Theory and Models of Type Ia Supernovae
or
How I Learned to Stop Worrying and Love Big
Thermonuclear Bombs

AST 301

Alan Calder

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Understanding Exploding Stars Helps Us Understand:

What happens when stars die?

Where are complex atoms produced?

How big is the Universe?

What will be the final fate of the Universe?
We observe remnants

SN 1006 (SNR 327.6+14.6)

NASA/CXC/Rutgers/J.Hughes et al
Crab in X-rays (left) and optical (right)

Kepler’s Supernova

NASA/CXC/NCSU/Reynolds et al
Astronomical Appearance

Observations: light curve, the observed intensity of light, and spectrum.

Light curve rises in days, falls off in weeks.

P. Nugent (LBNL)
Supernova Taxonomy (Observers)

Early Spectra:  No Hydrogen / Hydrogen

SN I  Si/ No Si
  SN Ia  1985A 1989B
  SN Ib  1983N 1984L
  SN Ic  1983I 1987K 1987V

He poor/He rich

SN II  ~3 mos. spectra
       He dominant/H dominant
  “Normal” SNII
  Light Curve decay after maximum: Linear / Plateau
  SN III
  SN IIP
  1980K 1979C

Believed to originate from deflagration or detonation of an accreting white dwarf.

Core Collapse. Most (NOT all) H is removed during evolution by tidal stripping.

Core Collapse of a massive progenitor with plenty of H.

M. Montes
Supernova Taxonomy (Theorists)

- Core collapse (Type Ib, Ic, and all II)
- Thermonuclear (Type Ia)
- Pair Production
What Are SNe Ia?

- discovery by Tycho de Brahe (Nov 11, 1572)

"Stella Nova" (1573), discovery chart

Tycho Brahes Glada Vänner
SNe Ia Astronomical Appearance

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P. Nugent (LBNL)
Mark Phillips considered the change in B-band magnitude with time.

Found fainter Ia’s fade faster.
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Brighter = broader leads to a one-parameter stretch factor (from templates)

“Standardizable candle”

Key property: the radioactive decay of $^{56}\text{Ni}$ powers the light curve.
Why Do We Care?

- SN Ia are crucial for galactic chemical evolution.
- SN Ia are also crucial for cosmology: probes allowing study of expansion and geometry \((\Omega_M, \Omega_\Lambda)\) of the Universe, nature of dark energy.
- Provide astrophysical setting for basic combustion problems.
Accuracy of “Standard Candles”

Type Ia supernovae appear *dimmer* in the Universe with non-zero $\Omega_\Lambda$.

Possible role of host galaxy extinction, environmental and metallicity effects (“population drift” with redshift), different evolutionary channels.
Favored Scenario

- Mass accretes from a companion onto a white dwarf that then ignites thermonuclear burning.

- Nature of that burning has been the fundamental problem for 30+ years.
  - Is it a deflagration (subsonic flame)?
  - Is it a detonation (supersonic flame)?
  - Will all of star burn? Burn to what?

- Can models reproduce observed nuclear abundances and light curves?
Modeling SN Ia's in SD Scenario

**Accretion**
- Stellar evolution code with accretion/binary evolution code

**Light curve**
- Free expansion of envelope
- Multi-group (non-LTE) radiation transport

**Smoldering**
- Subsonic convection in core of white dwarf
- Low Mach number flow solver
- Conductive heat transport

**Flame/Explosion**
- Initial deflagration
- DDT or expansion/recollapse
- FLASH (compressible module) with subgrid model for flame.

~ 1000 yr

~ 10^8 yr

~ seconds

Mark A. Garlick

P. Garnavich/CfA

Ignition

19
Possible observational signal

Kasen 2010
Physics of Type Ia Supernovae

- Studying SN Ia requires large-scale (~1000s of processors for days) fluid dynamics simulations for any hope of progress!
  - Realistic progenitor model
  - Multi-physics:
    - Reactive Euler equations with self-gravity (multi-dimensional!)
    - Equation of state for degenerate matter
    - Flame model (width/radius < 10^{-9})
    - Nuclear Energetics: \(^{12}\text{C} + ^{12}\text{C}\); burn to Nuclear Statistical Quasi-equilibrium (Si group); burn to Nuclear Statistical Equilibrium (Fe group).
    - Emission of ν’s result in energy loss, \(\Delta Y_e\) (neutronization)
    - Turbulence-flame interaction.

