White Dwarf Convection Preceding Type Ia Supernovae

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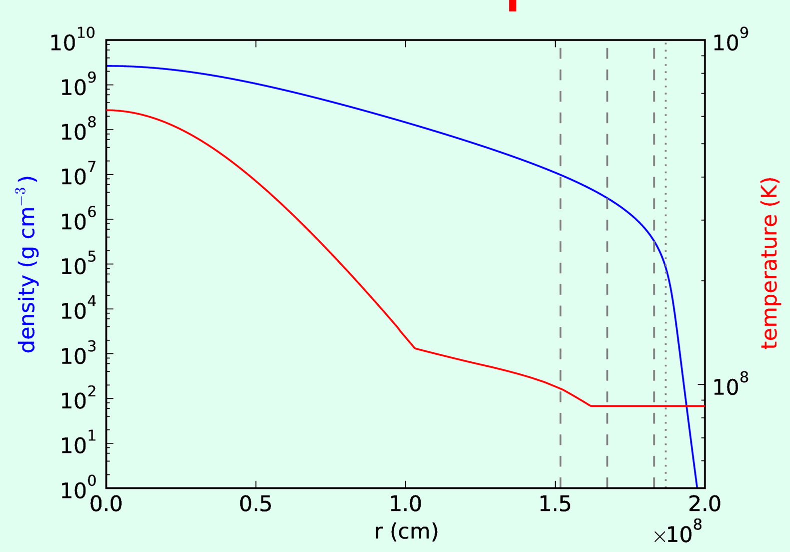
In the single degenerate scenario for Type Ia supernovae, a Chandrasekhar mass white dwarf "simmers" for centuries preceding the ultimate explosion. During this period, reactions near the center drive convection throughout most of the interior of the white dwarf. The details of this convective flow determine how the first flames in the white dwarf ignite. Simulating this phase is difficult because the flows are highly subsonic. Using the low Mach number hydrodynamics code, MAESTRO, we present 3-d, full star models of the final hours of this convective phase, up to the point of ignition of a Type Ia supernova. We discuss the details of the convective velocity field and the locations of the initial hot spots. Finally, we show some preliminary results with rotation.

Initial Model and Problem Setup

Our initial model is a Chandrasekhar mass white dwarf with a central T of 6.25×10^8 K and a central ρ of 2.6×10^9 g cm^{-3}. This model is mapped into a 3-d Cartesian domain with 384^3 zones. The entire star is modeled.

