Three-Dimensional Simulations of Thermonuclear Supernova Explosions

V. N. Gamezo, A. M. Khokhlov, E. S. Oran, and A. Y. Chtchelkanova*

Laboratory for Computational Physics and Fluid Dynamics Naval Research Laboratory, Washington, D.C. 20375, USA *Strategic Analysis Inc., Arlington, VA 22201, USA

Contact e-mail: gamezo@lcp.nrl.navy.mil

Key words: supernova, turbulent flame, deflagration, detonation, numerical simulations.

Thermonuclear explosions that produce type Ia supernovae (SNe Ia) [1] occur when a degenerate carbonoxygen star, called a white dwarf (WD), increases its own mass by attracting the material from outer layers of a companion star and approaches the Chandrasekhar limit, 1.4 solar masses. Near this limit, any small mass increase results in substantial contraction of the WD. The compression increases the temperature, accelerates nuclear fusion reactions, and eventually ignites a thermonuclear burning near the WD center. This starts a thermonuclear explosion that lasts only a few seconds, but releases $\simeq 10^{51}$ ergs, about as much energy as the Sun would radiate during 8 billion years. The energy is produced by a network of thermonuclear reactions that begins from original ¹²C and ¹⁶O nuclei and ends in ⁵⁶Ni and other iron-group elements. Considerable amounts of intermediate-mass elements, such as Ne, Mg, Si, S, Ca, are created as well. The reaction kinetics is well known from experiments in particle accelerators and theory.

The main energy-producing reactions occur in a thin layer, called a thermonuclear flame. At the beginning of the explosion, the flame is laminar and its propagation velocity is defined by reaction rates and transport properties of the material, and governed by the same laws that describe laminar flame structure in terrestrial chemical systems. The only substantial difference is that transport properties of degenerate matter are dominated by the electron heat conduction that controls the flame propagation. As the flame moves away from the center, it becomes turbulent and accelerates. At the same time, the WD expands due to the energy release. Eventually, the deflagration can transition to a detonation. The physics of deflagration-to-detonation transition in supernovae seems to be the same as in unconfined terrestrial chemical systems, but it is still not well understood in either case.

General ideas about possible explosion mechanisms have been extensively tested using one-dimensional (1D) numerical models [2-7] of SNe Ia. Delayed-detonation models [8-14], that postulate a deflagration-todetonation transition (DDT) at some stage of the thermonuclear explosion, are most successful in reproducing observed characteristics of SNe Ia. Many important details, however, including the mechanism of DDT, are still unknown because SN Ia explosions are intrinsically three-dimensional (3D) phenomena. Only a fullscale 3D numerical model can reproduce all key features of the explosion that involves propagation of a turbulent thermonuclear flame in the gravitational field of a WD. Building such a model is a complicated interdisciplinary problem on the leading edge of astrophysics, nuclear physics, combustion physics, and computational physics. Full-scale 3D numerical simulations of thermonuclear supernova explosions have become a reality during the last few years [15-17], in great part owing to the progress in computational technology.

This work presents the results of 3D simulations performed using the NRL supernova model [15,17]. The model is based on reactive Euler equations coupled with an equation of state for a degenerate matter and a simplified kinetics of energy release. The energy-release model provides the correct propagation velocity for a laminar flame and takes into account carbon burning, as well as nuclear statistical quasi-equilibrium and equilibrium relaxations. The simulations do not resolve the physical thickness of a laminar flame, which differs from the WD radius by up to 12 orders of magnitude. The flame is advanced using a flame-capturing technique that insures propagation of a flame front with a prescribed normal speed. The model for the turbulent burning on scales that are not resolved in the simulations is based on the assumption that burning on small scales is driven by the gravity-induced Rayleigh-Taylor (RT) instability [18,19]. A convergence study shows that at high resolutions, the results become practically independent on the computational cell size dx and insensitive to subgrid model parameters.

The initial conditions for the simulations were set up for a Chandrasekhar-mass WD in hydrostatic equilibrium with the initial radius $R_{WD} = 2 \times 10^3$ km, the initial central density $\rho_c = 2 \times 10^9$ g/cm³, the uniform initial temperature $T = 10^5$ K, and the uniform initial composition with equal mass fractions of 12 C and 16 O nuclei. The burning was initiated at the center of WD by filling a small spherical region at $r < 0.015 R_{WD}$ with hot reaction products without disturbing the hydrostatic equilibrium. We model one octant of the WD assuming mirror symmetry along the x = 0, y = 0 and z = 0 planes.

The simulations show that the flame becomes unstable due to buoyancy effects and develops multiple plumes characteristic of the RT instability. The flame plumes continue to grow, due partially to the flame propagation and partially to gravitational forces that cause the hot, burnt, low-density material inside the plumes to rise towards the WD surface. The same gravitational forces also pull the cold, high-density unburnt material between the plumes down towards the center. The resulting shear flows along the flame surface are unstable (Kelvin-Helmholtz (KH) instability) and quickly develop vortices. These vortices further distort the flame surface, and also contribute their energy into the turbulent cascade that creates turbulent motions at smaller scales, down to a few dx.

