Type Ia Supernovae
Supernovae

Type II, Ib, and Ic supernova are core-collapse supernova. Gravitational collapse powers the explosion.

Type Ia supernovae are the mononuclear explosions.
Nearby SNe Ia

• Tycho remnant
  – SNe Ia exploded in 1572
  – ~ 2.3 kpc away
  – Brightness rivaled Venus

Credit: NASA/CXC/Rutgers/J.Warren & J.Hughes et al.
Nearby SNe Ia

• Potential effects
  – Gamma-ray radiation
  – Night-time light and animal behavior
  – Ozone depletion
  – Cosmic rays

• Suggested “dangerous” distances ~ 10s of parsecs
  – See for example http://www.tass-survey.org/richmond/answers/snrisks.txt and references therein
Type Ia Supernovae

Let's review our understanding of Type Ia supernovae (SNe Ia)

- What do observations tell us about SNe Ia?
- What is the theoretical picture of these explosions?
- What are the outstanding questions?
- How do we further our understanding of SNe Ia?
Type Ia Supernovae Observations

- Brightness rivals that of host galaxy
- No H seen in spectra, but strong Si, Ca, and Fe lines
- Occur in old stellar populations
- Less frequent than SNe II
- Large amounts of $^{56}$Ni produced
  - Radioactivity powers the lightcurve
- No compact remnant
Supernovae Searches

Observers look for a sudden increase in the brightness of a galaxy, signaling a supernova.

Follow-up observations tell whether it is a Type Ia supernova.
Type Ia Supernovae Observations

One of the main observables for SNe Ia is the lightcurve. Observations of nearby events have shown that the variation in the lightcurves can be corrected for. In this way SNe Ia act as standard candles.

If we know how bright these explosions are intrinsically, and we measure how bright they appear to us, then we can measure their distance.

Phillips (1993), Perlmutter et al. (1997)
Type Ia Supernovae Observations

Plotting the distance verse redshift produces a Hubble diagram.

Distance supernovae allow us to determine the cosmological parameters.

In 1998, this led to the discovery that the expansion rate of the Universe is accelerating.
What makes SNe Ia explosions so robust?
Type Ia Supernovae Theory

- Best model for SNe Ia: thermonuclear explosion of a carbon/oxygen white dwarf
  - Electron degeneracy pressure provides support
    - Very different than thermal pressure
    - Heisenberg uncertainty principle + Pauli exclusion principle at work
- Chandrasekhar showed maximum mass supported by electron degeneracy pressure is 1.4 times the mass of the sun.
  - This maximum mass provides the robustness we are looking for.
Binary Evolution

(David A. Hardy & PPARC)
A white dwarf accreting from a companion compresses as material piles up on the surface. This heats up the center. When it reaches the Chandrasekhar mass, it explodes.

Since the star always explodes at the same mass, we expect the resulting energy to be the same.
Order of Magnitude Calculation

A Chandrasekhar mass white dwarf has a radius of \( \sim 2000 \text{ km} \)

The gravitational binding energy is

\[
U \sim \frac{GM^2}{R} = \frac{6.67 \times 10^{-8} \text{ dyn cm}^2 \text{ g}^{-2} \cdot (1.4 \cdot 2 \times 10^{33} \text{ g})^2}{2000 \cdot 10^5 \text{ cm}} \\
\sim 2.6 \times 10^{51} \text{ erg}
\]

Assuming pure \(^{12}\text{C}\) and burning it to \(^{56}\text{Ni}\) releases \(q \sim 9.2 \times 10^{17} \text{ erg/g}\), so the energy release by burning the whole star is:

\[
E_{\text{nucl}} \sim Mq = 1.4 \cdot 2 \times 10^{33} \text{ g} \cdot 9.2 \times 10^{17} \text{ erg g}^{-1} \sim 2.6 \times 10^{51} \text{ erg}
\]

A more detailed calculation gives lower values for both of these, but supports the idea that thermonuclear carbon burning can unbind the star.
Type Ia Supernovae Theory

For ~100 years preceding the explosion, reactions drive convection throughout the star.

