Supernovae and their remnants

- Introduction
- Evolution of low mass stars
- White dwarfs
- Evolution of high mass stars
- Supernovae Type II
  - Supernovae Type Ia
  - Supernova Remnants (SNR)

References:
- Rosswog & Bruggen - Chap.4
- Charles & Seward - Chap.3
Supernova Explosion Type Ia

Light curves

**SN type Ia** light curves are all similar

- Typically: $M_v = -19$

Common type of progenitor and explosion mechanism
- Type Ia & II optical spectra at maximum luminosity:

- Spectra with variety of lines → most lines difficult to identify
- Doppler broadened indicating velocities up to: $v \sim 15000\ km\ s^{-1}$
- Marked absence of Hydrogen lines in SN Type Ia
Supernova Explosion Type Ia

Progenitor star & location

Type II
- Young massive stars at end of their evolution in star forming regions $\rightarrow$ mainly spiral arms of spiral galaxies
  - Core collapse supernova

Type Ia
- Very old not very massive stars:
  $\rightarrow$ Rarer events in all kind of galaxies
  $\rightarrow$ No preference for spiral arms
  - Thermonuclear supernova

$\rightarrow$ White dwarf explosion in a binary system
Evolution of stars in the HR diagram

- **H-R diagram**

  - $M > 8M_{\odot}$
    - Fusion Ne, O, Si $\rightarrow$.. Ni, Fe
  - $4M_{\odot} < M < 8M_{\odot}$
    - Fusion C $\rightarrow$ O, Ne, Na, Mg
  - $0.4M_{\odot} < M < 4M_{\odot}$
    - Fusion He $\rightarrow$ C, O
  - $0.08M_{\odot} < M < 0.4M_{\odot}$
    - Fusion H $\rightarrow$ He

( Longair Fig.13.20 )

We know already that there are different types of WDs
White dwarf composition

- The composition of WD is correlated with their mass in the range:
  \[ M_{WD} \sim (0.2-1.4) \, M_\odot \rightarrow \text{peak at } 0.6 \, M_\odot \]
- Oxygen-Neon WDs only a small fraction of the total
- Helium WDs spectra cannot explain SN Type Ia

  The bulk of SN Type Ia produced by Carbon-Oxygen WDs

Nature of the companion star

- The exploding WD is part of a binary system \( \rightarrow \) two scenarios:
  \[ \begin{align*}
  \text{Double degenerate scenario} \\
  \text{Single degenerate scenario}
  \end{align*} \]
Double degenerate scenario

- Binary system of two carbon-oxygen white dwarfs (no hydrogen):

  WD \( (m>) \)  +  WD \( (m<) \)

  - Loss of energy and angular momentum by emission of gravitational waves:
    - WDs slowly spiral toward each other until:
    - Less massive (larger) fills the ‘Roche lobe’ of the other (see X-ray binaries)
    - Thick accretion disk around more massive WD
    - Explosion at the Chandrasekhar mass (*)
Supernova Explosion Type Ia

Single degenerate scenario

- One carbon-oxygen white dwarf and one main sequence star:

- Accretion of H from non-degenerate companion star into white dwarf
  
  - H steadily burnt at the WD surface (super-soft X-ray sources)
  
  - Accretion until WD reaches the Chandrasekhar mass (*) ➔ Explosion

- Most promising scenario for Type Ia supernovae
- Single degenerate scenario: system formation

1) Two sun-like stars in a close binary system

2) The more massive star evolves more rapidly and expands its outer layers. This material is either captured by the low mass star or flung into space.

