Lecture III: Supernova Explosions

- Nuclear Energetics of Supernovae and Supernova Models
  - “core collapse” supernovae - SNe Type II
  - “thermonuclear” supernovae - SNe Type Ia

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Discovery of a SNe Ia?

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
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.
- SNe Ia are crucial for cosmology: probes of the distance scale provide constraints upon the expansion and geometry ($\Omega_m$, $\Omega_k$) of the Universe and the nature of dark energy.

Supernovae Ia and Cosmology

In 1998, SNe Ia played a major role in the “science breakthrough of the year:”

Using SNe Ia as distance indicators (standard candles), two groups of astronomers found strong indications for an accelerating cosmic expansion.

Doggett and Branch 1985
**Type Ia and Type II Supernovae**

- The two broad classes of supernovae exhibit a variety of distinguishing characteristics:
  - Spectrum at Maximum Light
    - Type Ia spectra at maximum are devoid of hydrogen
    - Type II spectra at maximum are hydrogen rich (Solar)
  - Stellar Population
    - Type II occur only in young populations: spirals/irregulars
    - Type Ia occur in old and young populations - and are the only supernovae seen in elliptical galaxies

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**Supernova in Galaxies: Populations**

SNe 1994I (Type II)  Elliptical Galaxy M87
SNe 1987A (Type II)  High-z Supernova Search Team, HST, NASA
SNe 1994D (Type Ia)  Large Magellanic Cloud
Type Ia and Type II Supernovae

- The two broad classes of supernovae exhibit a variety of distinguishing characteristics:

  - Explosion Mechanism
    - Type Ia are “thermonuclear” supernovae, powered by energy release in burning $^{12}\text{C}$ and $^{16}\text{O}$ to iron-peak nuclei
    - Type II are “core collapse” supernovae, powered by the energy release in the formation of a neutron star or black hole remnant

  - Energetics
    - Type Ia supernovae release $10^{51}$ ergs in light and kinetic energy
    - Type II supernovae release $10^{51}$ ergs in light and kinetic energy and $\approx 3\times10^{51}$ ergs in neutrinos

Type Ia and Type II Supernovae

- The two broad classes of supernovae exhibit a variety of distinguishing characteristics:

  - Frequency of occurrence:
    - Type Ia occur about once per century in spirals, with a roughly comparable rate per unit mass in ellipticals
    - Type II occur about once per century in spirals

  - Light Curves
    - Type Ia are extremely regular & the peak brightness is correlated with light curve shape ($L_{\text{MAX}} \approx 10^9 L_\odot$)
    - Type II are more irregular in their light curves with a somewhat lower peak brightness ($L_{\text{MAX}} \approx 10^8 L_\odot$)
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.

**Supernova Light Curves: SNe Ia and SNe II**
The Phillips relation compensates for the observed variation in peak luminosity to give a standard candle.

Brighter SNe Ia decline more slowly.

"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: \(L_{\text{max}} \propto M(\text{^{56}Ni})\).
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 $^{56}$Fe.
  - Collapse of the $^{56}$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 $^{56}$Ni) and neutron capture products from krypton through uranium and thorium ($\tau_{\text{nucleosynthesis}} < 10^8$ yrs)
Massive stars (M > 10 M☉) evolve through a sequence of burning stages to the formation of an iron core surrounded by shells of, respectively, silicon, oxygen, neon, carbon, and helium.

The r-process heavy elements are also believed to be formed in these events.

(Kifonidis et al. 2000)
Cosmic Abundances

Solar system abundances
(at the time of solar system formation)

56Ni Production in Nucleosynthesis

- Pre-explosion compositions involve largely nuclei of $Z = N$, viz. $^{12}$C, $^{16}$O, $^{28}$Si.
- Explosive burning at $T \geq 4 \times 10^9$ 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.
56Ni Production in Nucleosynthesis

- Explosive (T>4x10^9 K) supernova incineration of 12C, 16O, and 28Si yields proton-rich iron-peak product nuclei of Z≈N (Ye≈0.5), viz. 44Ti, 48Cr, 52Fe, 56Ni, 60Zn, and 64Ge (Truran, Arnett, and Cameron 1967; Arnett, Truran, and Woosley 1971).

- Relatively small changes (decreases) in Ye can, however, influence the emerging abundance patterns.

- Such increases in N/Z (or decreases in Ye) can be introduced by weak interactions at higher densities – or by the presence of the neutron rich isotope 22Ne in the stellar matter.

