Multidimensional Simulations of Convection Preceding a Type I X-ray Burst on the Surface of a Neutron Star

Chris Malone

SUNY Stony Brook

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Outline

Topic

Acknowledgements

Wetware

- Mike Zingale (SUNY Stony Brook)
- Ann Almgren, John Bell and Andy Nonaka (CCSE LBNL)
- Andrew Cumming (McGill University)
- Stan Woosley (UCSC)

Hardware

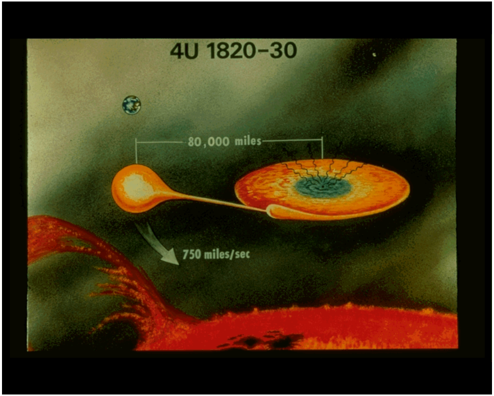
- `franklin` and `hopper` at LBNL's NERSC
- `nyblue` at BNL

What is a Type I X-ray Burst?

Properties

- Low Mass X-ray Binaries
- Accretion of H and/or He
- Ignition at base of acceted layer

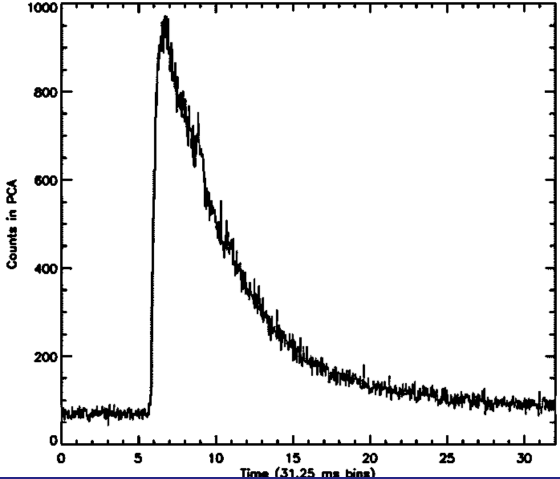
$$\begin{aligned} E &\sim 10^{39}\text{ergs} \\ \tau_{\text{rise}} &\sim \text{seconds} \\ \tau_{\text{dur.}} &\sim \text{10's–100's seconds} \\ \tau_{\text{recur.}} &\sim \text{hours to days} \end{aligned}$$



heasarc.gsfc.nasa.gov/Images/exosat/slide_gifs/exosat18.gif

What is a Type I X-ray Burst?: Lightcurve

4U 1728-34

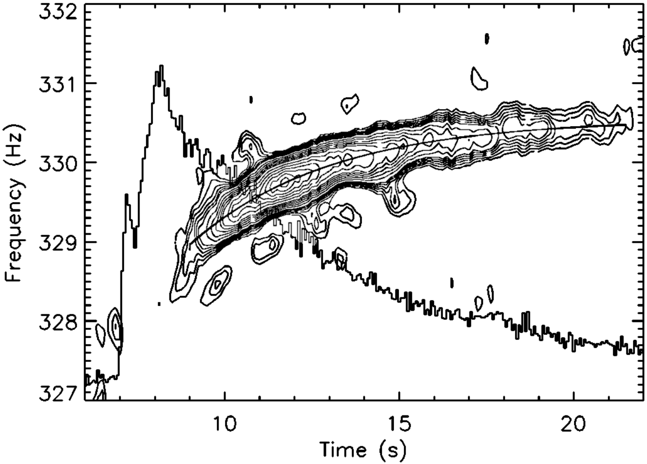


- Buring mode sets τ_{dur}.
- Inferred ignition column implies deflagration → subsonic flow

after
Strohmayer, T., et al., *ApJL*, 469, L9, (1996)

What is a Type I X-ray Burst?: Oscillations

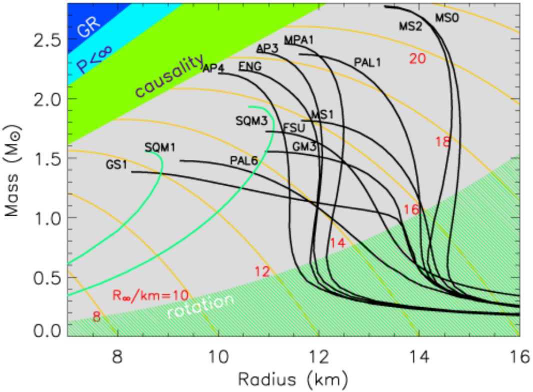
- Oscillations during rise – hot-spot spreading
- Oscillations during decay – unstable surface modes?



