# Astrophysics I: Stars and Stellar Evolution
## AST 4001

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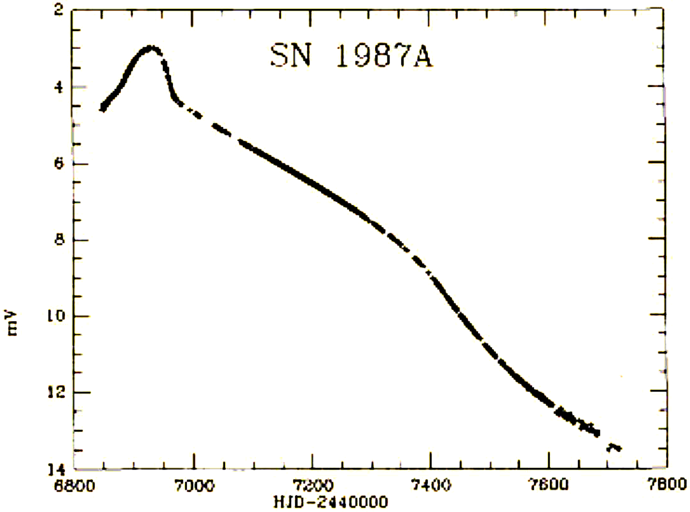
# Overview

1. Recap
2. Supernovae
   - Supernovae - Observations
   - SN 1987A
   - Supernova Remnants
3. Supernova Summary
   - Remnants as a Function of Mass
   - Supernovae as a Function of Mass and Metallicity
   - Remnants as a Function of Mass and Metallicity

# SN 1987A

# SN 1987A Visual Light Curve



# Overview

# Core Collapse Supernovae - Observations

Type Ib/Ic/II

- $\sim$ 75 % of all supernovae
  (the rest are "Type Ia")
- only occur in regions near young stars, molecular clouds $\Rightarrow$ originate from short-lived (i.e., most massive) stars
- neutron stars found associated with historical Type Ib/Ic/II
- now accepted that these are all "core-collapse" supernovae

# Core Collapse Supernovae - Observations

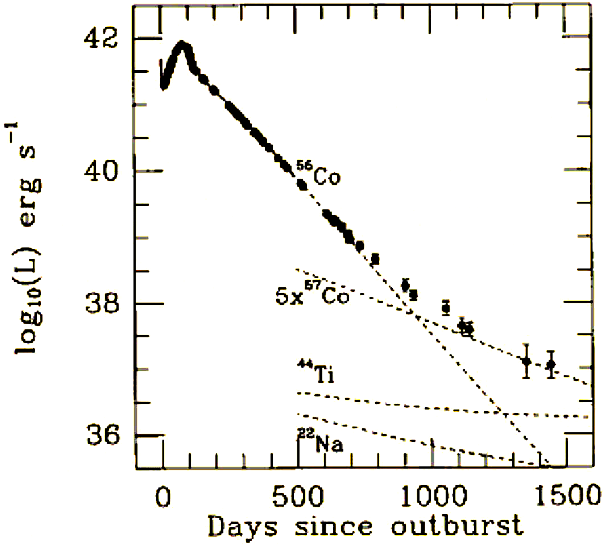
Different progenitor stars result in supernova subclasses

- II-P: normal isolated $10 - 30\,\mathrm{M}_\odot$ star
- II-L: as for II-P, but with smaller hydrogen envelope?
- Ib: very massive star; H envelope lost thrugh wind or binary
- Ic: as for Ib, but He envelope lost also? Hypernovae?
- IIn: explosion expands through dense clumpy wind?

# Core Collapse Supernovae - Observations

- Wide variation in brightness: $L_{\mathrm{peak}} \sim (0.4 - 4) \times 10^9\,\mathrm{L}_\odot$
- After peak, light curve dominated by radioactive decay
- new elements are unstable
- decay produces photons, e.g.,
  $^{56}\mathrm{Ni}(\mathrm{e}^+\nu_\mathrm{e})^{56}\mathrm{Co}$ (average life: 8.8 days)
  $^{56}\mathrm{Co}(\mathrm{e}^+\nu_\mathrm{e})^{56}\mathrm{Fe}$ (111 days)
  $^{57}\mathrm{Co}(\mathrm{e}^+\nu_\mathrm{e})^{57}\mathrm{Fe}$ (391 days)
  $^{44}\mathrm{Ti}(\mathrm{e}^+\nu_\mathrm{e})^{44}\mathrm{Sc}$ (87 years)
- mechanism underlying slow fade of "light curve"

