The Makings of Models for White Dwarf Supernovae

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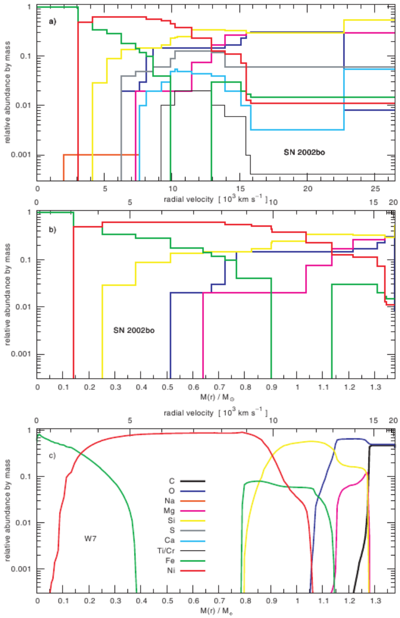
Outline

- SNIa as incineration of white dwarf
- Combustion modes and challenges for modeling them
- Two proposed scenarios for thermonuclear supernovae

Ejecta Abundance Profile

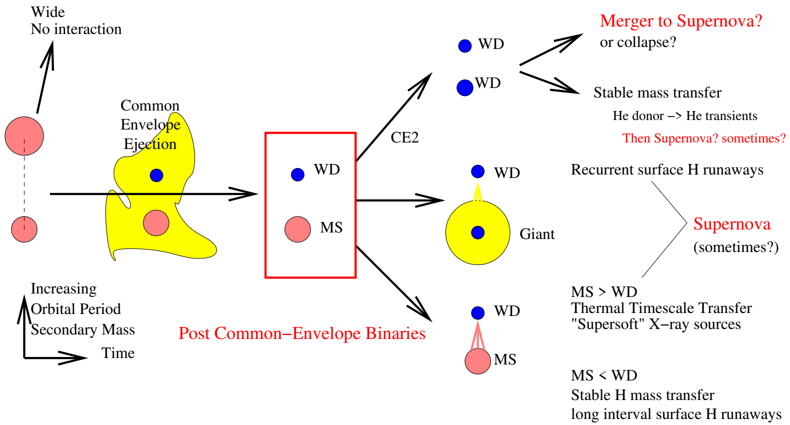


SN2002bo from Stehle et al. 2005, MNRAS, 360, 1231

From spectra at different times infer material in ejecta.
Mostly spherical structure.

- Model from Nomoto et al. 1984, case "W7" from various cases of reaction front propagation through $1.4M_\odot$ carbon-oxygen white dwarf
- Provides a surprisingly good match to gross structure of ejecta.
- Gives a basic sucessful explosion paradigm: Thermonuclear inceration of a white dwarf star.

(Murky) Binary Origin of SN Ia



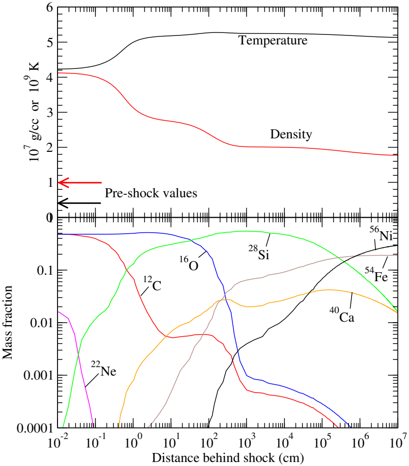
Exact origin (or origins) of WD supernovae unclear
(there are more complex cases than shown too)

If one can incinerate a white dwarf "just right" one gets something like observed SN Ia or SN Iax.
The devil is in the details - how and why?

