Simulating X-ray Burst Flame Propagation: From Parallel Plane to Full Star

Zhi Chen[1] and Mike Zingale[1]

[1]Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA

INTRODUCTION

An X-ray burst (XRB) is a thermonuclear runaway caused by the ignition of the accreted fuel on the surface of a neutron star. The burst oscillation behavior observed during the rise-time of the burst and difference between the accretion and burst timescales both suggest that nuclear ignition is likely to begin in a localized region (hotspot), and spread to the rest of the neutron star. **The goal is to use numerical simulations to study the XRB flame dynamics:**

1) Study the effect of nuclear reactions on ^{4}He flame propagation in a localized region on the rotating pole with 2D R-Z geometry.

2) Study the effect of variation in rotational forces on ^{4}He flame as it spreads across the full star with 2D R-θ geometry.

INITIAL MODEL

- Corotating frame with consideration of rotating pseudo forces.
- Assumed a 1.4 $M_\odot$ NS with R = 11 km and Ω = 1000 Hz.
- Pure Helium-4 accretion layer for pure Helium XRB.
- Initial model is in hydrostatic equilibrium.
- Isothermal base with $T = T_*$ and pure ^{56}Ni composition for $0 < z < H_*$ to represent the underlying neutron star.
- A transition phase with prescribed temperature and composition profiles that blend the base and atmosphere for $H_* < z < H_* + 3\delta_{atm}$.
- Isentropic atmosphere with pure ^{4}He composition for $z > H_* + 3\delta_{atm}$ to represent the accretion layer.
- A temperature perturbation on the left part of the domain to drive a rightward propagating flame, a spreading hotspot for our geometry.

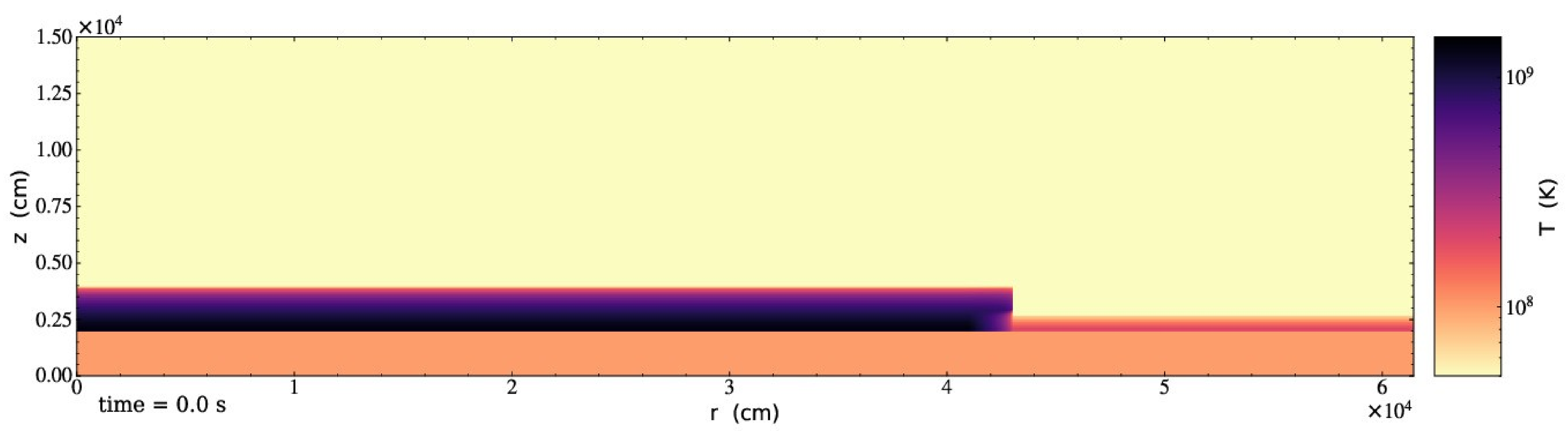

Fig: Zoom-in of the initial temperature profile. A temperature perturbation of 1.2 GK is set on the left edge of the domain to start the burning.

CODE

Castro | https://github.com/AMReX-Astro/Castro
Microphysics | https://github.com/AMReX-Astro/Microphysics
Pynucastro | https://github.com/pynucastro/pynucastro

New Contributions Are Welcome!

