The Viscous Evolution of White Dwarf Merger Remnants

Josiah Schwab, Ken J. Shen, Eliot Quataert, Marius Dan, Stephan Rosswog

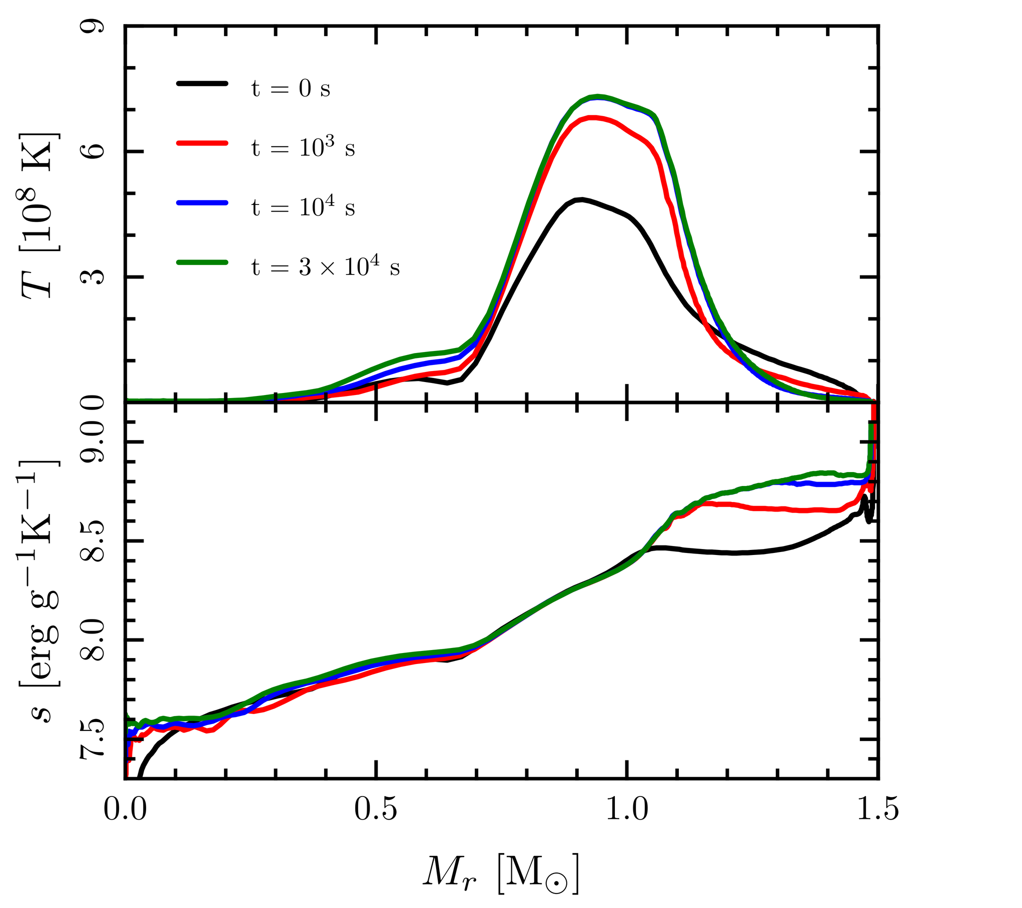
Abstract

The merger of two white dwarfs (WDs) creates a differentially rotating remnant which is unstable to magnetohydrodynamic instabilities. These instabilities can lead to viscous evolution on a time-scale short compared to the thermal evolution of the remnant. We present multi-dimensional hydrodynamic simulations of the evolution of WD merger remnants under the action of an α-viscosity. We initialize our calculations using the output of eight WD merger simulations from Dan et al. (2011), which span a range of mass ratios and total masses. We generically find that the merger remnants evolve towards spherical states on time-scales of hours, even though a significant fraction of the mass is initially rotationally supported. The viscous evolution unbinds only a very small amount of mass ($\lesssim 10^{-5} M_{\odot}$). Viscous heating causes some of the systems we study with He WD secondaries to reach conditions of nearly dynamical burning. It is thus possible that the post-merger viscous phase triggers detonation of the He envelope in some WD mergers, potentially producing a Type Ia supernova via a double detonation scenario. Our calculations provide the proper initial conditions for studying the long-term thermal evolution of WD merger remnants. This is important for understanding WD mergers as progenitors of Type Ia supernovae, neutron stars, R Coronae Borealis stars and other phenomena.