Strohmayer, T. and Markwardt, C., *ApJ*, **516**, L81, (1999)

Why do we care?

- They are explosions!
- Unique location for rp-process burning
- Flame propagation under extreme conditions
- Possible distance indicators (?)
- Constrain EOS for dense matter



Lattimer, J.M., *ApSS*, 308, 371 (2007)

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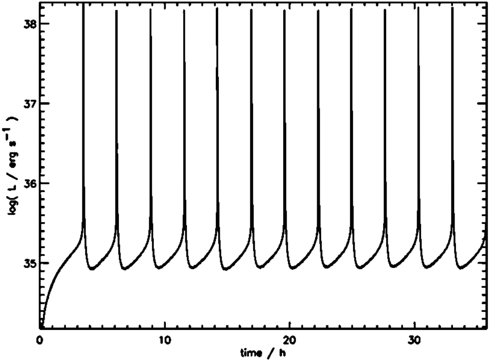
1-d Models of Type I X-ray Bursts

Pros

- Reproduce E, τ_{rise}, $\tau_{\text{dur.}}$, $\tau_{\text{recur.}}$
- Can use large reaction networks
- Computationally cheap

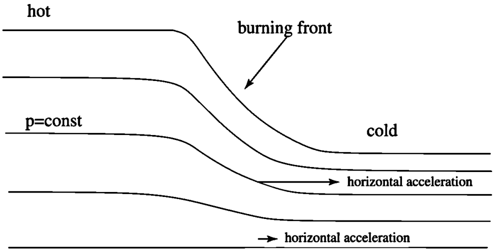
Cons

- Assume spherical symmetry
- Parameterized convection (MLT)
- Cannot study lateral flame propagation



Woosley et al., *ApJS*, 151, 75 (2004)

2-d Models of Type I X-ray Bursts



Spitkovsky et al., *ApJ*, 566, 1018 (2002)

- Very few!!
- Mostly treated as detonations—inconsistent with most observations
- Spitkovsky et al. used 2–layer, shallow water, incompressible, ideal gas to show importance of rotation

Modeling Type I X-ray Bursts

The problem domain is divided into zones, and discretized versions of the various conservation laws tell us how to evolve each zone over a small timestep.

Difficulty:

- Necessary condition for convergence of explicit hydrodynamics algorithm
  (CFL condition):
  Information can not propagate more than one grid zone in a single timestep.

Modeling Type I X-ray Bursts

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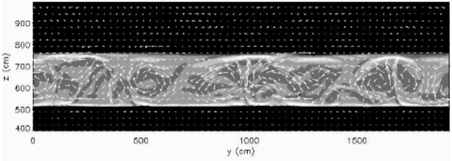
- Supersonic (detonations; $M \equiv \frac{U}{c_{\mathrm{s}}} \gg 1$): $\Delta t \lesssim \frac{\Delta x}{U}$
- Subsonic (deflagrations; $M \ll 1$):

$$\Delta t \lesssim \frac{\Delta x}{c_{\mathrm{s}}}$$

2-d Models of Type I X-ray Bursts

Low Mach Number Approximation Methods

- Filter acoustics—timestep size determined by *dynamics*: $\Delta t \lesssim \frac{\Delta x}{U}$
- Factor of $1/M$ increase in timestep size
- Common example: incompressible fluid — $\nabla \cdot \mathrm{U} = 0$
- Can assume background/base state in HSE and consider motions about this state



Lin et al., *ApJ*, 653, 545 (2006)

Lin et al. low Mach number method

- Important first step
- 1^{st} order accurate in space and time
- Didn't model top of atmosphere
- Time-independent base state

