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Exercises in Mainline Stellar Nuclear Burning

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ABSTRACT

The abstract will be fleshed out more at the conclusion of the calculations that will go into this paper

1. INTRODUCTION

Stellar nucleosynthesis follows a fairly well-understood sequence of burning stages. These are reviewed in a several text books, including Clayton (1983); Arnett (1996); Iliadis (2007). The purpose of this brief paper is to present a set of computational exercises using NucNet Tools to demonstrate these stages in a massive star.

Together we will walk through the basic stages of element fusion inside of stars, from Hydrogen and Helium to the more metallic ones such as Iron and Nickel.

2. HYDROGEN BURNING

The first stellar burning phase is hydrogen burning, which converts abundant hydrogen into helium. In a massive star this occurs at higher temperature but lower density than in the Sun.

Task 1:

Plotted below is the mass fraction of the Hydrogen and resulting Helium that is generated due to the pp chain reaction:

We can also examine the abundances of the Carbon, Neon and Oxygen isotopes during the CNO cycle:

As we see, there is a buildup of ^{14}N which can be attributed to the rather slow reaction time of the process, which comes after. Namely:

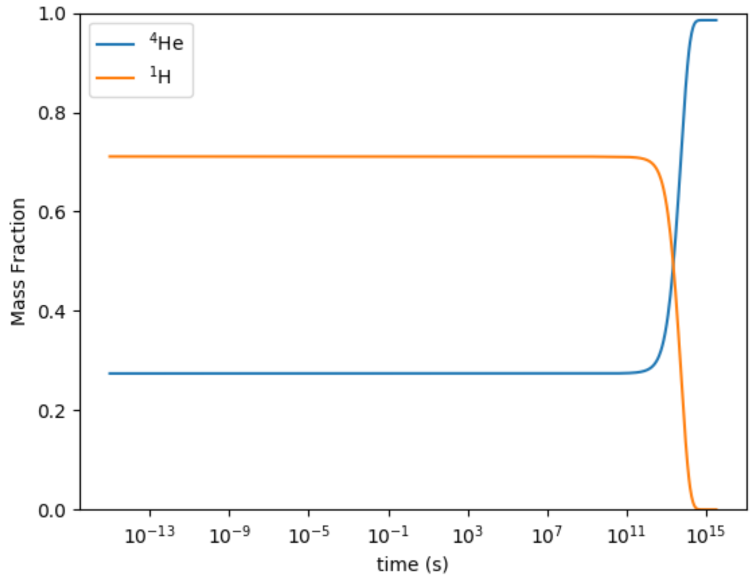


Figure 1. log plot of ^{1}H and ^{4}He as a function of time

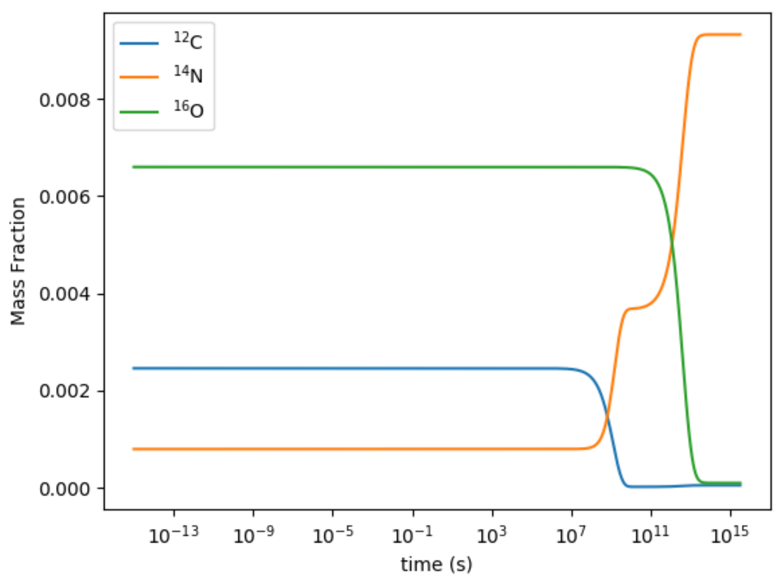


Figure 2. log plot of ^{12}C,^{14}N, and ^{16}O as a function of time

$$^{14}N \rightarrow^{15} O + \gamma \tag{1}$$

Because this reaction is so slow, there is a natural saturation of Nitrogen that occurs.

