Mechanisms for Deflagration-to-Detonation Transition (DDT) in Type Ia Supernovae and Terrestrial Systems

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Motivation

- Deflagration-to-detonation transition (DDT) remains the key unsolved problem for delayed-detonation models of SN Ia
- There has been a considerable progress in numerical modeling of DDT phenomena in terrestrial chemical systems.
- Similarities between the chemical combustion in terrestrial gaseous mixtures and the thermonuclear combustion in supernovae suggests that DDT mechanisms in these systems are also similar.
- Can we use similar approaches to study DDT phenomena in both cases?

How to initiate a detonation?

- directly by a strong shock

- through a gradient of reactivity (hot spot)

  Zeldovich's gradient mechanism: shocks form when velocity of spontaneous ignition wave = sound speed

Three stages of DDT

(1) flame evolution creates conditions for detonation initiation
(hot spots)

(2) detonation wave forms
(Zeldovich's gradient mechanism)

(3) detonation spreads into large areas
(this ensures the detonation survival)

How to create a hot spot?

Heat conduction, mass diffusion, viscous friction, compression, radiation...

DDT theories usually involve:

- Mixing hot burned and cold unburned materials (flame needs to be quenched)
- Shock compression

Mixing mechanism for DDT - Theory

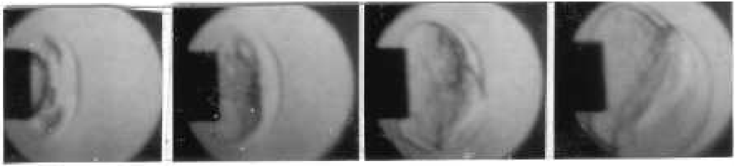
- Possible for distributed burning regimes
- Intense turbulence required
- Hot spot should be much larger than a detonation reaction zone:

  $10^2 - 10^3$ times for terrestrial systems

  $10^4 - 10^5$ times for supernovae
- Simulations require uniform 3D mesh 1000^3 cells or more

Mixing mechanism for DDT - Experiments

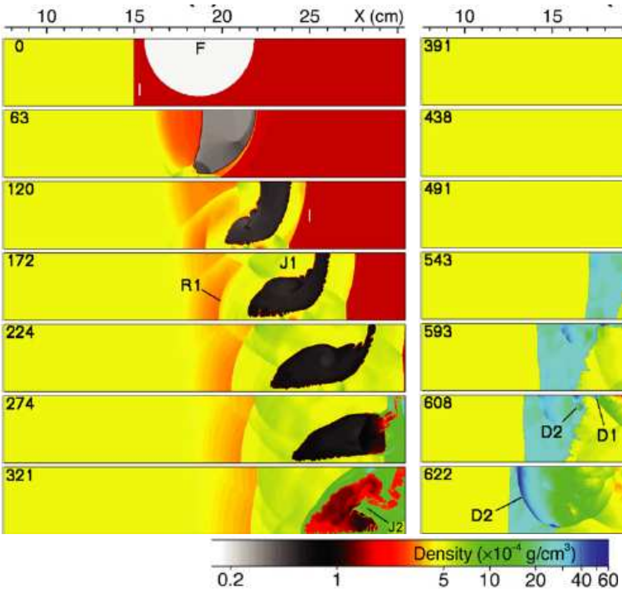
- Do not directly show that mixing occurs
- Always involve strong shocks



Thomas & Jones. *Combustion and Flame* 120:392-398 (2000)

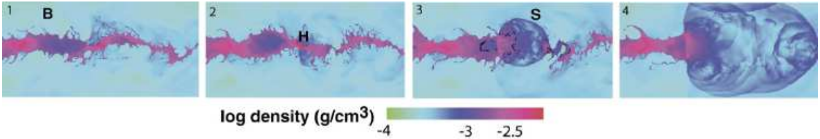
- There are no conclusive experiments that would show DDT in unconfined gaseous mixtures

Shock-flame interactions and DDT (ethylene-air mixture)



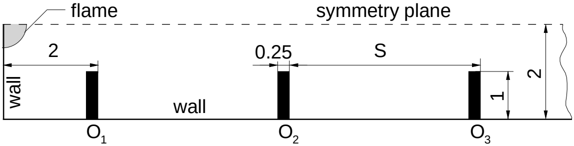
Shock-flame interactions and DDT

- Flames become turbulent (Richtmyer-Meshkov instabilities)
- Shocks accelerate
- Hot spots form in shock-compressed material (ahead of the flame and in funnels)