PARALLEL PLANE SIMULATION RESULTS

Plane Parallel Local Simulation:

- 9216 × 1536 zones or 20 cm resolution in finest grid
- **R** = [0, 1.843 × 10^5 cm] and **Z** = [0, 3.072 × 10^4 cm]
- ~ 3,000 GPU node hours to finish at t = 120 ms.
- Shows results between two networks: **aprox13** and **subch_simple**, they differ as **subch_simple** includes:

$$^{12}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{13}\mathrm{N} + \gamma \qquad {}^{13}\mathrm{N} + \alpha \rightarrow {}^{16}\mathrm{O} + {}^{1}\mathrm{H}$$

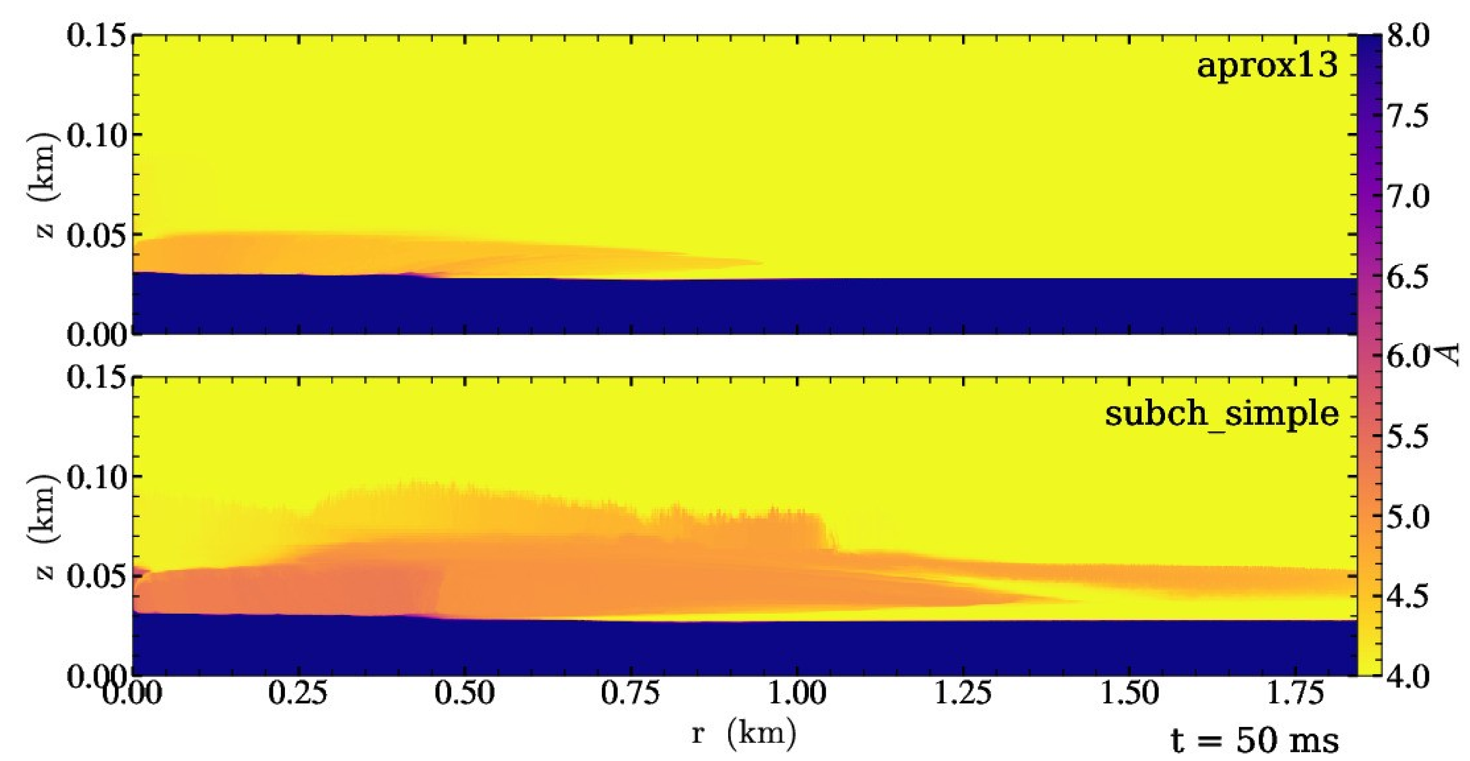

Fig: Slice plot showing average atomic weight at t = 50 ms.

