HIGH SCHOOL EDITION
Journal of Student Research

Volume 13 Issue 1 (2024)

Stellar Evolution of Main Sequence Stars Powered only by the PP Chain

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ABSTRACT

We explore how the main sequence evolution of 1-2$M_{\odot}$ stars depend on the different nuclear reactions that occur in its core. We employ MESA (Modules for Experiments in Stellar Astrophysics) to analyze the effects of adding or removing reactions. The simulations showed counter-intuitive results where the PP chain stars lasted longer on the main sequence, as and more luminous than the so called basic-net stars.

Introduction

Astrophysics is a major branch of science focused on discovering the fundamental rules that govern the Universe. This field has evolved from early observations of the sky by the first humans before recorded history, the invention of the telescope, to recently simulating collisions of objects that make the entirety of human creation seem microscopic. Throughout the field's evolution, humans have always looked up and made observations about the night sky. Amongst the thousands of objects in the night sky visible to the naked eye, stars are amongst the most numerous.

Stars come in many colors and sizes, ranging from a star like our Sun to stars hundreds of times larger than the Sun. Every star fights a viscous battle against the force of gravity pulling the star into itself, only getting stronger

as the star gets more massive. Some stars have been fighting this force for billions of years and have not collapsed. They do this with the power of nuclear fusion. Stars are made up of mostly light elements such as Hydrogen and Helium. Nuclear fusion is the process of" burning" lighter elements into heavier elements, which releases large amounts of energy at very high efficiencies (thousands of times more efficient than chemical processes) which increases the temperatures of the interior of the star. This increase in temperature leads to a difference in pressure, which provides a radially outward force. This balance is called hydrostatic equilibrium. As the mass increases in the star, the force of gravity increases, requiring more fusion, resulting in a shorter lifespan This change in lifespan is extremely drastic, as will be shown; a change of 1 $M_{\odot}$ will reduce the star's lifespan by a factor of 10. Solar masses are the units for mass in stellar astrophysics and is simply defined as the mass of the sun roughly: 2×10^{30}kg and is denoted as $M_{\odot}$.

Almost every observable quantity in a star has a mass dependence including but not limited to lifespan, total luminosity, temperature, density, pressure, nuclear energy output, and gravitational potential energy. Mass also controls when a star transitions to its next major evolutionary phase. For lower mass stars, the sequence in chronological order goes, protostar, main sequence, assent to giant branch, red giant, asymptotic giant branch, and finally to a white dwarf. The time it takes for a star to reach these markers is heavily dependent on its mass, more specifically the core mass of the star. In this paper, we will explore what effects changing the nuclear fusion in the main sequence of the star has on the star. There are two main reaction networks used in main sequence stars: the PP chain and the CNO cycle. A main sequence star is a star like our sun, fusing hydrogen into helium. The Main sequence is the longest part of a star's lifetime because it only ends when a star has no more hydrogen to burn. The PP chain is most effective for stars under 1.2-1.3 M⨀ where the CNO takes over in the higher mass regimes (Salaris, 2008). These results can be used to extend the work in simulating Population III stars (stars that are made from the primordial gas). Primordial gas is a mix of mainly hydrogen and helium with trace lithium, and beryllium amounts. This conversation includes many papers, just to name a few (Hirano, 2017), (Whalen, 2017), and (Kashlinsky, 1983)All these papers are using high mass Population III stars leading to different results than this paper. This paper is also like others that change 1 constant in stellar code, to see how the change affects the star. Changing the fundamental constants could be used to possibly simulate a star in our universe at a different time. Most of these papers also use Population III stars, for the reason stated above. These papers include: (Coc, 2010) and (Ekstrom, 2010) These papers also deal with high mass population III stars similar in mass to the papers mentioned above.

The proton-proton chain is the fundamental reaction network active in main sequence stars. Thermal energy is released upon burning hydrogen into helium. As shown in Figure 1 protons, neutrons, positrons, neutrinos, and gamma rays are involved in the reactions. The PP reaction begins with two sets of protons fusing into deuterium. This is the bottleneck of the reaction because one of the protons needs to decay into a neutron while emitting a positron and an electron neutrino. This is a rare event in most cases because the protons will fuse into a diproton (just two bound protons) which will immediately decay into two separate protons. On average most protons wait for billions of years in the core of the star before they fuse, however, due to the massive amounts of protons in the stellar core, the PP chain is efficient enough to produce the luminosity of Sun-like stars. (Langanke, 2001)

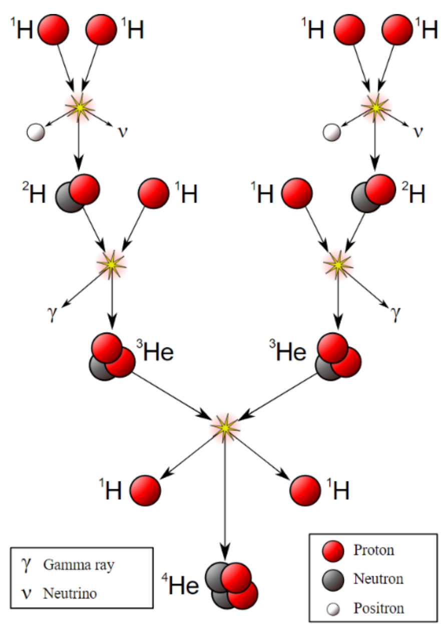

Figure 1. The PP Chain. (*File:Fusion in the Sun.svg - Wikimedia Commons*, 2016) (

