Supernovae

- Supernova basics
- Supernova types
- Light Curves
- SN Spectra – after explosion
- Supernova Remnants (SNRs)
- Collisional Ionization
Supernova Basics

• Supernova (SN) explosions in our Galaxy and others reach a peak luminosity of ~$10^{10} L_\odot$.
• Initial expansion velocities on the order of ~20,000 km/sec
• Due to collapse of white dwarf in a binary system (type Ia) or collapse of a massive star (type II, Ib, Ic), when electron degeneracy pressure can’t hold off overlying layers
• Produce shock fronts which compress and collisionally ionize the ISM (shock front slows down over time)
• Enrich the ISM with heavy elements, including those that cannot be produced other ways (elements heavier than Fe)
• Typical SN rates ~ 1/Galaxy/century
• “Recent” local supernovae: 1006 AD, 1054 AD (produced Crab nebula), Tycho’s (1572), Kepler’s (1604), SN 1987A (in the LMC)
Supernova Types

• Type based primarily on appearance of spectra near peak luminosity.
  • **Type I** – no Hydrogen lines
  • **Type II** – Hydrogen lines present
  • Subtypes (spectra obtained ~1 week after peak luminosity):
    Ia – strong Si II absorption
    Ib – strong He I absorption
    Ic – no He I and absent or weak Si II absorption
    II – Hydrogen (Balmer) lines in absorption and/or emission
Supernovae Spectra – Early Stages

(Filippenko, A.V. 1997, ARAA, 35, 309)
Supernovae Spectra – Later Stages

(Filippenko 1997)
Supernova Light Curves

I - homogeneous, peak followed by smooth decline
II - much dispersion, II-L: smooth decline, II-P: plateau
SN Ia Light Curve

$^{56}\text{Ni}$ decays to $^{56}\text{Co}$, which decays to $^{56}\text{Fe}$
Supernova Types - Interpretation

- **Type Ia**: binary white dwarf plus red giant or supergiant
  - white dwarf near Chandra limit: Mass = 1.4M_{Sun}
  - mass transfer from companion instigates WD collapse (can no longer support itself with electron degeneracy)
  - collapse leads to carbon deflagration (subsonic) runaway
  - WD is completely destroyed
- **Type II**: Collapse of high mass star (initial mass > 8 M_{\odot} on Main Sequence) due to exhaustion of nuclear fuel
  - neutron star (pulsar) or black hole remnant
  - rebound provides supernova explosion, neutrinos provide most of the force
- **Type Ib**: collapse of massive star, no H
- **Type Ic**: collapse of massive star, no H or He
  (Ib and Ic likely from Wolf-Rayet stars that have lost their outer envelopes due to stellar winds or other mass loss.)
Spectral Evolution

• Early spectra (~ 1 week after peak) show continuum emission from expansion of optically thick gas (“photosphere”)
  - absorption or P-Cygni lines from outer layers
  - widths of lines indicate velocities of ~20,000 km/sec
  - UV flux depressed due to “line blanketing”
• Later spectra (~ weeks to months) show strong low-ionization lines as gas cools off
  - Type Ia show strong [Fe II], [Fe III] lines
  - Type Ib, Ic show lines of intermediate mass elements (O, Ca)
  - Type II are similar to Ib and Ic, but show Balmer lines
• Eventually (years), collisions ionize the ISM, producing a supernova remnant, with typical nebular lines (O III], etc.)
• For young type II supernovae, a pulsar (e.g., the Crab Nebula pulsar) can ionize the gas by synchrotron radiation
Supernova Remnants - Evolution

- Extreme supersonic motion produces a shock wave
- Initial expansion is adiabatic.
- ISM gas passing through shock front is compressed and collisionally ionized.
- The shocked gas cools by radiation. Expansion is characterized by two different temperatures, pressures, and densities on either side of the shock.
- Ionization balance given by:

\[ n(X^i) \ n_e \ q_{\text{ion}}(X^i, T) = n(X^{i+1}) \ n_e \ \alpha(X^i, T) \]

where \( q_{\text{ion}}(X^i, T) = \int_{\chi=1/2mv^2}^{\infty} v \ \alpha_{\text{ion}}(X^i, v) f(v) \ dv \]

where \( \chi = \text{ionization potential} \)
Additional model considerations:
- recombination in shocked gas produces ionizing photons, which “pre-ionize” unshocked gas
- charge exchange is significant
- In high-density clumps, temperatures reach >30,000K (higher than photoionized nebulae)
  - confirmed by high [O III] λ4363/ λ5007 ratio
- X-ray penetrate deep into high-column clouds, to partially ionized gas
- In low density regions, shocked gas can reach temperatures of 10^6 K, which produces X-rays
- Mass swept up by shock wave: 10^2 – 10^3 M☉ !
Collisionally Ionized Gas

(Osterbrock, p. 300)

- require high gas temperatures to get highly ionized species
Ex) Cygnus Loop

- Older Supernova Remnant (SNR): 25,000 years
- $3^\circ$ in diameter on sky, many filaments
- No central remnant (i.e., pulsar) has been found
Cygnus Loop

(HST, narrow-band Hα)

- High and low-ionization filaments
- Expansion velocity ~ 100 km/sec
- Distance ~ 800 pc
- Collisionally ionized gas
Spectrum of Cygnus Loop Filament

- strong lines from a wide range in ionization
- strong [O III] \( \lambda 4363 \) indicates high temperature (30,000 K)

Crab Nebula

- Young SNR (remnant of SN in 1054 AD)
- Gas concentrated in filaments, high resolution shows knots like “beads on a string”
- Expansion velocity is $\sim 1500 \text{ km/sec}$, proper motion of filaments gives distance of $\sim 1800 \text{ pc}$
Spectrum of Crab Filament

- similar to AGN spectra, lines are narrower, [S II] and [O II] stronger

• Line ratios consistent with **photoionization** by “hard” continuum (X-rays in addition to EUV):

\[ F_v \propto v^{-\alpha} \quad \text{where} \quad \alpha \approx 0.5 \text{ at high } v \]

• Nebular spectrum: high and low-ionization filaments
  - mostly a density effect; remember the ionization parameter:
    \[
    U = \frac{\nu_0}{4\pi r^2 c n_e} \quad \text{lower density} \rightarrow \text{higher } U
    \]

• Luminosity of neutron star (pulsar) not enough to ionize gas
• Ionizing radiation is due to synchrotron (electrons spiraling in strong magnetic field) – produces the amorphous blue region
• X-rays create a partially ionized zone, deep in high column-density clouds – responsible for strong [O I], [S II] lines
Shock vs. Photoionized Gas

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(Osterbrock, p. 310)
Supernova 1987A (from Bob Kirshner)

Explosion of blue supergiant in the LMC
An explanation of the rings

Outer ring
at edge of swept-up gas from earlier mass loss

Inner ring
of swept-up red-supergiant gas

Supernova remnant. A dark, invisible outer portion surrounds the brighter inner region lit by radioactive decay.
Impact of shock front

2006