- Realistic models should include:
  - Rotation
  - Magnetic fields
Aside: Degenerate Equation of State

- Ideal Gas: \( PV = nRT \) \( \Rightarrow \) pressure is proportional to temperature.

- “Quantum Pressure”: In dense environments composed of Fermions (electrons) the Pauli exclusion principle determines the energy states of the particles. It acts as a pressure.

- EOS has little temperature dependence \( \Rightarrow \) little expansion with temperature \( \Rightarrow \) rapid, high temperature burning and violent outburst.

www.orbitals.com
Smoldering phase gradually heats the core and produces considerable turbulence.

Eventually a patch stagnates and gets hot enough that the energy generation exceeds convective cooling and a flame is born.

A period of deflagration (subsonic burning) ensues. The flame consumes some of the star, but it has time to react and it expands some.

A transition to a detonation (supersonic burning) occurs, incinerating the star and producing $\sim 0.6 \, M_{\text{solar}}$ $^{56}\text{Ni}$, which powers the light curve.

Note that much of what we will see applies to other pictures as well.
Evolution Equations

Euler:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]

\[ \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \nabla P = \rho \mathbf{g} \]

\[ \frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P) \mathbf{v} = \rho \mathbf{v} \cdot \mathbf{g} + S \]

\[ P = P (\rho, E) \]

Gravity:

\[ \mathbf{g} = -\nabla \Phi, \text{ where } \nabla^2 \Phi (\mathbf{r}) = 4\pi G \rho (\mathbf{r}) \]

Advection of scalars:

\[ \frac{\partial X \rho}{\partial t} + \nabla \cdot (X \rho \mathbf{v}) = 0 \]
Rayleigh-Taylor Instabilities

Density schematic:

- **Dense fluid** (cold fuel)
- **Light fluid** (hot ash)
Aside: Mesh Adaptivity and RTI

AMR allows an increased range of scales in a simulation by adding resolution where it is needed.

RTI increases the area of the flame, thereby boosting the burning rate.
Fluid Instability in a Type Ia Supernova

Fluid dynamics are very important. The simmering progenitor and Rayleigh-Taylor instabilities (RTI) generate turbulence.

Even with AMR, the disparate scales of Ia necessitate use of a model flame and a sub-grid-scale model for turbulent combustion.

Subgrid model should capture effects of RTI and the flame-turbulence interaction on unresolved scales.
Role of Flame and Ash Energetics

- Buoyancy of bubble is the key – depends on composition and energy produced in flame and in “ash”
  - Binding energy of NSE state at end of flame determines the composition and energy release (temperature)
  - Binding energy of NSE state continues to change as density decreases and composition changes in rising bubble
  - Weak interactions (neutronization) also produce composition changes and gain/loss of energy
- Accurate treatment of composition and energy are therefore essential
Review: Binding Energy

Nuclear binding energy = $\Delta mc^2$

For the alpha particle $\Delta m = 0.0304$ u which gives a binding energy of 28.3 MeV

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html
Review: Binding Energy

![Graph showing average binding energy per nucleon vs. number of nucleons in nucleus.](image)
Energetics Procedure

- Perform self-heating (one-zone) network calculations with contemporary reaction rates (including weak reactions) and Coulomb effects.
  - Energy release
  - Time scales for stages of burning
  - Compare to DNS flames where possible for verification.

- Describe long-term evolution of NSE (binding energy and neutronization) with NSE code consistent with network calculations.

- Incorporate both into multi-stage flame model and dynamic NSE ash.

- Test, test, test.
  - ADR scheme (verify and quantify noise and curvature effects)
  - Subgrid turbulence model
Energy released in flame and ash are both important.

Flame propagation →
NSE and Self-Heating Calculations

- **Nuclear Statistical Equilibrium code:**
  - Solves NSE equations for 238 nuclides
  - Recent work has more (443)
  - Includes excited states (Rauscher et al. 1997)
  - Includes Coulomb corrections to Helmholtz free energy
  - Calculates energy, $\nu$ loss rates, and neutronization rates
  - Details in Seitenzahl, et al. (2009)

- **Self-heating network code:** Isochoric (constant volume) and isobaric (constant pressure) burning
  - 200 nuclide network
  - Temperature dependent nuclear partition functions from Rauscher and Thielemann (2000)
  - Reverse rates derived for first time self-consistently from forward rates with Coulomb effects included
  - Include electron screening (Wallace et al. 1982)
  - Isobaric and isochoric results
Nuclides involved
Self-Heating Network Study