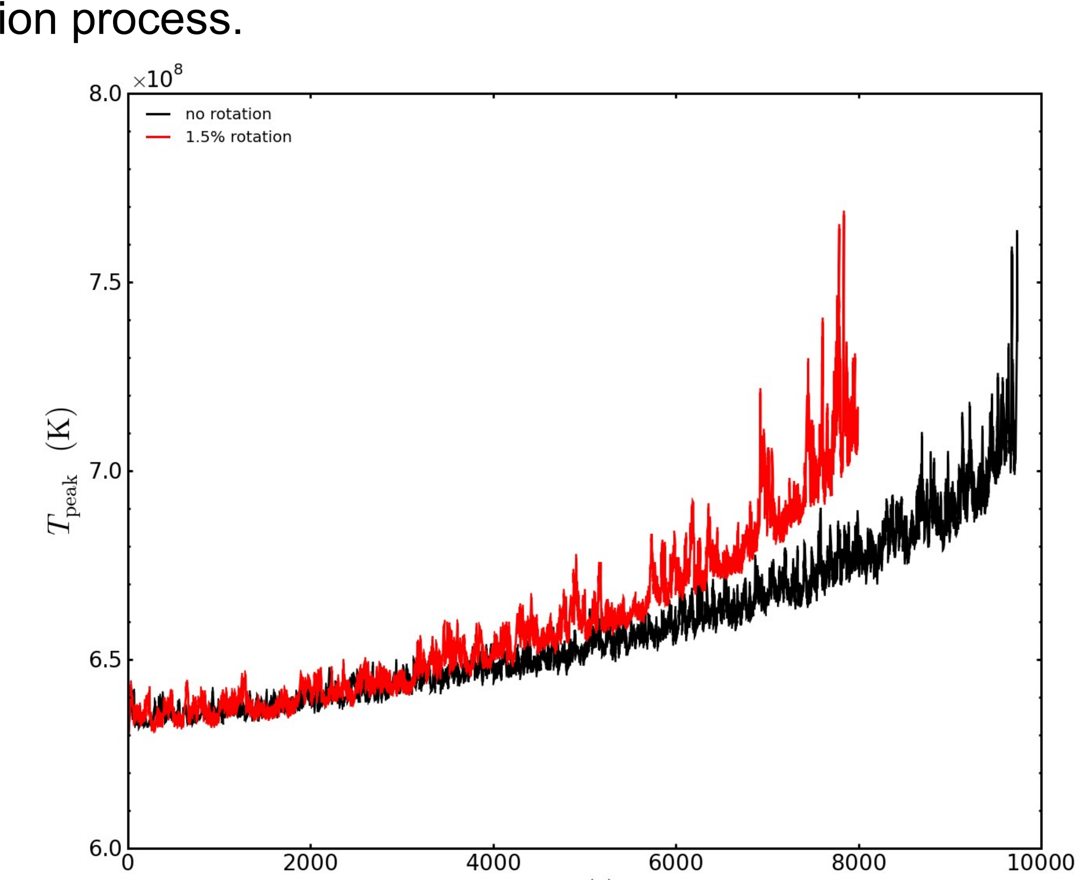


We use a general stellar equation of state with degenerate/relativistic electrons, ions, and radiation, and a simple ^{12}C + ^{12}C reaction rate.

Previously [4], we modeled the convection for the final 2 hours preceding ignition. The current calculations (in progress) use an improved advection method, better energetics, a time-dependent base state, and better coupling between the base state and the full state, and use the nuclear energy release corresponding to a more extensive network [6]. Additionally, we add the forces necessary to model rotation.

Convection Calculations with Rotation (in progress)

New calculations are exploring the effects of rotation on the ignition process.



▲ Peak temperature as a function of time for a (slowly) rotating and non-rotating white dwarf. These new calculations use better energetics, stronger coupling between the full and base states, and a time-dependent base state.

Summary

- Long timescale evolution of the convective flow preceding SNe Ia yields details of the convection and location of the first ignition points.
- Ongoing calculations are exploring the effect of rotation.
- Future parameter studies will map out the spatial distribution of the first flames.

MAESTRO: Low Mach Number Hydrodynamics

- Reformulation of compressible Euler Equations for highly subsonic flows [1,2,3,4,5]
  - Pressure decomposed into dynamic and thermodynamic components, with $\pi/p_0 \sim O(M^2)$
  - Thermodynamic pressure in hydrostatic equilibrium—defines base state, $\nabla p_0 = \rho_0 g$
- Timestep constraint based on bulk fluid velocity instead of sound speed
- Retain compressibility effects due to background stratification, thermonuclear reactions, and compositional mixing.
- Self-consistent evolution of background state due to heat release and large-scale mixing.

$$\frac{\partial(\rho X_k)}{\partial t} = -\nabla\cdot(\mathbf{U}\rho X_k) + \rho\dot\omega_k \ ,$$

$$\frac{\partial(\rho h)}{\partial t} = -\nabla\cdot(\mathbf{U}\rho h) + \frac{Dp_0}{Dt} + \rho H_{\rm nuc} \ ,$$

$$\frac{\partial \mathbf{U}}{\partial t} = -\mathbf{U}\cdot\nabla\mathbf{U} - \frac{1}{\rho}\nabla\pi - \frac{(\rho-\rho_0)}{\rho} g \mathbf{e}_r \ ,$$

$$\nabla\cdot(\beta_0 \mathbf{U}) = \beta_0\left(S - \frac{1}{\overline{\Gamma}_1 p_0}\frac{\partial p_0}{\partial t}\right) \ .$$

$$\beta_0(r,t) = \beta_0(0,t)\exp\left(\int_0^r \frac{1}{\overline{\Gamma} p_0}\frac{\partial p_0}{\partial r'}\,dr'\right)$$

$$S = \sigma\left[-\sum_k \left.\frac{\partial h}{\partial X_k}\right|_{T,p}\dot\omega_k + H_{\rm nuc}\right] + \frac{1}{\rho p_\rho}\sum_k \left.\frac{\partial p}{\partial X_k}\right|_{T,\rho}\dot\omega_k$$

