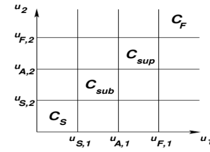
The internal structure and propagation of magneto-hydrodynamical thermonuclear flames



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Abstract

We present general equations for non-ideal, reactive flow magneto-hydrodynamics (RFMHD) in the form best suited for describing thermonuclear combustion in high-density degenerate matter of Type Ia supernovae. We analyze the relative importance of various non-ideal effects as a function of characteristic spatial and temporal scales of the problem. From the general RFMHD equations, we derive the one-dimensional ordinary differential equations describing the steady-state propagation of a planar thermonuclear flame front in a magnetic field. We consider two physical models to solve the governing set of equations, calculate internal flame front structure, and find the flame velocities, S_l and thicknesses, δ_l.

The idealized model – Assumes one-step Arrhenius kinetics, a perfect gas equation of state, and constant thermal conductivity coefficients.

The supernova model -- Treats carbon-oxygen degenerate material of supernovae using a realistic equation of state, transport properties, and detailed nuclear kinetics.

The magnetic field changes the flame behavior significantly as compared to the non-magnetic case of classical combustion. **(1)** The magnetic field influences the evolutionarity of a flame front and makes it impossible for a flame to propagate steadily in a wide range of magnetic field strengths and orientations relative to the front. **(2)** When the flame moves steadily, it can propagate in several distinct modes, the most important being the slow C_S and the super-Alfvenic C_{sup} modes. **(3)** The speed of the flame can be diminished or enhanced by up to several factors relative to the non-magnetic laminar flame speed.

Why magnetic fields?

Close to 10% of observed white dwarfs (WDs) have surface magnetic fields H > 10^6 G and even more of them show H > 10^3 G (Jordan et al. 2007). It is unknown if strong surface fields extend into the central parts of WDs, but it seems plausible that some non-zero magnetic field may also exist in WD interiors. Seed magnetic fields in WDs exploding as SNe Ia may be amplified by convection and turbulence immediately before as well as after the ignition.

Single-degenerate scenario – Assuming equipartition, the field may be amplified up to H = 10^{12} G during convective smoldering which precedes the ignition, and may be further amplified up to H = 10^{13} G during the stage of turbulent deflagration (Remming & Khokhlov 2014).

Double-degenerate scenario – A magnetic field of the order of H = 10^9 - 10^{10} G may be generated by the magnetorotational instability (MRI) in the disk formed during the merger (e.g. Ji et al. 2013). The field may be further amplified during smoldering and deflagration if the explosion is delayed until the solidly rotating core of the merger object approaches the Chandrasekhar mass limit and ignites near the center.

Method

To calculate the flame internal structure and to find the flame velocity, we integrate the set of 1D ordinary differential equations that describe the steady-state propagation of flame fronts in a magnetic field. We use iterative trial and error to find the flame speed. The problem is subject to the following boundary conditions.

$$z = -\infty : V = V_1, \quad T = T_1, \quad Y = Y_1.$$

$$z = \infty : \quad \frac{dT}{dt} = \frac{dV}{dt} = \frac{dY}{dt} = 0.$$

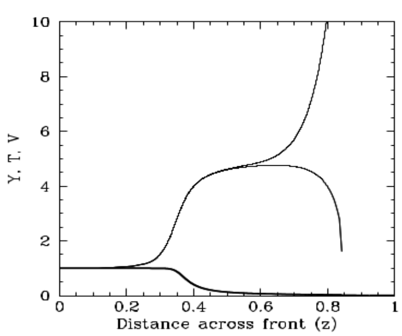
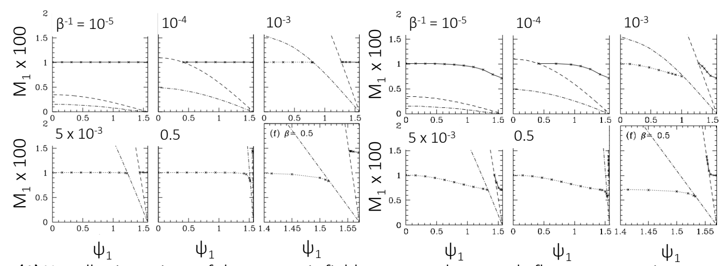


Fig 1. Illustration of the trial and error procedure. For a candidate speed less than (greater than) the actual flame speed, the temperature, T, and volume, V, integral curves diverge downward (upward). Only for the exact flame speed are the integral curves stationary in the products of burning.

