Sensitivity of He Flames in X-ray Bursts
to Nuclear Physics

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Introduction

Goals

- Study the dynamics of the propagating He flames in X-ray bursts via numerical simulation.
- Study the effects of various reaction networks.

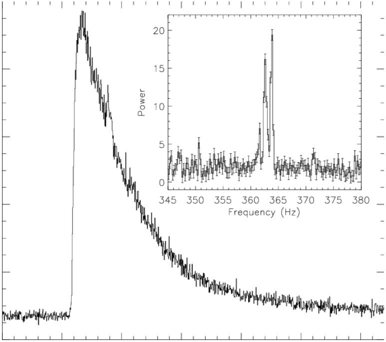

Figure: An X-ray burst light curve from 4U 1728–34 [1]

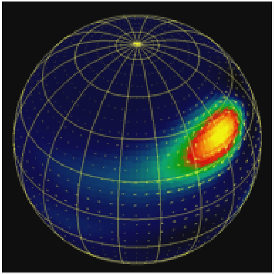

Image credit: Anatoly Spitkovsky

Network: `aprox13`

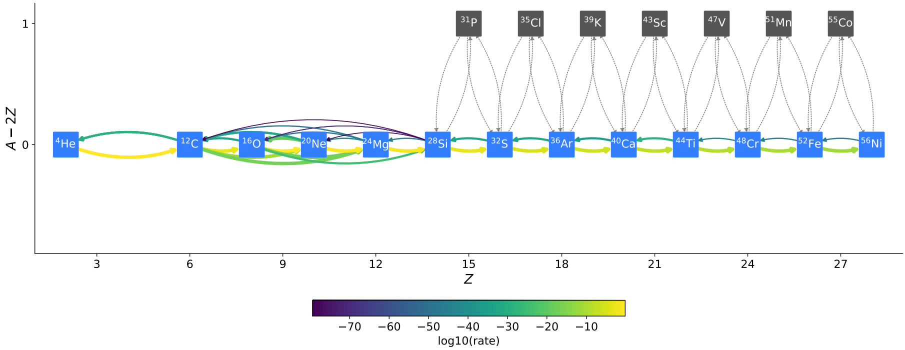

Figure: Overview of `aprox13`, rates with condition: $\rho = 10^6$ g cm^{-3} and $T = 2.0 \times 10^9$ K. Generated using pynucastro: `https://github.com/pynucastro/pynucastro`

Feature

- $(\alpha, \mathrm{p})(\mathrm{p}, \gamma)$ approximation
- 13 isotopes, 31 rates

Network: `subch full`

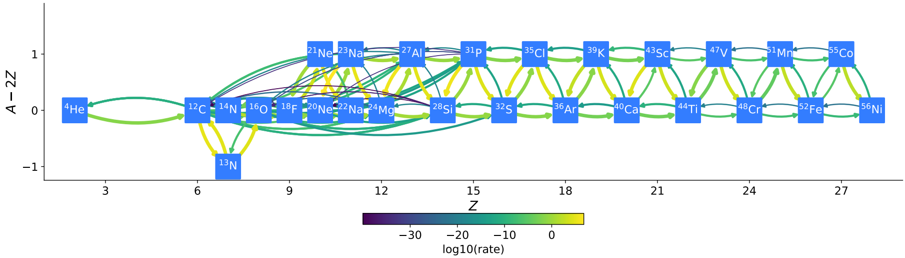

Figure: Overview of `subch full`, rates with condition $\rho = 10^6$ g cm^{-3} and $T = 2.0 \times 10^9$ K. Generated using pynucastro: `https://github.com/pynucastro/pynucastro`

Feature

- No $(\alpha, \mathrm{p})(\mathrm{p}, \gamma)$ approximation
- Additional rates, such as ^{12}C(^{12}C, p)^{23}Na to give complete representation on carbon and oxygen burning.
- Additional rates, ^{14}N$(\alpha, \gamma)^{18}$F$(\alpha, \mathrm{p})^{21}$Ne and ^{12}C$(\mathrm{p}, \gamma)^{13}N(\alpha, \mathrm{p})^{16}$O, discussed in Shen & Bildsten 2009 and Weinberg 2006 [2], [3].
- 28 isotopes, 107 rates

Network: `subch full mod`

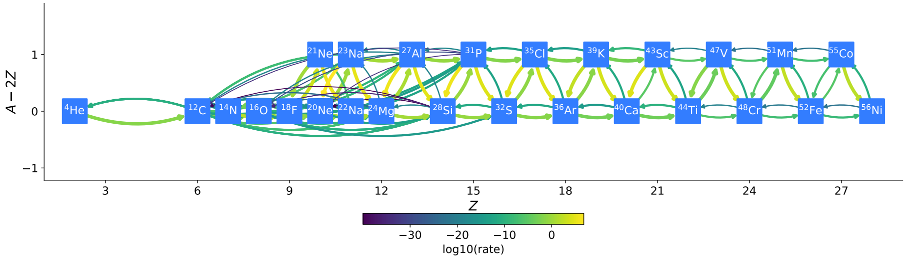

Figure: Overview of `subch full mod`, rates with condition $\rho = 10^6$ g cm^{-3} and $T = 2.0 \times 10^9$ K. Generated using pynucastro: `https://github.com/pynucastro/pynucastro`

