SN Ia DDT Explosions Powered by the Zeldovich Reactivity Gradient Mechanism

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Introduction

The deflagration-to-detonation transition (DDT) mechanism remains one of the major unsolved problems of combustion physics. Astrophysicists have suspected for almost 40 years that it is also directly responsible for a subclass of white dwarf (WD) explosions powering Type Ia supernovae (SN Ia). Much of the research on DDT in SN Ia has focused on the interactions of deflagration fronts with turbulence generated by the flame itself [1].

In our work, we construct and analyze weakly compressible turbulence combustion models for carbon/oxygen plasma at a density expected for DDT to occur. We observe formation of carbon deflagrations and transient carbon detonations at early times. As turbulence becomes increasingly inhomogeneous, sustained carbon detonations are initiated by the Zeldovich reactivity gradient mechanism. The fuel is suitably preconditioned by the action of compressive turbulent modes with wavelength comparable to the size of resolved turbulent eddies. Oxygen detonations are initiated either by aid of reactivity gradients or by collisions of carbon detonations.

The Model

We use the compressible, inviscid Euler equations to model fluid dynamics for both 2D and 3D models using an electron degenerate equation of state. Turbulence driving is modeled and allowed to heat the plasma through turbulent kinetic energy dissipation.

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 evolves until oxygen detonation occurs or max simulation time is reached.

The computational model uses the `Proteus` code (a fork of the University of Chicago hydrocode, `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 $(1-2) \times 10^{15}$ erg/g/s.

