Detonation Criteria in the GCD Model of Type Ia Supernovae

Ivo R. Seitenzahl[1,2], Casey A. Meakin[3,4], Don Lamb[2,3,4],
George C. Jordan[3,4], Dean Townsley[1,4], James Truran[1,4,5]
[1]JINA, [2]Enrico Fermi Institute, University of Chicago, [3]The Center for Astrophysical Thermonuclear Flashes,
[4]The Department of Astronomy & Astrophysics, University of Chicago, [5]Argonne National Labs

Gravitationally Confined Detonations (GCD). A new mechanism for Type Ia supernova explosions in massive white dwarfs has been developed at the Flash Center [1,2], based on work using the multi-physics modeling capabilities of the Flash Code [3]. The sequence of simulation images to the right depicts the sequence of events following the breakout of a deflagration bubble. The ejecta remains gravitationally bound, sweeps around the star, compresses at the antipodal point of breakout, and compresses the unburnt surface layers of the star, producing a high-temperature flow that penetrates upward into the star, reaching densities of 10^7 g cm^{-3} [4,5].

Initiation of Detonation. An essential element in the GCD model is the triggering of a detonation by the converging flow that occurs at the pole of the white dwarf (Fig. 1). The test problem that has been studied most thoroughly is one in which a spherical region is posited in which the temperature falls linearly from a maximum T_m at the center to a constant background temperature T_0 at a radius R (Fig. 2). This work determined the minimum radius R_{crit} needed to initiate a self-sustaining detonation [6,7] for several maximum temperatures T_m and densities. We have reproduced the results of [7], as illustrated in Table 1 and Figure 3, and extended it. The work we are doing is geared towards incorporating the fluid dynamic aspects of the initiation process, and will provide better detonation criteria for this crucial event in the GCD model.

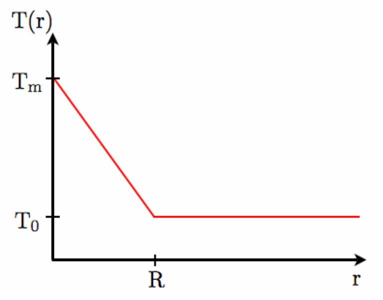

Figure 2. Initial temperature profile in 1D spherical coordinates used for the simulations.

Density [g cm^{-3}]	R_{NW}	R_{IRS}
1.0×10^7	1.0 - 2.0 km	1.5 - 1.6 km
3.0×10^7	25 - 50 m	38 - 40 m
1.0×10^8	1.0 - 2.0 m	1.40 - 1.45 m

Table 1: Comparison of critical radii calculated by Niemeyer & Woosley [7] (NW) and this work (IRS).

Simulation. We solve the compressible, reactive (13 nuclide network) Euler equations. By varying the radius, R, of the heated region, we determine the smallest radius, R_{crit}, for which a detonation ensues to better than 10%.

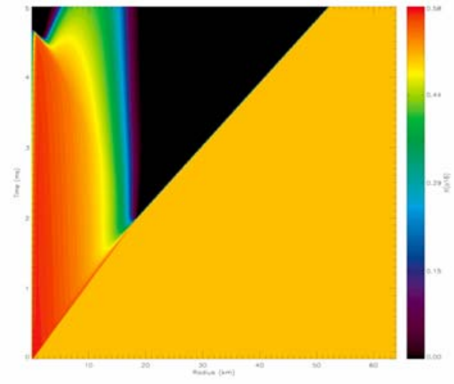

Figure 3. Space-time diagram of O mass fraction of successful detonation. Following O ignition, the detonation speed increases because of the additional energy that is released.

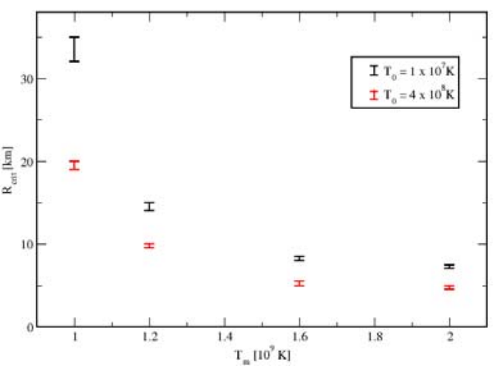

Figure 5. Summary of R_{crit} at a density of 10^9 g cm^{-3} for a composition consisting of equal parts He and C by number, and equal parts C and O by mass.

Presence of accreted Helium. Helium could be present in significant amounts in the outer regions of the white dwarf [8]. The addition of helium leads to a reduction in the critical radii for detonation (Fig. 5), since alpha capture on carbon nuclei proceeds at a lower activation temperature and releases more energy.