3. HELIUM BURNING

Task 2:

Once a star burns hydrogen to helium, it contracts and heats until the He ignites. The He burns to C and O (but not much Ne as we see below)

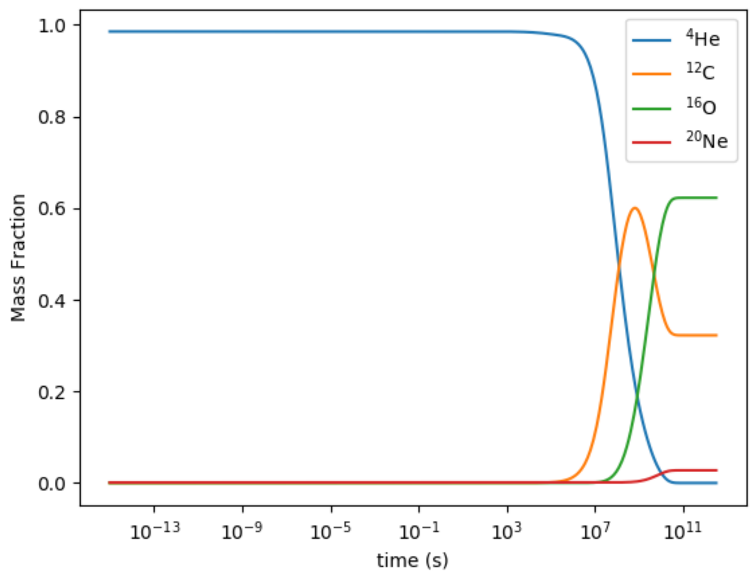


Figure 3. log plot of ^{4}He,^{12}C, ^{16}O as a function of time. $^{20]}$Ne is also plotted to show that Oxygen is really the stopping point for the triple alpha process

In this triple-α process, the ^{4}He 's combine together until they form Carbon and Oxygen, leading to the eventual buildup of the ^{16}O seen in the plot. However, ^{20}Ne is not formed as much, due to the fact that the energy needed to overcome the stability of the Oxygen, and the subsequent Coulomb barrier is too much. Only at extreme temperatures (closer to the core) do these elements start to form.

Task 3: We now wish to consider the s-process (”slow”) in Helium burning.

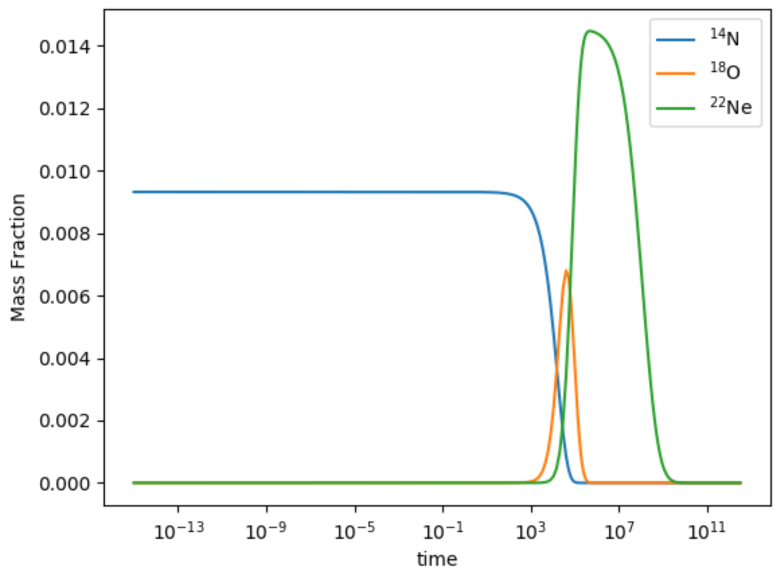
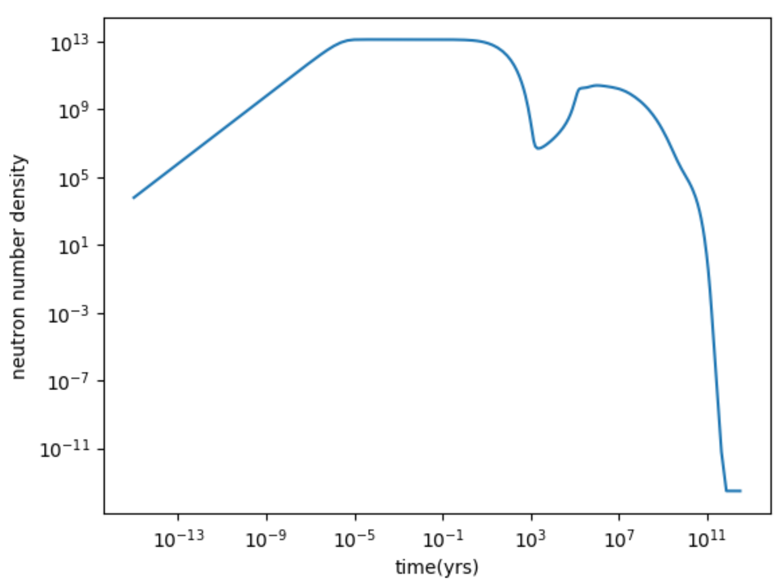