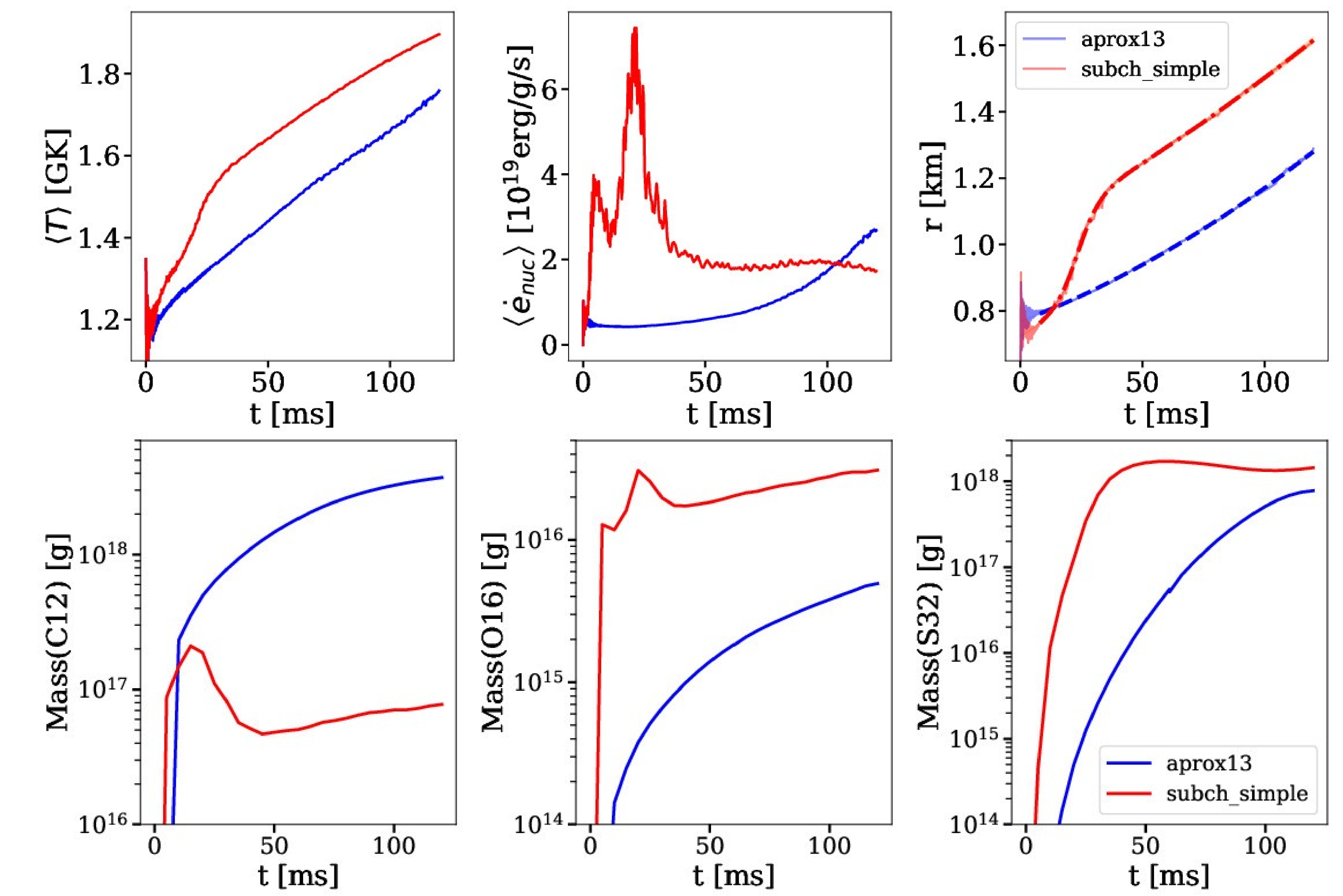

Fig: *Top Panels*: Time evolution of the density weighted T (left), nuclear energy generation rate (mid), and flame position (right). *Bot Panels*: Time evolution of total mass of ^{12}C, ^{16}O, and ^{32}S.

SPHERICAL POLAR SIMULATION RESULTS

Spherical Polar Local simulation:

- **R** = [1.1 × 10^6 cm, 1.13072 × 10^6 cm], **θ = [0, 10°]**
- 1536 × 9360 zones or 20 cm res
- ~ 2,000 node hours to reach 120 ms.
- A test run to demonstrate that the spherical-polar geometry is well behaved.