These reactions heat the fluid—plumes rise upward and cool via expansion. As material piles on the star, the central temperature increases and the reactions become more vigorous.

Eventually, the cooling cannot keep up with the energy release from reactions, and a burning front is born.

This burning front propagates outward from (near) the center of the star, consuming the carbon fuel.

(Kuhlen et al. 2006)
SNe Ia Unstable Flames

- Explosion begins as a flame in the interior of the white dwarf.
  - ~ 100 years of convection precede ignition
  - Subsonic propagation allows the star to expand.
- Hot ash is less dense than the cool fuel.
- Subjected to numerous instabilities.

Increase surface area \(\Rightarrow\) increase flame speed.
How Can A Burning Front Propagate?

**Deflagration**

subsonic → fuel and ash are in pressure equilibrium

heat diffusing from the hot ash raises the temperature of the fuel to the point of ignition

**Detonation**

supersonic

shock heats fuel to point of ignition

heat release in fuel sustains detonation

A detonation does not give the star time to expand

All the C+O will burn at high density to nickel. No intermediate mass elements produced!
Wrinkling the Flame

Rayleigh-Taylor Instability:

This is a buoyancy driven instability. The hot ash behind the flame rises and the cool fuel ahead of the flame falls downward.

Large amounts of surface area generated.

Turbulence:

Turbulence is characterized by random motions. Instabilities create vorticity on the large scales that cascades down to smaller and smaller scales.

adapted from Peters (2000)
Differences Between 2- and 3-D

The real world is three-dimensional—turbulence behaves differently. We demonstrated that the turbulence that arises in 3-d R-T unstable flames obeys Kolmogorov statistics.

Zingale, Woosley, Bell, Day, & Rendleman 2005, J Phys Conf Series, 16, 405
Large Scale Simulations

- Instabilities are the dominant acceleration mechanism.
- Pure deflagrations can unbind the star.
- Some flame model is required.
  - Stellar scale $\sim 10^8$ cm
  - Flame width $\sim 10^{-5} - 10$ cm
Large scale simulations resolve the star with resolution of ~1 km. 

subgrid model needed

Large scale simulations show a flame can successfully unbind the star.

Roepke and Hillebrandt show that a pure deflagration can unbind the star. However these tend to be weak explosions, and leave unburned C and O at the center.

Gamezo et al. Show that if, at some point, a detonation forms, then the resulting supernova explosion better matches observations.
Off-center Ignition

The distribution of hot spots has a large influence on the outcome of the explosion. The most extreme example is off-center ignition:

▶ Roepke and Woosley tested this in 3-d and found that this mechanism was not robust.

▼ Jordan et al. argued that the “gravitationally confined detonation” first discussed by Plewa et al. 2004 can occur in 3-d

... what does nature do?
Outstanding Questions

- **What is the progenitor?**
  - Modeling merging WDs requires a different type of code

- **Does the burning front remain subsonic or does it transition to a detonation?**
  - This is something that small scale simulations can address

- **What are the initial conditions?**
  - This requires a code that is tuned to long time integration.

- **Do the first burning bubbles succeed in burning the entire star?**
  - Can the explosion fail and pulsate?

- **What is the physical basis for the width-luminosity relationship in the lightcurve?**
  - This is a problem of radiative transfer.
Merging WDs

Figure 2. Dynamical evolution of the coalescence of a 0.6 $M_\odot$ + 0.9 $M_\odot$ CO white dwarf binary. The panels in the left column show the density in the orbital plane, the panels in the right column the temperature in units of $10^6$ K. Lengths are in code units ($= 10^9$ cm).
Merging WDs

Figure 3. Dynamical evolution of the coalescence of a 0.6 $M_\odot + 0.9 M_\odot$ CO white dwarf binary. Continued from Fig. 2.
Outstanding Questions

• Are there different paths to a Type Ia supernova explosion and do these occur at different rates throughout the history of the Universe?

• Does the burning front remain subsonic or does it transition to a detonation?

• Do the first burning bubbles succeed in burning the entire star? Or does the explosion fail and pulsate?

• What are the initial conditions?