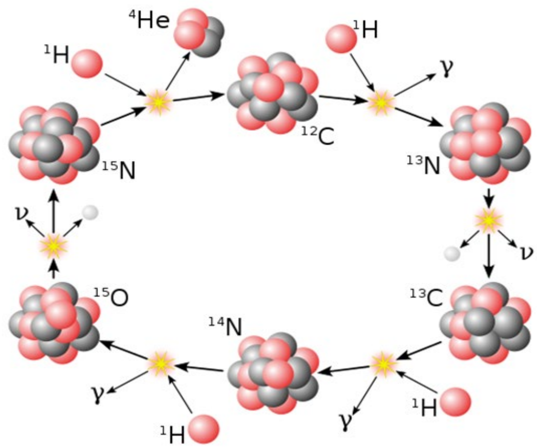

Figure 2. The CNO Cycle. (File:CNO cycle.svg - Wikimedia Commons, n.d.)

The CNO cycle is the other nuclear reaction net active in main sequence stars, dominating in stars with masses 1.2-1.3 times the mass of the Sun (Salaris, 2008). As seen in Figure 2, it is a catalytic cycle whose net result is to consume the protons to fuse into helium nuclei. Using carbon, nitrogen, and oxygen as catalysts, four protons fuse into a single stable helium nucleus, 2 positrons, and 2 electron neutrinos. The CNO cycle can only become self-sufficient at high temperatures such as 12×10^6K compared to the PP-chain which sustains at 4×10^6K. However, the energy output rises with temperature, dominating over the PP-chain at 17×10^6K, (Reid, 2005).

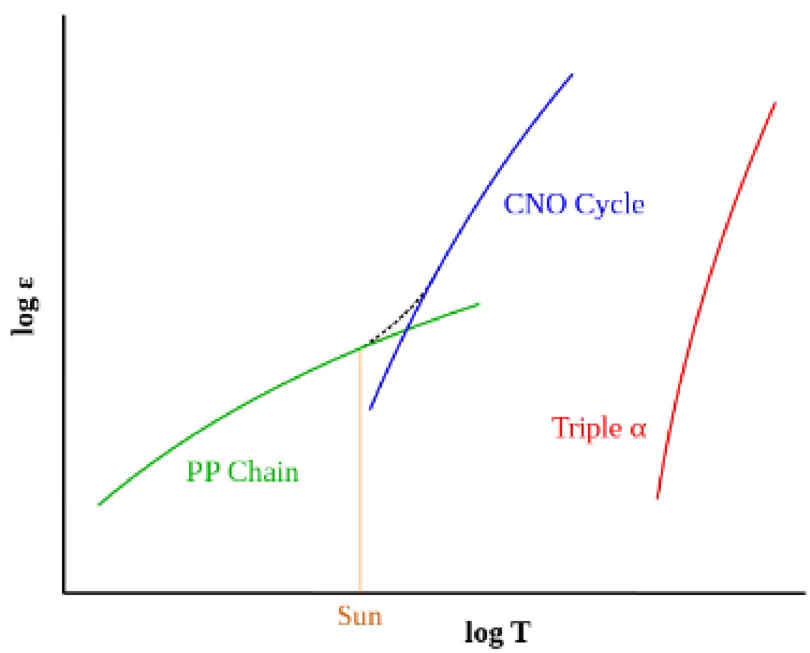

Figure 3. Reaction Dominance (*File:Nuclear Energy generation.svg - Wikimedia Commons*, 2008)

As seen in Figure 3 the CNO cycle rapidly takes over in higher temperature regimes, which are present in more massive stars.

Methods

We use the MESA (Modules for Experiments in Stellar Astrophysics) (Timmes, 2010) software to numerically solve the stellar evolution equations shown below. MESA is modular and allows for individual toggling or altering specific variables. MESA works by getting the user specified information from "inlist" files, which we use to change our experimental parameters. Then MESA then begins numerically solving the stellar evolution equations:

$$1.\ \frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \varrho}$$
$$2.\ \frac{\partial P}{\partial m} = \frac{-Gm}{4\pi r^4}$$
$$3.\ \frac{\partial l}{\partial m} = \varepsilon_n - \varepsilon_v - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\varrho}\frac{\partial P}{\partial t}$$
$$4.\ \frac{\partial T}{\partial m} = \frac{-GmT}{4\pi r^4 P}$$
$$5.\ \frac{\partial X_i}{\partial t} = \frac{m_i}{\varrho}\left(\sum_j r_{ji} - \sum_k r_{ik}\right)$$

(Kippenhahn, 2012)

