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

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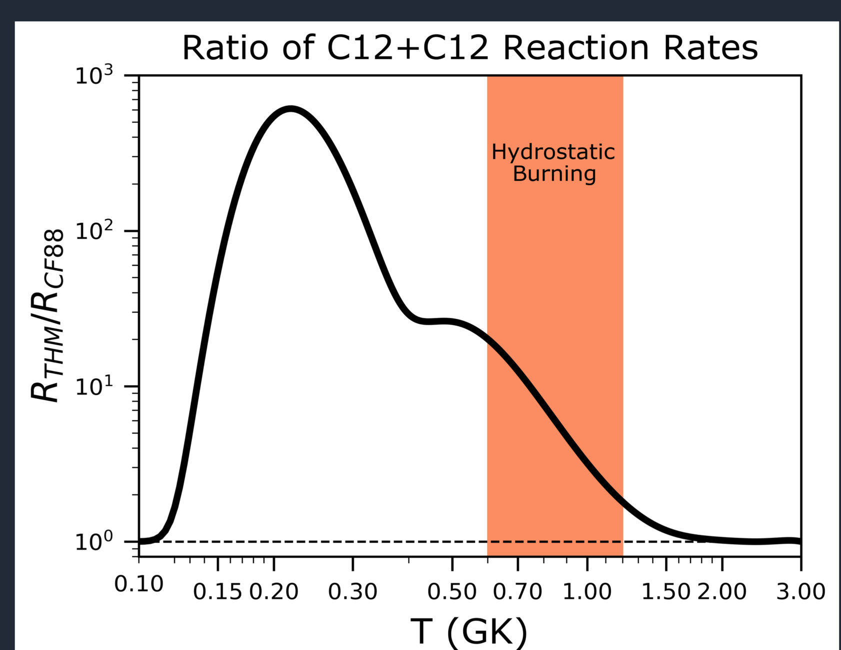
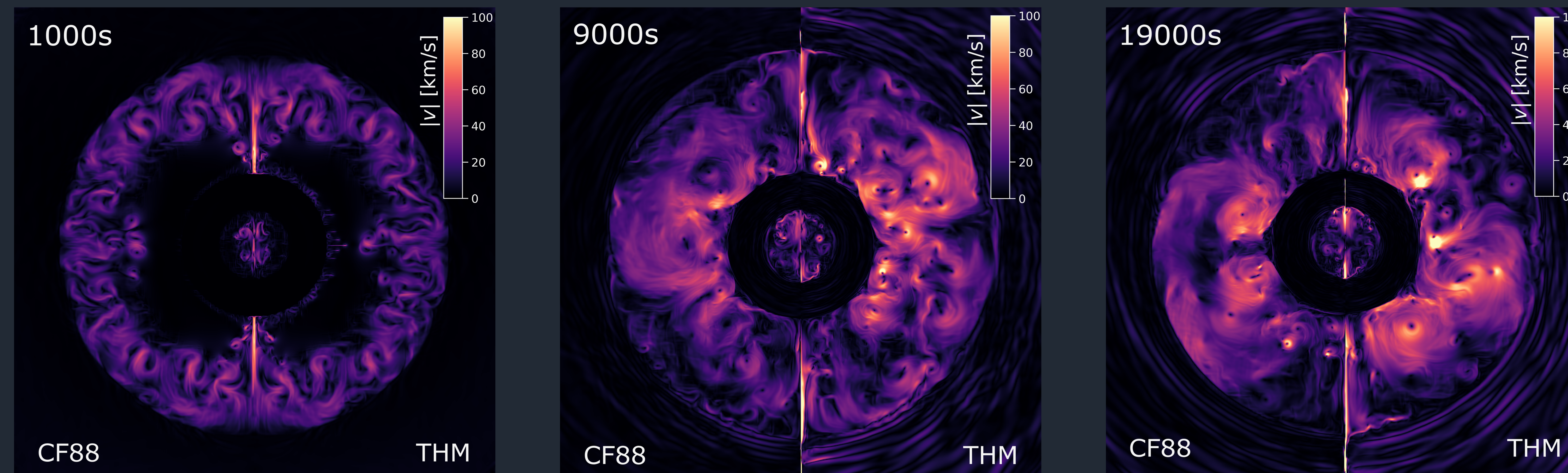
Introduction