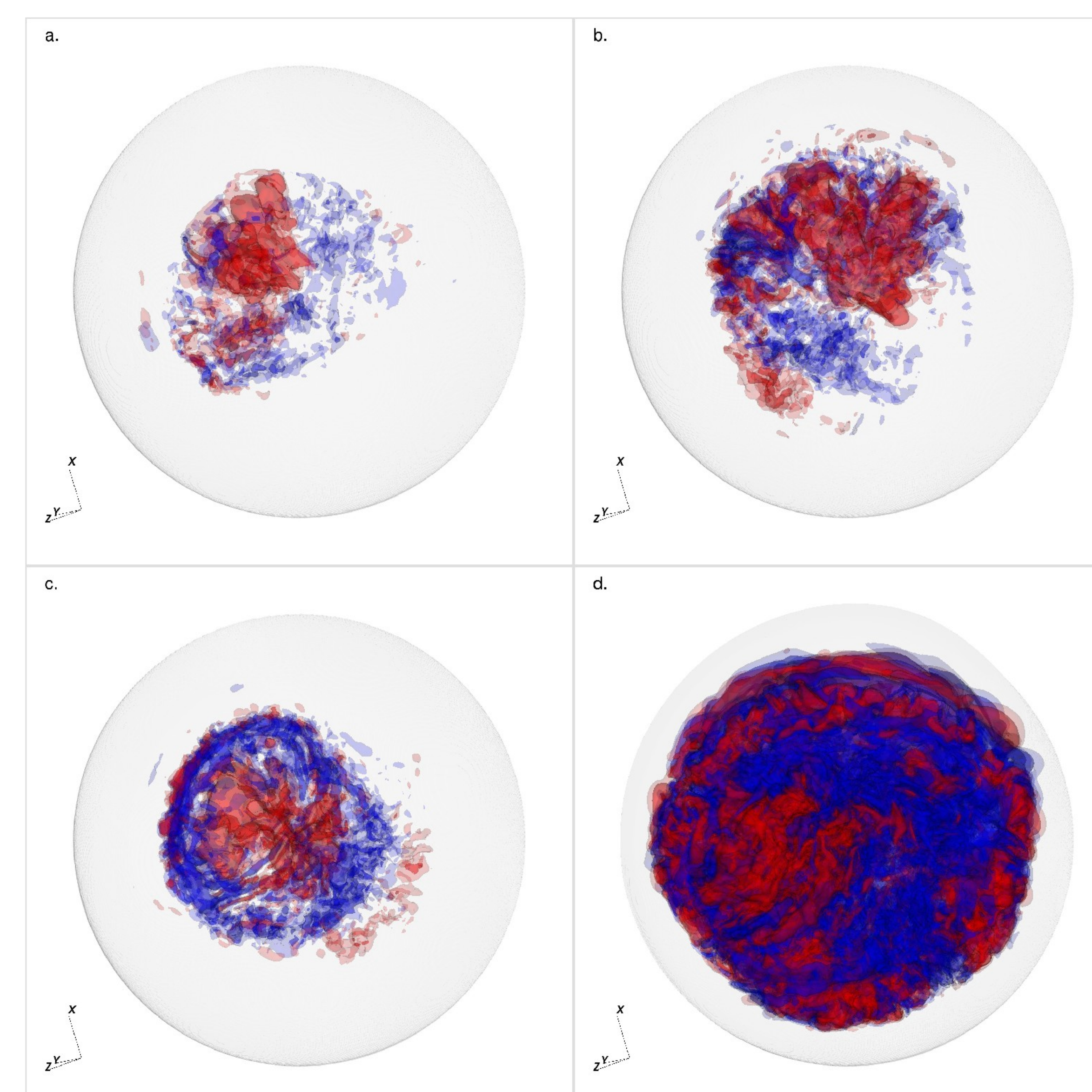
$$\sigma = \frac{p_T}{\rho c_p p_\rho} \qquad p_\rho = \left.\frac{\partial p}{\partial \rho}\right|_{T,X_k} \qquad p_T = \left.\frac{\partial p}{\partial T}\right|_{\rho,X_k}$$