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MAESTRO

as described in Nonaka et al., *ApJSS*, **188**, 358 (2010)

- Second order accurate in space and time
- Time-dependent base state
- Uses Adaptive Mesh Refinement
- Filters acoustics while retaining important compressible effects, such as stratification, thermal diffusion and composition change

Filtering Acoustics

MAESTRO low Mach number equation set

- Decompose pressure field: $p(\mathbf{x}, r, t) = p_0(r, t) + \pi(\mathbf{x}, r, t)$

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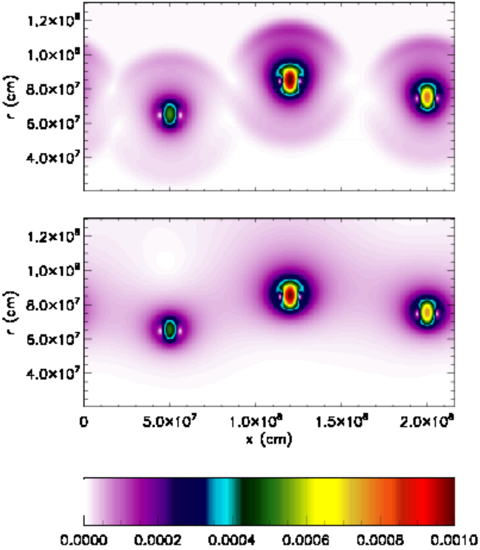
$$\begin{aligned}
\frac{\partial(\rho X_k)}{\partial t} &= -\nabla \cdot (\rho X_k \mathbf{U}) + \rho\dot{\omega} \\
\frac{\partial \mathbf{U}}{\partial t} &= -\mathbf{U} \cdot \nabla \mathbf{U} - \frac{1}{\rho}\nabla\pi - \frac{\rho - \rho_0}{\rho} g\boldsymbol{e}_r \\
\frac{\partial(\rho h)}{\partial t} &= -\nabla \cdot (\rho h \mathbf{U}) + \frac{Dp_0}{Dt} + \rho H_{\rm nuc} + \nabla \cdot (\kappa \nabla T) \\
\nabla \cdot (\beta_0 \mathbf{U}) &= \beta_0 \left(S - \frac{1}{\overline{\Gamma}_1 p_0} \frac{\partial p_0}{\partial t} \right)
\end{aligned}$$

Filtering Acoustics

- compressible
- MAESTRO

Mach Number

astro.sunysb.edu/mzingale/Maestro



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Initial 1-d Model Generation

Discussed in Malone et al., (2010) submitted to ApJ

- Construct simple atmosphere in HSE and thermal equilibrium; (similar to Cumming & Bildsten, *ApJ*, 544, 453 (2000))

$$\begin{aligned} \frac{dT}{dy} &= \frac{3\kappa}{4acT^3}F \\ \frac{dF}{dy} &= 0 \end{aligned}$$

where $dy = -\rho dr$ with y as column depth

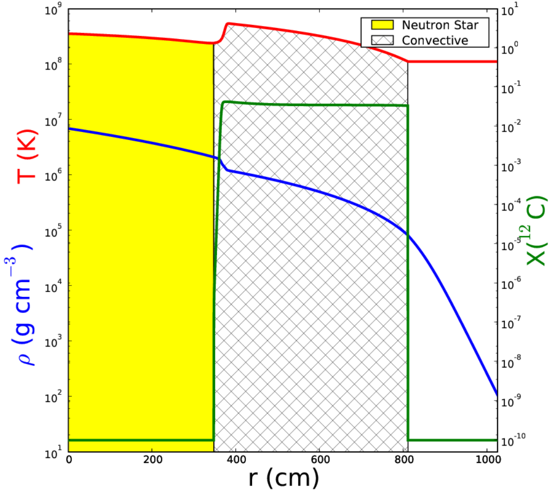
- Include constant heat flux from deep crustal heating: $F = 200$ keV / nucleon
- Base should be thermally unstable: $\frac{d\epsilon_{\text{nuc}}}{dT} > \frac{d\epsilon_{\text{cool}}}{dT}$
- Typically ϵ_{cool} is approximated as $\epsilon_{\text{cool}} \approx \frac{acT^4}{3\kappa y^2}$

Initial 1-d Model Generation

When mapping to multi-d:

- System can cool from convective overturn
- Approximation to cooling needs to be augmented for the system to be unstable

  $$\epsilon_{\rm cool} \approx \frac{acT^4}{3\kappa y^2} + \epsilon_{\rm conv.}$$
- Effective convective cooling provided MLT in the Kepler code (thanks to Stan Woosley)



Onwards toward Multi-d. . .

