Simulating Enhanced C12+C12 Reaction Rates in Massive Stars During Carbon Shell Burning

Matt Bundas

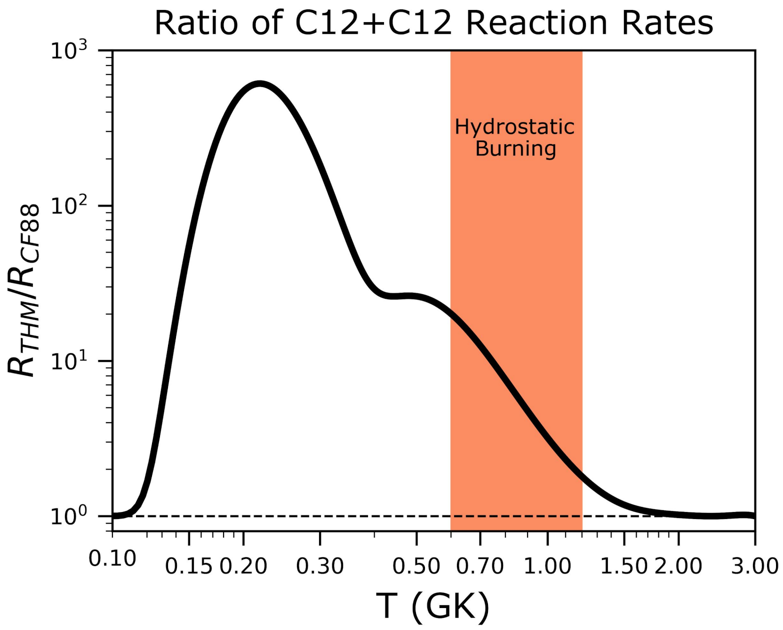
Advised by Jennifer Ranta, Dr. Sean Couch

Overview

- A paper found enhanced Carbon 12 - Carbon 12 fusion reaction rates
- Ran one simulation with enhanced rates, one with traditional rates
- Compared simulations to see impact of enhanced rates
    - Nuclear Energy
    - Convection
    - Isotope Abundance

Trojan Horse Method Reaction Rates

- Reaction rate is given certain conditions, how many fusion reactions will take place
- Hard to measure
- A. Tumino et al. 2018 used Trojan Horse Method to measure rates below Coulomb barrier
  - Found resonances at low energies
  - 2-20 times as fast as Caughlan-Fowler 88 rates

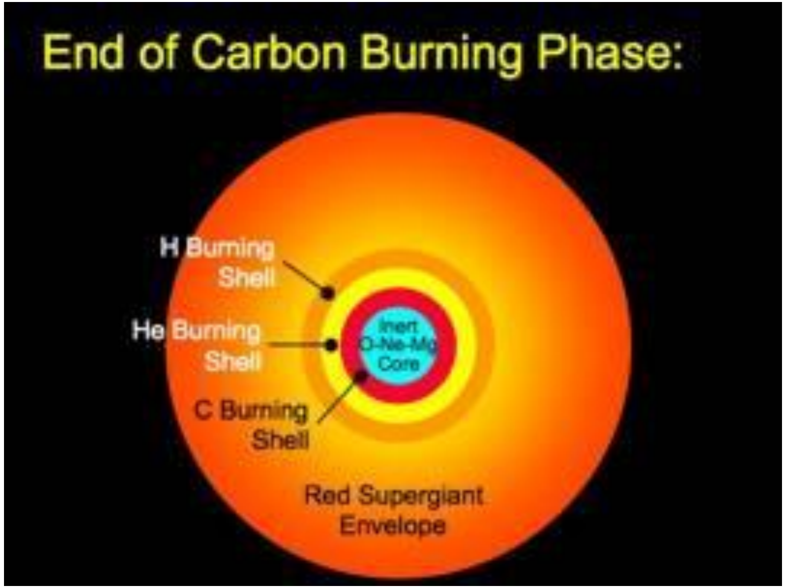


Carbon Shell Burning

- Stars > 8 MSun burn carbon for ~1000 years
- Three main channels:

$$^{12}\mathrm{C}+{}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* \rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He}\ (\mathrm{Q} = +\ 4.616\ \mathrm{MeV})$$
$$^{12}\mathrm{C}+{}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* \rightarrow {}^{23}\mathrm{Na} + \mathrm{p}\ (\mathrm{Q} = +\ 2.238\ \mathrm{MeV})$$
$$^{12}\mathrm{C}+{}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* \rightarrow {}^{23}\mathrm{Mg} + \mathrm{n}\ (\mathrm{Q} = -\ 2.605\ \mathrm{MeV})$$

- Simulation has a rate which encapsulates all of these channels
- Fusion occurs on inner surface of shell



http://www.astronomy.ohio-state.edu/~jaj/Ast162/lectures/notesWL17.html

My Simulations

- Two identical simulations except one implements CF88 C12-C12 rate, one implements THM C12-C12 Rate
- Used the magnetohydrodynamic code FLASH, written in Fortran 90
- 25 solar mass star undergoing carbon shell burning, from MESA
- Half of a star in 2-D
- 20,000s (5.5 hours), several turnover times
- Made use of MSU’s HPCC

Implementing the Rates

- Nuclear reaction network made up of 21 isotopes
- FLASH calls a subroutine every timestep calculating the rate of each reaction

THM

$$N_A \langle \sigma v \rangle = \sum_{i=1}^{3} f_i = \sum_{i=1}^{3} \exp\left[a_{i1} + a_{i2} T^{-1} + a_{i3} T^{-1/3} + a_{i4} T^{1/3} + a_{i5} T + a_{i6} T^{5/3} + a_{i7} \ln(T)\right]$$

a_{ij}	f_1	f_2	f_3	f_{1u}	f_{2u}	f_{3u}	f_{1l}	f_{2l}	f_{3l}
a_{i1}	1.22657×10^2	9.03221×10^1	2.28039×10^2	1.22687×10^2	9.03982×10^1	2.28056×10^2	3.21570×10^2	6.08741×10^2	3.14593×10^3
a_{i2}	0.557112	-8.35888	-1.16039×10^1	0.557664	-8.35720	-1.15681×10^1	-0.815182	-1.42976×10^1	-2.26169×10^1
a_{i3}	-905657×10^1	-6.17552×10^1	-2.40364×10^2	-9.05616×10^1	-6.17282×10^1	-2.40343×10^2	3.17671×10^1	3.43845×10^2	1.36110×10^3
a_{i4}	-6.83561×10^1	-1.07514×10^2	-9.21375×10^1	-6.83178×10^1	-1.07358×10^2	-9.21156×10^1	-4.22173×10^2	-1.11874×10^3	-5.16494×10^3
a_{i5}	1.42906×10^1	7.20344×10^1	1.25411×10^2	1.42891×10^1	7.20835×10^1	1.25484×10^2	5.23691×10^1	1.73098×10^2	7.85965×10^2
a_{i6}	-2.43583	-1.37501×10^1	-3.25984×10^1	-2.46506	-1.38060×10^1	-3.24417×10^1	-6.35869	-2.33743×10^1	-1.29447×10^2
a_{i7}	9.32623	-1.91793×10^1	-1.10903×10^2	9.35304	-1.91920×10^1	-1.10961×10^2	1.34509×10^2	3.60334×10^2	1.60224×10^3