Equation 1 represents the definition of mass within the star yielding the function M(r) when integrated. Equation 2 is the equation of hydrostatic equilibrium, which as discussed above, is the balance between gravity compressing the star, and the pressure gradient pushing against the force of gravity. 3 is the equation representing energy production in the star, where t ε_n is nuclear energy production. Equation 4 is the equation of energy transfer in stars, and how temperature changes on a mass coordinate throughout the star. Equation 5 is the equation representing the nuclear chemistry in the star. Our focus will be the one term from Equation 3 being t ε_n which represents the energy from nuclear reaction release. We can treat $\varepsilon_n$as the sum of the energy released by each network $\varepsilon_n = \varepsilon_{PP} + \varepsilon_{CNO} + \varepsilon_{3A}$. Where ε_{pp}, ε_{cno}, ε_{3a} are the total energy output of the PP chain, CNO cycle, and triple alpha burning respectively. In the Basic Net, these are all at their usual values whatever they might be at the current time. In the test case, the terms representing the output CNO, and triple alpha have been set to zero, which forces the star to survive only on the power of the PP chain. In MESA, this is done in the /data/net_data/nets folder, waiting for you there are files that each represent a reaction net. The easiest way to force a star to only use the PP chain is to make a copy of the basic.net file and delete the lines adding the CNO and Triple Alpha. This was done for 6 stars with masses starting from $M_\odot$ up to $2M_\odot$. This mass range encapsulates the theoretical swap in dominance between the PP and CNO reactions at approximately in the range of 1.2-1.4$M_\odot$ as predicted by (Salaris, 2008).

Data & Analysis

The Interior of the Star

To look at the interior of the stars, we need to look at" profile" plots. These show how a value changes on a mass coordinate system. In this coordinate system 0 is at the core of the star, and the mass of the star is the highest value on the horizontal axis. The profile plots viewing the internal structure of the star, and how certain values such as temperature, density, and nuclear energy release change throughout the star. These can allow for better visualization of the changes between regions in the star, most notably from the core and the radiative zone. Below is the abundance, temperature, and nuclear energy release profile for the 1.6 PP only star.

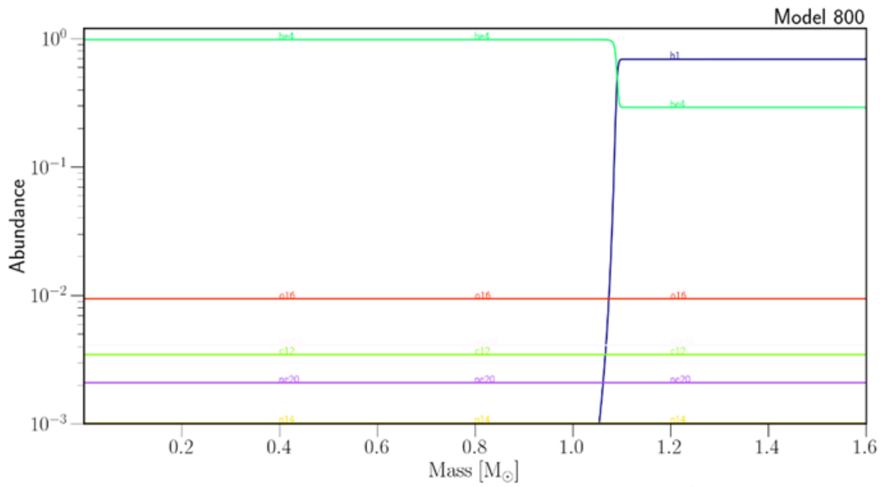

Figure 4. Abundance of Elements in the 1.6 $M_{\odot}$PP chain only star

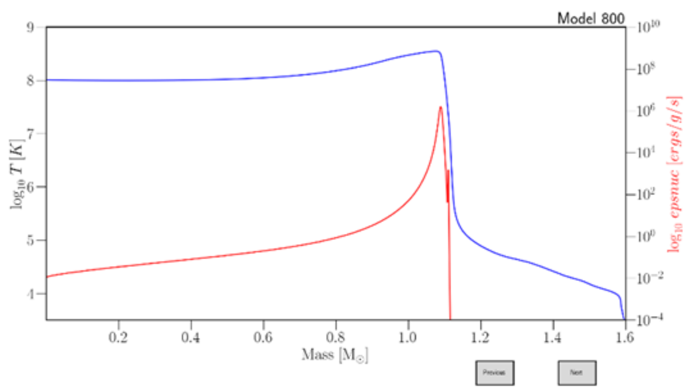

Figure 5. Temperature/Energy Release Profiles for a 1.6 $M_{\odot}$ star

Another type of plot is called an Hertzsprung-Russel (HR) diagram. This is a log plot of luminosity vs temperature. Luminosity is the measure of the total power output of a star and for a blackbody is, $L = 4\pi r^2 \sigma T^4$ where σ is the Stefan-Boltzmann constant, T is the effective surface temperature and r is the radius of the star. These graphs allow us to track the star's evolutionary progress. Below is the standard HR diagram for a low mass star.

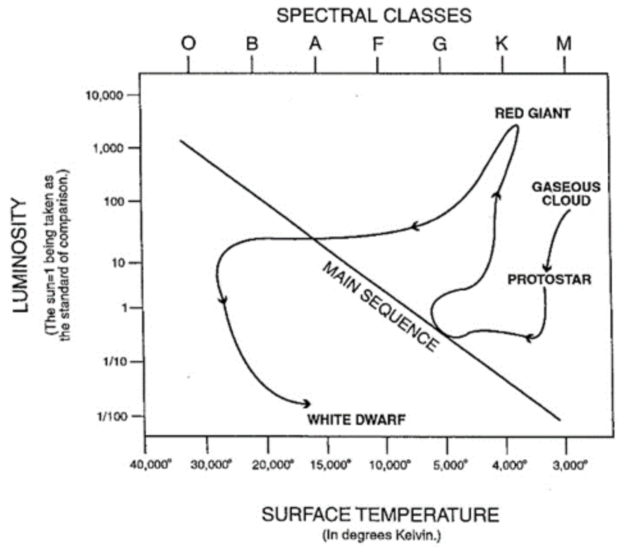

Figure 6. Standard HR Diagram for Low Mass Star (<5$M_{\odot}$) (Smith, n.d.)

