Thermonuclear Supernovae: Stellar Explosions in Three Dimensions

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Type Ia supernovae are one class of stellar explosions that are among the most powerful explosions in the Universe. These events play an important nucleosynthetic role in galactic chemical evolution as well as an crucial role in the study of cosmology, where they are used as "standard candles" to determine distance. These events are thought to be thermonuclear explosions of white dwarfs, one type of compact stars, composed principally of carbon and oxygen.

The exact nature of the explosion mechanism remains unsolved issue, but observations of intermediate-mass elements such as silicon, sulfur, and magnesium in these events indicates that the thermonuclear burning must begin as a deflagration. Consequently, most models involve either a pure deflagration or a transition from a deflagration to a detonation. The disparate length scales of the 4000 Km diameter white dwarf and the cm scale nuclear flame prevent direct numerical simulation of these events, so simulations require the development of a subgrid model for the deflagration.

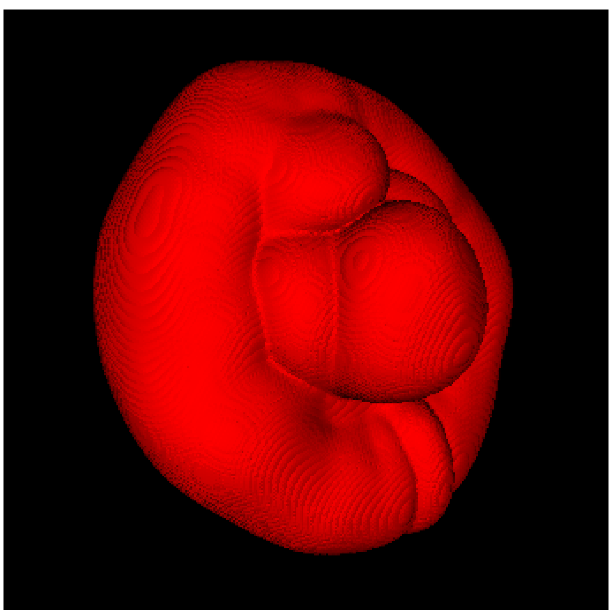

Figure 1: Image of the rising bubble of magnesium resulting from an initially off-center carbon deflagration in a carbon/oxygen white dwarf. Shown is an isosurface of magnesium abundance.

We are currently carrying out state-of-the-art full star simulations using large ASCI systems (Frost, QSC). All of the multidimensional Type Ia models calculated to date rely on some sort of subgrid model for the evolution of the thermonuclear burning front. It is believed that such fronts are subject to Rayleigh-Taylor instability while they propagate from the stellar core to the surface. This instability causes the flame to increase its surface and results in increased effective speed of flame propagation. This increase in speed, however, has a dramatic consequence on the Rayleigh-Taylor instability: if the flame is moving too quickly there is not enough time for the perturbations to grow and the flame surface cannot grow anymore. This self-regulation mechanism was first observed in numerical simulations in the late 1990s. Current state-of-the-art models, with twice the resolution (2.5 km) of the first models (5 km) but still limited to only one octant of the whole star, provided the first indication that the self-regulation mechanism might be robust.

These whole-star simulations of deflagrating white dwarfs are performed with the FLASH code, a parallel adaptive-mesh multi-physics code for the study of many astrophysical phenomena [1]. The FLASH code solves the Euler equations for compressible flow and the Poisson equation for self-gravity. A recent addition to the code is a flame capturing scheme ("thick flame" model) for the sub-grid-scale nuclear flames. The model is a custom implementation following the recipe of Khokhlov [2]. The evolution of the flame is determined by the evolving a passive scalar variable with an advection-diffusion-reaction equation. A step-like reaction profile is adopted and reaction and diffusion coefficients are chosen to reproduce the results of direct numerical simulation of the laminar and turbulent nuclear flames. Specifically, the flame speed is determined as the maximum of the laminar flame speed [3] or a turbulent flame speed based on the assumption that the turbulent burning on macroscopic scales is driven by the Rayleigh-Taylor instability [2].

We present three-dimensional simulations of deflagrating white dwarfs in which the carbon deflagration starts deep in the stellar core. These full three-dimensional models allow us to investigate the problem of the ignition mechanism (by varying the way burning is initiated) and constrain existing analytic and theoretical models. In particular, we present a model in which the ignition point is placed slightly off-center. We demonstrate that such an initial configuration leads to a result that is not compatible with observations and provides strong constraints on the conditions persisting in the central region of the white dwarf prior to the ignition.

References

[1] Fryxell, B., et al. 2000, ApJS, 131, 273

[2] Khokhlov, A. M., 1995, ApJ, 449, 695

[3] Timmes, F. X. & Woosley, S. E., 1992, ApJ, 396, 649