Full – Star simulation:

- **R** = [1.1 × 10^6 cm, 1.13072 × 10^6 cm], **θ = [0, π]**
- 1536 × 172,800 zones or 20 x 20 cm resolution
- Will need ~100,000 node hours to finish.
- **Ongoing simulation!**

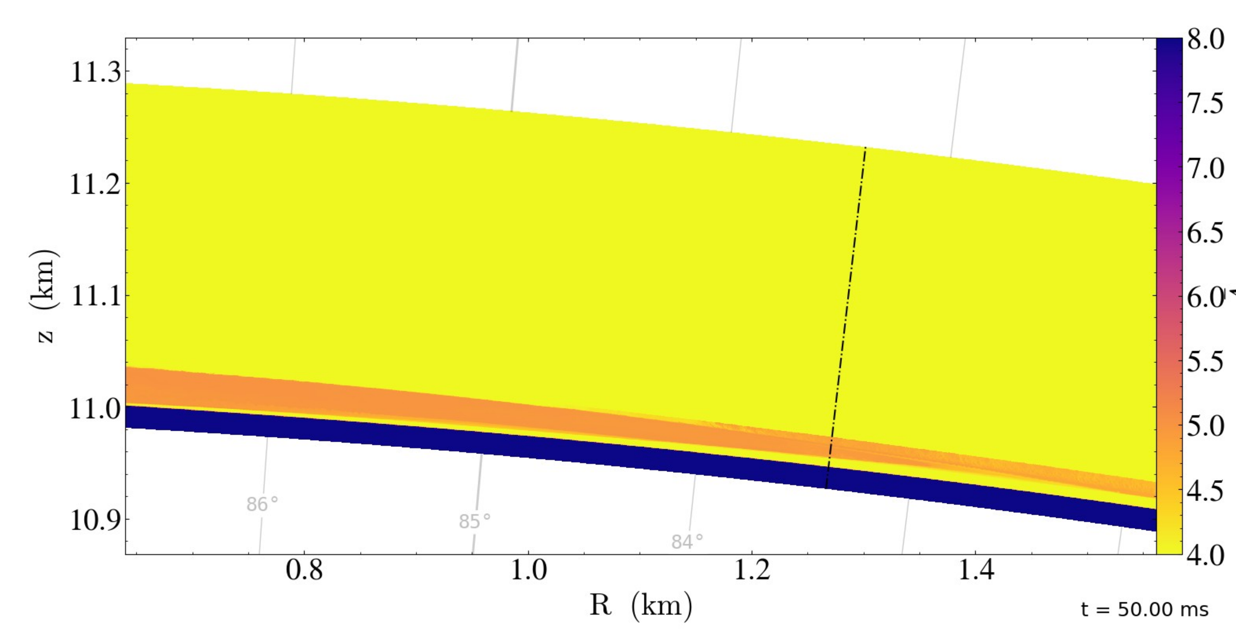

Fig: Slice plot showing average atomic weight at t = 50 ms. Black Dashed line indicates the flame front position, determined by the leading edge of the energy generation rate. Burning ash is more uniform compared to the plane-parallel run.

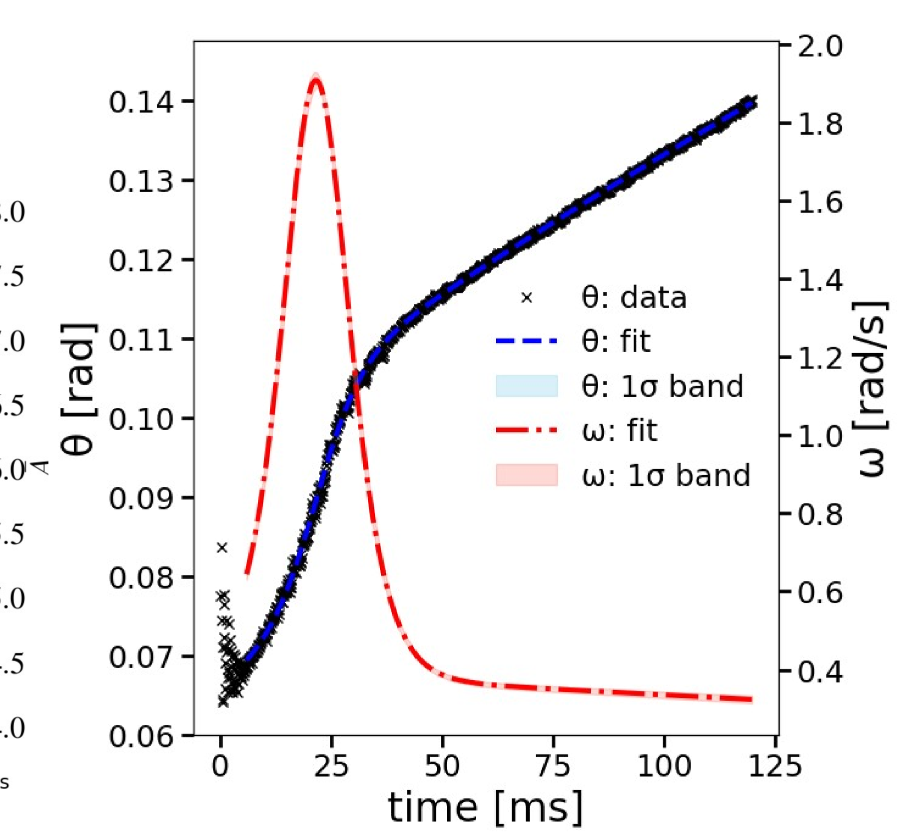

Fig: Time evolution of the flame front position with fitted curve shown in Blue. Derived fitted angular velocity shown in Red.

