, and to store the data in an easily accessible format. Using the stellar evolution code, Modules for Experiments in Stellar Astrophysics (MESA), a model grid was created, with each point on the grid containing data from a simulation of a specific star's lifetime. A basic user interface was created, allowing the data from desired simulations to be extracted and utilized easily.

Introduction

Star lifetime's are much greater than our own, meaning it is not possible for us to observe full evolution. This is why researchers use simulations to model stellar evolution. Stellar evolution describes how a star's properties change over it's lifetime. Initial properties of the star such as mass and metallicity determine how long a star takes to evolve, and which path of evolution it takes. Stars are made primarily of hydrogen and helium and the metallicity of a star is the abundance of chemical elements that aren't hydrogen or helium. The model grid designed in this project will provide easy access to data from a wide variety of stars, and this data can be used to explore how initial mass and metallicity effect the properties of a star.

A star will spend most of its life on the main sequence. A main sequence star fuses hydrogen atoms into helium atoms within the core via nuclear fusion. Nuclear fusion is a reaction in which lighter atoms like hydrogen, fuse together to form heavier atoms, in this case helium. To achieve nuclear fusion, a great deal of energy is required and it occurs in stars due to the immense pressure and hot temperatures found in the core. For example, the centre of the sun is 15 million degrees Celsius. Because stars are so massive, gravity exerts a huge force on them, which is what creates these intense pressures and temperatures at the centre. Although nuclear fusion requires a lot of energy, it also releases a huge amount. This energy generation results in a force, known as gas pressure, which acts outwards from the centre of the star. This outward force balances the force due to gravity which is acting inwards, causing the star to be stable. This balance is known as hydrostatic equilibrium.

As a star evolves it undergoes many changes which are mainly determined by the initial mass. The initial mass defines the mechanisms for energy transport. Energy transport mechanisms describe the way the energy generated from nuclear burning travels from the core of the star to the surface, where it is radiated as light. In main sequence stars the main two energy transport mechanisms are radiation and convection. In radiative energy transfer, light particles called photons carry energy from the core to the surface. It is this same mechanism that allows heat to travel from the sun, to us at earth. In convective energy transfer, hot gas will rise to cooler regions, transferring energy as it does, much like a boiling pan of water. Both mass, metallicity and age of the star affect which transport mechanism dominates.

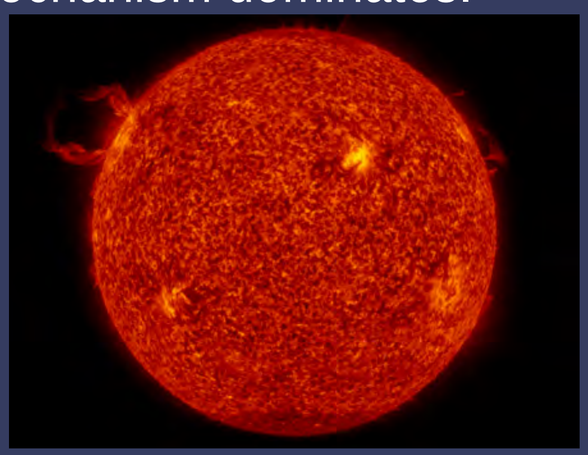

Fig. 1[1]: A photo of the sun. It has a mass of 1.99 x 10^{30} kilograms, which is 330,000 times bigger than the earth. The light seen is due to the two energy transfer mechanisms, the most dominant being radiative. The radiative zone surrounds the core and makes up approximately 45%[2] of the sun's radius. The convective zone surrounds the radiative zone, and accounts for 30% of the sun's radius.

Method

Modules for Experiments in Stellar Astrophysics (MESA) is an open-source stellar astrophysics code which combines many numerical and physical modules in order to simulate stellar evolution. It uses a wide range of these modules, each of which is responsible for modelling a different aspect of stellar structure. For example, there will be a module responsible for solving the equations for convection and one for modelling the nuclear reactions in the core. All of these modules are then combined to gain a full simulation of the star. MESA outputs raw data (called a stellar profile) at specific ages of the star. The profiles contain arrays of various properties of the star such as density, temperature, and radius.

