Shock Breakout from Type Ia Supernovae

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Summary

An outstanding problem is what mode the explosive burning takes during Type Ia supernovae (SNe Ia). The burning is generally thought to begin as a subsonic deflagration, but it has been suggested that this can transition into a supersonic detonation (the DDT). We argue that this transition leads to a breakout shock flash, which would provide the first unambiguous evidence that DDTs occur. Its main features are a hard X-ray flash lasting 0.01 seconds with a total radiated energy of 10^{40} ergs. This is followed by a cooling tail in the UV/optical with a peak absolute visual magnitude of M = -9 to -10 at ~1 day, which depends sensitively on the white dwarf radius at the time of DDT. Since this feature should accompany every SNe Ia, future deep surveys (e.g., m = 24 limited) will see it out to a distance of ~80 Mpc, giving a maximum rate of 60 per year. As the cooling wave diffuses through the star, differences in composition of the surface layers may imprint clues about the nature of the SNe Ia progenitor. If you have any questions or comments, feel free to contact me at tpiro@berkeley.edu

Delayed Detonation Transition (DDT)

It is generally agreed that the explosive burning in SNe Ia begins as a subsonic deflagration (Nomoto et al. 1976, 1984) to match the observed nucleosynthesis and light curves (Filippenko 1997), but the later propagation is more uncertain. Motivated by terrestrial combustion, it has been argued there may occur a transition to a supersonic detonation (the DDT, Khokhlov 1991; Woosley & Weaver 1994). Indeed, both comparisons to observations and physical arguments suggest a DDT may occur at a density of ~10^7 g cm^{-3}. (Niemeyer & Woosley 1997; Niemeyer 1999; Livne et al. 2005; Woosley 2007; Woosley et al. 2008).

Shock Runaway

As the detonation moves toward the surface of the star, it traverses increasingly lower densities. The detonation speed therefore increases while the burning rate decreases. Eventually the burning cannot keep up with the speed of the detonation. At this point, the shock runs away from the detonation. Both analytic arguments and 1-D numerical calculations find this occurs at ~3×10^6 g cm^{-3}, or after ~0.1 solar masses have been burned in the detonation.

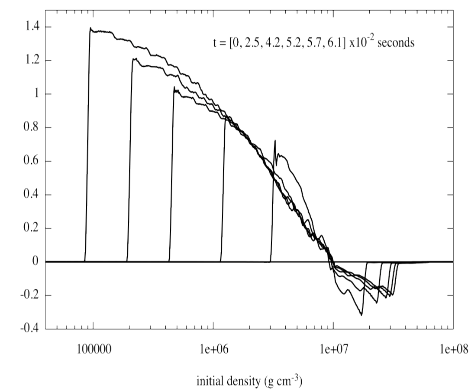

Figure 1 A 1-D hydrodynamic, detonation calculation following the fluid velocities imparted by the detonation. The detonation is placed at a density of 10^7 g cm^{-3}. This sends a shock wave both toward the surface and into the core. The detonation wave transitions to a pure shock at 3×10^6 g cm^{-3} because the burning rate fails to keep up with the shock speed. The shock increases its velocity following the power law $V_S \sim \rho^{-0.18}$ (Sakurai 1960), as it propagates down the density gradient. This post-shock profile provides the initial conditions for our shock breakout flash calculation.

The light curve from shock breakout can be broken into 3 sections:

- **Prompt shock breakout** When the shock has reached a sufficiently low optical depth such that $\tau < c/V_s$, photons from the radiative shock freely stream out. This produces a flash of hard (~20 keV) X-rays with a total radiated energy of 10^{40} ergs. Light travel effects will smear this over a time t~R/c~0.01 sec. If the DDT does not start everywhere at once, this flash may be further smeared out.

- **Early time cooling** A cooling wave diffuses through the shock-heated envelope, producing a cooling light curve. Before R/V_S~0.03 s, the scale height has expanded, but the radius is still roughly fixed. The luminosity is set by 1-D adiabatic expansion.

- **Late time cooling** After R/V_S~0.03 s, the radius has expanded significantly. This further adiabatically cools the envelope, but also increases the emitting surface area.

In these three limits, we can derive analytic, power-law solutions for the light curve (see Fig. 2), which we provide in Piro, Chang, & Weinberg (2009, submitted for publication).

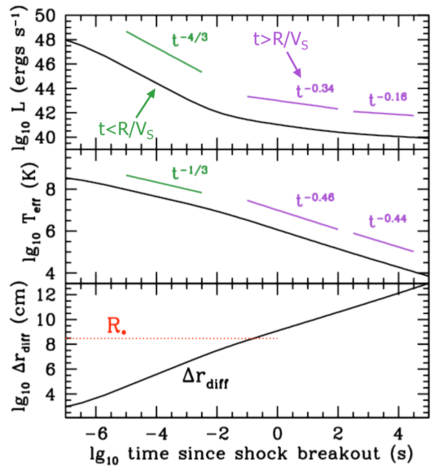

Figure 2 Time-dependent properties of the cooling shock-heated WD envelope. The luminosity (*top panel*) and effective temperature (*middle panel*) go through two distinct stages of cooling. These are well-approximated by power-law solutions. The very late time power law is due to the shocking of originally degenerate material. The bottom panel shows the distance from the stellar surface to the thermal diffusion depth, Δr_{diff}, in comparison to the initial radius, R (*red dotted line*).

Possible UV/optical Feature?

Following a 10^{40} erg hard X-ray flash lasting 10^{-2} s (also see Imshennik et al. 1981), we predict a UV/optical feature that peaks at ~1 day. This is about as bright as a classical novae, and should be seen by an m=24 limited survey well beyond the Virgo Cluster. Events observed out to 80 Mpc implies a rate of ~60 per year (Dilday et al. 2008).

Clues About SNe Ia Progenitors?

As the cooling wave diffuses through the star, the composition of the surface layers may imprint clues about the nature of the progenitor. For a helium (hydrogen) layer of 10^{-3} (10^{-5}) solar masses, the thermal diffusion wave reaches this depth at a time of 10^4 (10^3) seconds. Detailed calculations of the shock cooling spectra as a function of time would be useful for determining the impact of this differing composition.

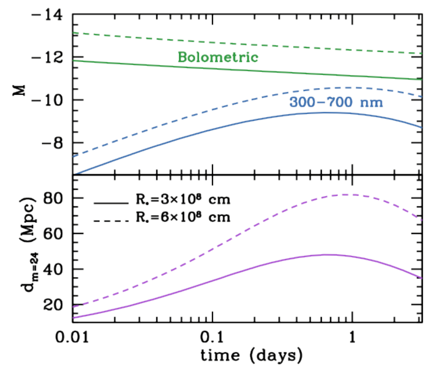

Figure 3 Absolute magnitude for the post-shock cooling light curve. The WD radius at the time of DDT is taken to be either 3×10^8 cm (*solid lines*) or 6×10^8 cm (*dashed lines*). The bottom panel shows the distance out to which an m=24 limited survey could see such a feature.