These graphs give valuable insight on the structure of the star, but they also allow confirmation that the PP chain star is only using the PP chain. We know this because the only elements that change throughout the entire life of the star are Helium-4 and Hydrogen-1 as seen in Fig:4. It is also clear that the temperature of the core is nearly constant. This applies to the density profile as well. We can also see a clear spike of ϵ_n, at the edge between the core and the next zone out. This spike is significant because ϵ_n is plotted on a logarithmic scale. This spike clearly indicates shell burning, since fusion is not happening in the core compared to this small shell. In Fig:6, we can see the general path that a low mass star follows as it evolves on the HR Diagram starting from a gaseous cloud and ending as a white dwarf. The models that were used start at the bend transitioning from protostar to main sequence. A useful feature to keep track of is the rapid growth in luminosity just before the red giant branch. This is known as the ascent to the red giant.

Luminosity Dependance On Time

Looking at the Luminosity Vs. Time graphs, allows for detailed analysis of the "power output" of the star. Plotting the luminosity vs time for all 6 test cases, each shows a structure like Figure 7.

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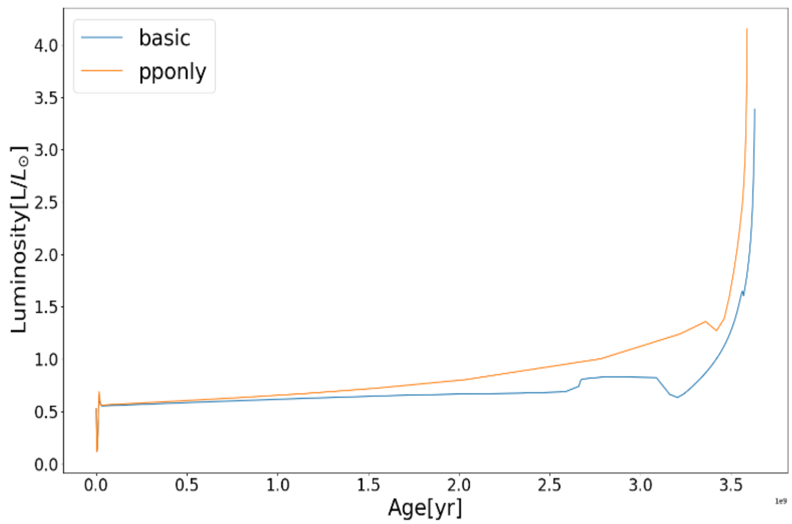

Figure 7. The Luminosity Vs. Time of both types of stars at $1.4M_\odot$

It is important to note that each star starts a slow increase of luminosity, then it hits a bend. This is the start of the red giant branch. To understand how the change in reaction net affects the duration of the main sequence, the time at which the bend was identified and graphed below.

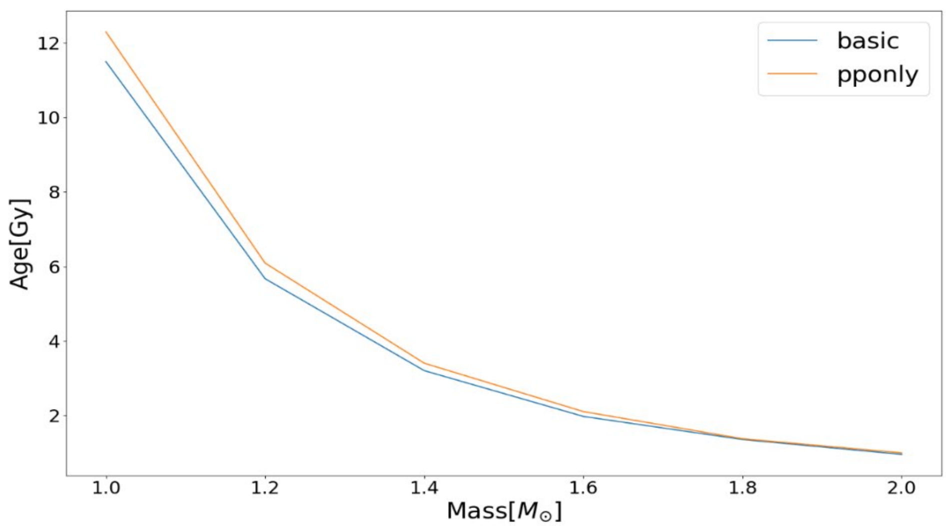

Figure 8. The time of small dip of luminosity for both stars' vs Mass[M⊙]

As we can see, in Fig:8, the lines do not cross, but they asymptotically get closer as the masses get larger. It is interesting to note that the stars that are using the combination of the CNO cycle and PP chain always get to the ascent faster than the stars only using the PP chain. A possible explanation is that since both reactions are consuming hydrogen, the star gets to the critical helium core mass to transition to the ascent branch faster. Oddly enough even at masses above $1.4M_\odot$ where the CNO should be dominating, the star still reaches the bend earlier, but has a slower assent than the PP chain stars. Thus, a valuable next step would be to look at the temperature, density and ϵ_n profiles to see what is happening at this dip in luminosity.