The code uses an array of masses and metallicities to create the model grid. For each mass and metallicity combination, it changes the required parameters in MESA and then submits the simulation as a job on the Rocket High Performance Computer (HPC). The HPC is a cluster of computers, which is beneficial as individual computers can work together to run computations too large for a desktop computer to handle. This allows multiple simulations to be ran simultaneously which means the model grid can be constructed quickly and efficiently.

Once the simulations have ran, the profiles are saved in folders, specifying the mass and metallicity. The code also uses data from the profiles to calculate other stellar properties that may be required, and outputs the properties in a format compatible with the hydrodynamics code, a code used by many researchers at Newcastle University. A basic user interface was created, such that a user can input the desired mass, metallicity and age of a star and the associated data will be available to export or to use to create plots.

Results and Discussion

The beauty of the model grid is that it allows a large range of different properties to be explored. Below are a few of examples of graphs that can be produced from the data stored in the model grid.

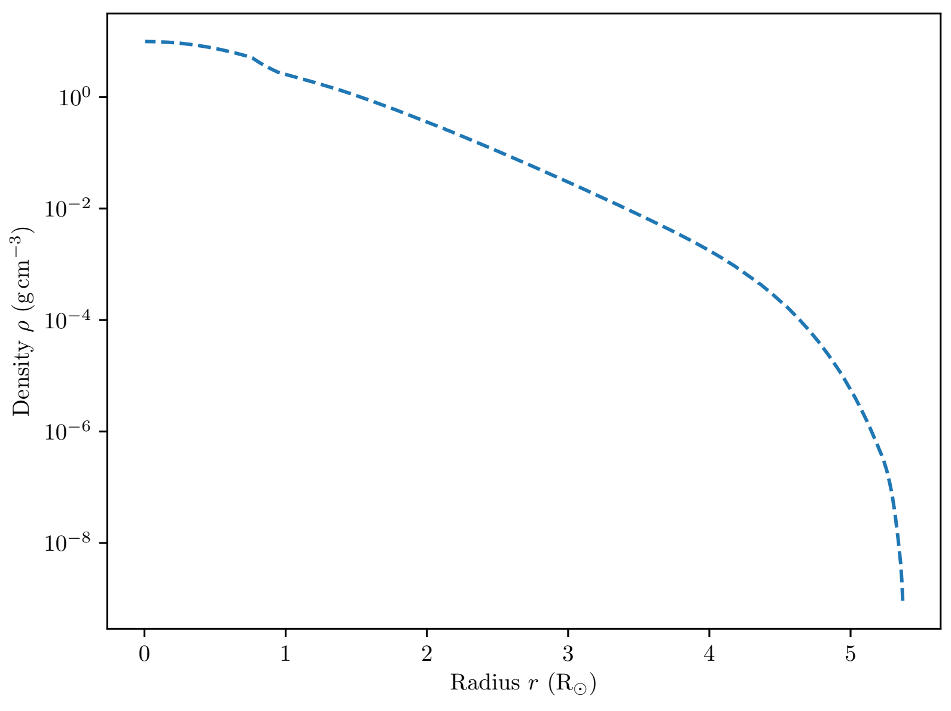

Fig 2: A graph to show how density varies with radius for a 15 $M_\odot$ star. $M_\odot$ means solar mass, so the star is 15 times larger than the sun.