# SN 1987A - Radioactive Decay



# SN 1987A - Facts

- 23 Feb 1987: new SN in Large Magellanic Cloud ($d = 50\,\mathrm{kpc}$)
- Peak magnitude $V \sim 3$: first naked eye SN since 1604!
- 19 neutrinos detected! Energy, composition, time, direction all consistent with formation of a neutron star
- Progenitor star was Sk -69°202, a (blue) supergiant
- No neutron star / black hole detected yet
- Light curve clearly shows phases of radioactive decay

# Supernova Energetics

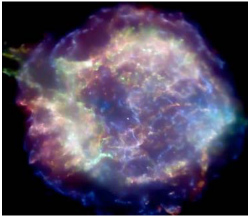
- Core collapse Supernovae (neutron star - Type Ib/c, II)
  - $\sim 3\times10^{53}$ erg in neutrinos
  - $\sim 10^{51}$ erg in mechanical (kinetic) energy
  - $\sim 10^{49}$ erg in (visible) photons
  - $\sim 0.1\,M_\odot$ $^{56}$Ni
- Type Ia supernovae (thermonuclear)
  - $\sim 10^{51}$ erg in mechanical (kinetic) energy
  - $\sim (2-3)\times10^{49}$ erg in (visible) photons
  - $\sim 0.5\,M_\odot$ $^{56}$Ni

origin of $^{56}$Fe in the sun:

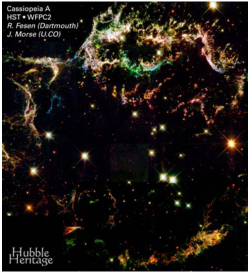
- $\sim \frac{1}{3}$ from core collapse supernovae
- $\sim \frac{2}{3}$ from Type Ia supernovae

# Supernova Remnants

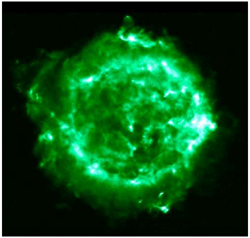
- Radioactivity fades in 50-100 years
- Explosion drives shock wave into surrounding gas supernova remnant (SNR)
- Shock acceleration: synchrotron emission (radio)
- Shock heating: bremsstrahlung (X-rays)
- Collisions with clumps and clouds: emission lines (optical)



Cas A: X-ray




optical



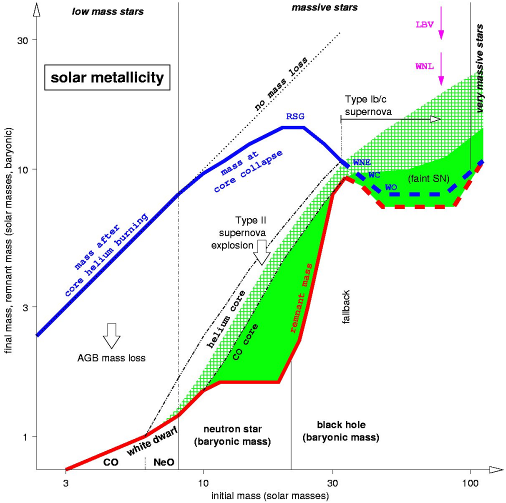
radio

# Supernova Remnant Evolution

- "Free expansion": ejecta expand freely with $E_{SN} = \frac{1}{2} M_{ejecta} v^2$
- "Adiabatic" or "Sedov-Taylor" phase
  - begins when mass swept up > mass ejected
  - energy conserved (very little escapes in radiation)
  - 50 % of energy is kinetic, 50 % of energy is thermal
  - $R = \left(\frac{25}{3\pi}\right)^{1/5} \left(\frac{E_{SN}}{\rho}\right)^{1/5} t^{2/5}$
- "Radiative" or "snowplow" phase
  - begins when 25 % of total energy lost as radiation (typically when $v \sim 200\,\mathrm{km/s}$)
  - expansion now driven by conservation of momentum
  - evolution: $R \propto t^{1/4}$
- "Dissipation" - SNR stops expanding and becomes static, hot, bubble when $v < c_{sound} \Rightarrow t_{fade} \sim 3\,\mathrm{Myr}$, $R_{fade} \sim 75\,\mathrm{pc}$

# Overview

# Stellar Mass Ranges - Solar Metallicity



# Stellar Mass Ranges - Population III Stars