Results

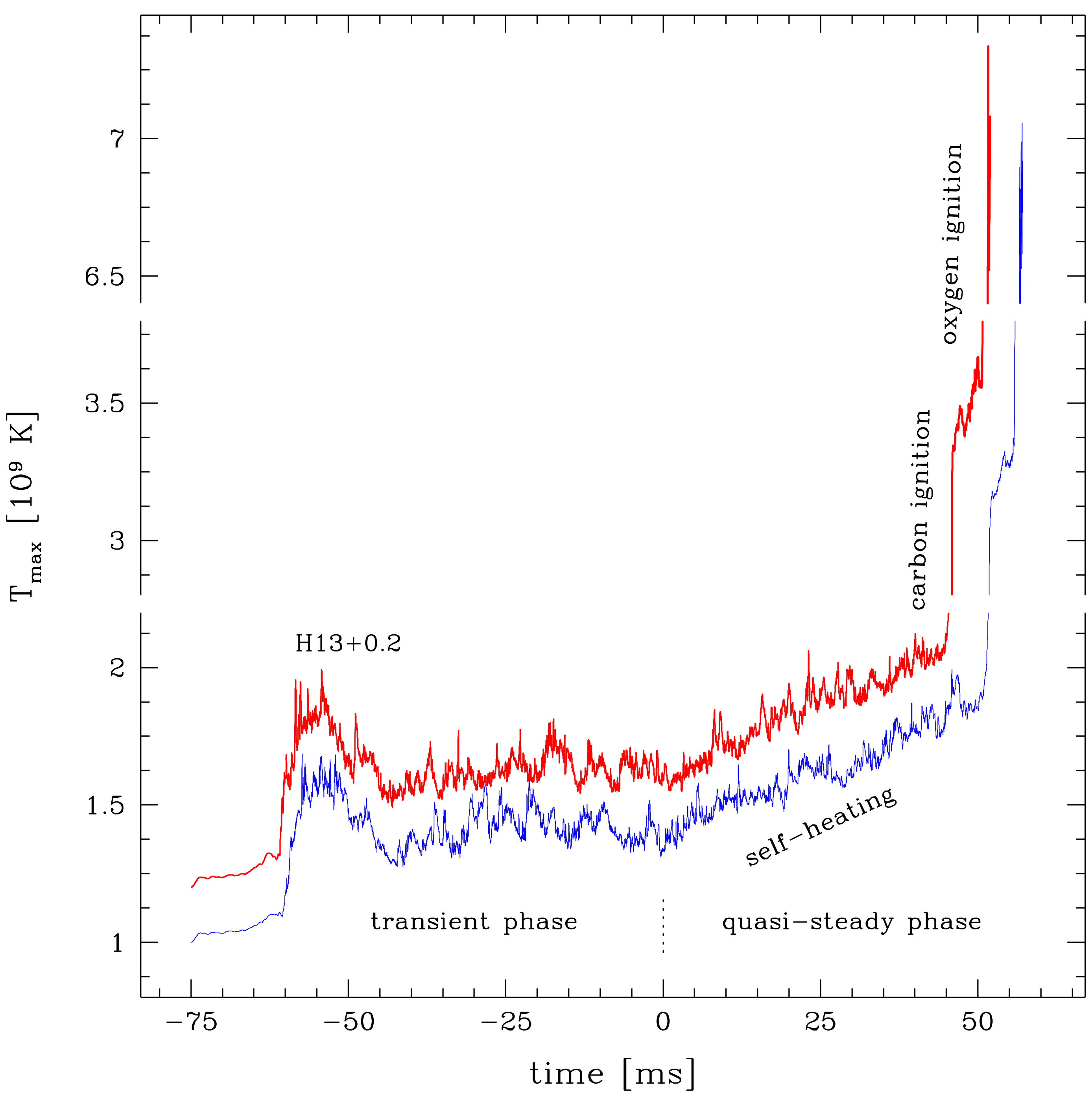

Figure 1. Evolution of maximum temperature in two high-resolution 3D models. Note the temperature remains roughly constant by the end of the transient phase ($t = 0$ ms) and on average gradually increases after that time due to self-heating and the dissipation of turbulent kinetic energy. In both models, the temperature sharply rises in two stages, first when carbon is ignited and subsequently when oxygen detonates. Note the temperature scale is broken into three separate segments and H13 data is offset to improve readability.

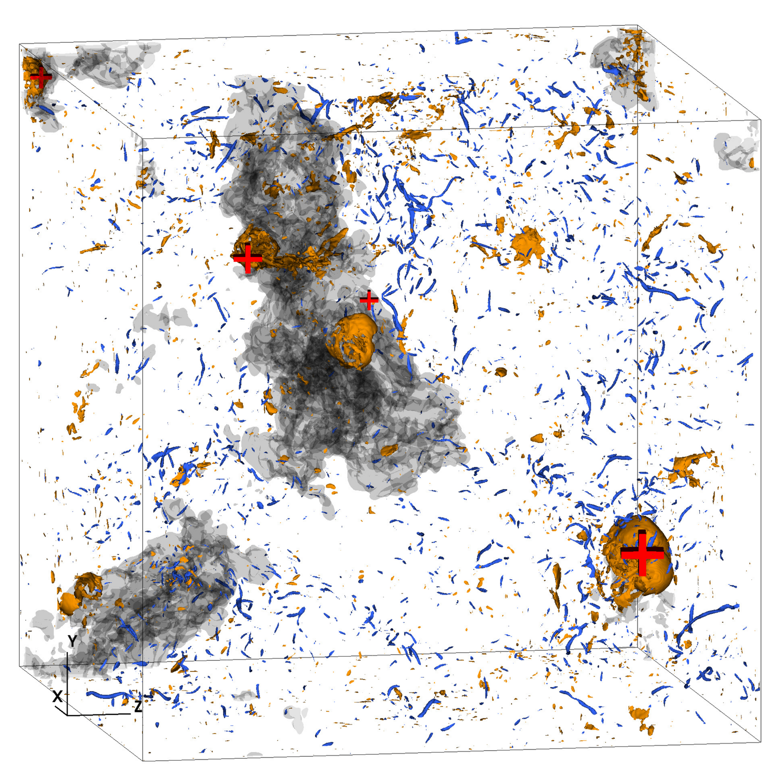

Figure 2. Development of carbon deflagration plumes (gray/black) in a high resolution 3D turbulent combustion box model. The locations of red crosses are regions where detonation waves are born from deflagrations coexisting in regions with local compression (orange) and low mixing motion (blue). Due to the challenges of analyzing 3D data, we constructed 2D models that demonstrated the same explosion process as our 3D models.