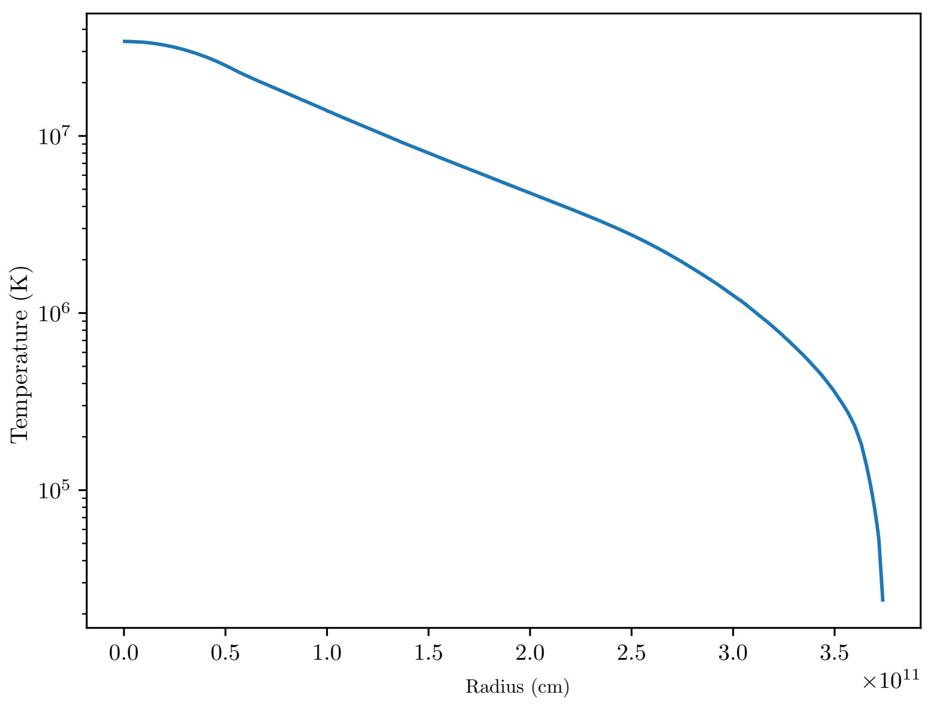

Fig 3: A graph to show how temperature varies with radius for a 15 $M_\odot$ star.

Figure 2 shows how the density varies as a function of radius outwards from the core of the star to the surface. It shows that the core is much denser than the surrounding regions, and that density drops off steeply close to the surface. This is because as you move radially inwards from the surface, the force due to gravity increases, which results in an increase of pressure. It's this immense pressure which causes the core to be extremely dense. Similarly in Figure 3, the temperature follows a similar pattern which is again due to the increase in pressure. The high density and temperature of the star's core results in nuclear fusion.

Due to the model grid providing data from a wide variety of stars, it is easy to plot graphs showing how mass affects different properties of the star. Figure 4 shows how the convective cores of high mass stars change with time for different masses. High mass stars have convective cores and radiative outer regions. This is because the temperature in the core of high mass stars is much greater than stars like our sun. This means the mechanism in which hydrogen is converted into helium is different to that of lower mass stars: it is much more temperature dependent and therefore generates energy at a faster rate. This means radiative energy transfer doesn't transfer energy as fast as it's being generated, meaning convection is a much more efficient method, hence high mass stars have convective cores.

For all the masses in Figure 4, the cores decrease in size over the star's main sequence lifetime. This is due to nuclear fusion, transforming hydrogen into helium[3]. There is a mass difference between the hydrogen atoms fused together and the resultant helium atom. This mass difference is what generates the huge amounts of energy, but it does result in the star losing mass, hence the core shrinks.