- 1-d model is laterally mapped across multi-d domain
- No multi-d velocity information from Kepler
- Symmetry broken by small ($\Delta T/T \sim 10^{-5}$) perturbation—this seeds convection

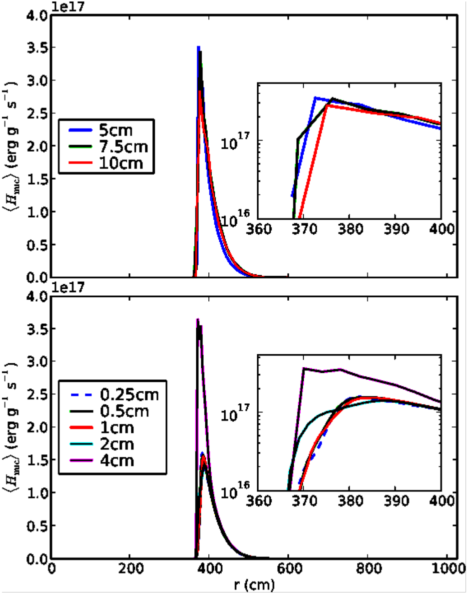
This Study

- We assumed pure ^{4}He accretion (similar to 4U 1820–30) ontop of a pure ^{56}Fe neutron star substrate.
- We only included forward and reverse 3α burning rates from Caughlan & Fowler (1988).

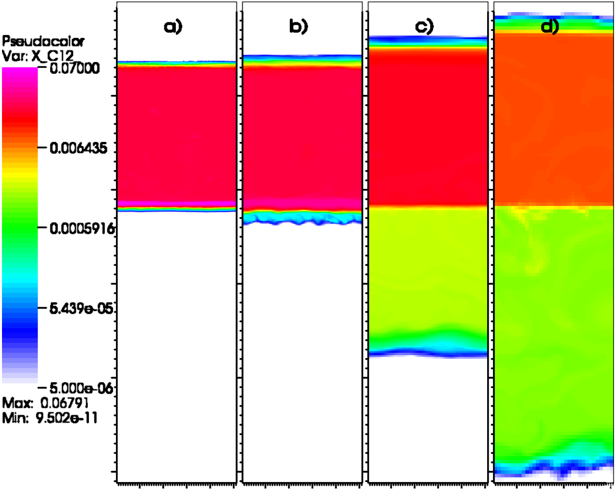
Resolution Studies

Resolution issues

- Sharp jump in T creates very peaked $H_{\rm nuc}(\sim T^{40})$
- Requires high resolution ($\sim$ 0.5 cm / zone) to resolve thin burning layer
- Comparison: Lin et al. used 5 cm / zone
  note their model used a pure ^{12}C substrate and had a much smoother thermal profile



Resolution Studies: Under-resolving=BAD!