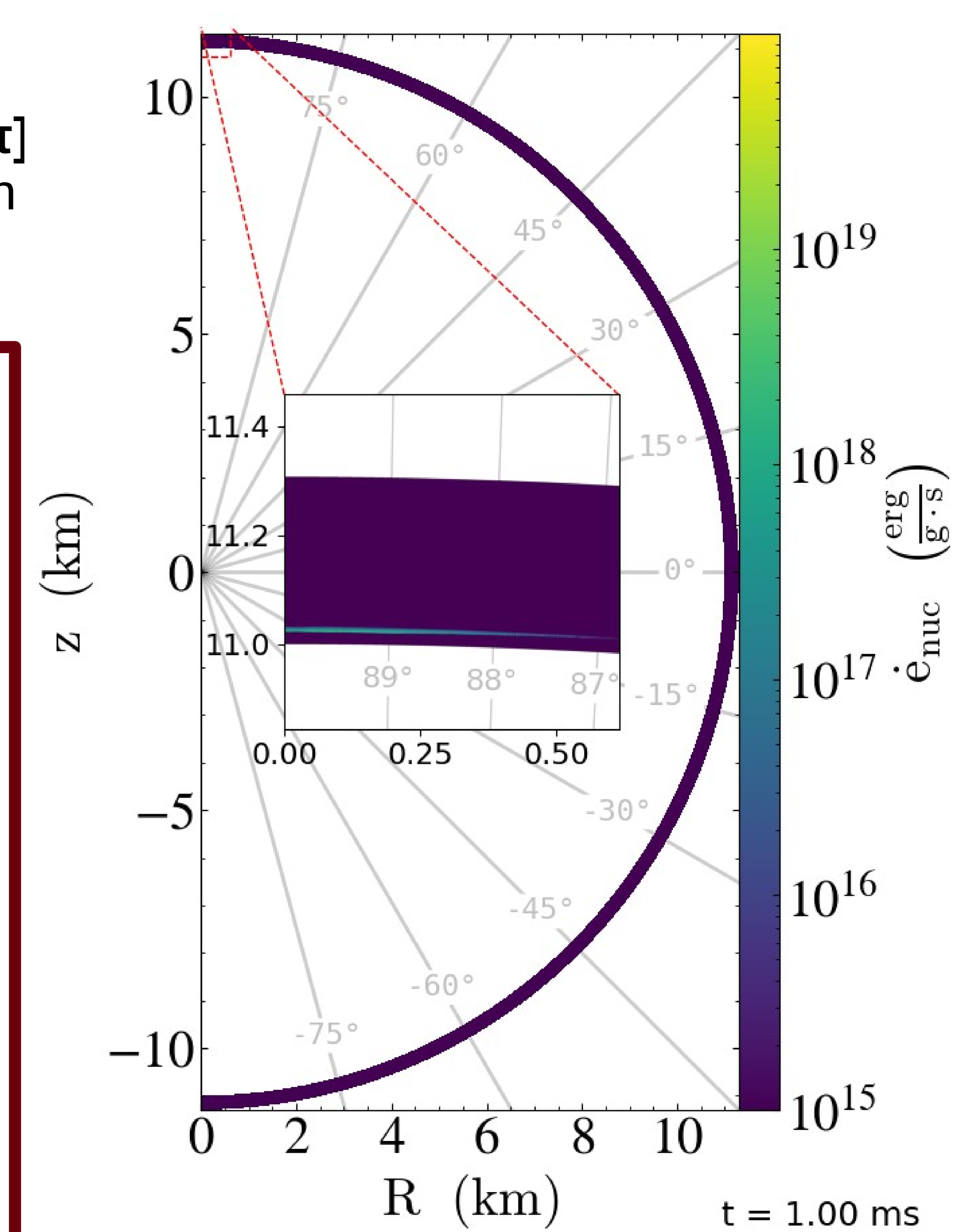

Fig: Full Star slice plot with zoom-in shown in the center, showing nuclear energy generation rate.

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Stony Brook University