(see the poster by Andy Nonaka for full details)

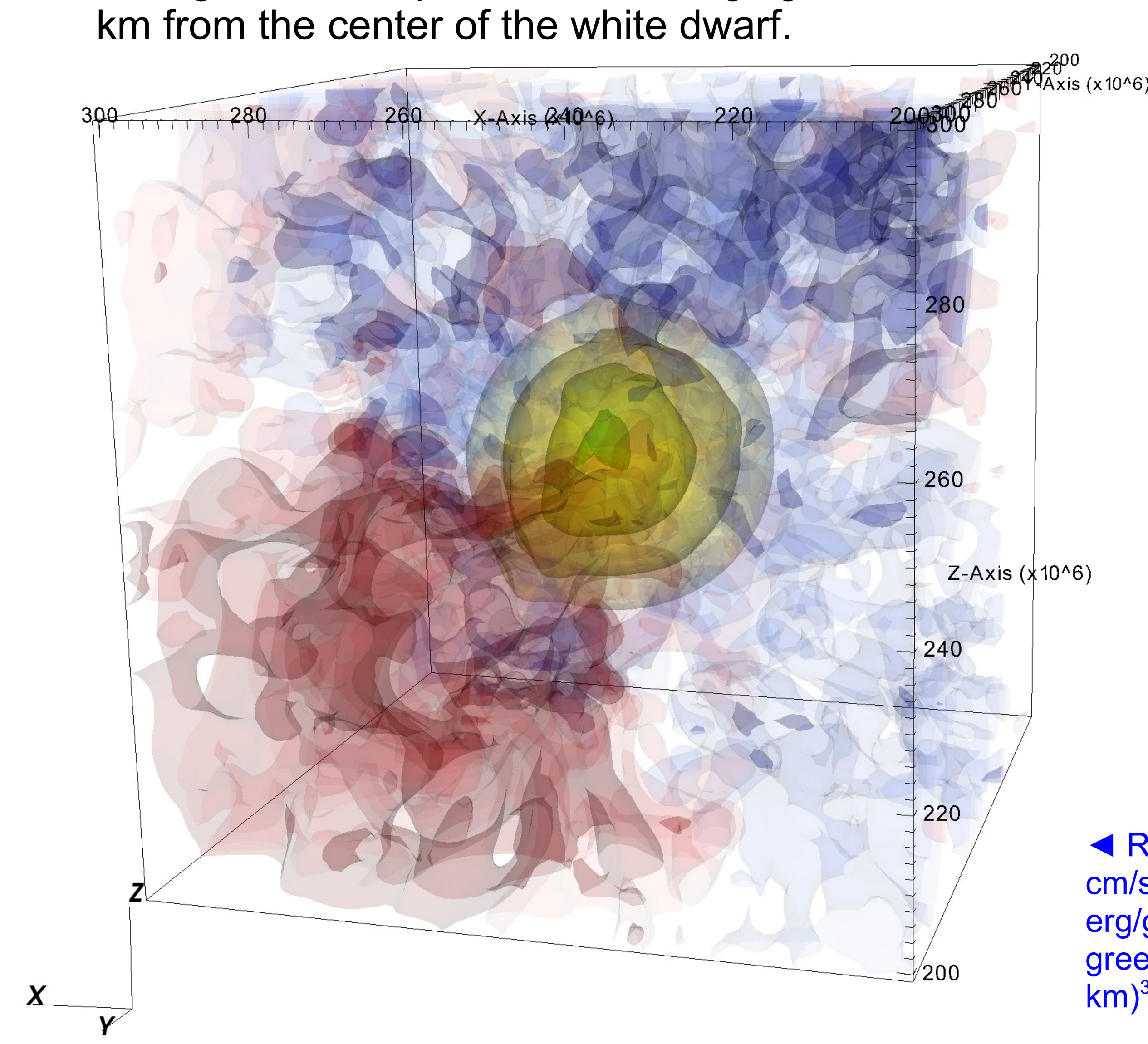
Initial Convection Calculations

Our first set of white dwarf convection calculations [4] demonstrated that MAESTRO is able to follow the convective flows for long timescales, up to the point of ignition of the first flame. These runs did not evolve the base state in time.