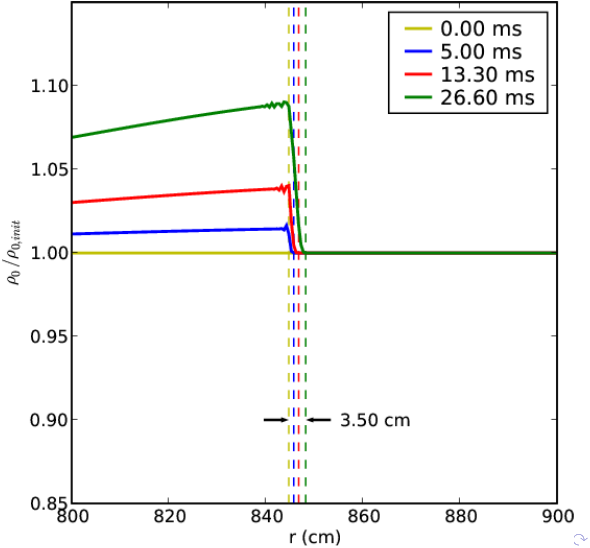


a) 0.5 cm zone^{-1}; b) 2 cm zone^{-1}; c) 4 cm zone^{-1}; d) 7.5 cm zone^{-1}

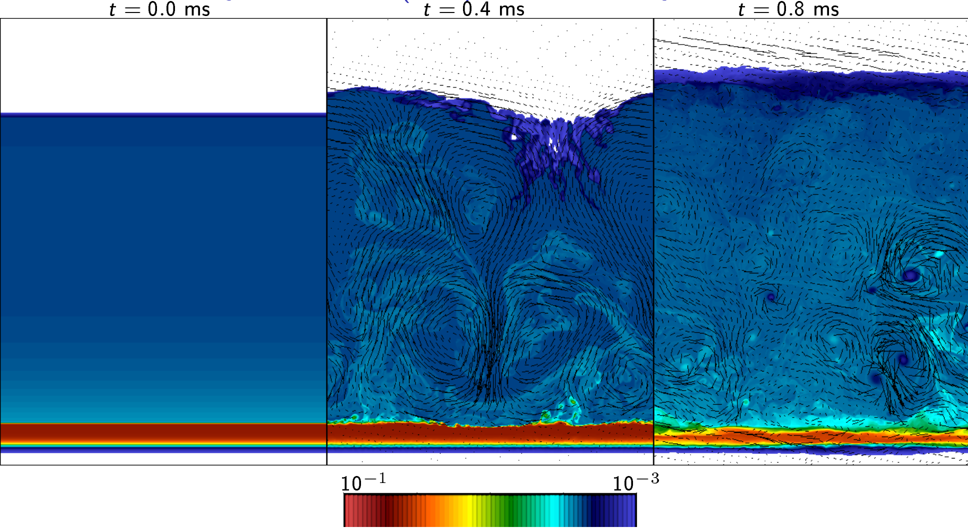
Expansion of Atmosphere

With MAESTRO we can model the surface of the star without numerical complications.

Furthermore, we use a time-dependent base state, which allows us to capture the expansion of the atmosphere from heating.



Convective Dynamics: $X(^{12}C)$ and Velocity Vectors



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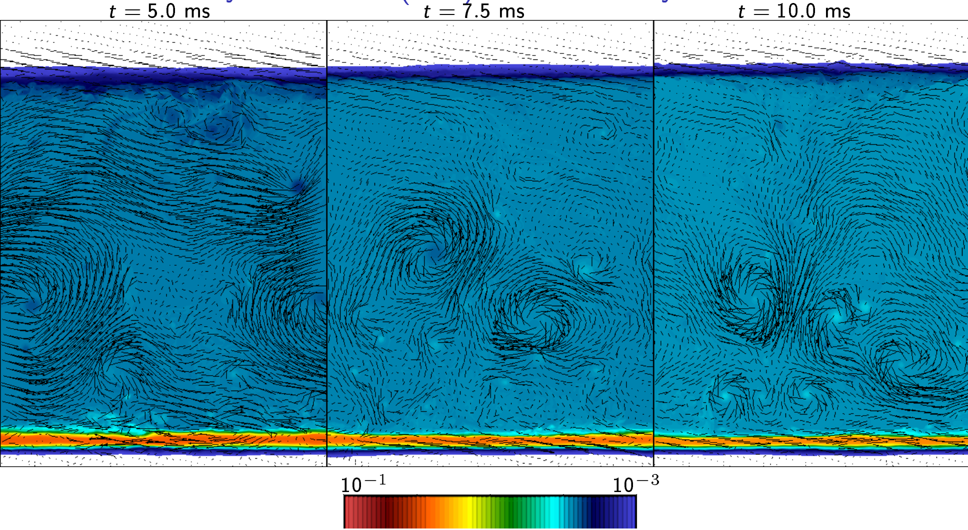

