Detonability of white dwarf plasma: Turbulence models at transition densities

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Introduction: Turbulent Combustion and DDT

The deflagration-to-detonation transition (DDT) mechanism has been long studied but remains one of the major unsolved problems of theoretical combustion. It has been directly observed in a number of laboratory experiments and has been extensively studied through numerous numerical simulations [1]. Also, astrophysicists have suspected for almost 40 years that it is directly responsible for at least a subclass of white dwarf explosions powering Type Ia supernovae (SN Ia). Astrophysical observational evidence for the DDT is, however, only indirect, which hinders progress in understanding the SN Ia explosion mechanism.

Regardless of whether or not the deflagration exists, the viable explosion mechanism requires conditions in which the flow is energized and sizeable parcels of fuel attain a critical burning temperature. The question then is, what is the source of that energy? One possibility might be turbulence existing in the white dwarf plasma. As recently shown by Davidovits & Fisch [2], the sudden compression of viscous turbulence may lead to the rapid release of turbulent kinetic energy. In the SN Ia context this could result in the initiation of a detonation if the released energy is sufficiently large.

We build upon our previous study by Fenn & Plewa [3], and consider the sensitivity of nuclear burning to the intensity of turbulence.

The Model

We use the compressible, inviscid Euler equations to model fluid dynamics for boh 2D and 3D models. Turbulence driving is modeled and allowed to heat the plasma through turbulent kinetic energy dissipation. Additionally, the plasma is an electron degenerate carbon/oxygen mixture with nuclear burning physics implemented in the model.

The simulation begins with the fluid at rest and is spectrally driven for $t = 75$ ms to establish steady-state turbulence. From there, turbulent dissipation heating and nuclear burning is enabled. The system is allowed to evolve until either an oxygen detonation is produced or max simulation time is reached.

The computational model uses the `Proteus` code (a fork of `FLASH`). The initial conditions for density, temperature, and composition are $\rho = 1 \times 10^7$ g/cm^3, $T = 1 \times 10^9$ K, and $50\%/50\%$ carbon/oxygen, respectively. The max simulation time is $t = 150$ ms. The compressibility of driving is 50% for turbulent kinetic driving energies ranging from $(1-4) \times 10^{15}$ erg/g/s.

Results

Depending on the turbulent driving energy, we find a range of behaviors from non-explosive scenarios to cases involving partially burned fuel as well as situations when complete burning occurs. Our preliminary 2D results are shown in Figure 1. For the lowest driving energies considered, we found no explosive burning for several turbulent turnover times ($T_{\max} < 2\times10^9$ K). As the driving energy increases, ignitions first involve only carbon ($T_{\max} \approx 3\times10^9$ K) and for still higher drive energies, oxygen is also ignited ($T_{\max} \approx (5-7)\times10^9$ K). The sudden drop in Mach number for detonating models is due to the emergence of the detonation wave modifying the sound speed values in the data.