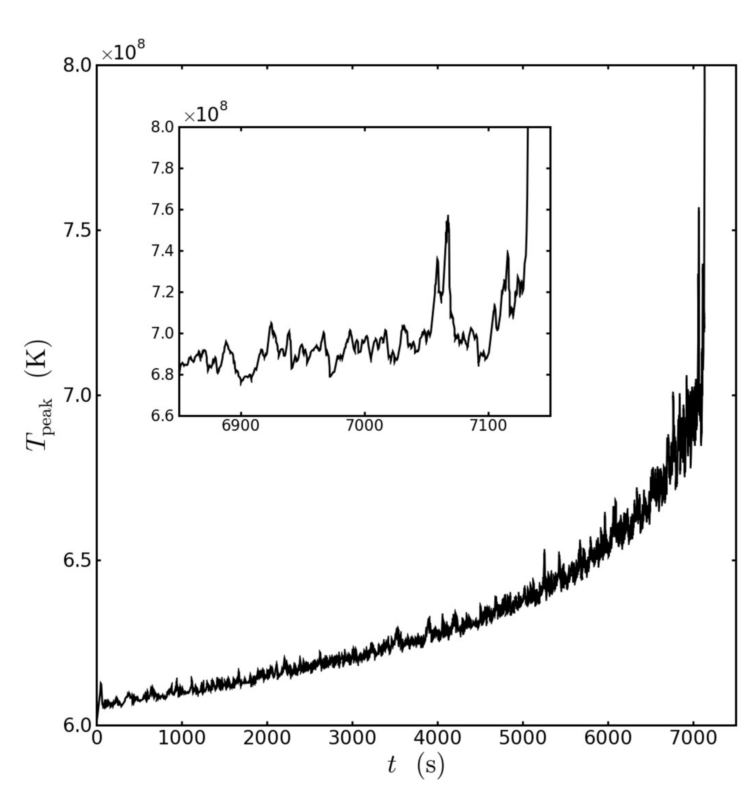
We performed several runs at varying resolution and saw ignition take place at radii ranging from 22 to 85 km from the center of the white dwarf.



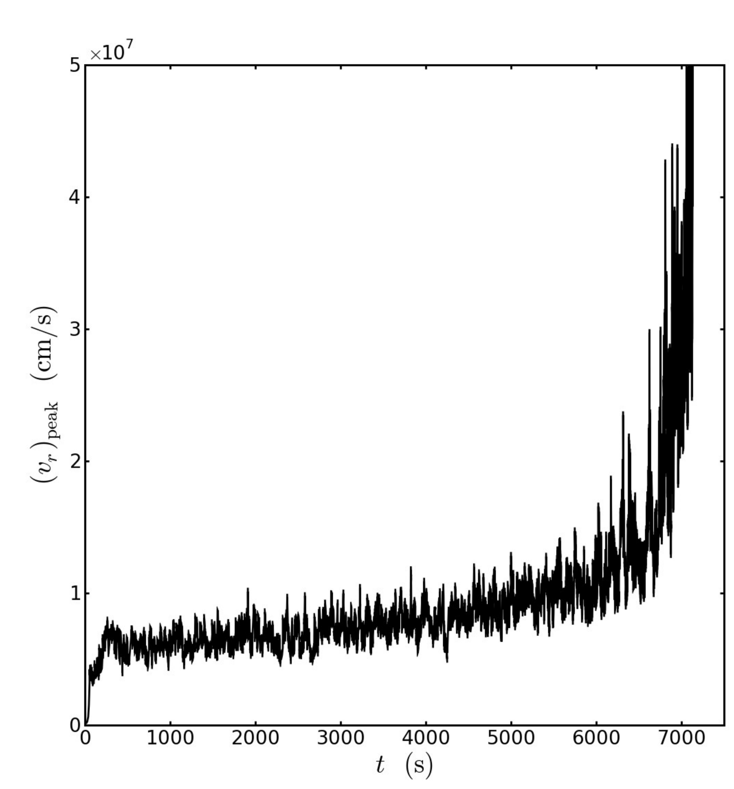
▲ Radial velocity countours (red = outward flowing; blue = inward flowing) shown at a. 800 s; b. 3200 s; c. 3420 s; d. 7131.79 s. We see the dipole-nature to the flow, first reported in [7]. The late-time behavior of the flow is a subject of our current set of calculations.