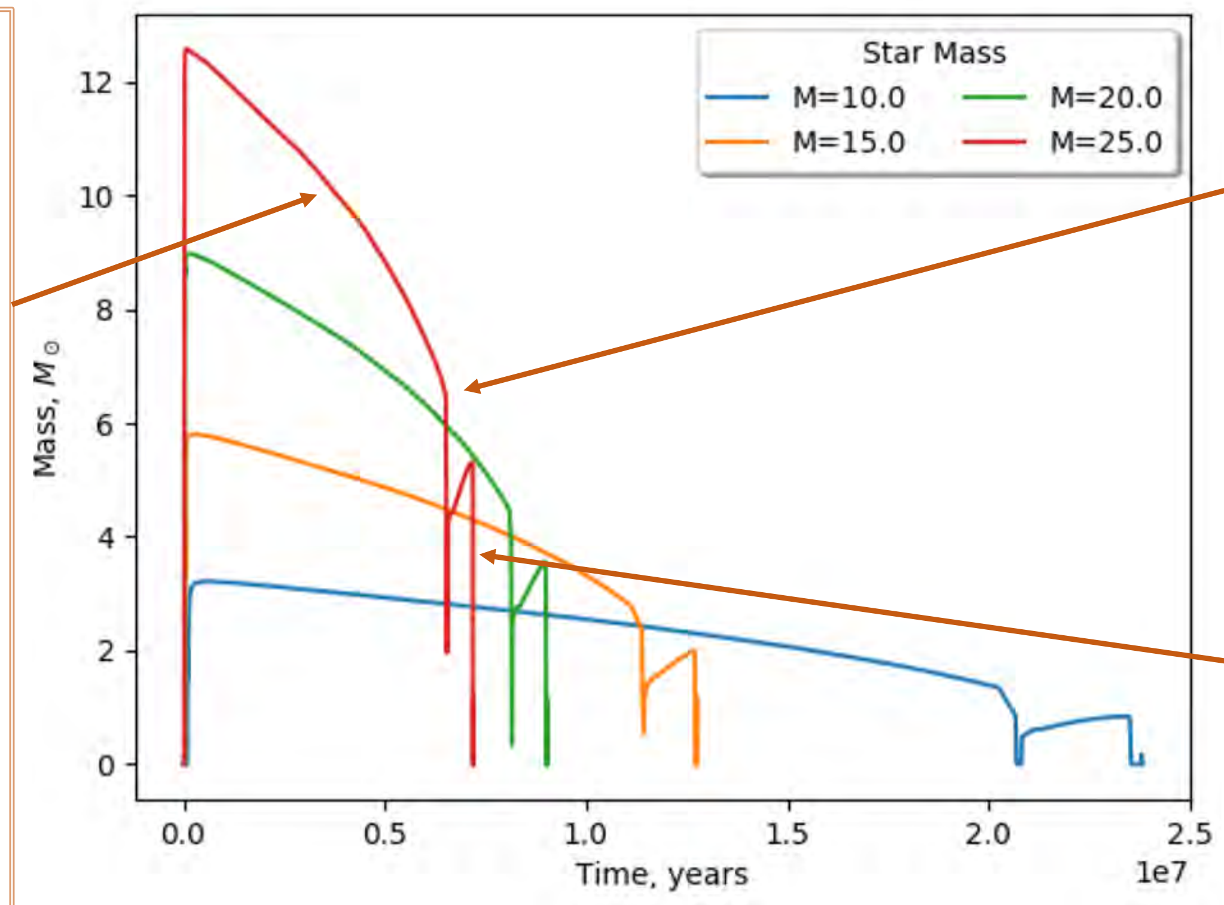

Fig. 4: A graph to show how the convective cores for various mass stars change with time. Less massive stars have much longer lifetimes as their cores are lower in temperature meaning they burn through nuclear fuel slower.

The first sharp decrease in the lines in Figure 4 signifies the end of hydrogen burning. Once all the hydrogen has been depleted, the core will contract causing an increase in pressure and temperature. Once it is hot enough, helium will fuse into lithium, the next heaviest atom, and this will be the source of gas pressure.

Once all the helium has been depleted, the core shrinks again, shown by the second sharp decrease in Figure 4. This again causes the core to heat up, until it's hot enough for lithium to fuse into the next heaviest atom. This process continues until the element iron, as the core can never reach temperatures hot enough to fuse iron. The rest of these processes cannot be seen in Figure 4 as the time scales are too short to be distinguishable.

Conclusion

The model grid produced in this project provides fast access to a large amount of data and can be ran with minimal effort from the user. It makes plotting and comparing stellar properties simple and can be easily tailored to the needs of the individual using it. It provides an efficient way of exploring a large variety of properties throughout the main sequence evolution of stars of any initial mass and metallicity.

References

[1] GMS: SDO First Light High Resolution Stills (2018) [Online]. 2018. Available at: https://svs.gsfc.nasa.gov/10610. (Accessed: 3 October 2018).
[2] How the Sun Works (2018) [Online]. 2018. Available at: https://science.howstuffworks.com/sun3.htm. (Accessed: 3 October 2018).
[3] Hansen, C. (2012) Stellar interiors. Springer-Verlag New York.