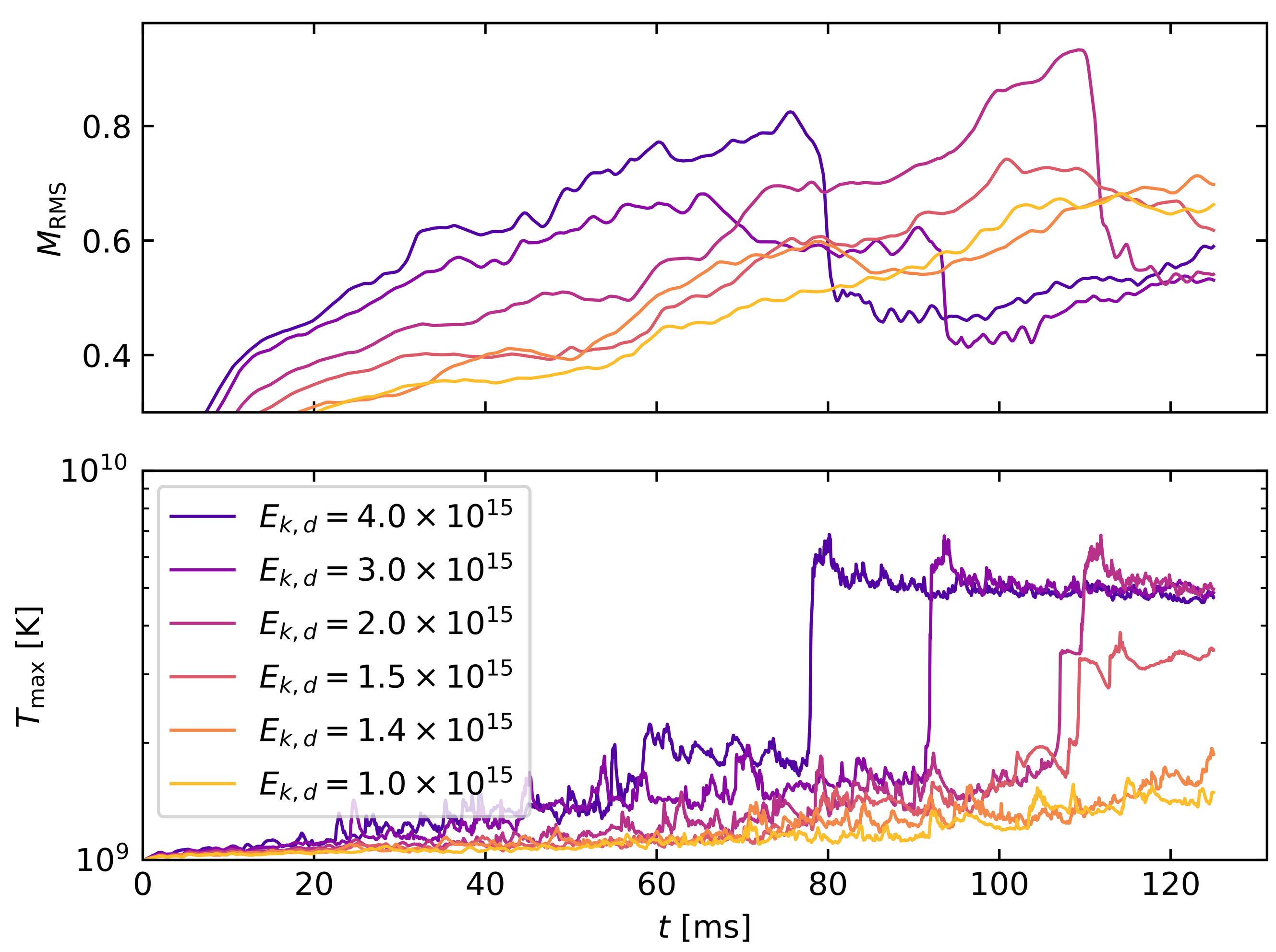

Figure 1. Turbulent combustion models in 2D. Evolution of the root-mean-square Mach number, $M_{\rm RMS}$, and of the maximum temperature, $T_{\max}$, are shown in the top and bottom panels, respectively, for different energies of turbulent drive, $E_{k,d}$. See text for details.