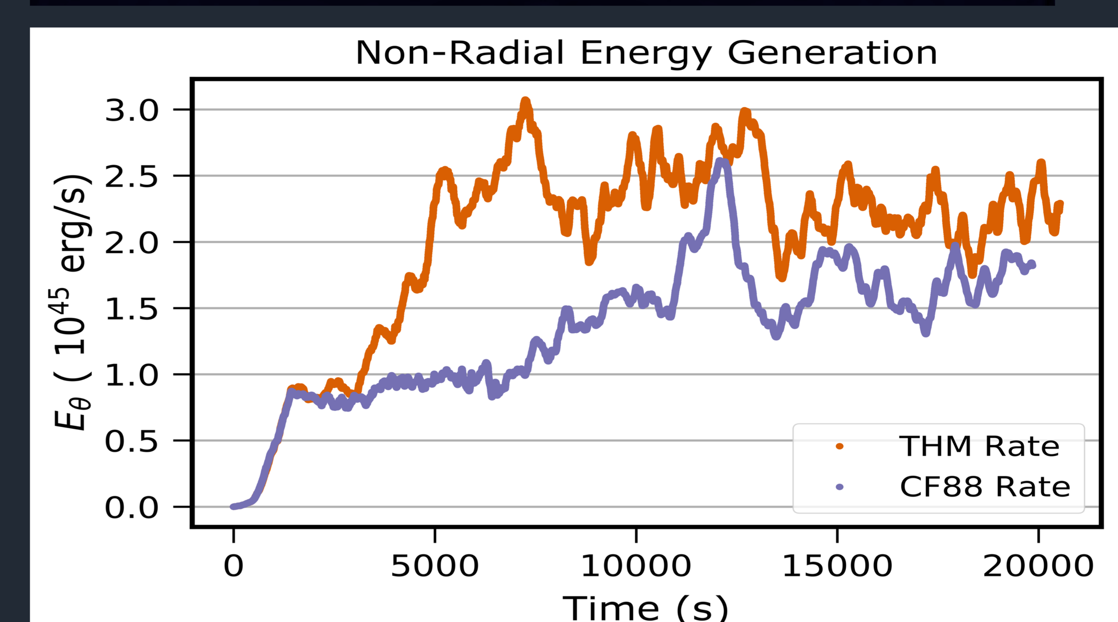
A major factor in the dynamics of stars as they pass through burning stages is how easily a given fusion reaction takes place, which is tied to the reaction rate. Reaction rates directly affect the composition and structure of a star which in turn affects other processes in the star. Reaction rates and in particular the Carbon-12 + Carbon-12 (C12-C12) reaction rate are not easily measured in a laboratory setting under similar conditions present in stellar environments, leading to dispute in their values. A recent paper from A. Tumino et. Al (2018) experimentally found using the Trojan Horse Method (THM) underlying resonances in the C12-C12 to Mg 24 reaction rate, leading to a highly enhanced rate compared to the standard Caughlan-Fowler 88 (CF88) rate.



To test the potential effects of the newly found THM rate we ran two 20,000s 2-D simulations of a 25 solar mass star undergoing carbon shell burning using the hydrodynamical astrophysical code FLASH, one implementing the CF88 C12-C12 rate and one implementing the THM rate. We examine the increase in nuclear energy production, increase in strength of convection and change in element abundance within the star as a result of this enhanced rate.