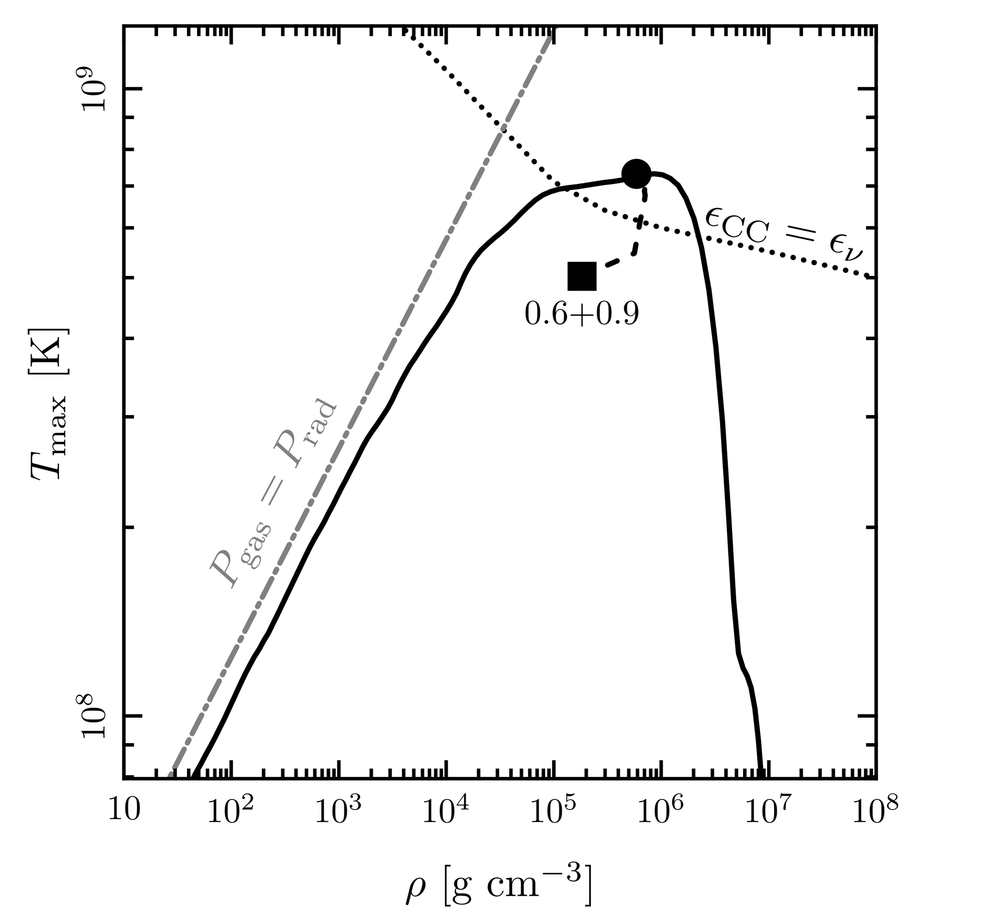
Numerical Methods

We use the ZEUS-MP/2 code (Hayes et al., 2006) modified to include an explicit shear viscosity ($\nu = \alpha c_s^2/\Omega_k; \alpha = 3 \times 10^{-2}$), the Helmholtz equation of state (Timmes & Swesty, 2000) and a simple α-chain reaction network. The calculations are performed in 2D spherical coordinates (assuming ϕ-symmetry). The initial conditions are set by mapping the output of SPH simulations onto a static 2D grid.