Feature

- Identical to `subch full` but ^{12}C$(\mathrm{p},\gamma)^{13}$N$(\alpha,\mathrm{p})^{16}$O and its reverse rate are disabled.
- 27 isotopes, 103 rates

Network: `subch simple`

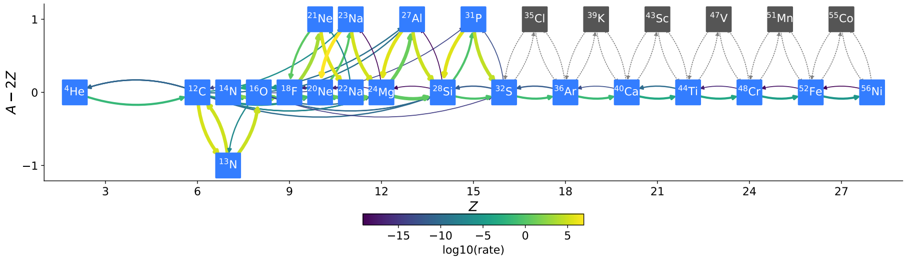

Figure: Overview of `subch simple`, rates with condition $\rho = 10^6\ \mathrm{g\,cm^{-3}}$ and $T = 2.0 \times 10^9$ K. Generated using pynucastro: `https://github.com/pynucastro/pynucastro`

Feature

- $(\alpha, \mathrm{p})(\mathrm{p}, \gamma)$ approximation for heavy isotopes
- The reverse rates of all $^{12}\mathrm{C} + {}^{12}\mathrm{C}$, $^{16}\mathrm{O} + {}^{16}\mathrm{O}$, and $^{16}\mathrm{O} + {}^{12}\mathrm{C}$ are removed.
- Forward and reverse rates of $^{12}\mathrm{C} + {}^{20}\mathrm{Ne}$, $^{23}\mathrm{Na}(\alpha, \gamma)^{27}\mathrm{Al}$, and $^{27}\mathrm{Al}(\alpha, \gamma)^{31}\mathrm{P}$ are removed
- 22 isotopes, 57 rates

General Numerical Settings

CASTRO

An adaptive mesh, astrophysical compressible hydrodynamics simulation code. Freely available at `https://github.com/AMReX-Astro/Castro`.

Microphysics

Software that contains a collection of microphysics routines such as Equation of State and the RHS of reaction networks. Freely available at `https://github.com/AMReX-Astro/Microphysics`.

General Simulation Domain

- 2-D $r - z$ cylindrical coordinate system assuming azimuthal symmetry.
- Corotating Frame
- Pure ^{4}He accretion layer

Initial Model

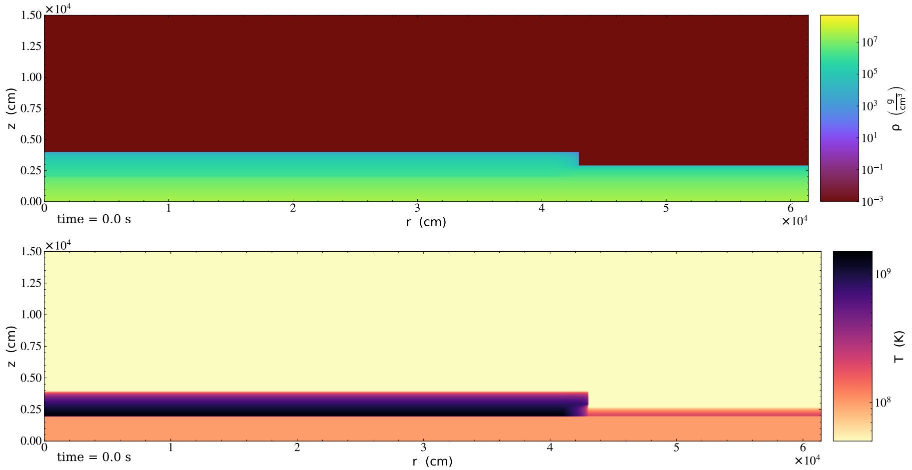

Figure: Initial temperature and density profile showing 1/3 of the full domain.