3) The massive star eventually becomes a Carbon-Oxygen white-dwarf.
- Single degenerate scenario: system formation

3) The second star evolves to the red-giant phase expanding its outer layers

4) Transfer of matter from the giant to the white dwarf begins
5) When the WD mass reaches the Chandrasekhar limit (*):
   → Increase pressure in the core → C & O nuclear fusion in the core
   → WD interior temperature increases without expanding (degenerate)
   → Nuclear reactions proceed at higher rate and spread outward until:

   **Explosive C burning**
   Deflagration & detonation of the WD in a few seconds

- The WD contained mainly C & O and almost no H & He:
  → Absence H and He lines in the spectrum

- There is no core-collapse:
  → No massive production of neutrinos

- Nuclear fusion creates a solar mass of radioactive $^{56}$Ni destroying the star:
  → Delayed energy release by $^{56}$Ni decay in expanding debris (light curve)
- (*) There are two classes of explosion models:

Chandrasekhar mass central carbon ignition

- Ignition of C in the centre of WD when the mass: $M_{WD} \sim M_{\text{Chandr}}$

$\rightarrow$ Explains homogeneity but problem with observed rates (most popular)

Sub-Chandrasekhar mass helium ignition

- Off-centre ignition of He shell on top of a C-O WD with: $M_{WD} < M_{\text{Chandr}}$

$\rightarrow$ Explains observed SN rate
Let’s summarise the properties of SN types Ia & II:

<table>
<thead>
<tr>
<th></th>
<th>SN Type Ia</th>
<th>SN Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progenitor type</td>
<td>Old white dwarf in binary system</td>
<td>Young massive star at end of its life</td>
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<tr>
<td>Explosion Mechanism</td>
<td>Thermonuclear explosion</td>
<td>Core collapse</td>
</tr>
<tr>
<td>Hydrogen lines</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Light curves (variable)</td>
<td>Most of them identical 85% (same progenitor)</td>
<td>Variable (different progenitor)</td>
</tr>
<tr>
<td>Max magnitude</td>
<td>~ -19</td>
<td>~ -17</td>
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<tr>
<td>Luminosity peak duration</td>
<td>~2 weeks</td>
<td>~ 3 months</td>
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<tr>
<td>Neutrinos</td>
<td>No emission</td>
<td>Emission</td>
</tr>
<tr>
<td>Location</td>
<td>Spiral and elliptical galaxies</td>
<td>Spiral arms of spiral galaxies</td>
</tr>
<tr>
<td>Occurrence</td>
<td>1 every 300 yrs in our Galaxy</td>
<td>1 every 30-50 yrs in our Galaxy</td>
</tr>
<tr>
<td>Remnant</td>
<td>Probably complete disruption star</td>
<td>Neutron star or black hole</td>
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</tbody>
</table>
Supernovae and their remnants

- Introduction
- Evolution of low mass stars
- White dwarfs
- Evolution of high mass stars
- Supernovae Type II
- Supernovae Type I
- **Supernova Remnants (SNR)**
  - SNRs evolution
  - Young SNRs
  - Old SNRs
  - Very young SNRs

References:

- Rosswog & Bruggen - Chap.4
- Charles & Seward - Chap.3
- Nearby ‘recent’ supernovae:

<table>
<thead>
<tr>
<th>Date</th>
<th>Name</th>
<th>Type</th>
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<td>I?</td>
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<td>I</td>
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<td>Crab Nebula</td>
<td>II</td>
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<td>?</td>
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<td>Kepler</td>
<td>I</td>
<td>-3</td>
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<tr>
<td>1680</td>
<td>Cas A</td>
<td>II</td>
<td>?</td>
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<tr>
<td>1987</td>
<td>SN 1987A</td>
<td>II</td>
<td>3</td>
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</tbody>
</table>

- **Galactic** supernovae (every 30-50 years) are mostly Type II

- **Extragalactic** supernovae events:
  - Generally impossible to detect progenitor
- SNRs in X-rays

- The majority of SNRs are Shell-like SNRs

- Another class is called ‘Plerions’: SNRs with emitting central pulsar
- The evolution of a SNR can be divided in four phases:

  Phase I - *Free expansion*

  Phase II - *Adiabatic expansion*

  Phase III - *Radiative phase*

  Phase IV - *Sub-sonic stage*
Phase I - ‘Free expansion’ (100-1000 years)