Evolution of the merger remnant of a 0.6 + 0.9 $M_{\odot}$ system



The evolution of the temperature (top) and specific entropy (bottom) profiles of the fiducial 0.6+0.9 $M_{\odot}$ CO+CO remnant. Viscous heating increases the peak temperature by roughly a factor of two. Convection and viscous heating both contribute to the entropy evolution of the material from the disrupted secondary. These curves are 1D spherical averages of our 2D simulations.



The evolution of the temperature peak in the $\rho - T$ plane. The dotted line indicates the break-even point where the energy release from carbon burning is equal to neutrino losses. The filled square (circle) is the peak temperature and corresponding density at the start (end) of the simulation, and the dashed line that connects them traces its evolution. The solid line is the full 1D $\rho - T$ profile of the quasi-spherical end state. The grey dash-dot line indicates where gas and radiation pressure are equal.

Conclusions

- The merger remnants of binary white dwarfs are differentially rotating and unstable to MHD instabilities like the MRI. MHD stresses give rise to a viscous phase of evolution which occurs on a time-scale much less than the thermal time. This confirms the arguments in Shen et al. (2012) that the post-merger evolution of WD merger remnants is via viscous redistribution of angular momentum that leads to nearly solid body rotation. The transport of angular momentum outwards removes rotational support from the majority of the mass leading to a nearly spherical remnant. *The dynamics during this phase is not consistent with accretion at the Eddington limit,* as in previous models of WD merger remnants. Instead, the viscous evolution of WD merger remnants is much more analogous to that of a differentially rotating star.
- Viscous heating causes one of the systems we simulate to reach conditions of nearly dynamical He burning, so it is possible that the post-merger viscous evolution triggers a detonation in some cases. We estimate that the number of systems which reach conditions of dynamical burning during the viscous phase but do not reach such conditions during the earlier dynamical phases of the merger is likely to be small. If other earlier detonation mechanisms do not prove to be robust, viscous heating could potentially trigger a surface detonation after the merger, causing either a .Ia supernovae (Bildsten et al., 2007) or a Type Ia supernova via a double detonation scenario.
- The end states of our calculations provide a starting point for investigations of the long-term thermal evolution of WD merger remnants. We expect that the luminosity from the nuclear burning will drive convection, establishing an extended convective envelope with a radius comparable to that of a giant star and correspondingly a relatively cool effective temperature like the models presented in Shen et al. (2012).

Future Work

There are clear opportunities for future work in the self-consistent thermal evolution of these objects and their consequences for Type Ia supernovae, neutron stars, R Coronae Borealis stars and other phenomena. We are in the process of exploring this using the MESA stellar evolution code. We are also working to more systematically determine the regions of parameter space where one might possibly expect dynamical He burning.