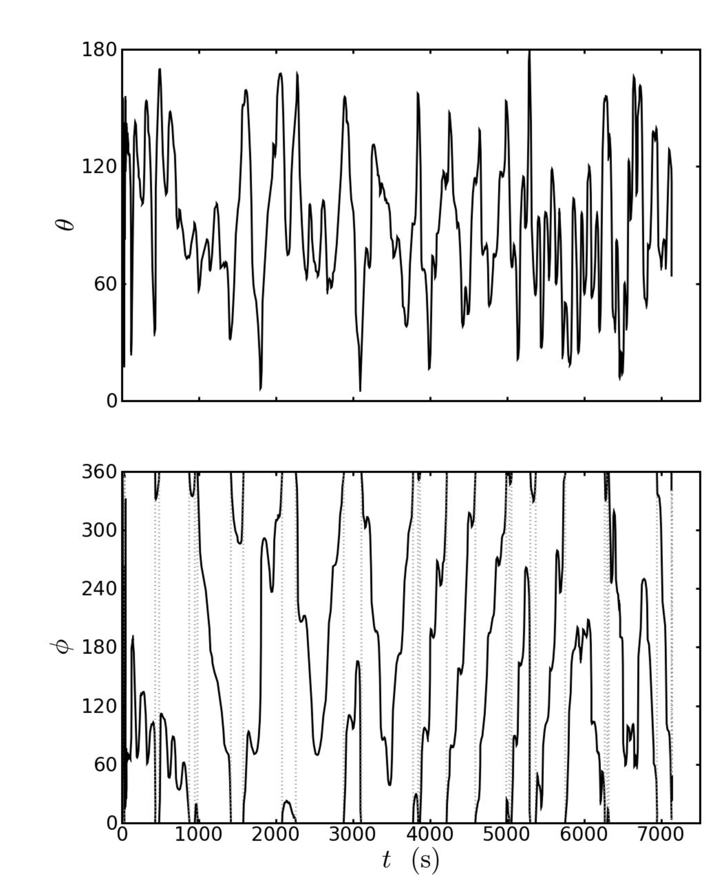
◀ Radial velocity surfaces (red: 4×10^6 cm/s and 2×10^6 cm/s; blue: -4×10^6 cm/s and -2×10^6 cm/s) and nuclear energy generation rate (yellow: 3.2×10^{12} erg/g/s; yellow-orange: 1×10^{13} erg/g/s; light green: 3.2×10^{13} erg/g/s; dark green: 1×10^{14} erg/g/s) shown 1 second before ignition. Only the inner (1000 km)^3 are shown.



▲ Peak temperature as a function of time, showing the non-linear rise leading up to ignition. The inset plot shows some hotspots fail to ignite just before the ignition of the first flame. Ignition occurs once the peak temperature exceeds ~ 800 million K.



▲ Peak radial velocity in the white dwarf as a function of time. The velocities leading up to ignition are O(10^7 cm/s), comparable to the initial laminar flame speed, indicating that the flow at the point of ignition can have an effect on the initial flame propagation.



▲ Dipole direction, in terms of spherical angles θ and φ, measured by considering the Favre-average of the radial velocity components in the convective region. The dipole direction changes rapidly with time.

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