Astronomers generally group supernovae into two broad classes: Type I and Type II. This lecture will provide an overview of these two classes including:

- their outburst mechanisms
- their distinguishing observational characteristics
- their remnants
- their contributions to nucleosynthesis
One evening when I was contemplating as usual the celestial vault, whose aspect was so familiar to me, I saw, with inexpressible astonishment, near the zenith, in Cassiopeia, a radiant star of extraordinary magnitude. Struck with surprise, I could hardly believe my eyes.

Tycho Brahe,
November 1572
The expected rate in the Milky Way is about 1 every 50 years, with SNe II being roughly 3 times more frequent than SNe Ia.
Significance of Supernovae

Supernovae are the most spectacular of galactic events:

- They release ≈ $10^{51}$ ergs of light and kinetic energy.
- As the brightest objects in galaxies, they allow probes of the distance scale of the Universe.
- They enrich the Galaxy in “heavy” elements (heavier than helium) to levels of order 2 percent (Solar Abundance).
- They provide energy sufficient to power the acceleration of cosmic rays.
- They leave condensed remnants - neutron stars and black holes - whose presence in binary systems give rise to X-ray bursts and other high energy phenomena.
Significance of Supernovae

- SNe Ia contribute to the chemical enrichment of galaxies - synthesis of iron-peak elements.
- SNe Ia are crucial for cosmology: probes of the distance scale provide constraints upon the expansion and geometry ($\Omega_M, \Omega_\Lambda$) of the Universe and the nature of dark energy.
- SNe II contribute to the chemical enrichment of galaxies - synthesis of the elements from oxygen to zinc and of heavy elements from krypton through uranium.
Supernovae

- Astronomical observations reveal the existence of two broad classes of supernovae: Types Ia and II.

- Distinguishing features include:
  - Stellar Population:
    - Type II’s in young populations (e.g. spiral arms of Spirals)
    - Type Ia’s in older populations (e.g. Elliptical galaxies)
  - Supernova spectra:
    - Type II’s are hydrogen rich (early ejecta of ~ Solar composition)
    - Type Ia spectra reveal absence of hydrogen in ejecta
  - Remnants:
    - Type II supernovae leave neutron star or black hole remnants
    - Type Ia supernovae leave no condensed remnants
  - Light curves
Supernovae and Supernova Remnants

Cygnus Loop
HST - WFPC2

SN 1572: Tycho

N132D
SN Remnant in LMC
HST - WFPC2

SN C1680: Cas A

Supernova 1987A Rings
Hubble Space Telescope
Wide Field Planetary Camera 2

SAO: Chandra

SN 1572: Tycho

SAO: Chandra

SN C1680: Cas A
Supernovae and Supernova Remnants

SNe 1054 Supernova Remnant
(Crab Nebula in Taurus)

NASA: IRAS

Infrared

NASA: UIT

Far UV

NRAO: 1992

Malin/Pasakoff/Caltech

Radio

Optical

SAO: Chandra

X-ray
Supernovae and Supernova Remnants

Cassiopeia Supernova Remnant
(estimated occurrence: 1680)
Supernova Light Curves: SNe Ia and SNe II

Type Ia Supernova Light Curve

Type II Supernova Light Curve

Supernova in Galaxies: Populations

**Elliptical Galaxy M87**

**SNe 1994I (Type II)**

**SNe 1987A (Type II)**

**Large Magellanic Cloud**

**SNe 1994D (Type Ia)**

Supernova Near Nucleus of Galaxy M51

High-z Supernova Search Team, HST, NASA

Hubble Space Telescope • Wide Field Planetary Camera 2

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Supernova Remnants

Crab Pulsar - Off

Crab Pulsar - On

Einstein X-Ray Observatory

CENTAURUS X-3: A HIGH MASS X-RAY BINARY

X-ray emission: pulses

www.lsw.uni-heidelberg.de/~mcamenzi/NS_Mass.html
Stellar and Supernova Remnants
Figure 21.8 Type I and Type II supernovae have different causes. These sequences depict the evolutionary history of each type. (a) A Type I supernova usually results when a carbon-rich white dwarf pulls matter onto itself from a nearby red giant companion. (b) A Type II supernova occurs when the core of a more massive star collapses, then rebounds in a catastrophic explosion.
Type Ia Supernovae: Theory

- “Standard model” (Hoyle & Fowler 1960):
  - SNe Ia are thermonuclear explosions of C+O white dwarf stars.