A. Tumino et al. 2018

CF88

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C12+C12 (MG24)  Q= 13.933   4.27E+26*T9A56/T932*EXP(-84.165/T9A13-2.12E-03*T9**3)
                            T9A = T9/(1.+0.0396*T9)
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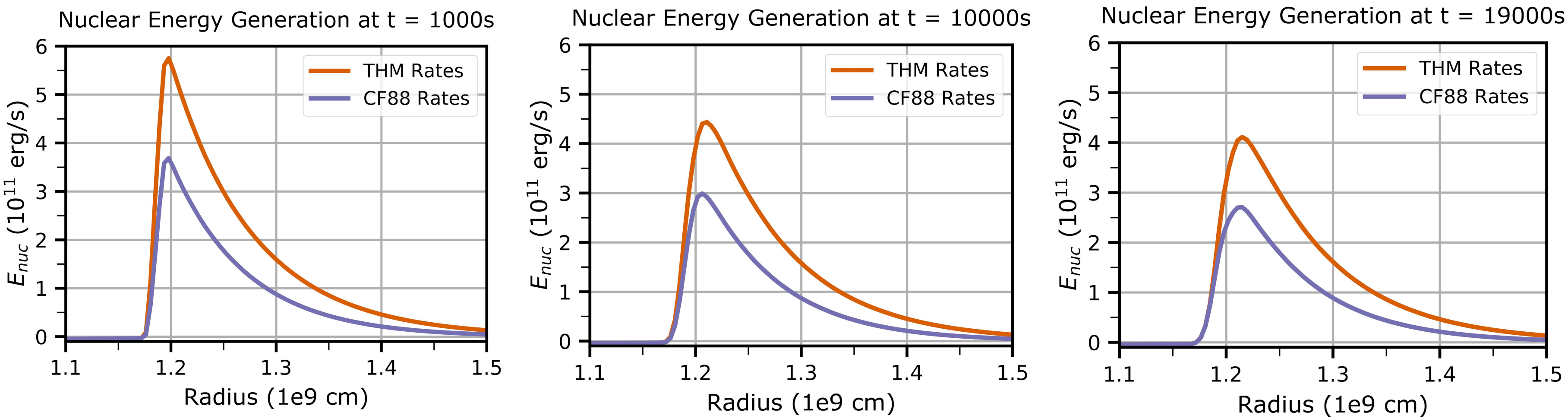
Caughlan, Fowler 1988

Results - Nuclear Energy Production

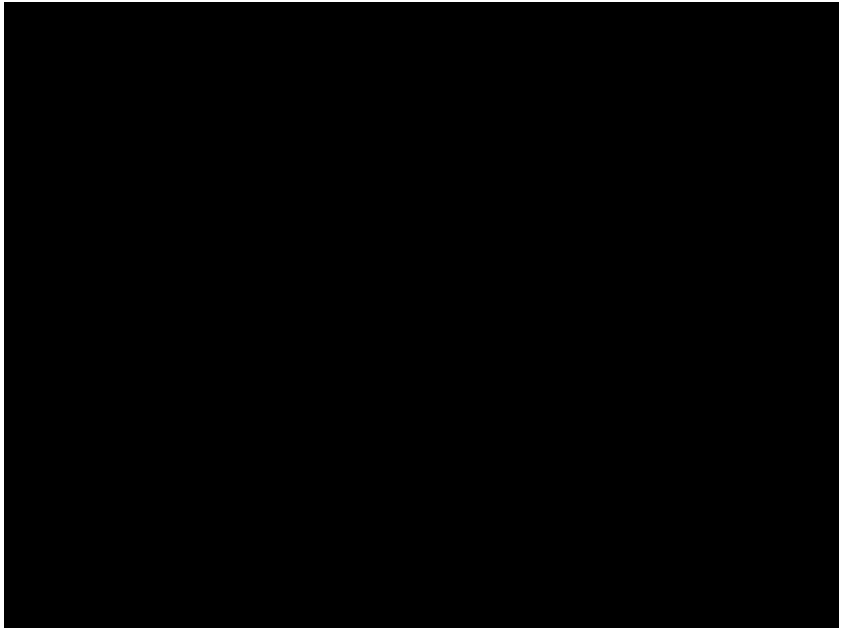
- Amount of energy produced from nuclear reactions
- More fusion reactions, more nuclear energy in THM simulation, about 1.5x



Energy needs to go somewhere!!