Combustion modes:

- Detonation - supersonically propagating reaction front
- Deflagration - subsonically propagating reaction front

Detonations



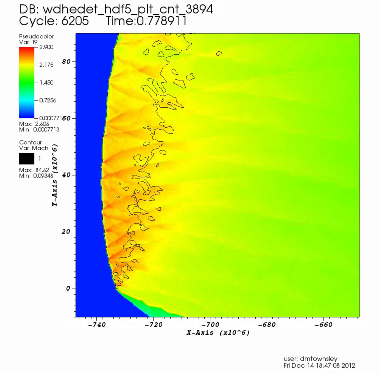
Burning occurs behind a propagating supersonic shock

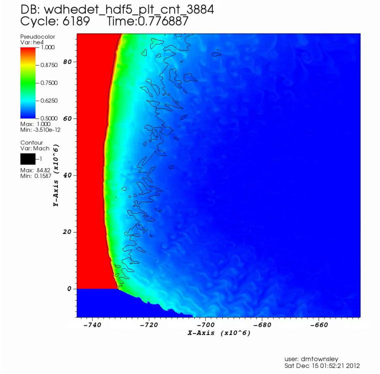
- Heat release supports onward propagation of shock
- Only a small subset of nuclides shown
  (actually 200 in this calculation)
- Burning structure manifest at a wide range of scales from microns to kilometers
- 3 main stages: (also in deflagration)
  C consumption
  O consumption
  Si $\rightarrow$ Fe-group
- Si results from "incomplete" burning

Detail of detonation structure

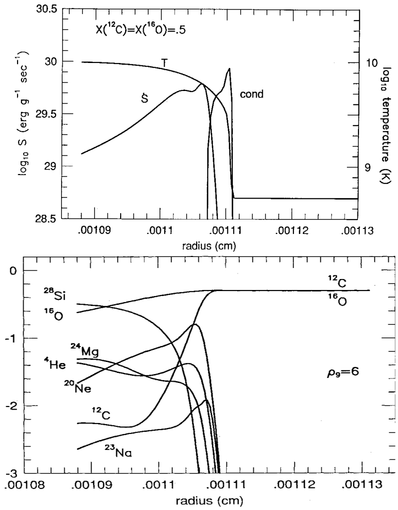
Now a Helium detonation, mostly resolved:
(can't do every simulation like this!)

A single hot layer case in plane parallel, constant gravity
Investigate steady-state structure of detonation





Deflagration Front



Timmes & Woosley 1992, ApJ, 396, 649

Thermonuclear burning begins with subsonic propagating flame front. (negligible pressure jump across burning front)

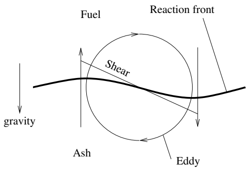
Thin flame: planar reaction front propagating in direction of normal

- Heat released in burning propagates diffuses into fresh fuel
- Balance between heat production and and diffusion sets propagation speed of planar reaction front

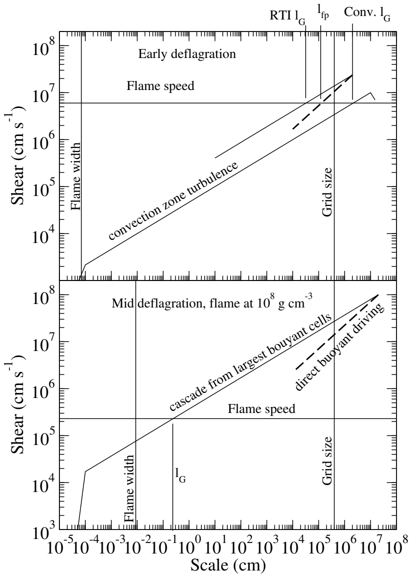
Key differences from terrestrial premixed combustion

- heat diffusion (via electron conduction) is much more effective than species diffusion
- viscous cutoff scale small compared to flame width