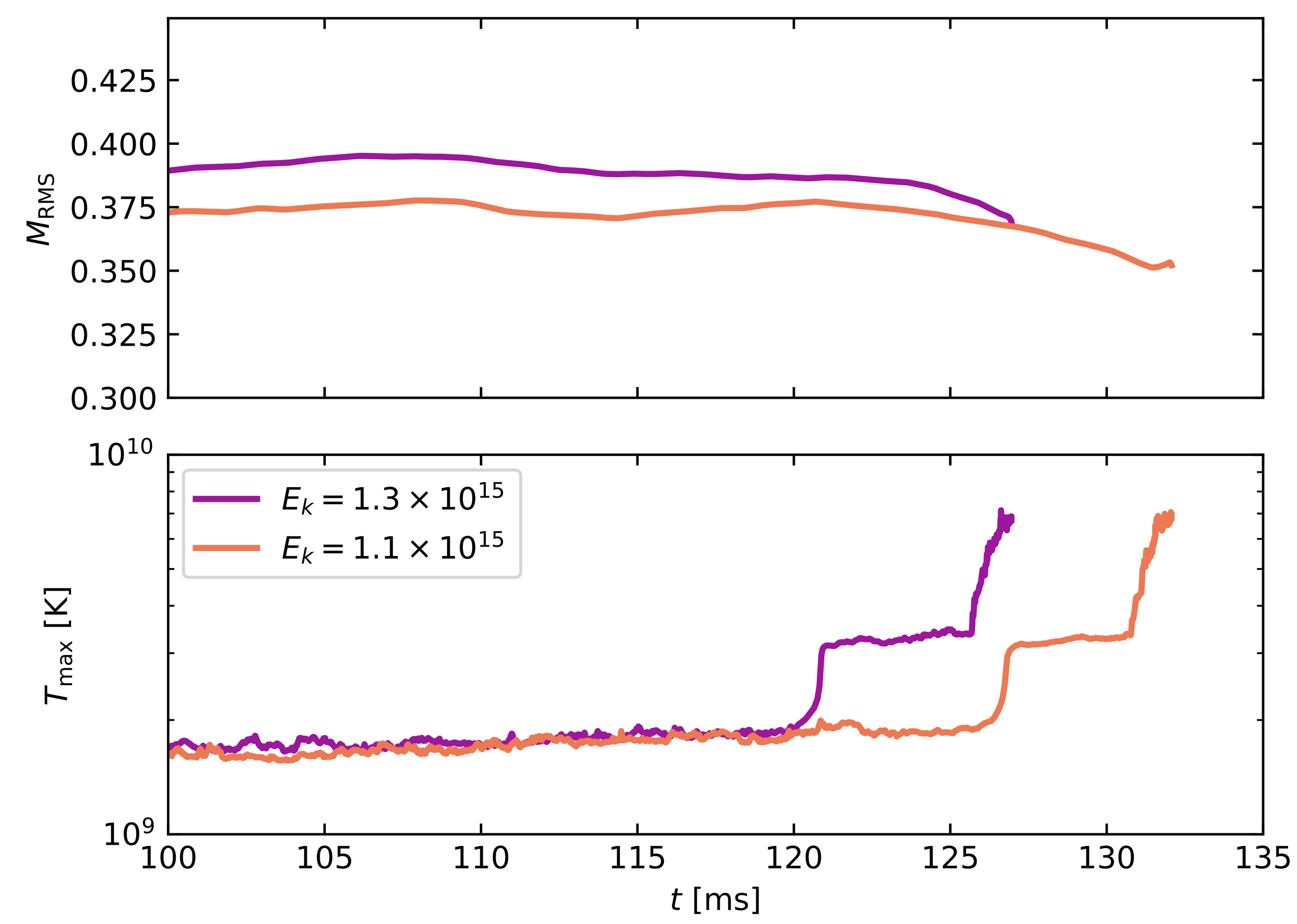

Figure 2. Turbulent combustion models in 3D. Evolution of the root-mean-square Mach number, $M_{\rm RMS}$, and of the maximum temperature, $T_{\max}$, are shown in the top and bottom panels, respectively, for different energies of turbulent drive, $E_{k,d}$. See text for details.

In Figure 2, we see a continuation of trends seen in the 2D results of Figure 1. Both models detonate oxygen, however, the period between carbon ignition and oxygen ignition is extended (the flat, plateau-like features in the temperature plot, Figure 2 bottom panel). This indicates that extensive carbon deflagration occurs prior to oxygen ignition.