Figure 4. log plot of ^{14}N,^{18}O, ^{22}Ne as a function of time.

The Nitrogen slowly combines with alpha particles to form ^{18}O, which can then combine with more Helium to form the ^{22}Ne.

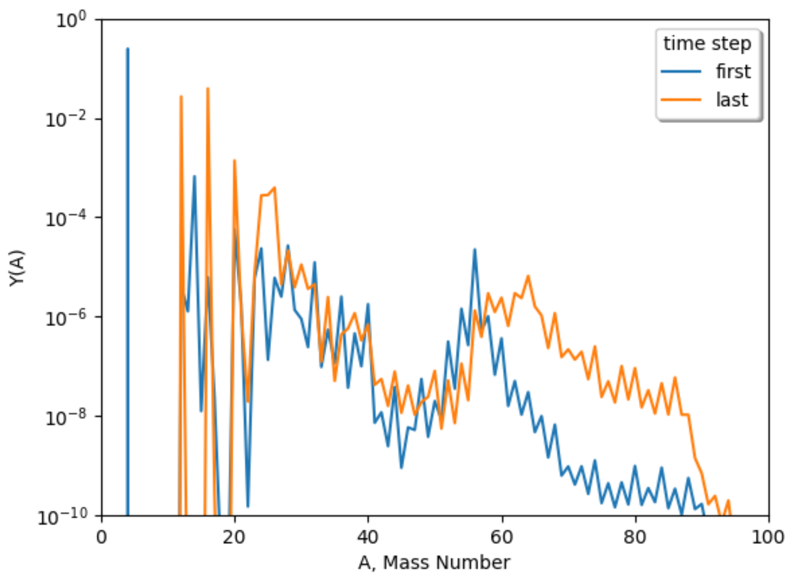


Here we plot the number density of neutrons over time. In particular, there is a short burst from the reaction:

$$^{13}C +^{4} He \rightarrow^{16} O + n \tag{2}$$

The products include a neutron, leading to the increase of n_n. Then, there is a more steady supply once the ^{22}Ne has formed as mentioned above.

Finally, we examine the abundances of each element at the beginning and end of the calculation to see the evolution of the composition of the star.



Notice how the final calculation yields higher abundances of heavier elements, which is to be expected given that the hydrogen and helium is being depleted to fuse more metallic elements. The graph spikes right around Carbon and Oxygen, as we expect.

4. CARBON BURNING

The principal products of helium burning are ^{12}C and ^{16}O. As the star contracts and heats, carbon burning begins.