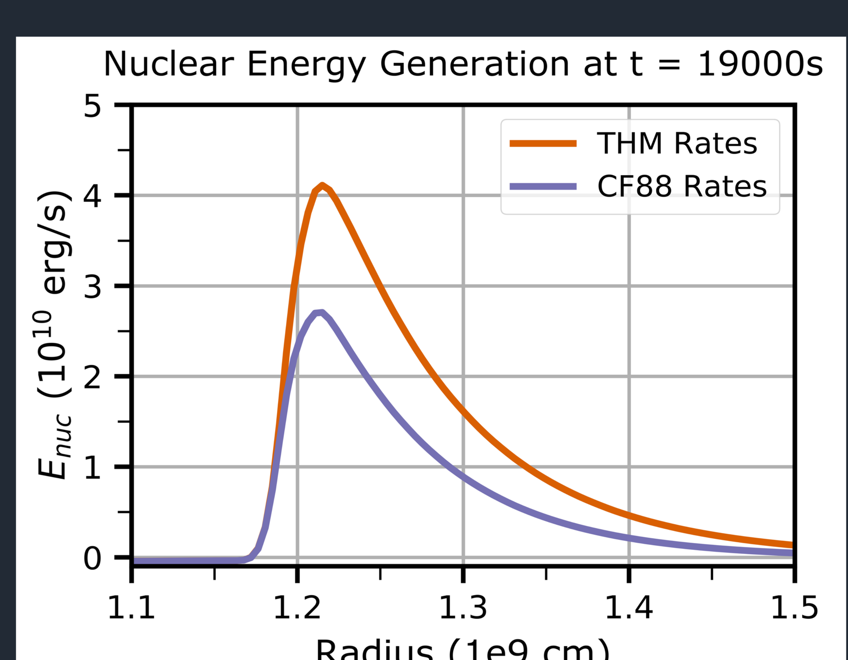
Convection





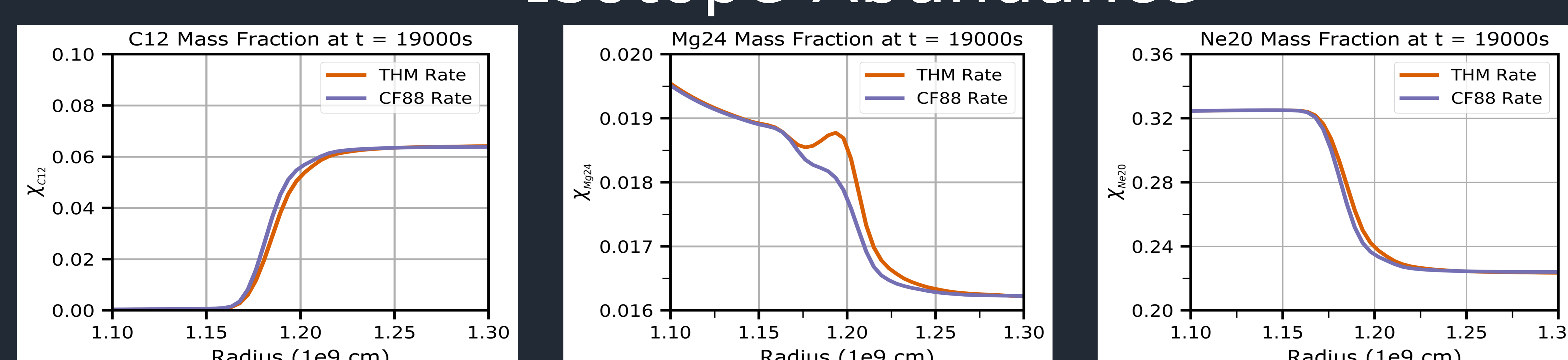
Above shows the velocity of material within roughly the inner half of the stars at the beginning, middle and end of our simulations. We see in the first snapshot carbon igniting in the THM simulation prior to the CF88 simulation. In the final two snapshots we see greatly increased velocity of material in the THM method simulation as well as more numerous and energetic convective cells. The left figure shows the non-radial energy in the star with time. This is essentially a direct way to measure the strength of convection as it displays how energetic the stellar material is. In these figures we see an increase in strength of convection in the THM simulation as a result of the enhanced rate. Because more carbon is being burned, more energy is being released and this energy needs to escape somewhere and does so in the form of convection. An increase in convection leads to greater mixing of stellar material and pulls additional carbon towards the carbon burning region allowing for more efficient burning. This increase in convection undoubtedly would have an impact on a star's structure, dynamics, and evolution.

Nuclear Energy



Above is a radial profile of the nuclear energy production at the end of our simulation, centered around the region of carbon shell burning. The enhanced THM rate allows for more C12-C12 fusion reactions to take place, leading to an increase in nuclear energy production within this region. This nuclear energy must diffuse throughout the star affecting other processes in the star, in particular convection.

Isotope Abundance



$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^{*} \rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He}(Q = +4.616\,\mathrm{MeV}),$$

In the above plots we show the mass fraction of three isotopes at the end of our simulation which are involved in the high probability carbon fusion channel showed above. In these plots we see that all three abundances noticeably change due to the enhanced C12-C12 THM reaction rate. In the THM simulation we are increasing the rate at which the C12-C12 reaction occurs and as a result see a decrease in C12 and an increase in its direct product Mg24 and indirect product, Ne20. Mg24 builds up along the carbon burning region, accumulating before decaying into Ne20 by alpha decay. Also not shown in these plots we have found a significant increase in He4 abundance and H abundance. An increase in He4 abundance is due to an increase in alpha decay (as alpha particles are He4 nuclei), while the increase in H abundance is due to another carbon fusion channel which results in Mg24 decaying into Na23 and a proton. The enhanced THM C12-C12 rate has resulted in a significant change in element composition in our relatively short 20,000s simulation. This change in composition will impact the star's evolution and dynamics further as these isotopes could all be used in future reactions whose efficiency depends on abundance.

What's Next

Moving forward we would like to continue moving past showing that there are noticeable significant differences in star's dynamics and composition due to the enhanced THM C12 rate and into showing how this might affect the evolution of the star. It is difficult to run simulations in FLASH on the order of stellar lifetimes, so we will need to take advantage of other codes such as MESA (Modules for Experiments in Stellar Astrophysics, a 1D stellar evolution code). We can also expand on our current research and explore how the changed rate might affect differing mass stars or modifying other fusion reaction rates other than C12-C12.

References

A. Tumino et. al, 2018, "An increase in the 12C + 12C fusion rate from resonances at astrophysical energies".

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M. Bennett et. al, 2012, "The effect of 12C +12C rate uncertainties on the evolution and nucleosynthesis of massive stars