Understanding Ignition in Type Ia Supernovae

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1 Ignition and Type Ia Supernovae

A Type Ia supernova (SNde Ia) is the thermonuclear explosion of a carbon/oxygen white dwarf—the dense remnant of low-mass stellar evolution. For many years, the standard model for these explosions was a binary system with a white dwarf approaching the Chandrasekhar mass (the maximum mass of a white dwarf, beyond which degenerate electrons cannot support the star against collapse). In this model, as the white dwarf continues to gain mass, the increase in temperature and density at the center ignites carbon fusion reactions which further heat the interior and drive convection throughout. Heated fluid parcels buoyantly rise and cool by expanding in the stratified stellar background. Eventually the reactions proceed so vigorously that expansion cannot quench the burning and a burning front is formed. This front propagates through the white dwarf in seconds, releasing enough energy to unbind the star.

Observations show a diversity amongst SN Ia and their host galaxies, and alternate models have begun to gain favor. Merging white dwarfs and a single, sub-Chandrasekhar mass white dwarf in a binary system are currently the most popular alternatives. In the sub-Chandra model, again a single white dwarf accretes from a companion, but now the white dwarf is much lower in mass. Over time, a helium layer builds up and if the conditions are right, a detonation can ignite in this layer, driving a shock into the carbon/oxygen core and igniting this core via compression (see, e.g., [1]), again leading to enough energy release to unbind the star. As with the Chandrasekhar model, convection dominates the early evolution of this system, and the number of ignition points and the potential for detonation is set by the conditions in this helium layer. In the merging white dwarf scenario, the stars inspiral as orbital energy is lost via gravitational radiation. As they get closer, the lower mass object can become tidally disrupted, leading to accretion onto the more massive object, and potentially to an explosion.

We focus on the Chandra and sub-Chandra models. In both of these models, turbulence dominates the convective flows, with typical Reynolds numbers in the white dwarf $\mathcal{O}(10^{14})$ [2]. The pressure of a degenerate gas is only very weakly sensitive to temperature, so a lot of energy can be deposited into the star without it expanding in response. Furthermore, the nuclear reaction rates that govern the burning are extremely temperature sensitive, $\sim T^{40}$ for helium burning, so small temperature fluctuations in the convective background can be amplified easily in the run-up to ignition. These properties set the stage for explosion.

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There are phases in both models where turbulent deflagrations and detonations are important, so understanding how these burning fronts ignite and propagate through the star is key to understanding SN Ia. Over the years, a strong connection between the astrophysics community and the terrestrial combustion community has helped advance the state of the field.

2 Methodology

To explore the ignition process in both the Chandrasekhar-mass and sub-Chandra models, we perform high-resolution three-dimensional simulations of the convection and burning in the last hours leading up to the explosion [3–5]. Our simulation code, Maestro [6], is optimized to efficiently model highly subsonic flows by filtering soundwaves from the equations of hydrodynamics while retaining the compressibility effects due to localized heat release, compositional mixing, and the background stratification of the star.

Our goal in these simulations is to understand the spatial and temporal location of the hotspots that lead to the ignition of the burning front in SN Ia. Coupled with subsequent explosion models (e.g., [7]), the hope is that this "end-to-end" modeling of convection-ignition-explosion can help us understand which of these progenitor models can be realized in nature.

3 Results

Our simulations of the Chandra model have shown that the ignition of the burning front likely takes place off-center and at a single point. Analysis of the timescales involved suggest that there is not enough time for a second ignition to take place before the explosion. The off-center ignition suggests that the explosion could be asymmetric, which may produce observational signatures. The turbulent velocity field in the convective zone at the time of ignition is too weak to significantly alter the flame structure, but large-scale jet-like features through the center of the star can be important in setting the ignition radius.

Our investigation of convection in the helium layer on sub-Chandra mass white dwarfs is currently underway. In the Chandra model, the convection is driven by reactions at the center of the star, and extends throughout the inner half (in radius) of the star. In contrast, in the sub-Chandra model, the convection takes place in a surface layer, thinner than the radius of the underlying white dwarf. This wide aspect ratio of the convection zone breaks the convective flow into cells. A wide variety of outcomes are seen, depending on the mass of the helium layer and white dwarf. Analysis underway will determine how far above the base of the helium layer ignition takes place. as well as how many potential ignition points exist.

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