Flame is Wrinkled to Small Scales



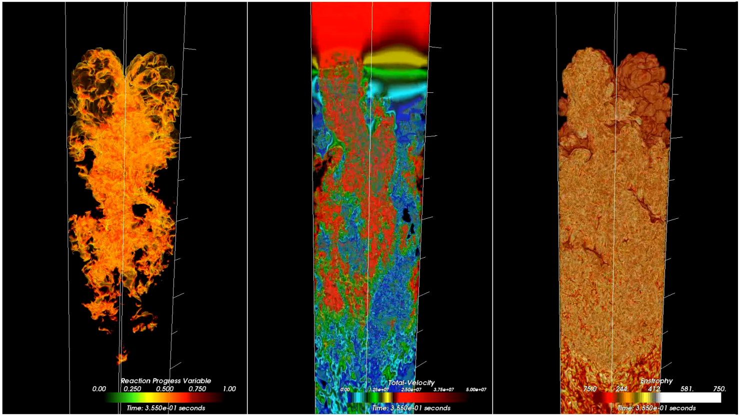
Turbulence and boyancy shear the flame causing wrinkles, or eventually possibly detonation.



from Jackson, Townsley, Calder 2014, ApJ

Wrinkling of Flame

Buoyantly unstable flame rising through a channel (very wrinkly)



Now have the pieces, lets make something out of them!

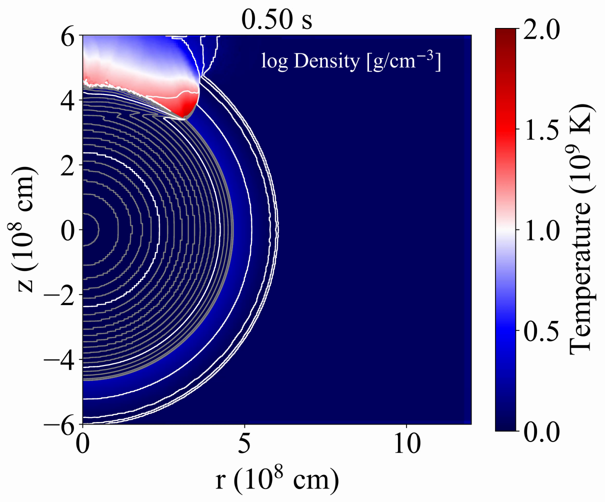
A Couple of Current Leading Scenarios

Two leading proposed scenarios:

- Helium-ignited Double Detonation
  - Sub-Chandrasekhar mass WD
  - Notable recent "improvements"
- Deflagration model for SN Iax
  - Deflagration only
  - Near Chandrasekhar mass WD

Not the only scenarios!
Note "classic" Deflagration-Detonation Transition (DDT) model.
Also important whether the binary star system is a WD-WD system or a WD-normal star system.

Helium Ignited Double Detonation



Double Det: Pros and Cons

Pros:

- Easier to make white dwarf star (only $1M_\odot$ or so)

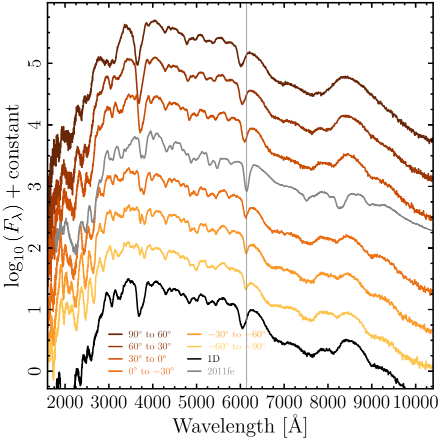
Cons:

- ~~Helium layers may make peculiar spectra~~
- ~~Decline too quickly from maximum light~~
- ~~Have not seen "failed" cases with too thick helium shells~~

All these have been overturned in the last decade!

Thin shells realistic and spectra normal

Comparison of spectra from various viewing angles: (Grey is actual normal SN Ia)



Thin He shells enriched in nitrogen (CNO burning ashes) can host detonation while not producing Ti & Cr (would make spectrum too red).

