Low Mach Number Simulations of Type Ia Supernovae

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Summary

Low Mach number modeling of Type Ia supernovae has enabled new understanding of fundamental issues in these large thermonuclear explosions. Recent small-scale simulations have explored the mechanisms by which a flame can accelerate through the star and release sufficient energy to unbind the star. New methodology has also been developed to explore the question of how ignition first happens, following almost a century of full-star convection. This methodology will enable us to span the space and time scales necessary to address this and other fundamental questions about Type Ia supernovae.

Type Ia supernovae are the largest thermonuclear explosions in the universe. Their light output can be seen across great distances and their use as "standard candles" has led to the discovery that the expansion rate of the universe is accelerating. The standard theoretical picture of a Type Ia supernova is the thermonuclear explosion of a carbon/oxygen white dwarf that accretes material from a companion star. When the mass of the white dwarf exceeds a certain critical value, the temperature of the star in its interior rises to the point that carbon begins to fuse. For the first century or so, the energy release from this thermonuclear burning is balanced by convection and local cooling. Eventually, however, the balance can no longer be maintained and ignition occurs.

Precisely where and how this ignition occurs is still an open question. Numerical simulation of this phenomenon requires long-time simulation of the "smoldering" convective flow that precedes ignition as well as the ignition process itself.

Conventional numerical approaches can be used to model either the long-time convection or the accelerated flame front immediately before explosion, but cannot be efficiently used to find out what happens in-between: how ignition occurs, and how the resultant small-scale flames become powerful enough to explode the star.

In collaboration with Stan Woosley (UCSC) and Mike Zingale (SUNY-SB) we are developing low Mach number methodology that allows us to exploit the separation of scales inherent in this type of physical phenomenon. During the time period of interest, both the flame and the stellar material itself move much more slowly than the sound waves that carry information throughout the star. Asymptotic expansion in Mach number, the ratio of fluid velocity to sound speed, allows us to eliminate sound waves from the mathematical formulation and separate the dynamic motions of the stellar material from the slow variation of the hydrostatic background state. A numerical method based on this separation

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of scales enables us to simulate the flow for a longer physical time using less computational time than with a conventional method. Low Mach number methods have been applied to other fluid dynamical problems such as incompressible flows and low speed combustion, but their potential has yet to be realized for stellar dynamics.

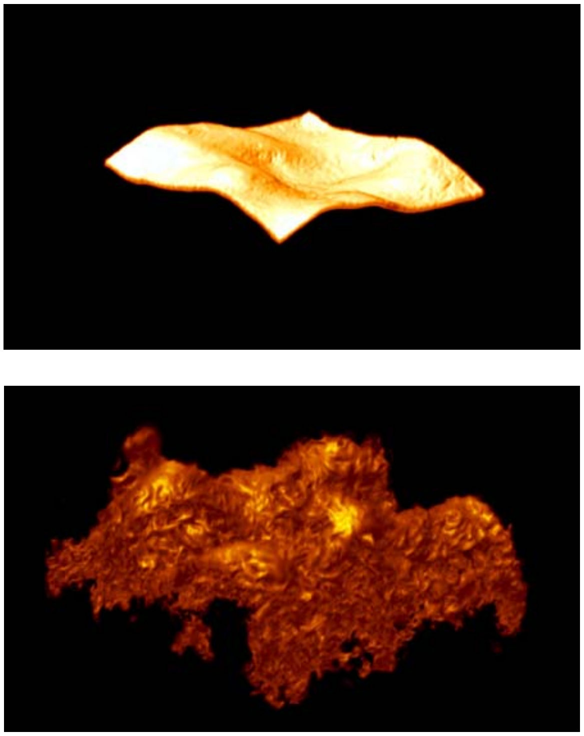

Figure 1. Three-dimensional turbulent flames at higher (top) and lower (bottom) ambient densities; lower density corresponds to increased distance from the center of the star.

There is a large range of spatial scales as well; the regions of ignition and resulting flamelets are very small on the scale of the entire star. We use adaptive mesh refinement in order to focus our computational effort on the regions where the interesting phenomena are occurring. The combination of the low Mach number approach and adaptive mesh refinement allows a sufficient increase in computational efficiency that we have been able to tackle problems previously inaccessible using conventional methods.

Figure 1 shows snapshots from two recent calculations demonstrating different types of burning that occur in a Type Ia supernova. Near the interior of the star the flame surface appears relatively smooth. As the flame progresses radially outward it encounters lower density material and the flame transitions into the distributed burning regime, characterized by a much more wrinkled flame surface. This simulation addresses the question of whether the deflagration transitions to detonation before the star unbinds.

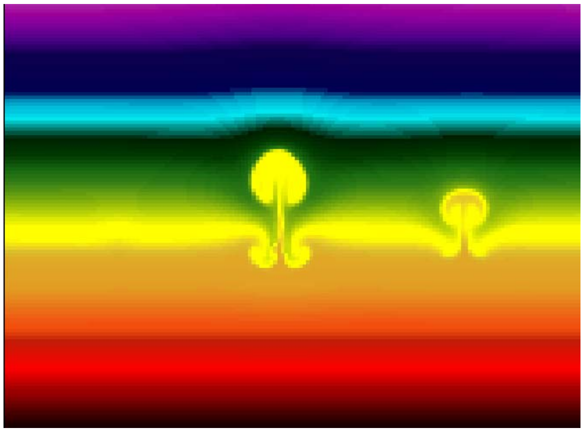

Figure 2. "Hot spots" within a heated layer generate plumes that rise above the heated layer in this two-dimensional slice of a region of the star.

Figure 2 shows a snapshot of a two-dimensional calculation of the beginning of ignition. Here a horizontal layer is heated uniformly with the exception of several "hot spots". The entire star expands due to the uniform heating, and the "hot spots" generate buoyant plumes that rise through the star. This simulation begins to address the question of how and where ignition is likely to occur.

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