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Temperature, Density, and ϵ_n Profiles

Looking at the temperature and Density Profile at the point where the dip occurs may be helpful in trying to determine what is going on what is happening in the star. Temperature is important to look at because temperature is how energy in a star is transferred and distributed in a star, thus allowing us to see where the energy from the star's fusion is going. A look at density is needed because it is the only non-fixed variable determining how often particles interact with each other, thus it can act like a rate of reaction profile. We can derive an expression for the number of interactions that a particle experiences over a time Δt. Assuming a particle has a radius of d, this means that the diameter for the effective collision area must be $2d$, since the furthest possible collision is when the centers of the two particles are d apart. Which leaves a collision cross section of πd^2 which we can abbreviate as σ. Let the velocity of the particle be represented by v. This means that the particle traces out a cylinder of volume $\sigma v \, \Delta \, t$, multiplying this by the particle density n_v we arrive at the number of particles that the particle collides with. Dividing by Δt leaves us with a rate of collision ($\dot{N}$): $\dot{N} = \sigma v n_v$. As expected, as particle density n_v or the size of the particle (σ) grows, so does the number of collisions. Note that σ does not have to be the size of the particle, it could be the size of a field around a particle, which has other applications. In our case we can interpret the rate as the rate of possible fusion events. Another useful variable to graph on a profile is eps nuc (ε_n), since this allows us to see where the fusion is in each star, like what was done above. This is useful because it allows us to see exactly when the switch to shell burning occurs in the star. All graphs shown below are a snapshot of the interior, just as the star exits the main sequence.