- Material ejected ~ isotropically
- Expansion at constant velocity:
  \[ v \sim 15000 \text{ km s}^{-1} \]

- Progenitor star embedded in uniform ISM, where:
  \[ v_{\text{ISM}}^{\text{Sound}} \sim 10 \text{ km s}^{-1} \]

- Supersonic expansion into ISM because:
  \[ v \gg v_{\text{ISM}}^{\text{Sound}} \]

→ Shock-wave in boundary with ISM
Phase I - ‘Free expansion’

- Ejected material sweeps-up surrounding ISM

- The pressure increases and temperature reaches:

\[ T \sim 10^7 - 10^8 \, K \]

→ The medium becomes a plasma

→ X-ray emission from a large hollow low density optically thin shell

- Most SNRs with approximately spherical shape
- Low density region left in the interior
Phase I - ‘Free expansion’

- Phase I lasts until:

\[
M_{\text{Swept-up}} \approx M_{\text{Ejected}} \quad \rightarrow \quad \delta_{\text{ISM}} m_p \frac{4}{3} \pi R^3 = 1M_\odot
\]

- This corresponds to a shell radius:

\[
R = \sqrt[3]{\frac{3}{4\pi} \frac{M_\odot}{\delta_{\text{ISM}} m_p}} = \sqrt[3]{\frac{3}{4\pi} \frac{2 \times 10^{30}}{0.3 \times 10^6 \times 1.67 \times 10^{-27}}} = \sqrt[3]{0.95 \times 10^{51}} = 9.8 \times 10^{16} m
\]

\( (1pc = 3.1 \times 10^{16} m) \quad \rightarrow \quad R \approx 3 pc \)

- The age of the remnant will be:

\[
\tau \equiv \frac{R}{v} = \frac{3 \times 3.1 \times 10^{16}}{15 \times 10^6} = 0.62 \times 10^{10} \text{ sec} \quad \rightarrow \quad \tau \approx 200 \text{ years}
\]
Phase II - ‘Adiabatic expansion’ (1000-30000 years) (‘Sedov-Taylor’ phase)

- Swept-up ISM mass large compared with ejecta mass:

\[ M_{\text{Swept-up}} > M_{\text{Ejected}} \]

- Remnant sweeps cold ISM, its mass increases and cools down

→ Expansion slows down

→ Emission of heated hot gas observable in X-rays
Phase II - ‘Adiabatic expansion’

- The energy radiated by the shell material $\ll$ SNR internal energy:

$$E_{\text{Rad}}^{\text{Shell}} \ll E_{\text{SNR}}^{\text{Int}}$$

- Within the remnant the thermal energy is constant:

$$E_{\text{SNR}}^{\text{Int}} \cong 0.72 E_{\text{SN}}$$

$\rightarrow$ The shock front expansion is determined only by the initial energy $E_{\text{SN}}$ and the density $n$ of the ISM:

$$R_{\text{SF}} = 14 \text{ pc} \left( \frac{E_{\text{SN}}}{10^{44} \text{ J}} \right)^{1/5} \left( \frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1/5} \left( \frac{t}{10^4 \text{ yr}} \right)^{2/5}$$

- Shock Front Radius

$$T_{\text{SF}} = 10^{10} \ K \left( \frac{E_{\text{SN}}}{10^{44} \text{ J}} \right) \left( \frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1} \left( \frac{R}{\text{pc}} \right)^{-3}$$

- Shock Front Temperature
- The ejecta kinetic energy is transferred to the interstellar gas
- This is swept up and moves with the ‘ejecta’

→ The material is accumulated in a shell behind the shock wave

Example

- Small explosion of dynamite:
- There are actually **two shock waves**:
  - An ‘outer shock’ into the gas ahead of the ejecta
  - A ‘reverse shock’ that propagates backwards

- **Contact discontinuity**: boundary between circumstellar medium and ejecta
Phase III - ‘Radiative phase’ (30000-10^5 years)