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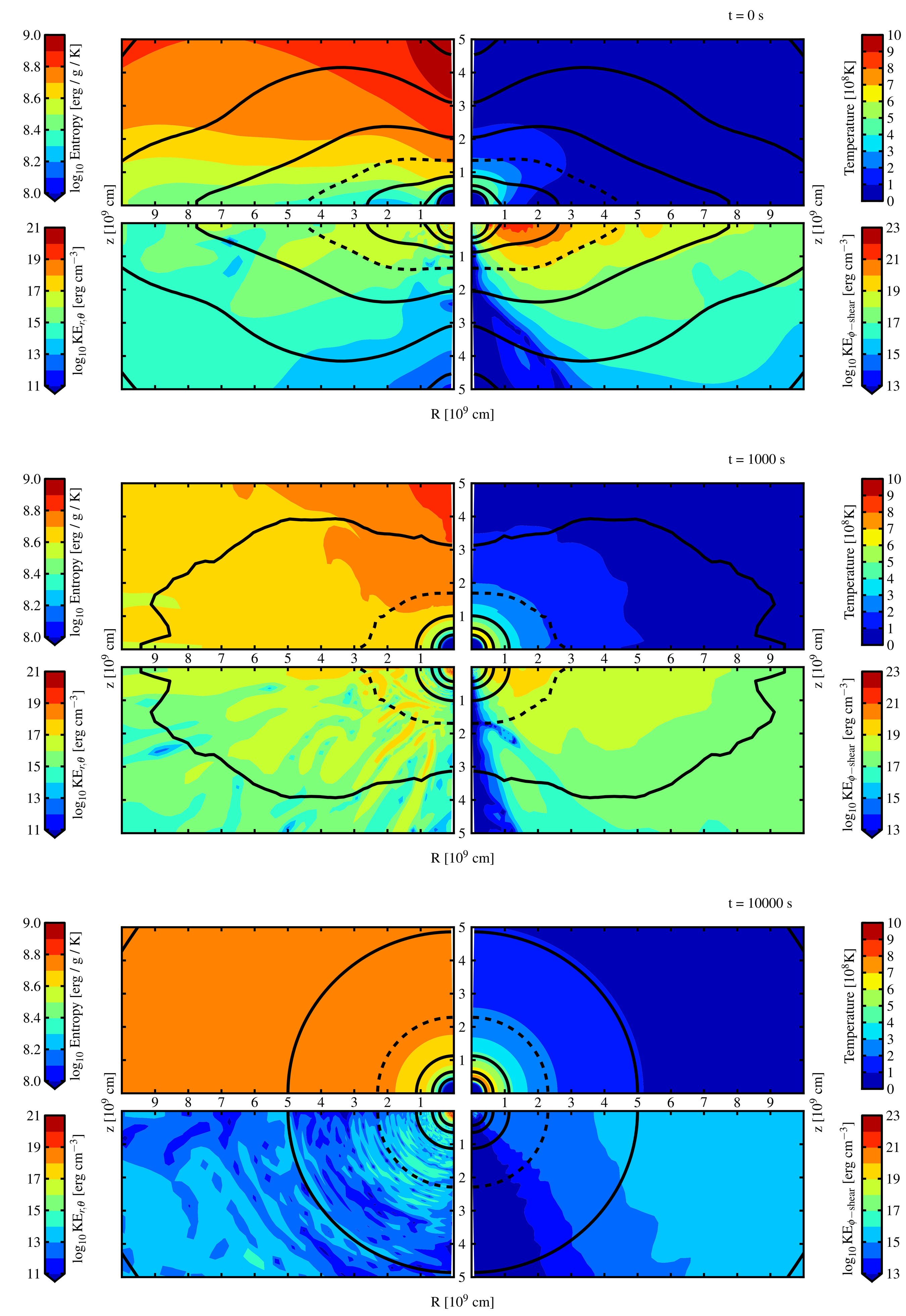
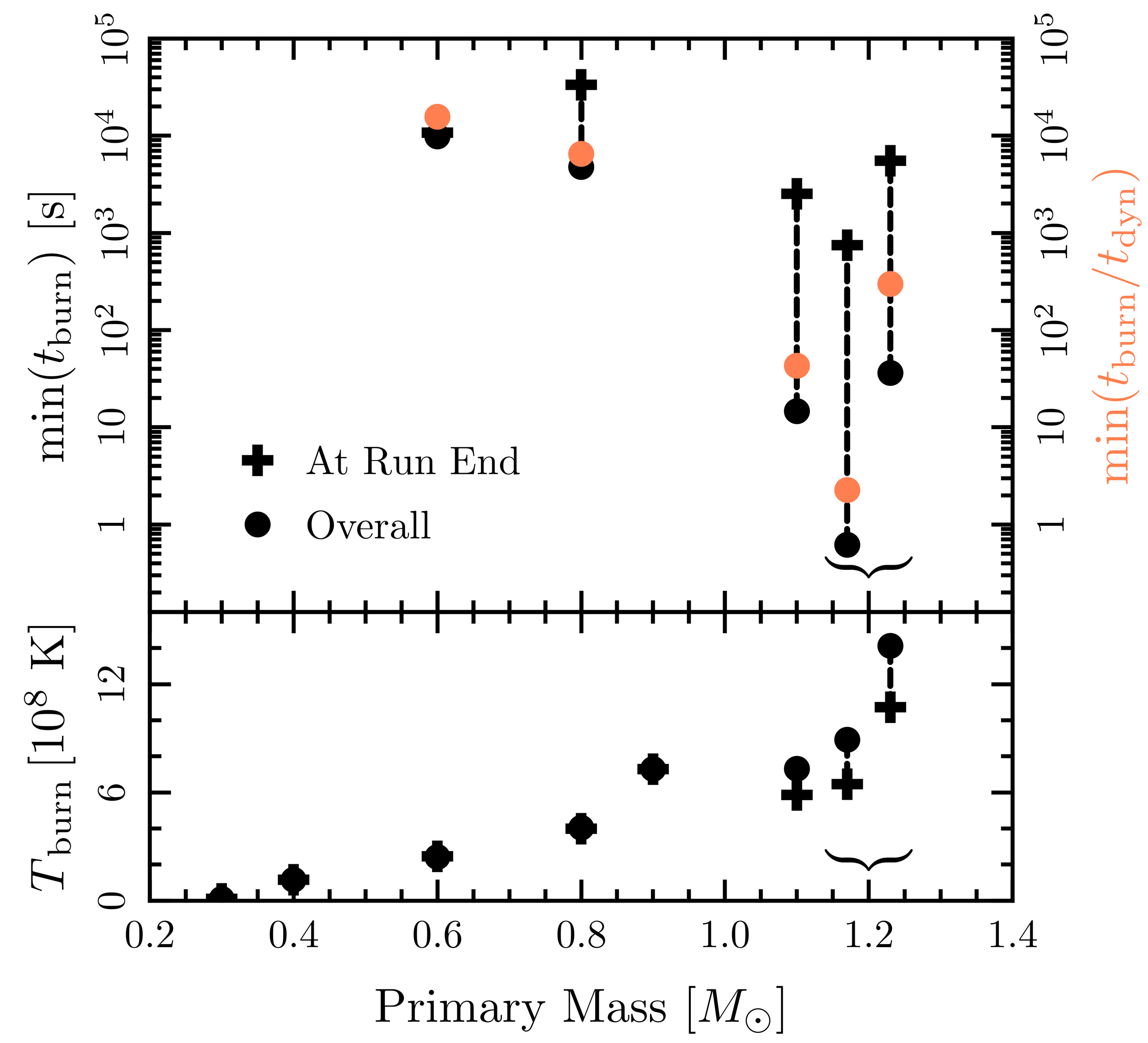
2D Evolution of the 0.6 + 0.9 $M_{\odot}$ merger remnant