- Evolution to criticality:
  - Accretion from a binary companion leads to growth of the WD to the critical (Chandrasekhar) mass (1.4 solar masses).
  - After ~1000 years of slow thermonuclear “cooking”, a violent explosion is triggered at or near the center.
  - Complete incineration occurs within two seconds, leaving no compact remnant.

- Nucleosynthesis contributions: 1/2 to 2/3 iron-peak nuclei. ($\tau_{\text{nucleosynthesis}} > 10^9$ yrs)

- Their light curves are powered by the radioactive decay of $^{56}\text{Ni}$. Their peak luminosities: $L_{\text{max}} \propto M(^{56}\text{Ni})$. 
Light Curve and Spectrum of SNe Ia
Binary Origin of SNe Ia Progenitors
**Type II Supernovae: Theory**

- **“Standard model”** (Hoyle & Fowler 1960):
  - SNe II are the product of the evolution of massive stars $10 < M < 100\, M_\odot$.

- **Evolution to criticality**:
  - A succession of nuclear burning stages yield a layered compositional structure and a core dominated by $^{56}\text{Fe}$.
  - Collapse of the $^{56}\text{Fe}$ core yields a neutron star.
  - The gravitational energy is released in the form of neutrinos, which interact with the overlying matter and drive explosion.

- **Remnants**: Neutron star and black hole remnants are both possible SNe II remnants.

- **Nucleosynthesis contributions**: elements from oxygen to iron (formed as $^{56}\text{Ni}$) and neutron capture products from krypton through uranium and thorium. ($\tau_{\text{nucleosynthesis}} < 10^8\, \text{yrs}$)

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*Courtesy Mike Guidry: guidry@utk.edu*
The Universe emerged from the cosmological Big Bang with a composition consisting of hydrogen, helium, $^2\text{D}$, $^3\text{He}$, and $^7\text{Li}$.

Galaxies and the first stars within them were born with this primordial composition.

The heavy elements with which we are familiar - from carbon to iron to uranium - are the products of nuclear processes associated with the evolution of stars and supernovae of Types Ia and II.
The primordial abundance pattern (Brian Fields 2002)

What the Big Bang Made

Courtesy: Alex Heger 2004
Cosmic Abundances of the Elements
Nucleosynthesis Sites

- Massive star \((M > 10 \, M_\odot)\) and SNe II synthesis of the nuclear species from oxygen to zinc, and the r-process heavy elements

- Red Giant \((1 < M < 10 \, M_\odot)\) synthesis of carbon and s-process elements

- SNe Ia synthesis of the 1/2-2/3 of the iron peak nuclei not produced by SNe II
Stellar and Supernova Nucleosynthesis

AGB Star - Planetary Nebula

Massive Star - SNII

Kaufmann “Universe” 1994
Representative Nuclear Reaction Network

(Nuclear Reaction Network)

- Stable Isotopes

Basic Nuclear Reaction Links

(Truran 1965)
Pre-explosion compositions involve primarily nuclei of Z ≡ N, viz: $^{12}$C, $^{16}$O, $^{28}$Si …. Explosive burning at $T \geq 5 \times 10^9$°K typically occurs on timescales $\leq$ seconds. Supernova nucleosynthesis sees reactions occurring on a dynamical timescale. Weak interactions proceed too slowly to convert any significant fraction of protons to neutrons. 

$$e^- + (Z, A) \rightarrow (Z-1, A) + \nu_e$$

It follows that the (in situ) iron-peak products of explosive nucleosynthesis in supernovae are proton-rich nuclei of Z≈N, viz. $^{44}$Ti, $^{48}$Cr, $^{52}$Fe, $^{56}$Ni, $^{60}$Zn, and $^{64}$Ge. Of these, $^{56}$Ni is far the most abundant.
Massive star (M > 10 M☉) and associated SNe II synthesize most of the nuclear species from oxygen to zinc. The “intermediate mass” nuclei (oxygen through calcium) are found to be overproduced relative to “iron peak” nuclei by a factor ≈ 2-3.