- Shell-like structure where swept-up material radiates
- Most of the internal energy is radiated away

- Shell keeps expanding with constant radial momentum:
  \[ M \nu \sim \text{const} \]

- Material behind the shock cools but when:
  \[ T_{SF} < 2 \times 10^5 K \]

  → The energy radiation rate actually increases

- This is because the electrons recombines with ions:
  → Cooling via emission UV lines
Phase IV - *Sub-sonic stage* (\( >10^5 \) years)

- Shell expansion slows down to sub-sonic speeds:

\[ v \leq 20 \text{ km s}^{-1} \]

→ Shell becomes fainter and fainter until it is indistinguishable from surrounding ISM → Not observable anymore
Supernova Remnants Evolution

- Summary of the four SNR evolution phases:

Phase I: $v = \text{const}$, $T = 10^8 \text{ K}$, $v = 10^4 \text{ km/s}$

Phase II: $E = \text{const}$, $T = 10^6 \text{ K}$, $v = 200 \text{ km/s}$

Phase III: $p = \text{const}$, $T = 10^4 \text{ K}$, $v = 10 \text{ km/s}$

Phase IV: $r \approx \text{const}$
SNRs Radiation Emission

- Wavebands and relative radiation processes

**X-ray**

- Phases I & II
  - Hot material behind shock wave $T > 10^6 \text{K}$:
    - Thermal Bremsstrahlung & elements line emission
  - High energy $e^{-}$ in strong magnetic field:
    - Synchrotron emission

**Optical**

- Phase III
  - Bright filaments
  - $T \sim 10^4 \text{K}$ → Discrete emission lines

**Ultraviolet**

- Within X-ray emitting shell
  - Heated dust immersed in the hot gas → Thermal radiation

**Infrared**

- Phases I, II & III
  - Vicinity of the shock & cooling filaments
  - High energy $e^{-}$ in strong magnetic field → Synchrotron emission

**Radio**
Progenitor star easier to find in young SNRs:
- Observed material is predominantly the ejecta
- Mass and composition SNR → Mass progenitor star

SN energy released can be calculated measuring:
- the mass and the velocity of expansion

SNR geometry can be irregular:
- Can be caused by the explosion itself
- Asymmetries in the spatial distribution of the surrounding medium

Rayleigh-Taylor instability:
- The compressed ejecta into interstellar gas is unstable:
  → it is expected to break into clumps
  (ex: like large blob of falling water breaking into small droplets)
- SNRs comparison

- The material is hot only between the two shock waves:
  → Young remnants bright shell → X-ray emission

- Central region material not hot and freely expanding
- Tycho’s Supernova

- Discovered by Tycho Brahe in 1572

- From Tycho’s light curve:
  - it was a SN Type I

- Remnant observed in Radio, Optical and X-ray respectively in
  - 1952, 1949 and 1965
- Tycho’s SNR

Dimensions:
- Solar system ~ $4 \times 10^{-4}$ pc
- Tycho SNR ~ 6 pc:
  $\rightarrow$ Sun +15 nearby stars

- X-rays Einstein observations clearly show the ejecta

- Emission from shell broken into clumps following outer shock
  $\rightarrow$ Brightest part of the X-ray emission (80%)
  $\rightarrow$ Thermal Bremsstrahlung

- Estimated progenitor star mass $\sim 1-2$ $M_\odot$ as expected for a SN Type Ia
- Tycho’s SNR X-ray spectrum

- SNRs material composition revealed by X-ray spectrum
  ➔ Direct observation material from the star explosion

- Strong emission lines of medium weight elements:
  ➔ Hot plasma thermal emission
  ➔ Derivation of material temperature and composition
- Tycho’s SNR

Densities:
- Brightest clump:  
  \( \sim 3 \text{ atoms/cm}^3 \)
- Circumstellar H cloud:  
  \( \sim 0.4 \text{ atoms/cm}^3 \)