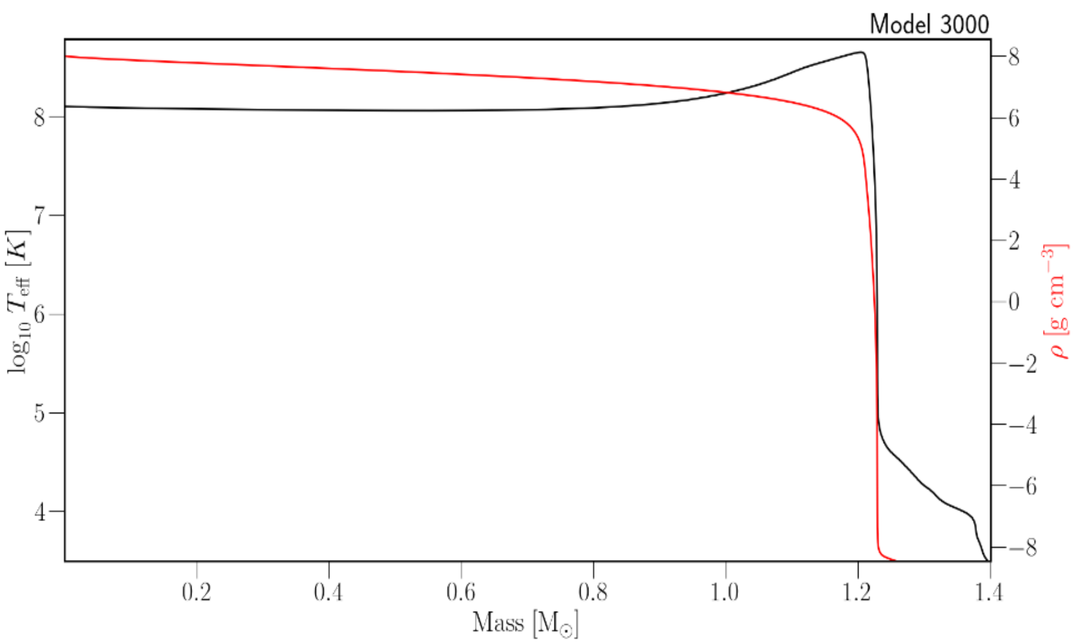

Figure 9. The Temperature Density of the $1.4M_{\odot}$ PP Chain Star

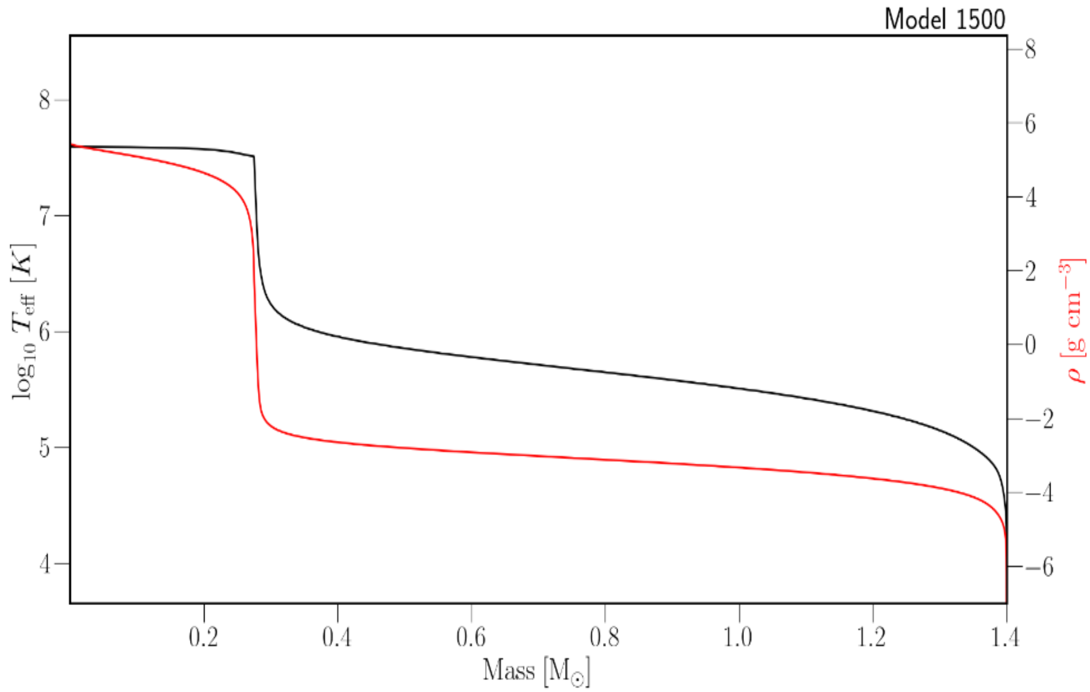

Figure 10. The Temperature Density of the $1.4M_\odot$ Basic Net Star

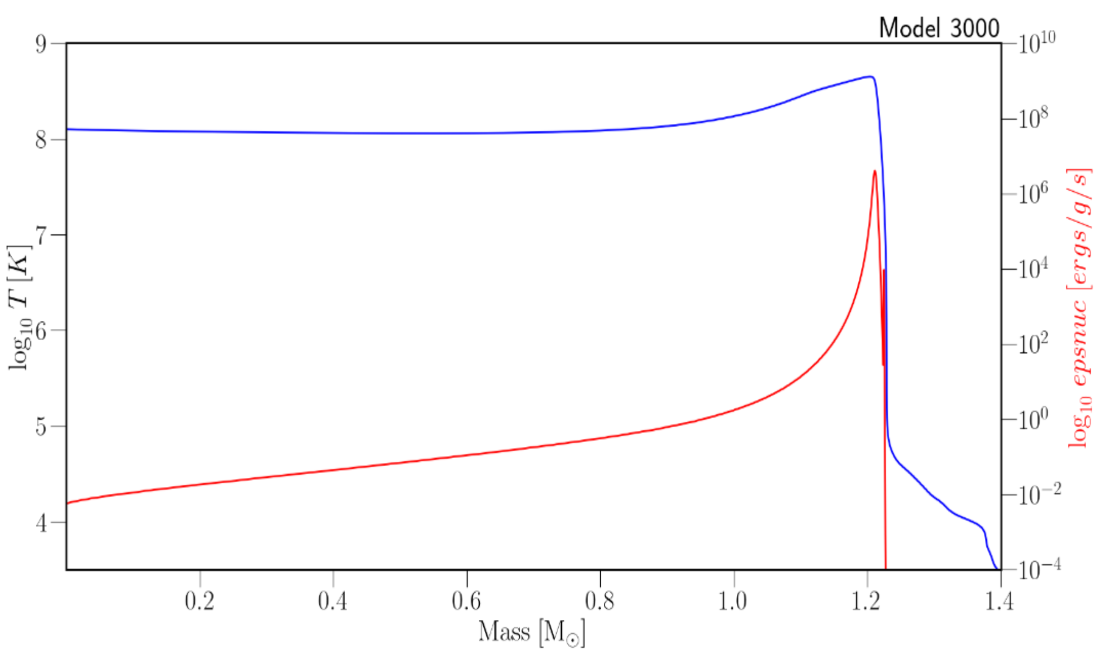

Figure 11. The Temperature and epsnuc profile for the $1.4M_\odot$ PP Chain Star

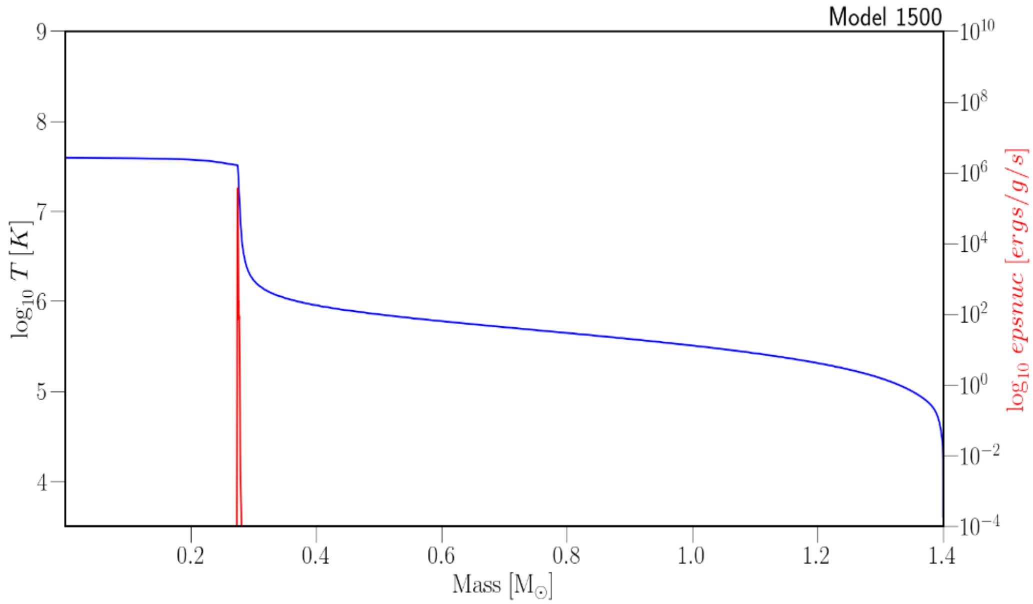

Figure 12. The Temperature and epsnuc profile for the $1.4M_\odot$ Basic Net Star