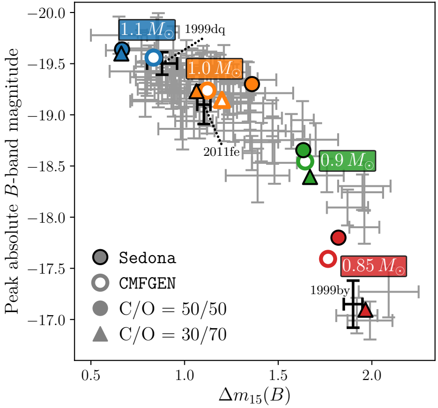
- Can host detonation
- Spectroscopically normal

Thick shells are still spectroscopically peculiar

Townsley et al. (2019, ApJ, 878, L38)

Brightness-Decline Rate Relation is Normal

Comparison of peak brightness and decline rate (Sedona and CMFGEN different radiative transfer computations):



When ionization and atomic level populations computed (not assumed to be in local thermal equilibrium) Phillips relation is reproduced.

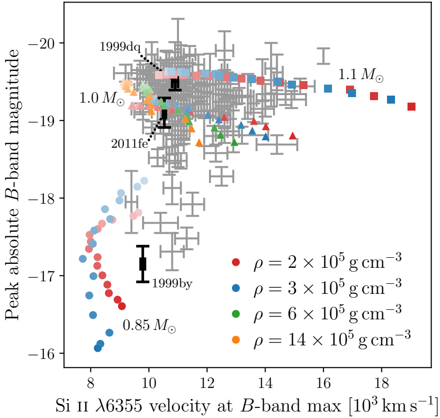
- Requiring non-LTE makes multi-dimensional models challenging
- Mainly problem in B band

The single parameter of the Phillips relation is white dwarf mass

Shen et al. (2021, ApJ, 909, L18)

Diversity of Si line velocity

Comparison of blueshift of dominant Si line: (Shading = lines of sight)



Shen et al. (in prep)

(data Burrow et al. 2020, ApJ, 901, 154)

Si shell is at higher velocity on He ignition side of ejecta and for higher mass WDs.

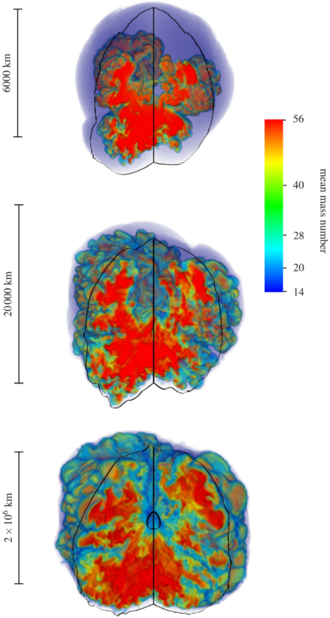
- Various lines of sight show variety of line velocities
- Reasonable range of masses and lines of sight cover observed range

(0.85 seems a bit too dim and slow here, may be below limit of successful secondary detonation)

Full deflagrations as candidates for SN Iax
(SN Ia with lower peak luminosity and lower velocities)

Deflagration-only

Time sequence of burned material:



Deflagration only burns incompletely

- Chandrasekhar mass WD
- Mixed ejecta
- Less ejecta
- Bound remnant

Fink et al. 2014, MNRAS, 438, 1762

Spectra compare well to SN Iax

Spectra from cases with stronger and weaker deflagrations:
(Gray normal SNIa, Black SNIax)

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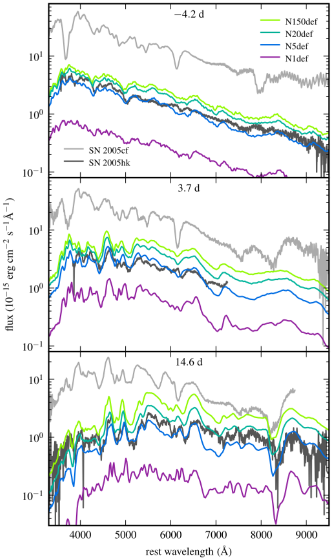
Fink et al. 2014, MNRAS, 438, 1762



Summary

- Type Ia supernovae well understoood as thermonuclear incineration of white dwarf star. Explains brightness and spectrum in detail
- Some combination of supersonic (detonation) and subsonic (deflagration) combustion
- Double detonation scenario captures many features of SNIa, while deflagrations capture many of SNIax
- There are other scenarios and other classes as well