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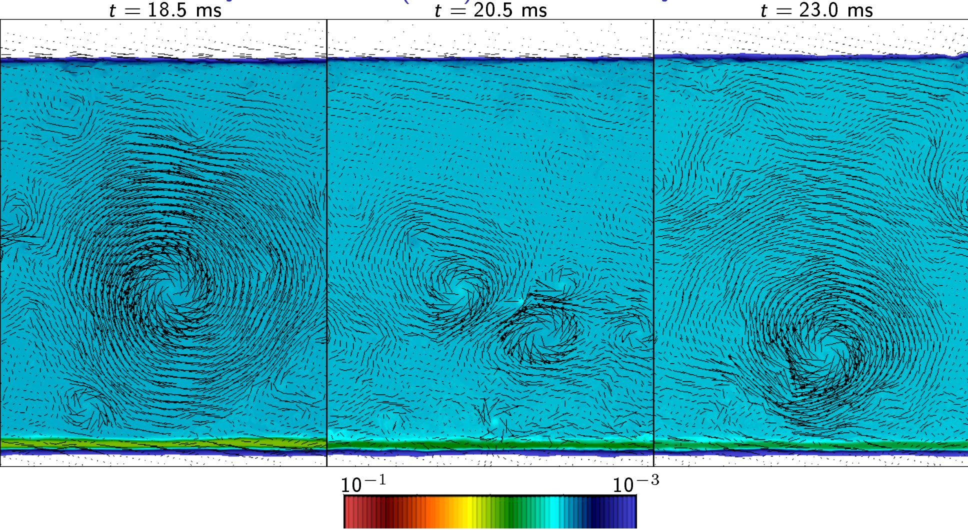

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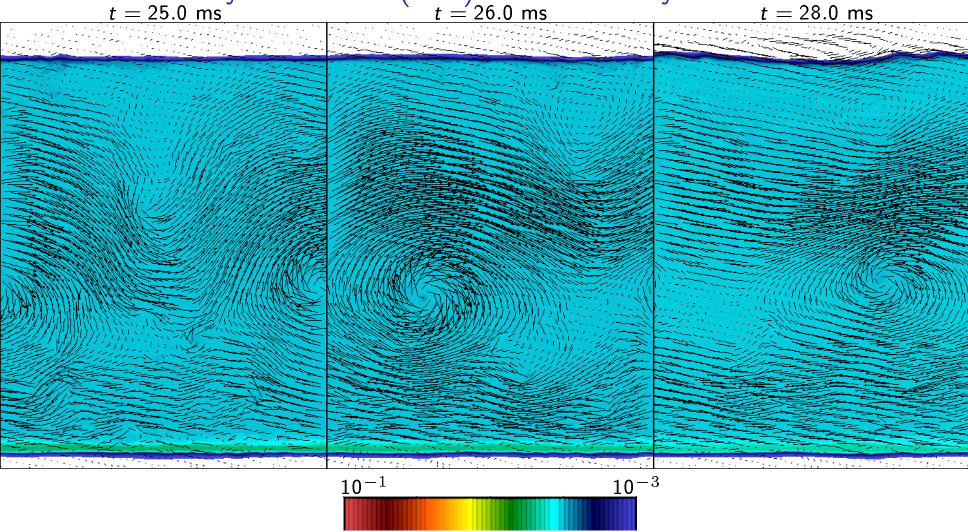
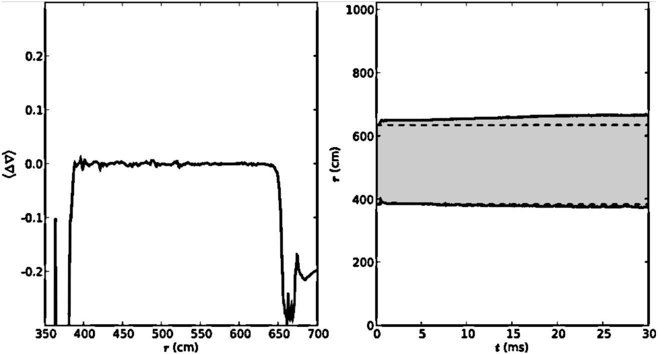


Convective Dynamics: Extent of Convective Region

Adiabatic Excess

$$\Delta\nabla = \frac{\nabla(\ln T)\cdot \boldsymbol{e}_r}{\nabla(\ln p)\cdot \boldsymbol{e}_r} - \left(\frac{d\ln T}{d\ln p}\right)_s$$