Results – idealized model

Fig 2. Plot of laminar flame solution points on the $M_1 - \psi_1$ plane for various field strengths with $\alpha = \kappa_{perp} / \kappa_{para}$ = 1.0 (left) and 0.5 (right) (super-Alfvenic solutions are connected with solid lines and slow solutions with dashed lines).



(1) Not all orientations of the magnetic field accommodate steady flame propagation; a fact that is unique to MHD combustion. **(2)** For large field strengths and large field orientations the steady flame solution speed is above the non-magnetic laminar speed by several factors.

Results – supernova model

Fig 3. The flame in general propagates due to the electron and photon heat conduction. The electron heat conduction dominates at high densities $\rho_1 > 10^9$ g cm^{-3}. At lower densities the heat conduction is dominated by photons with photon scattering off electrons being the main source of the photon opacity. The free-free contribution to the opacity inside the flame is largely insignificant. At high densities the angle-dependence of the electron heat conductivity leads to flame propagation anisotropy.

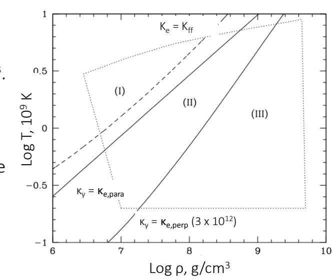


Fig 4. $0.5C^{12} + 0.5O^{16}$, $T_1 = 10^8$ K. $\rho_1 = 10^7$ g cm^{-3} (left) and $\rho_1 = 3 \times 10^9$ g cm^{-3} (right).

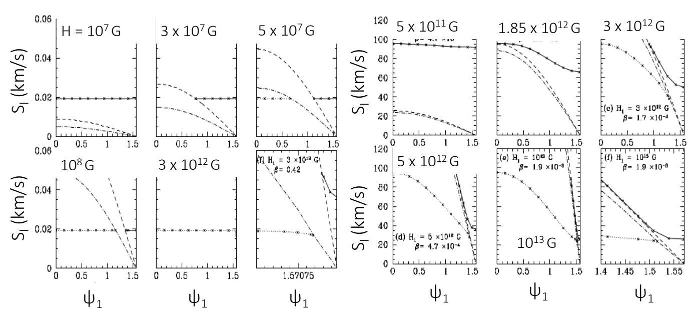
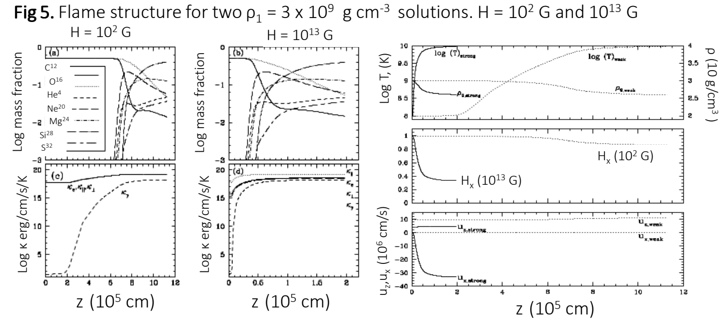


Fig 5. Flame structure for two $\rho_1 = 3 \times 10^9$ g cm^{-3} solutions. H = 10^2 G and 10^{13} G



Subgrid modeling

Our results show that for a magnetized explosion, the laminar flame speed is a function of not only temperature, density, and composition but also of the magnetic parameters. In the high density core of the white dwarf, the laminar flame speed will be suppressed by the magnetic field, which will slow the energy release rate and expansion in the initial stages of the explosion. In the outer layers, where the material is less dense, the magnetic field may lead to laminar flame acceleration, speeding up the burning rate. The higher speed, in comparison to the non-magnetized laminar flame speed, will compete more effectively with the turbulent Rayleigh-Taylor flame speed, perhaps leading to less wrinkling of the flame surface on resolved scales. The rate and magnitude of flame surface wrinkling in turn affect the global properties of the explosion.

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