SNe Ia synthesize ≈ 1/2-2/3 of the iron peak nuclei (those not produced by SNe II) and small but critical concentrations of intermediate mass elements.

Given that SNe Ia produce ≈ 0.6 M☉ per event while SNe II produce rather ≈ 0.1 M☉ per event, the ratio SNe II/ SNe Ia by number is ≈ 3 over Galactic history.
Early studies of Type Ia models and associated nucleosynthesis focused on the “carbon detonation model” of Arnett (1969).

We now recognize that this results in the burning of the entire core to $^{56}$Ni, in disagreement with recent spectroscopic studies of SNe Ia ejecta which reveal the presence of intermediate mass elements.

⇒ Not a Pure Detonation

(Truran, Arnett, and Woosley 1971)
Nearly all one-dimensional Chandrasekhar mass models of Type Ia supernovae produce most of their $^{56}\text{Ni}$ in a nuclear statistical equilibrium environment between the mass shells $0.2 \ M_{\odot}$ and $0.8 \ M_{\odot}$.

W7 model of Nomoto, Thielemann, & Yokoi (1984)
Supernova II Nucleosynthesis

SN II NUCLEOSYNTHESIS

(THIELEMANN, NOMOTO AND HASHIMOTO 1992)

MASS FRACTIONS OF SEVERAL MAJOR NUCLEI AS THEY RESULT FROM POST-SHOCK SUPERNOVA PROCESSING

2.2 Million km

$\text{t} = 1170 \text{ sec}$

(Kifonidis et al. 2000)
Supernova Ia Nucleosynthesis

Off-center Deflagration Simulation
(Calder et al. 2004)

Evolution of Core Composition
(Timmes, Brown, Truran 2003)
**SN Ia: Deflagration and Nucleosynthesis**

**Off-center Deflagration Simulation**
(Calder et al. 2004)

**Evolution of Core Composition**
(Timmes, Brown, Truran 2003)
SNe Ia: Deflagration and Nucleosynthesis

Possible Consequences of Breakout
(Plewa et al 2004)
SN 1987A in the Large Magellanic Cloud

An Exciting Recent Supernova Event

30 Doradus Nebula prior to explosion of SN 1987A

30 Doradus subsequent to explosion of SN 1987A
SN 1987A, whose brightness at maximum was of order $10^9\ L_\odot$, was of great significance to supernova theorists:

- It was the first local supernova since 1604 (Kepler).
- The progenitor star was identified and found to be a massive star: $M \sim 20\ M_\odot$ and luminosity $L \sim 20\ L_\odot$.
- Most of its energy release ($\sim 3 \times 10^{53}\ \text{ergs}$) was in the form of neutrinos - which were detected.
- The magnitude of this energy release confirmed the formation of a condensed remnant - a neutron star or black hole of mass $\geq 1.4\ M_\odot$.
- Its light curve was powered by the decay of the $\approx 0.07\ M_\odot$ of $^{56}\text{Ni}$ ejected as: $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, confirmed by detection of $\gamma$-rays from $^{56}\text{Co}$ and $^{57}\text{Co}$.
- It ejected $5-6\ M_\odot$ of heavy elements - from oxygen to iron - and on to uranium and thorium.
SN 1987A in the Large Magellanic Cloud

A likely supernova candidate for the next millennium: Betelgeuse

Courtesy: Ernst Rehm, ANL
The light curve of SN 1987A revealed the decay of nickel through cobalt to iron of approximately $0.07 \, M_\odot$ of ejecta.
Challenges in Supernova Theory

- Understanding Basic Mechanisms:
  - SNe Ia: evolution of burning front
  - SNe II: neutrino energy transport

- Nucleosynthesis:
  - production of oxygen to iron elements
  - site of the r-process of neutron capture

- Remnants:
  - powering of nebular remnants
  - black hole verses Neutron Star

- Population impact on SNe Ia lightcurves