X-ray:
- Red 0.95-1.26 keV,
- Green 1.63-2.26 keV,
- Blue 4.1-6.1 keV

- Latest Chandra observations:
  - Red and green bands:
    \( \rightarrow \) the expanding plasma with \( T \sim 10^7 \text{K} \) (note Rayleigh-Taylor instability)
  - Blue filamentary outer shell:
    \( \rightarrow \) shock wave with \( T \sim 2 \times 10^7 \text{K} \) \( \rightarrow \) extremely high energy electrons

NASA/CXC/Rutgers/J.Warren & J.Hughes et al.
- Tycho’s SNR

- Radio emission due to Synchrotron:
  - interstellar magnetic field compressed and amplified by shock wave
  - high energy electrons in strong magnetic field

- Infrared thermal emission:
  - From dust grains heated by the hot X-ray emitting gas
Particle acceleration in SNRs 1/4

- Radio and X-ray emission comparison

**Radio**

- **Spectrum**: follows power-law (varies between SNRs)
- **Polarisation**: average ~20% (B pattern smaller than resolution observations)

  → Synchrotron emission from relativistic electrons with several GeV

**But there is a strong correlation between Radio and X-ray map emissions**

**X-ray**

- **Thermal Bremsstrahlung** component from hot gas $T > 10^6$ K
- **Non-thermal** power-law component:

  → Synchrotron emission from relativistic electrons (which energies?)
- Kepler’s SN

- Green: (0.3-1.4 keV)
  - X-ray from cooler heated material expelled from the explosion

- Blue: (4-6 keV)
  - X-ray emission from hottest gas → Synchrotron radiation
- SN 1006

- SN Type I: it was brighter than Venus, probably the brightest on record
- Red: X-ray emission from few $10^6$K ejected gas
- Blue filaments:
  - X-ray synchrotron emission from extremely high energy electrons
- SN 1006 - Particle acceleration (XMM)

- Accelerated high energy particles (X-rays) more concentrated in the limbs than lower energy particles (Radio):
  - polar caps corresponding to direction of pre-supernova magnetic field
- Where the shock propagates along B lines:
  - more particles accelerated → both in X-rays & Radio
  - particles accelerated faster → X-rays
Particle acceleration in SNRs 2/4

- Non-thermal X-rays are detected at energies of:

\[ E_\gamma \approx 10 \text{ KeV} \rightarrow \nu \approx 2.4 \times 10^{19} \text{ Hz} \]

- The synchrotron emission peaks roughly at the critical frequency:

\[ \nu_c \approx 4.2 \times 10^{10} \gamma^2 B \text{ [Hz]} \]

- Assuming a magnetic field strength of: \( B \approx 10^{-5} \text{ G} \) (derived from filaments size)

- The electron energy can be derived:

\[ \gamma \approx \sqrt{\frac{\nu}{4.2 \times 10^{10} \times B}} = \sqrt{\frac{2.4 \times 10^{19}}{4.2 \times 10^{10} \times 10^{-5} \times 10^{-4}}} \approx 8 \times 10^8 \]

\[ E = \gamma mc^2 \approx 7.6 \times 10^8 \times 511 \text{ MeV} \approx 4 \times 10^{14} \text{ eV} \]

\[ E \approx 400 \text{ TeV} \]

Particles in SNRs are accelerated to energies up to hundreds of TeV
Particle acceleration in SNRs 3/4

- Acceleration mechanism

- Shock wave Fermi-I acceleration (not derived here):

- The maximum particle energy limited by different factors:
  - Time available for acceleration
  - Escape of high-energy particles from acceleration region
  - Balance between energy gain and losses

- Examples of losses:

- Detailed calculations give:
  - Maximum energy achievable by electrons → \( \sim 10^{15} \text{ eV} \)
  - Protons can reach much higher energies (smaller Synchrotron losses)

SNRs able to supply the bulk of particles of Galactic Cosmic Rays
Particle acceleration in SNRs