![Graph showing timescales for NSE and NSQB with/without screening vs. density (g cm⁻³)].
Self-Heating Network Study

[Graph showing the relationship between density and binding energy]
Neutronization Rates

\[ Y_e = 0.5 \]
Turbulence-Flame Interaction
Current research

We are in a golden age of SNe Ia observing. Observations suggest (among many other things)
- Brightness variations \(\rightarrow\) considerable intrinsic scatter in \(^{56}\text{Ni}\) yield
- There may be two populations of SNe Ia.

Questions: Can we find theoretical evidence for these? Can we estimate the intrinsic scatter of these events?

Model SNe Ia in the deflagration to detonation paradigm- rising plumes from a central ignition transition to a detonation near the surface of the white dwarf. DDT models produce results consistent with observations and are readily parameterized.

Models allow us to investigate role of metallicity, central density, etc., of the progenitor to look for systematic effects on the \(^{56}\text{Ni}\) yield.

Study these issues with a well-controlled statistical sample (Townsley, et al. 2009)
Observation compared with W7 model

Mazzali et al. (2008)
Octant (3-d)

Volume rendering of flame front
Whole Star (3-d) deflagration

Volume rendering of flame front
Deflagration Models: Incomplete Burning

Energy of explosion is too small
Significant mass of unburned C+O
No composition stratification: complete mixing of Ni, Si, C+O throughout the star

Khokhlov (2001)
3-D Delayed Detonation Model

Average chemical composition as function of radius

3-D pure deflagration

3-D deflagration followed by detonation
Ignited “by hand” at the center of the pre-expanded star.

Resulting stratified compositions are in better agreement with observations! “Classic” DDT scenario

Gamezo et al. (2003)
Gravitationally Confined Detonation

Jordan, et al. 2008
The mechanism by which a DDT might occur is not well understood!

One proposed way follows from the wrinkling of the flame with decreasing density.

At some point, the net burning rate is fast enough that the equivalent flame would be supersonic → DDT!

1.5 x 10⁷ g/cm³  1.0 x 10⁷ g/cm³  6.67 x 10⁶ g/cm³

fuel

ash

Carbon mass fraction

M. Zingale
Simulations in the DDT paradigm
Simulations in the DDT paradigm
Central Density Study

![Graph showing the relationship between $^{56}$Ni mass ($M_{\odot}$) and progenitor central density ($10^9$ g/cm$^3$) with error bands and trend lines.]

Krueger et al. (2010)
Relationship between central density and age

- A WD cools after it forms until the onset of accretion.

- Once accretion starts, the core temperature begins to rise.

- An initially cooler WD has a higher central density when the core reaches the ignition temperature (7-8 \times 10^9 \text{ K}). (Lesaffre 2006)

- We find the increased rates of weak interactions (neutronization) at higher densities produce less $^{56}\text{Ni}$ and thus a dimmer event.

- A SN Ia in an older population may have undergone a longer period of isolation, leading to a higher central density.

- Therefore, we study the effect of central density on $^{56}\text{Ni}$ yield as a proxy for the relationship between age and brightness.

- (Some) observations indicate older stellar populations have dimmer SN Ia.
Trend confronted with observations.

Krueger et al. (2010)
Conclusions

- This is a fun time to be observing or modeling SNe Ia!

- Models are increasing in sophistication and are now able to explore systematic effects such as properties of host galaxy (active vs. passive, metallicity).

- Many questions remain and models still rely on un-validated assumptions.

- We find little effect from including $^{22}\text{Ne}$ as a proxy for metallicity in DDT simulations beyond the direct modification by neutron excess described in Timmes, Brown, & Truran (2003).

- But, by considering the DDT density, we find the change in $^{56}\text{Ni}$ yield with metallicity to be a decrease 0.09 $\text{M}_{\odot}$ for a 1 $Z_{\odot}$ increase. This result is about twice that of TBT.

- We find a significant dependence of $^{56}\text{Ni}$ yield on progenitor density, suggesting a cooling time/age dependence.
...and that leads us to

QUESTIONS AND DISCUSSION
Bibliography

- Seitenzahl, et al. ADNDT, 95, 96 (2009)
- Townsley et al. in prep