Results: Weighted T and $\dot{e}_{nuc}$ Time Profiles

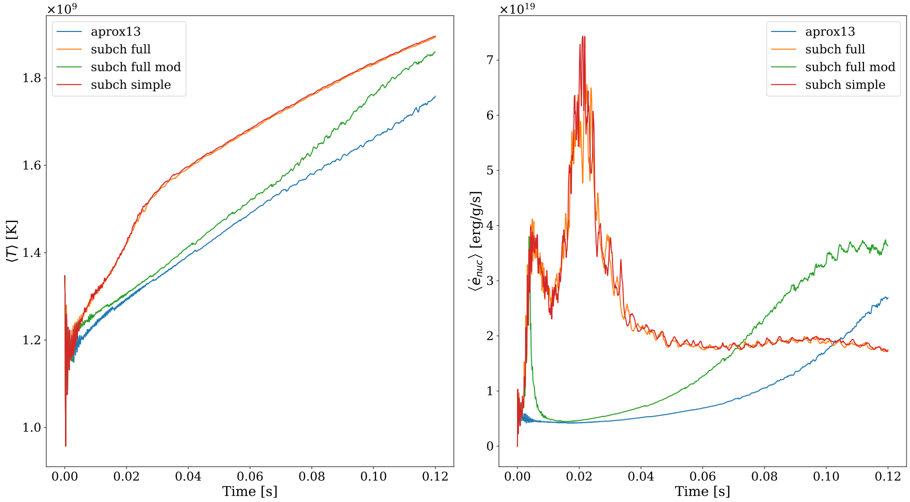

Figure: *Left*: The weighted temperature time profile. *Right*: The weighted nuclear energy generation rate time profile.

Results: Species Evolution Profiles

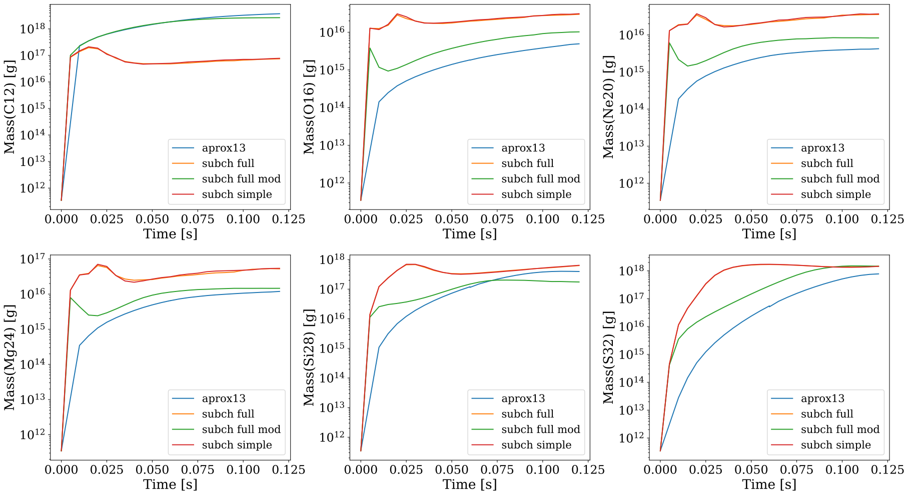

Figure: The evolution of the total mass for ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, and ^{32}S.

Results: Front Position vs. Time

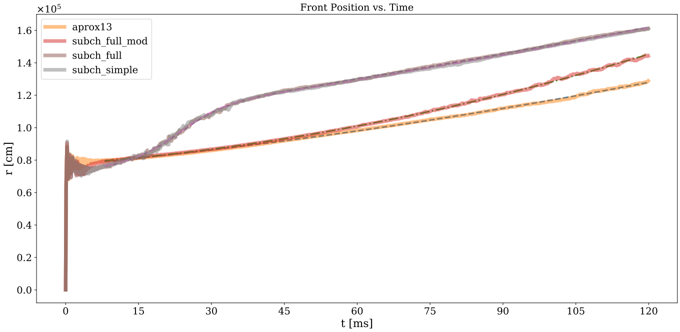

Figure: The flame front position as a function time for aprox13, subch full, subch full mod, and subch simple. *Solid* Lines: Data. *Dashed* lines: fit.

Name	v_{23} [km s^{-1}]	v_{100} [km s^{-1}]	t_{10} [s]
aprox13	3.369 ± 0.016	5.234 ± 0.027	0.7647
subch full	20.732 ± 0.284	5.411 ± 0.105	0.9917
subch full mod	3.468 ± 0.017	7.975 ± 0.029	0.4873
subch simple	21.095 ± 0.332	5.521 ± 0.120	0.8483

Table: This table shows the instantaneous flame propagation speed at $t = 23$ ms and $t = 100$ ms calculated using the fitting function. t_{10} shows the expected time for the flame to reach $r = 10$ km using the fitting function.