As clearly visible in Fig: 9 and Fig:10, both the temperature and density of the PP chain stars are much higher than those found in the Basic Net. We can also see that the surface temp of the PP chain star is under 1×10^4K (the division between orange and red), indicating a red star, whereas the Basic Net star at a surface temp of approximately $1 \times 10^4 K$ indicating a more orange star. Looking at Fig: 12, we can see that the shell is contracted because, the actual shell where hydrogen is being "burnt" is extremely tiny, which means that there must be an extremely low-density envelope surrounding the compressed core, which can be confirmed by looking at Fig: 10. With the PP chain Star, instead of having an extremely small shell of hydrogen "burning" there is a totally different approach with a star that is turning into a large ball of pure helium forcing the hydrogen fraction to drop much faster than in the Basic Net Stars, as well as producing much higher luminosities. This, along with a few factors including the absence of a luminosity spike, means that the transition from core burning to shell burning is not well defined in the PP chain star. The core is always expanding and never gets compressed to transition into a shell burning phase, instead the fusion layer naturally starts moving radially outward following the dropping hydrogen composition. Seeing when the main sequence ends in both stars would be the next step in understanding the timescale differences between both types of burning.

The End of the Main Sequence

We define the end of the main sequence to be when the star exhausts all the hydrogen in its core. It then transitions to the sub-giant to then ascend onto the red giant. To find the time at which the main sequence ends, a graph of the center hydrogen was used to see when the core hydrogen drops to zero. Each of the graphs depicting Core Hydrogen % vs Time had a similar shape to Fig: 13. The only two graphs that do not have the same shape are the graphs of the 1 and $2M_\odot$ stars. Notice that the point that the Basic Net star hits 0 is the same point as Fig: 7, where the Basic Net star has a small jump in luminosity midway through the main sequence. This is where the core in the Basic Net starts shell burning, resulting in a small jump in luminosity.

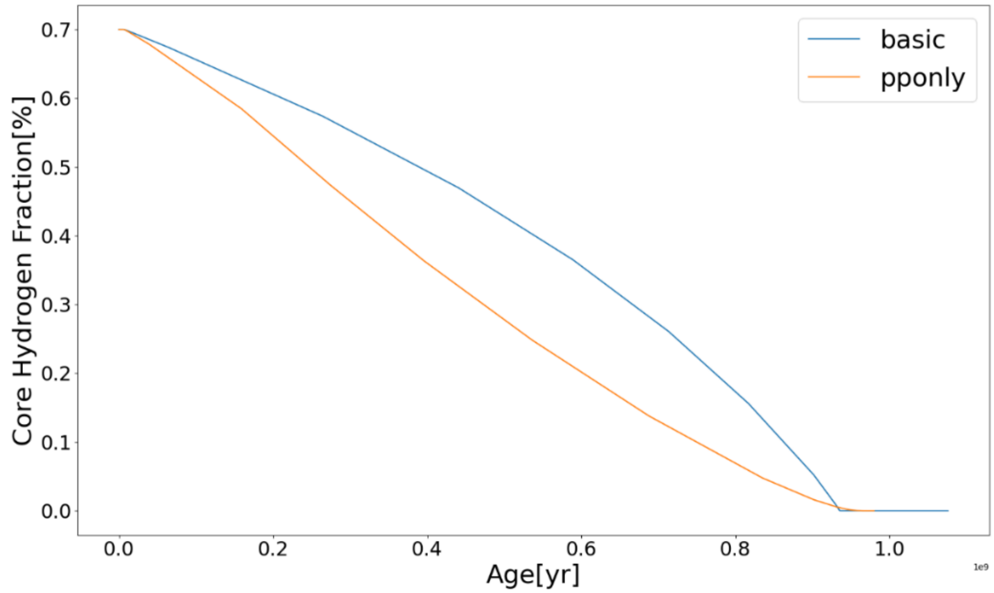

Figure 13. Graph of hydrogen composition in the core for both $1.4M_{\odot}$ stars