The main panels are snapshots of our fiducial simulation at the indicated times. Within each panel, the top two subpanels are thermodynamic quantities (s, T) and the bottom two subpanels are kinetic energy densities (non-azimuthal, ϕ-shear). The black contours are density, spaced one per decade. The dashed contour is $\rho = 10^3$ g cm^{-3}. *Top Panel*: The initial conditions, note the large "free" energy apparent in the shearing, Keplerian disc. *Middle Panel*: The action of viscosity has dissipated some of the shear and heated the material. The remnant has become convectively unstable as can be seen in the striation of the non-azimuthal KE. *Bottom Panel*: The remnant has settled down into a quasi-spherical steady state.

Can viscous heating trigger dynamical He burning?



The shortest burning time (top panel) and corresponding temperature (bottom panel) for each of our simulated systems. The x-axis is the mass of the primary WD. Two systems have the same primary mass of 1.2 $M_{\odot}$ and are slightly offset on the x-axis for visual clarity. In the top panel, the circle represents the shortest burning time reached overall, that is at any point during the simulation; the cross represents the burning time at the end of the simulation. They are connected by a dashed line to guide the eye and indicate that intermediate values are achieved. The same symbols in the bottom panel show the temperatures at the corresponding locations. Because of varying chemical composition, the temperature associated with the shortest burning time is not necessarily the global peak temperature. The right axis of the top panel and the orange circles show the ratio $t_{\rm burn}/t_{\rm dyn}$ at conditions corresponding to the black circles.

References

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