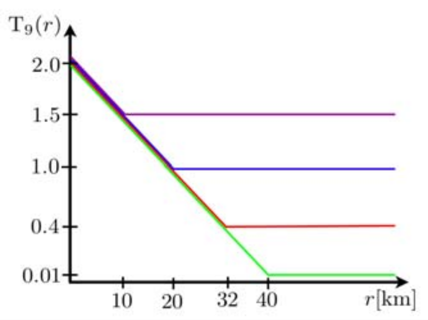

Figure 6. Shown are the initial temperature profiles for the minimum radii leading to detonation for C/O material at a density of 7×10^6 g cm^{-3} and T_m=2.0. Note the constancy of the slopes in this regime.

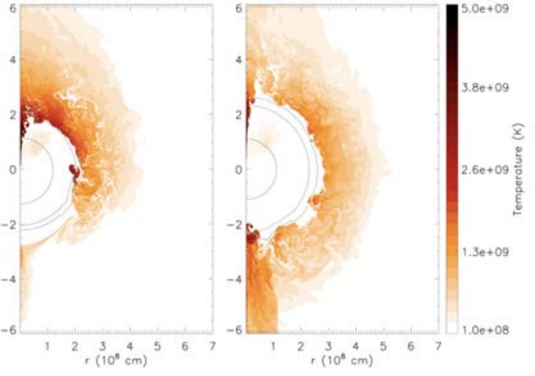

Figure 1: Temperature of the white dwarf following the breakout of a deflagration bubble, which sweeps around the star and forms a high-temperature flow that penetrates into the star [4,5].

Critical Radii for C/O matter. We have determined R_{crit} for matter consisting of equal parts O and C by mass for a range of densities, background temperatures T_0 and peak temperatures T_m (Fig. 4). It is evident that, at the larger densities, T_m has a larger effect on R_{crit} than T_0, whereas at the lower densities T_0 affects R_{crit} much more than does T_m .

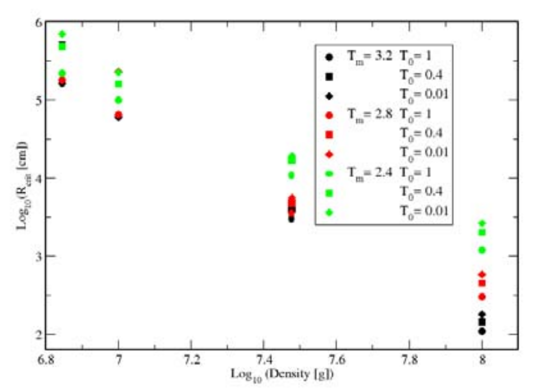

Figure 4. Summary of R_{crit} for various initiation temperatures (T_m) and ambient conditions (density, T_0) in units of 10^9 K.

Correlations. We find several interesting correlations among the detonation criteria. At a density of 7×10^6 g cm^{-3}, for example, the slope of the temperature profile is the same (and therefore R_{crit} varies) when T_m is small, regardless of T_0 (Fig. 6), whereas R_{crit} are virtually the same (and therefore the slope varies) with T_0 when T_m is large (Fig. 7).

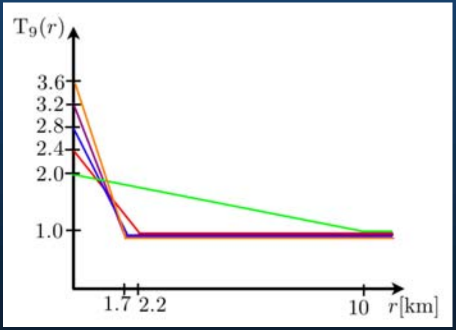

Figure 7. Shown are the initial temperature profiles for the minimum radii leading to detonation for C/O material at a density of 7×10^6 g cm^{-3} and T_0=1.0. Note the constant R_{crit} for the larger values of T_m .

References

[1] Plewa, Calder, Lamb (2004), The Astrophysical Journal Letters, 612, L37
[2] Plewa (2006), astro-ph/0611776
[3] Fryxell, et al., (2000), The Astrophysical Journal Supplemental Series, 131, 273
[4] Jordan et al., (2007), submitted to The Astrophysical Journal
[5] Townsley et al. (2007), submitted to The Astrophysical Journal
[6] Arnett & Livne, (1994), The Astrophysical Journal, 427, 330
[7] Niemeyer & Woosley, (1997), The Astrophysical Journal, 475, 740
[8] Yoon & Langer (2003), Astronomy & Astrophysics, 412, 53

This work is supported under NSF Grant PHY 02-16783 to the Joint Institute for Nuclear Astrophysics, an NSF Physics Frontier Center and by the Department of Energy under grant B523820 to the Center for Astrophysical Thermonuclear Flashes at the University of Chicago.