Conclusion

Takeaways: Network Study

- $(\alpha, \mathrm{p})(\mathrm{p}, \gamma)$ approximation continues to be an accurate approach in simulating thermonuclear flames propagations in XRBs.
- The $^{12}\mathrm{C}(\mathrm{p}, \gamma)^{13}\mathrm{N}(\alpha, \mathrm{p})^{16}\mathrm{O}$ is a critical alternative path for burning $^{12}\mathrm{C}$. At $T \gtrsim 10^9$ K, these reactions dominate over the triple-α and the slow α capture processes from $^{12}\mathrm{C}$ to $^{16}\mathrm{O}$. This allows a depletion of $^{12}\mathrm{C}$, leading to a burst of energy and flame acceleration as temperature reaches $\sim 1.3 \times 10^9$ K.
- Flame speed is on the order of km/s and a simple estimate shows the rise time is on the order of ~ 1 second.
- `subch_simple` network proved to be the most effective. It is the smallest network that captures the initial acceleration of the propagating flame, which drastically alters the overall flame dynamics.

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References I

[1] E. Strohmayer, W. Zhang, H. Swank, *et al.*, "Millisecond x-ray variability from an accreting neutron star system," *The Astrophysical Journal Letters*, vol. 469, p. L9, Jan. 2009. DOI: 10.1086/310261.

[2] K. J. Shen and L. Bildsten, "UNSTABLE HELIUM SHELL BURNING ON ACCRETING WHITE DWARFS," *The Astrophysical Journal*, vol. 699, no. 2, pp. 1365–1373, Jun. 2009. DOI: 10.1088/0004-637x/699/2/1365. [Online]. Available: https://doi.org/10.1088%2F0004-637x%2F699%2F2%2F1365.

[3] N. N. Weinberg, L. Bildsten, and H. Schatz, "Exposing the Nuclear Burning Ashes of Radius Expansion Type I X-Ray Bursts,", vol. 639, no. 2, pp. 1018–1032, Mar. 2006. DOI: 10.1086/499426. arXiv: astro-ph/0511247 [astro-ph].

Network: $\bar{A}$ Comparison

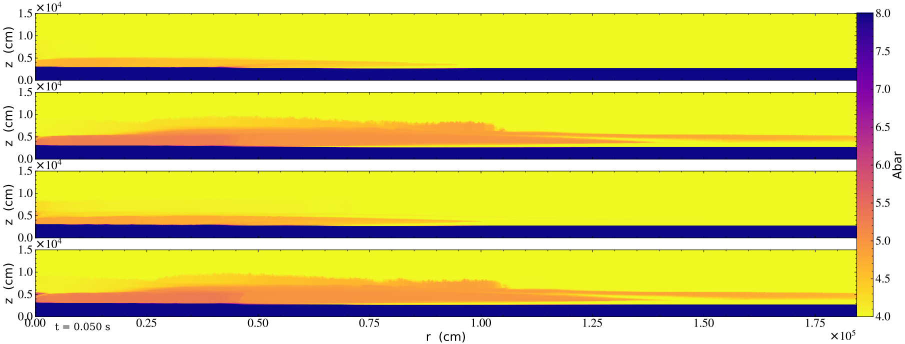

Figure: Slice plots of the flame propagation comparing average atomic weight, $\bar{A}$, for `aprox13` (top panel), `subch full` (second panel from top), `subch full mod` (third panel), and `subch simple` (last panel) at 50ms.

Network: $\dot{e}_{nuc}$ Comparison

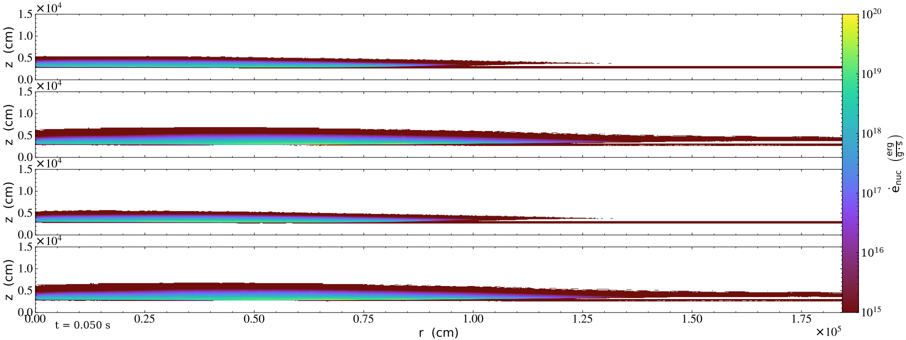

Figure: This figure shows 4 slice plots of the flame propagation comparing specific energy generation rate, $\dot{e}_{nuc}$, for `aprox13` (top panel), `subch full` (second panel from top), `subch full mod` (third panel), and `subch simple` (last panel) at 50ms.