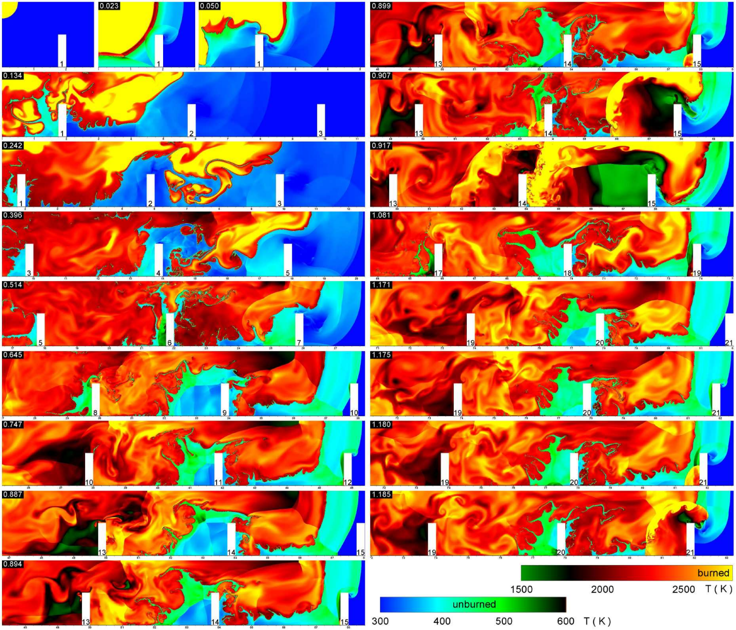
- Hot spots ignite producing new flames or detonations (Zeldovich's gradient mechanism)
- No mixing required
- Simulations reproduce experiments

Flame acceleration and DDT in channels with obstacles



- Obstacles create velocity gradients and reflect shocks
- Velocity gradients and shock-flame interactions increase the flame surface area
- Burning rate increases, shocks become stronger
- DDT occurs when a strong shock collides with an obstacle
- No mixing required
- Simulations reproduce experiments

Flame acceleration and DDT in H_2-air mixture



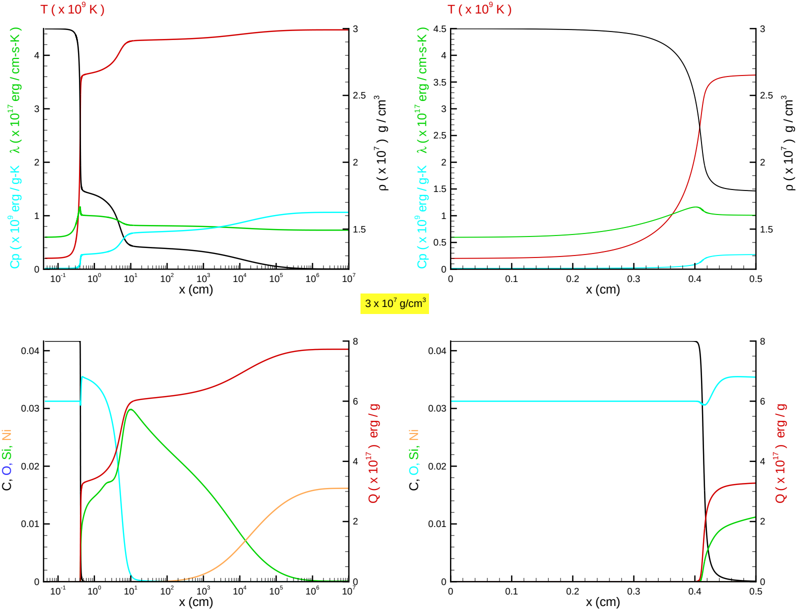
Shock-flame interactions in SN Ia ?

- Flames are turbulent and they accelerate flow

- Accelerating flows can produce shocks

- How shocks interact with a thermonuclear flame?

1D structure of a laminar thermonucler flame



3 x 10^7 g/cm^3

Conclusions

- Relatively slow oxygen burning in thermonuclear flames provids new mechanism for shock acceleration (not observed in terrestrial systems)
- Shocks that propagate through the hot and relatively thick oxygen burning zone can pick up energy
- Oxygen detonations are possible in hot material depleted of carbon
- Oxygen detonations can ignite regular carbon-oxygen detonations (for densities below $\sim 8 \times 10^8$ g/cm^3)
- Shock-flame interactions can help to create hot spots and ignite detonations in a white dwarf.