When the original flame plumes grow large enough, secondary RT instabilities develop on their surface,

thus producing the next level of "mushrooms" that also grow and may become subject to the RT instability at a smaller scale, etc. These smaller gravity-induced mushrooms interact with the turbulence created by the previous generation of larger flame plumes, and also produce some turbulence themselves through the KH instability. The resulting complicated turbulent flame surface is shown in Fig. 1.

As the turbulent flame develops, the energy released by the thermonuclear burning causes the WD to expand. The expansion accelerates and becomes nonuniform as the rising plumes approach the star surface. We continued the simulations until the star surface reached the computational domain boundary. The resulting star surface and the radial velocity field at 1.88 s are shown in Fig. 1. By that time, the radius of the expanding star increased by about a factor of 2.6, the outer layers accelerated to about 1.2×10^4 km/s, and the density of unburnt material near the star center decreased to about 5×10^7 g/cm³. The area around the center still contains a significant amount of unburnt material that sinks at 10^3 km/s towards the center between large flame plumes. The velocity of the large flame plumes is essentially zero relative to the expanding matter, that is, the plumes have practically stopped rising. This effect of freezing of the RT-instability on large scales due to expansion is also related to freezing of large-scale turbulence [18].



Figure 1. Star surface and radial velocity field (left) and turbulent flame surface (right) for an exploding white dwarf at 1.88 seconds after ignition. Half of the material is burned. Minimum computational cell size 2.6 km. Computational domain contains 10^8 cells.

From the point of view of astronomical observations, the unburned carbon and oxygen that remain between the flame plumes near the WD center should produce spectral signatures at expansion velocities close to zero. Analyses of SN Ia spectra, however, imply C and O only at high velocities, as would be produced by the acceleration of expanding outer layers.

We thus conclude that the deflagration model of a SN Ia explosion is incomplete. The most natural solution to this problem that would make the results consistent with observations would be to assume that the turbulent flame triggers a detonation. A thermonuclear detonation wave could propagate through the WD with velocities $\sim 10^4$ km/s [20,21] and would quickly burn all the material near the center leaving only the low-density outer layers unburnt.

References

- 1. J. C. Wheeler, Am. J. Phys., 71, 11 (2003)
- 2. W. D. Arnett, Astrophys. Space Sci. 5, 180 (1969)
- 3. C. J. Hansen, J. C. Wheeler, Astrophys. Space Sci. 3, 464 (1969)
- 4. K. Nomoto, D. Sugimoto, S. Neo, Astrophys. Space Sci. 39, L37 (1976)
- 5. K. Nomoto, F.-K. Thielemann, K. Yokoi, Astrophys. J. 286, 644 (1984)
- 6. S. E. Woosley, T. A. Weaver, Annu. Rev. Astron. Astrophys. 24, 205 (1986)
- 7. J. C. Wheeler, R. P. Harkness, A. M. Khokhlov, P. A. Höflich, Phys. Rep. 256, 211 (1995)
- 8. A. M. Khokhlov, Astron. Astrophys. 245, 114 (1991)
- 9. H. Yamaoka, K. Nomoto, T. Shigeyama, F.-K.Thielemann, Astrophys. J. 393, L55 (1992)
- 10. A. M. Khokhlov, E. Müller, P. A. Höflich, Astron. Astrophys. 270, 223 (1993)
- 11. D. Arnett, E. Livne, Astrophys. J. 427, 315; 330 (1994)
- 12. P. A. Höflich, Astrophys. J. 443, 89 (1995)
- 13. P. A. Höflich, A. M. Khokhlov, J. C. Wheeler, Astrophys. J. 444, 831 (1995)
- 14. P. A. Höflich, A. M. Khokhlov, Astrophys. J. 457, 500 (1996)
- 15. A. M. Khokhlov, http://www.arxiv.org/astro-ph/0008463 (2000)
- 16. M. Reinecke, W. Hillebrandt, J. C. Niemeyer, Astron. Astrophys. 386, 936; 391, 1167 (2002)
- 17. V. N. Gamezo, A. M. Khokhlov, E.S. Oran, A.Y. Chtchelkanova, R.O. Rosenberg, Science 299, 77 (2003)
- 18. A. M. Khokhlov, Astrophys. J. 449, 695 (1995)
- 19. A. M. Khokhlov, E. S. Oran, J. C. Wheeler, Combust. Flame 105, 28 (1996)
- 20. A. M. Khokhlov, Mon. Not. R. Astron. Soc. 239, 785 (1989)
- 21. V. N. Gamezo, J. C. Wheeler, A. M. Khokhlov, E. S. Oran, Astrophys. J. 512, 827 (1999)