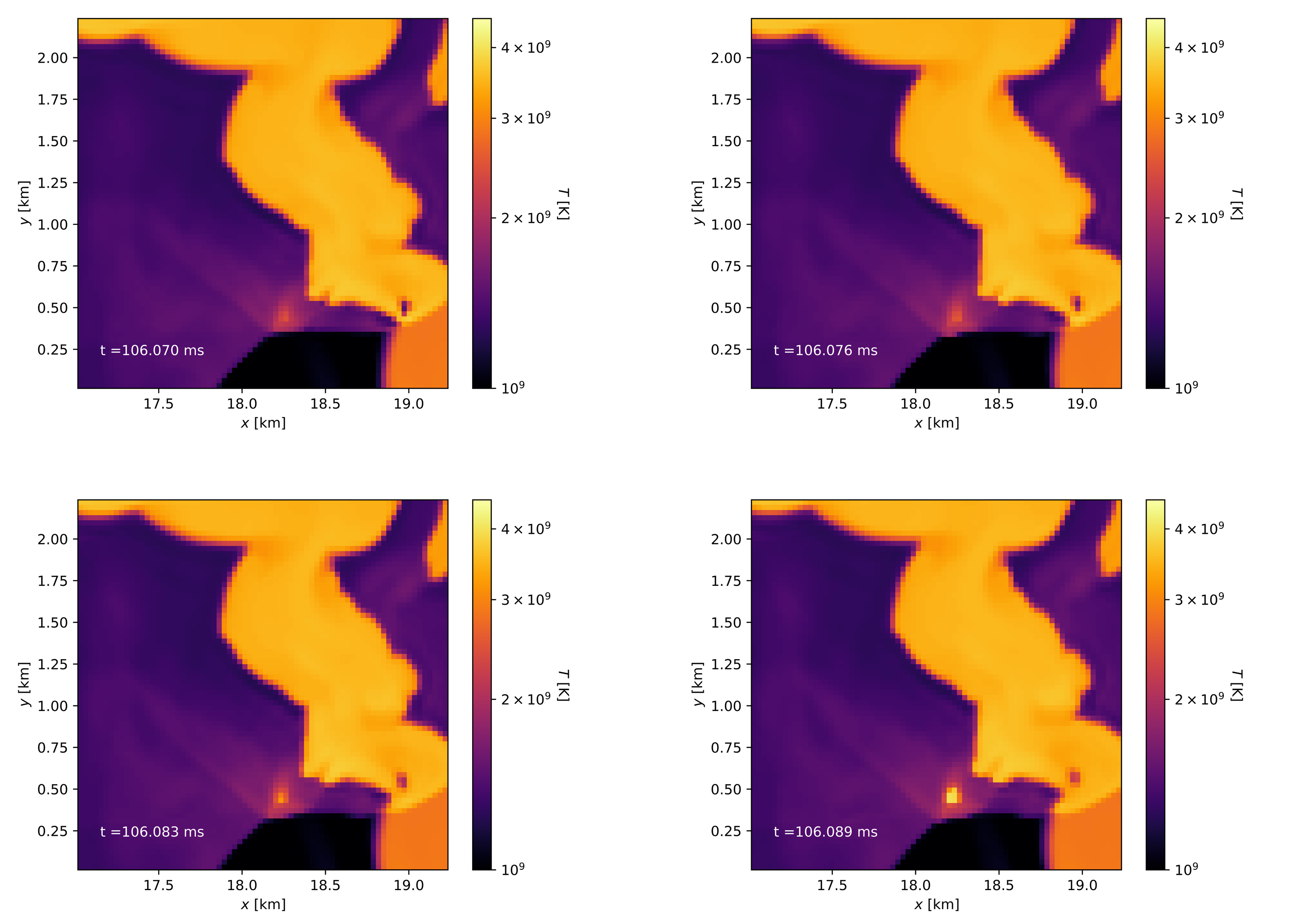

Figure 3. High resolution, 2D model of turbulent combustion. Temperature distribution in the model driven with $E_{k,d} = 2.0 \times 10^{15}$ erg/s/cm^2, is shown with color-contour plot during the time leading up to oxygen detonation. The detonation kernel can be seen as a small region of gradually increasing temperature located near $(x, y) \approx (18.25, 0.5)$ km. Top Left) Tiny hot spot develops in center-bottom, Top Right) Hot spot grows slightly hotter and larger in size , Bottom Left) Hot spot continues to approach critical carbon ignition temperature, Bottom Right) Mild carbon ignition fully develops.

Preliminary Discussion

Our preliminary conclusion is that only sufficiently energetic, yet subsonic, turbulence can induce successful SN Ia explosions. We see this trend in both our 2D and 3D models.

Additionally, we have observed a potential ignition mechanism in both our 2D and 3D models and are currently developing a cross correlation analysis methodology to quantitatively explore our hypotheses. We are able to well resolve our 2D models spatially and temporally (Figure 3, as an example) for testing the cross correlation analysis. Visual inspection indicates a correlation between compression, material mixing and carbon/oxygen ignition, as well as a reactivity gradient mechanism at play known as the Zel'dovich mechanism. The cross correlation analysis will make it easier to draw conclusions for 3D results that are significantly more difficult to visually analyze.

Our future work will first involve completing the cross correlation analysis and then we will begin exploring additional sources of plasma heating, besides kinetic energy dissipation.

References

[1] E.S. Oran, V.N. Gamezo Origins of the deflagration-to-detonation transition in gas-phase combustion *Combustion and Flame*, 148, 4, 2007

[2] S. Davidovits, N.J. Fisch Compressing turbulence and sudden viscous dissipation with compression-dependent ionization state *Physical Review Letters*, 94, 053206, 2016

[3] D. Fenn, T. Plewa Detonability of white dwarf plasma: turbulence models at low densities *Monthly Royal Notices in Astronomy*, 468, 1361, 2017