Task 4: Run a carbon burning calculation on the last zone out your He burning output at $T_9 = 0.9$ and density $\rho = 15,000$ g/cc for 10^5 years.

Graph the mass fractions of ^{12}C, ^{16}O, ^{20}Ne, and ^{24}Mg as a function of time (we suggest log x vs. linear y and the x range from 0.01 to 1.e4 years). Comment on what is going on. In particular, note the key reactions ^{12}C + ^{12}C and ^{12}C + ^{16}O. Also note that if the star forms a white dwarf after this burning, it will be a O/Ne/Mg white dwarf, not a C/O white dwarf, as it would have been after helium burning.

5. NEON BURNING

Following carbon burning, the star will contract, heat, and undergo neon burning. This burning stage comprises $^{20}\mathrm{Ne}+\gamma \rightarrow^{16}\mathrm{O}+^{4}\mathrm{He}$ and $^{20}\mathrm{Ne}+^{4}\mathrm{He} \rightarrow^{24}\mathrm{Mg}+\gamma$, which effectively is $^{20}\mathrm{Ne}+^{20}\mathrm{Ne} \rightarrow^{16}\mathrm{O}+^{24}\mathrm{Mg}$.

Task 5: Using the output from your carbon burning calculation, run a neon burning calculation at $T_9 = 1.4$ and $\rho = 1.5 \times 10^5$ for 1000 years. Graph the mass fractions of ^{16}O, ^{20}Ne, ^{24}Mg, and ^{28}Si as a function of time (same layout as the carbon burning plot). Note the rise of ^{28}Si late from ^{24}Mg + ^{4}He.

6. OXYGEN BURNING

After neon burning, the next stage is oxygen burning. The principal reaction is $^{16}\mathrm{O}+^{16}\mathrm{O} \rightarrow^{32}\mathrm{S}^*$. The excited ^{32}S nucleus then de-excites mostly to ^{28}Si (and an alpha) or ^{32}S.

Task 6: Use the output from your neon burning to compute oxygen burning at $T_9 = 2.1$ and $\rho = 1.5 \times 10^6$ g/cc for one year. Graph the mass fractions of ^{16}O, ^{28}Si, and ^{32}S as a function of time and comment.

Also occurring during oxygen burning is the “gamma” process. The initially present heavy nuclei are disintegrated. First neutrons then protons and alphas are emitted. The nuclei “flow” down the proton-rich side of the stable nuclei. If this matter “freezes out”, proton-rich nuclei are formed (the so-called “p-nuclei”).

Task 7: Graph the abundances vs. mass number at the beginning and end of your oxygen burning calculation. Note how nuclei “melt” towards the iron-group region. You might also make an abundances vs. nucleon movie and/or a movie of the network abundances.

7. SILICON BURNING

The final mainline burning stage is Si burning. Here ^{28}Si converts to ^{56}Ni, which decays to ^{56}Fe. The burning proceeds through a complicated sequence–some Si disintegrates and the light particles that result capture onto the remaining Si to create heavier nuclei. In fact the burning proceeds through a quasi-equilibrium Bodansky et al. (1968); Meyer et al. (1998).

Task 8: Use your output from your oxygen burning to run silicon burning at $T_9 = 3.5$ and $\rho = 1.5e7$ g/cc for one year. Plot the mass fractions of ^{28}Si, ^{56}Fe, and ^{56}Ni vs. time and discuss.

You might be surprised that the abundance of ^{56}Ni is never particularly large. The reason is that the silicon burning is sufficiently slow that weak decays have time to occur during the burning and thus change the neutron richness of the nuclei present. Also, at this temperature, there is a preference for ^{54}Fe and two protons over ^{56}Ni–see this by adding fe54 to your task 8 plot.

8. CONCLUSION

Of course stellar burning really occurs in the context of an evolving star. The temperature and density are not constant, as treated in these exercises, but rather evolve as nuclear fuel is consumed. Furthermore, in many cases, stellar layers are convective, which tends to mix the composition of those layers during the burning. Nevertheless, we hope that by carrying out the above exercises, one will get a good sense of the nature of the mainline stellar burning phases.

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