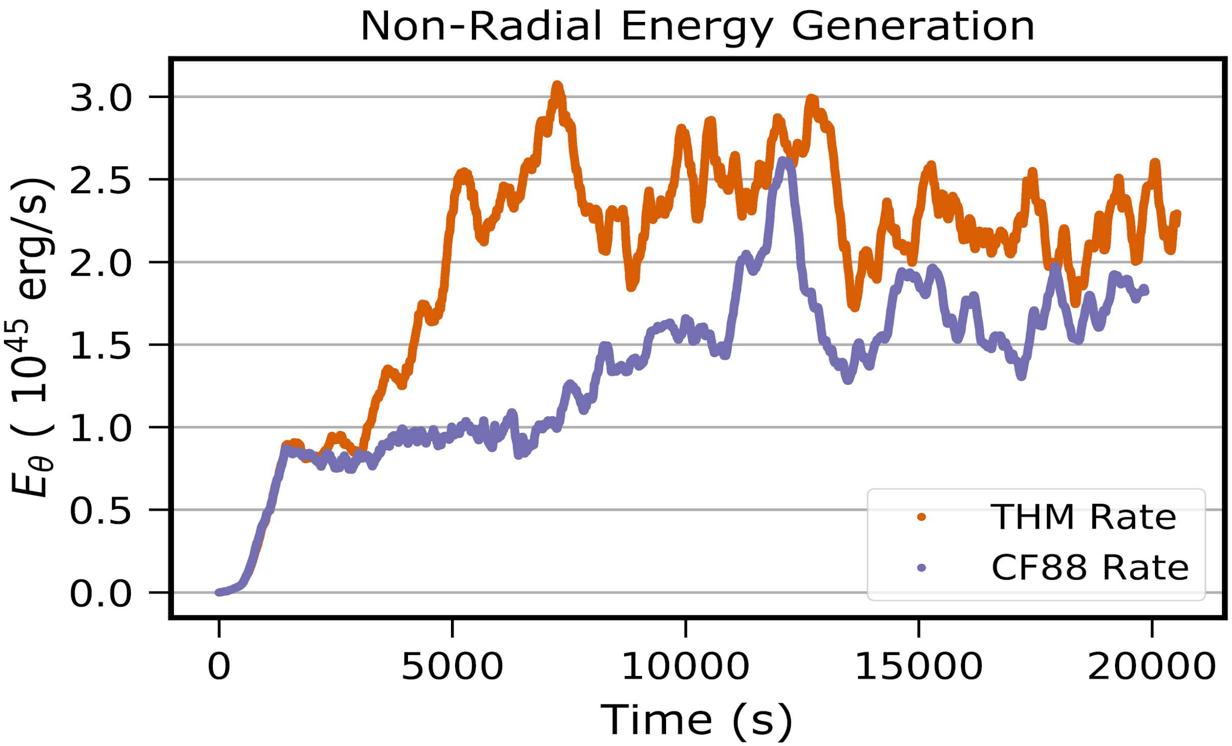
Results - Convection, Velocity of Material

- Convection occurs when material is hotter than its surroundings and rises
- Provides mechanism for mixing of material, isotopes



THM simulation continually shows faster moving material, more and stronger convective nodes