- Young SNRs spectra

Non-thermal power-law distributions

Hard X-ray spectra consistent with shock acceleration mechanisms
- Tycho’s SNR

- The SN remnant emits also at $\gamma$-ray frequencies
  $\Rightarrow$ New insights about cosmic rays origin in SN explosions
- Cas A

- Strongest radio source in the northern sky, youngest galactic SNR (1680)
- Remnant mass \( \sim 10-15 \, M_\odot \rightarrow \) SN type II
- Hot point-like source found in the center \( \rightarrow \) possibly a neutron star
SN type Ia white dwarf explosion $\rightarrow$ material stripped off companion star $\rightarrow$ the shock wave created the arc visible at X-rays
- The arc has blocked debris from the explosion $\rightarrow$ ‘shadow’
- The explosion imparted a kick to the companion star
Old Supernova Remnants 1/5

Phase III

- Old remnants examples:
  - Large radio shells containing an array of optical filaments
    - Observations can be challenging due to their large solid angle
  - X-ray emission from bright clumps
  - X-ray sometimes similar to radio structures

- Morphology:
  - Large radio shells containing an array of optical filaments

<table>
<thead>
<tr>
<th>Age</th>
<th>Name</th>
<th>Diam</th>
</tr>
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<tbody>
<tr>
<td>~ 3000</td>
<td>IC 443</td>
<td>22 pc</td>
</tr>
<tr>
<td>~ 4000</td>
<td>Pup A</td>
<td>26 pc</td>
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<td>~ 10000</td>
<td>Vela XYZ</td>
<td>48 pc</td>
</tr>
<tr>
<td>~ 20000</td>
<td>Cyg Loop</td>
<td>40 pc</td>
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</table>

- Surrounding interstellar material:
  - Likely to be originally part of the progenitor star:
    - stellar winds from outer layers star
    - after few $10^6$ yr star surrounded by bubble of hydrogen
  - Original inhomogeneous ISM pushed away
Old Supernova Remnants 2/5

- Old SNRs in X-rays

- Different morphology:
  - Shock wave through low density circumstellar H bubble (<1 atom/cm³):
    → shocked H not very strong X-ray source
  - Shock wave through high density cloud (~10-100 atoms/cm³):
    → compression and evaporation of some material from surface cloud
    → density increase → increase in X-ray emission

- Dimensions: a 40pc SNR → Sun + few $10^3$ nearby stars ! (a fraction of galactic disc)
Old Supernova Remnants 3/5

- Formation of optical filaments

- Gas within a large SNR ~ in pressure equilibrium
- Boundary force high density cold gas balanced by low density hot gas

- Hot gas cools down slowly until recombination → UV emission
  → cooling rate increases → pressure drops
  → cloud compressed by the surrounding material
  → increase density and radiation rate
  → rapid formation dense elongated cloud remains
Old Supernova Remnants 4/5

- Puppis A

- Note the SNR asymmetry

- The magnetic fields within the clouds are frozen and compressed into the ionised material:

  → Radio bright filaments correlated with X-rays emission
- Puppis A Remnant

- The SN explosion created and ejected the neutron star in one direction and much of the debris in the other
  → A fast moving neutron star as a cosmic cannonball!
- Material clumps massive enough for momentum conservation
- SN 1987A rings

- SN 1987A is in phase I → Free expansion
- Three rings of material expelled ~ 20000 years before SN explosion → maybe during transition between red and blue supergiant
- SN 1987A internal ring evolution

- Bright spots due to collision between the shock wave and the cooler outer layers shed before the star explosion
Very Young Supernova Remnants 3/3

- SN 1987A ring evolution

- SNR monitored by different observatories

→ Multi-wavelength observations of SNR evolution
Supernova Remnants with Neutron Stars

- Crab Nebula SNR

- Chinese and Japanese astronomers recorded this event in 1054

- There is a rapidly spinning neutron star embedded in the center of the SNR
  → it is the dynamo powering the nebula's interior glow
Supernovae and their remnants

Neutron Stars and Black Holes