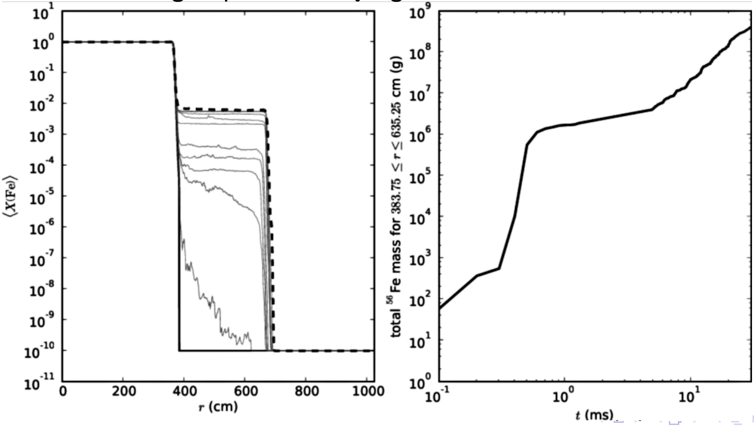
$t = 7.9$ ms



Upper boundary expands upward by 32.5 cm; lower boundary expands downward by 9.5 cm

Convective Dynamics: Iron Dredge-up

- Eddies interact with lower convective boundary
- Shearing occurs
- Dredge-up of underlying neutron star material



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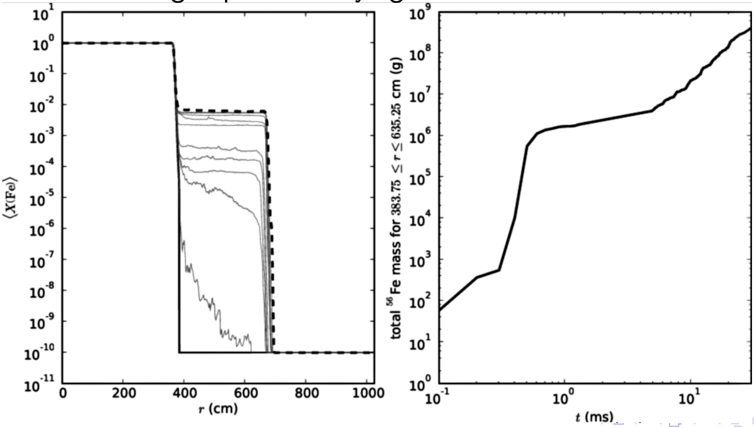
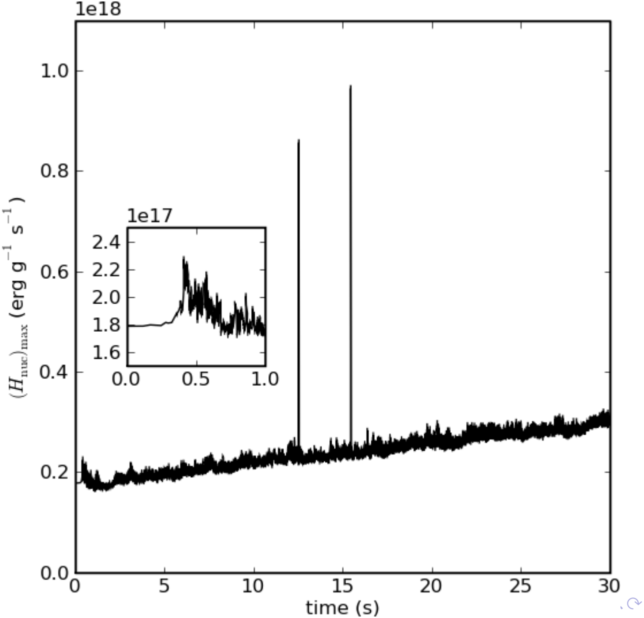


This affects conductivity!

Energy Generation

- Still linear—no flame ignition yet
- Interesting short–lived spikes when turbulence brings fresh fuel to hotter layers



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Wrap-up

Conclusions

- For a system that is close to runaway in mult-d, ϵ_{cool} needs to include convective terms.
- Our models suggest an order of magnitude more resolution than what has been used previously.
- The strong convection interacts with and churns up the underlying neutron star material.

Future Work

- Investigate different initial models—maybe relax resolution requirement
- Investigate mixed H/He bursts—maybe relax resolution requirement
- Compare 3-d runs with 2-d runs—does dredge-up still occur?