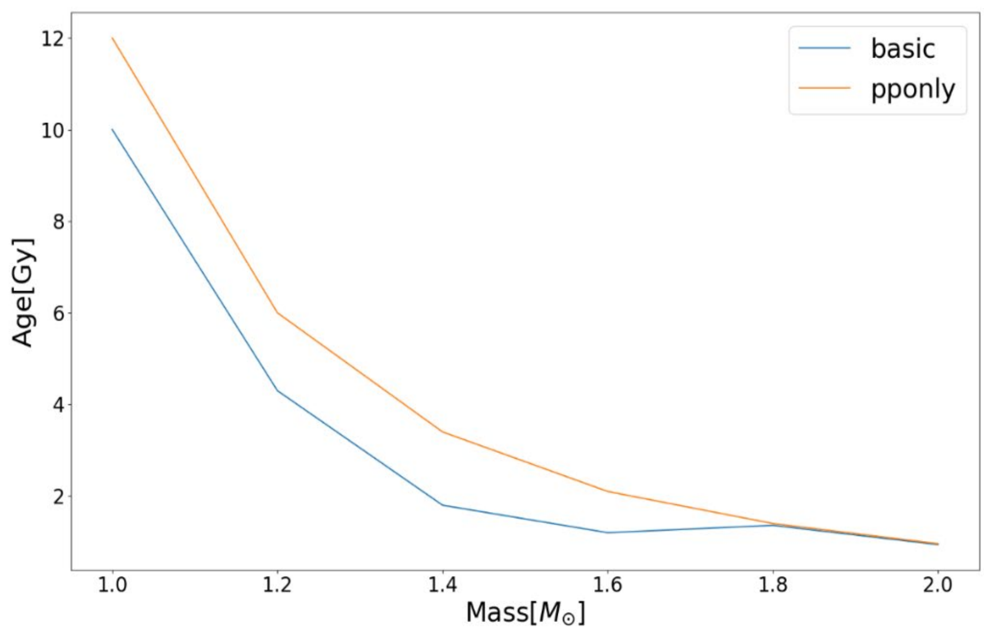

Figure 14. Time on the main sequence (Gy) vs Mass ($M_{\odot}$)

Notice that in each trial the Basic Net runs through the main sequence faster than the PP chain, however we know that the Basic Net star is burning hydrogen slower because by looking at a graph of helium fraction vs time such as Fig: 15, the PP chain star is using much more hydrogen than the helium star is. This indicates that some strange effects are occurring to the stellar structure, other than the noted lack of shell burning.

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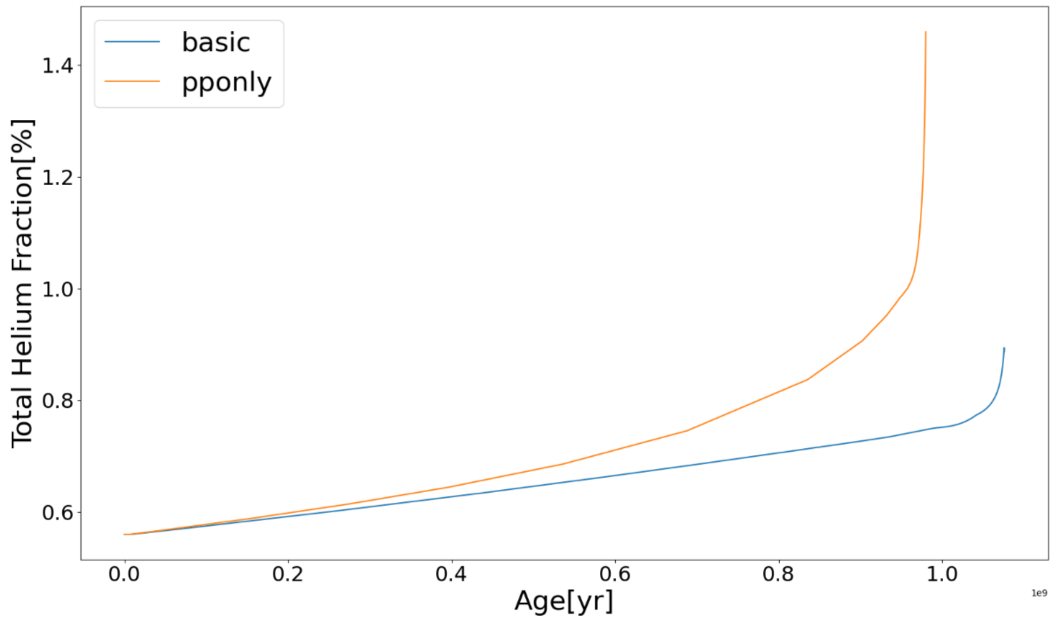

Figure 15. The helium fraction in both types of stars at $1.4M_{\odot}$

Discussion

Because the main sequence lifetime in the PP chain stars is longer than the Basic Net stars, there must be something interesting happening in the core/surrounding layers. Because the core of the PP chain stars is isothermal, which rules out convection. However, noting that the surrounding convective envelope is at a much lower temperature, another possible explanation is that there is a major effect from a convective overshoot. Convective overshoot occurs when convection carries some material from beyond the boundary of convective zones, into a stable region. In this case, material from the convective envelope is given sufficiently high momentum, to travel deep into the core. This would bring in fresh hydrogen, and thus extend the main sequence lifetime of the star. The idea of convective overshoot in lower mass stars extending the main sequence lifetime has already been discussed (Claret, 2016). Perhaps the difference in reaction networks between the PP and CNO produces a thermal structure more conducive to convective overshooting.

Conclusion

We found by running MESA models that the stars running the PP chain only have a core that is not only larger but also more dense and hotter. The PP chain stars can stay on the Main Sequence for longer, and on average they are also more luminous. This luminosity difference means that the PP chain star will burn through its hydrogen faster than the Basic Net Stars. Another notable difference is that the PP chain stars at the end of evolution, will be large spheres of hot helium, slowly cooling, like a white dwarf. Another group of stars only running the CNO chain would have been an excellent idea to provide a median graph between the PP chain and Basic Net stars. A star only running CNO with some adjustments to starting metallicity, could simulate our universe later in cosmological evolution, as the percent composition slowly changes throughout.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

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