Results - Convection, Non Radial Energy

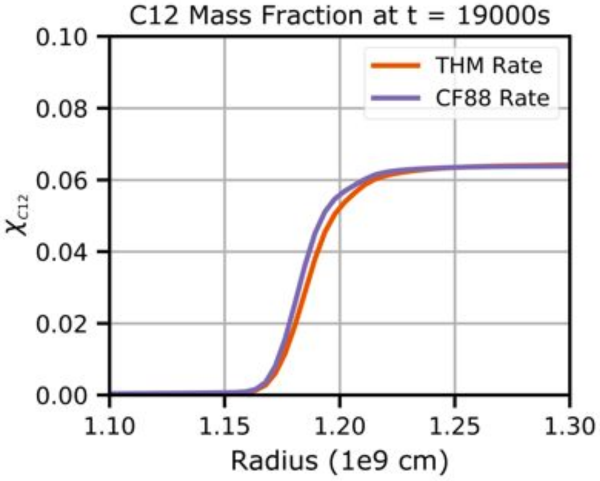


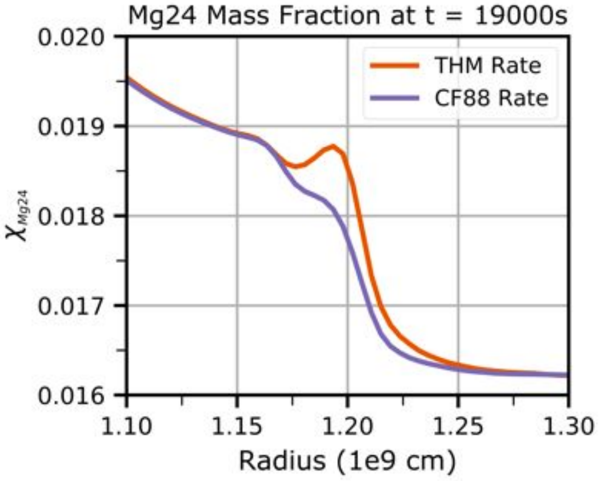
Non-radial energy is energy in theta direction, essentially direct measure of strength of convection

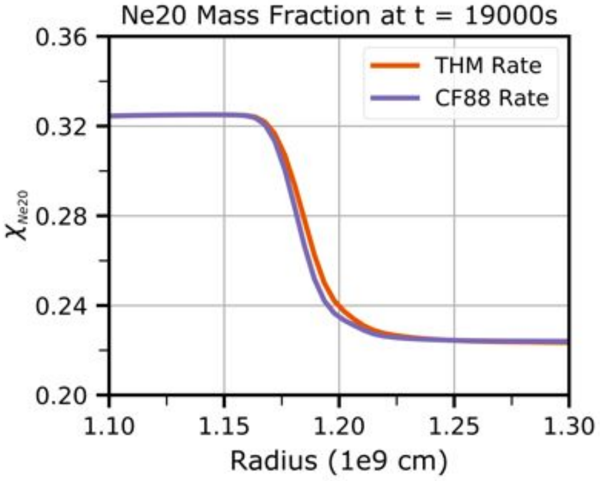
THM simulation continually shows higher non-radial energy generation. Stronger convection!

Results - Isotope Abundance

C12 + C12 ⟶ Mg24 ⟶ Ne20 + He4







Also found increases in He4 and p in THM simulation. More fuel for proton and alpha captures!

Conclusion and Looking Forward

- Found significant impact with THM rates
    - 1.5x increase in nuclear energy production
    - Stronger convection
    - Isotope abundance
- “Only” 20,000s, would rather simulate entire lifetime
    - Would need to be in 1-D, likely MESA
- Found stronger convection, change in isotope abundance, but what does it mean?

Resources

1) Caughlan, Fowler,1988, “Thermonuclear reaction rates V”
2) A. Tumino et al., 2018, “An increase in the 12C + 12C fusion rate from resonances at astrophysical energies”
3) M. Pignatari et al., 2012, “The 12C + 12C reaction and the impact on nucleosynthesis in massive stars.”
4) Jiang C. L. et al., 2018, “Reaction rate for carbon burning in massive stars
5) FLASH code, http://flash.uchicago.edu/site/flashcode/
6) Paxton et al., 2018, “Modules for Experiments in Stellar Astrophysics (MESA): Convective Boundaries, Element Diffusion, and Massive Star Explosions”