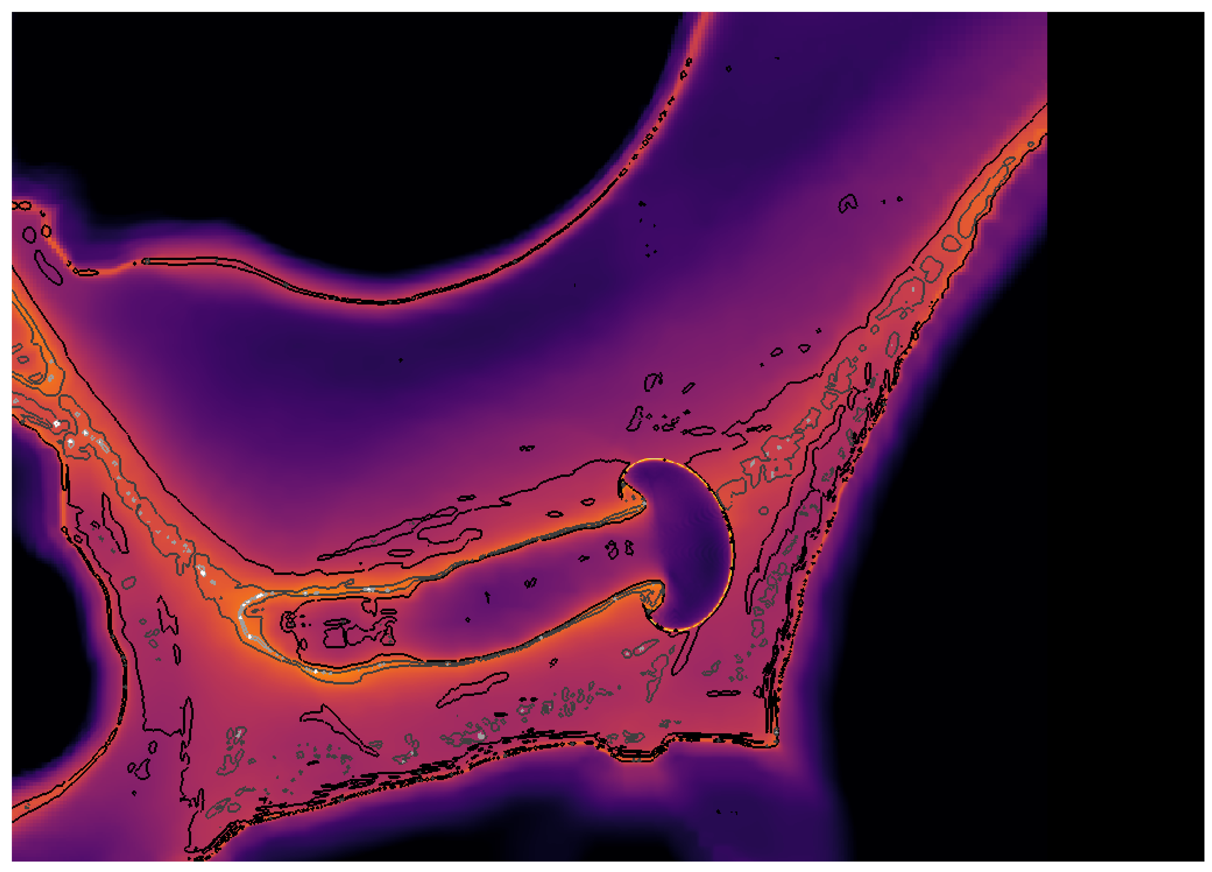

Figure 3. Highly spatio-temporally resolved 2D model, with ignition time as a colorized map. High to low ignition times correspond to darker to brighter colors. Grayscale contour lines show the speed of reactivity of the fuel normalized by the sound speed, darker to lighter contours indicate lower to higher reactivity speed. We see a carbon deflagration born in a channel of C/O fuel preconditioned by compression from two converging deflagration ash plumes. However this deflagration is also transitioning to a detonation along a region with relatively high reactivity speed on the order of Mach 2-3 (see the mushroom-like cap). This process resembles the Zeldovich reactivity gradient mechanism, a theoretical driver of DDT in a preconditioned fuel.

Future Outlook

Our results support the possibility for the Zeldovich mechanism to operate as a DDT driver in thermonuclear explosions of centrally ignited delayed detonation models of white dwarf stars. The outstanding question, however, is if there is sufficient time for this DDT process to occur in the fuel turbulerized by the central deflagration? Over a decade ago, researchers using data from Röpke et al. (2007) characterized this turbulence and concluded that while DDT is possible at densities similar to those used in our work, the probability of occurrence is low [2,3]. However, these results were generated rather crudely and should be updated now that higher resolution simulations can be obtained with more realistic progenitor initial conditions and improved flame models at our disposal for modeling deflagrating white dwarf explosions.

To this end, I have developed a toolkit to estimate the driving energy and compressibility of turbulence that can be applied to Rayleigh-Taylor unstable deflagrations of centrally ignited white dwarf simulations. This toolkit has been tested using data from a deflagration-in-a-box model with conditions somewhat applicable to those found in a white dwarf star and compared to the known turbulent properties of our 2D/3D turbulent combustion box models. Early tests indicate the flame-generated turbulence is nearly incompressible and weaker by 1-2 orders of magnitude than the turbulence used in our previous studies.

In our continuing work, we will seek to improve the estimates and characterization of the turbulence that is developed due to Rayleigh-Taylor unstable deflagration flames in the centrally ignited white dwarf supernova scenario. One important aspect is to determine the gravitational acceleration at DDT-amenable densities as this in large part determine how strongly driven the flame-generated turbulence will be. This will help to further our understanding of the viability of the detonation mechanism we propose for at least a subclass of luminous Type Ia supernova explosions.

References

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