Nuclear Statistical Equilibrium Conditions
The Standard Model for SNe Ia

- White dwarf in a binary system
- Growth to the Chandrasekhar limit by mass transfer
Evolution Towards SN Ia

Accretion
- stellar evolution code with accretion/binary evolution code

Smoldering
- subsonic convection in core of white dwarf
- low Mach number flow solver
- conductive heat transport

Light curve
- free expansion of envelope
- multi-group (non-LTE) radiation transport

Flame
- initial deflagration
- DDT or expansion/recollapse
- FLASH (compressible module) with subgrid model or front-tracking
- conductive heat transport

>10^8 yr

~ seconds

~ 1000 yr

ignition
Main Characters: Deflagrations and Detonations

- Deflagrations (“Flames”):
  - Subsonic burning fronts, propagating by heat conduction. Laminar flame speed and flame width (Timmes & Woosley 1992):
    - $S_L \sim 0.001 \, u_{\text{sound}}$, $d \sim 1 \mu m ... 1 cm$

- Detonations:
  - Supersonic burning fronts, propagating by shock heating.
    - Detonation width and speed:
      - $S_D \sim u_{\text{sound}}$, $d \sim 0.1 mm ... 1 m$

**Supernova Ia Nucleosynthesis**

- 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 $^{56}\text{Ni}$, in disagreement with recent spectroscopic studies of SNe Ia ejecta which reveal the presence of intermediate mass elements.
  - $\Rightarrow$ Not a Pure Detonation

(Truran, Arnett, and Woosley 1971)
Deflagration Model: Flame Morphology

Multiple Point Spherical Ignition

(Roepke et al. 2004)
Consequences of Off-Center Ignition

Off-center Deflagration Simulation


Possible Consequences of Breakout
Nickel Variations

- 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 mass shells $0.2 \, M_\odot$ and $0.8 \, M_\odot$.
- In this region weak reactions occur on long timescales and the degree of neutron enrichment is contained in the $^{22}\text{Ne}$ abundance.

(Iwamoto et al. 1999)
Supernova Ia Nucleosynthesis

The brightness of a Type Ia supernova at maximum is a function of the mass of $^{56}$Ni produced.

$^{56}$Ni is formed in nuclear statistical equilibrium in matter characterized by a $Y_e$ approaching 0.5 (e.g. $Z \sim N$).

The critical region of formation in Type Ia events is that from $\sim 0.2$-0.8 solar masses.

The mass of $^{56}$Ni formed in NSE in this critical region is sensitive to the initial composition of the star ($^{22}$Ne).

The observed scatter in metallicity in the galactic disk, to values several times solar, introduces a scatter in peak brightness of order 30 percent.

Metal rich galaxies (e.g. E galaxies) may be expected to have fewer bright Sne Ia.

Conclusions: Metallicity Dependence
TYPE II SUPERNOVAE

Blue Giant (Red Giant: 100)

Fe-Ni core

Neutron star

30,000,000 km
1500 km
15 km
Core collapse supernovae:
- Prompt explosion mechanism does not work (explored during the 1970's and 1980's; commonly accepted early 1990's)

- Shock wave forms close to sonic point \((M \sim 0.7 \, M_{\odot})\)
  initial energy: \((5 \ldots 8) \times 10^{51} \text{ erg}\)

- Severe energy losses during shock propagation (8 MeV/nucleon or \(1.6 \times 10^{51} \text{ erg}/0.1M_{\odot}\))

- Current paradigm: neutrino-driven delayed explosions
  (discovered through computer simulations by Wilson '82, and first analyzed by Wilson & Bethe '95)

  In its simplest form: Seems to work for low-mass core only!  (Kitaura et al '05)
- **Observations** imply: non-radial flow and mixing are common in core collapse supernovae

- **Theoretical models** based on delayed explosion mechanism predict non-radial flow and mixing due to:
  - Ledoux convection inside the proto-neutron star (deleptonization and neutrino diffusion)
  - Convection inside neutrino heated hot bubble (neutrino energy deposition behind the shock)
  - Rayleigh-Taylor instabilities in stellar envelope (non-steady shock propagation; hot bubble)

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**Mixing in Type II Supernovae**
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

© Anglo-Australian Observatory
SN 1987A in the Large Magellanic Cloud

- 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.

A likely supernova candidate for the next millenium: 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.