Stellar Winds and Supernova Remnants: Interaction with the ISM
Stellar Evolution: Low Mass Stars

- Planetary nebula
- Double shell-burning red giant
- Helium-burning star
- Red giant
- Subgiant
- Sun
- White dwarf

Luminosity (solar units)

Surface temperature (Kelvin)

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Observations of detached shells

Thin molecular shell around TT Cyg (Olofsson et al. 1998)

Circumstellar envelope of R Scl (Olofsson et al. 2010)
Mass loss during a He-shell flash

Variation of mass loss during a He-shell flash: comparison of models
(Mattsson, Höfner & Herwig 2007)
Mass loss during a He-shell flash

variation of wind properties leading to the formation of a detached shell: snapshots of velocity (top) and density (bottom) (Mattsson et al. 2007)
Large-scale structure of the CSE

V-band image of IRC+10216 showing shell-like structures in the circumstellar envelope (90"x 90")
Mauron & Huggins (2010)

GALEX images of IRC+10216 (left: composite NUV+FUV, right: FUV) showing wind - ISM interaction (field of view 62'x 62')
Sahai & Chronopoulos (2010)
Wind of Mira interacting with ISM

NASA's Galaxy Evolution Explorer (GALEX) discovered an exceptionally long (13 light years) tail of material trailing behind the cool giant star Mira (ο Ceti). The tail is only visible in ultraviolet light (top left), and does not show up in visible light (bottom left).

First periodic variable star ever discovered!

www.nasa.gov/mission_pages/galex/20070815/a.html
Stellar Evolution: Low Mass Stars
PN: mass loss made visible

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www.nasa.gov/mission_pages/galex/20070815/a.html

A fascinating picture of stellar mass loss and the cosmic matter cycle at work...
Stellar Evolution: High Mass Stars

- Luminosity (solar units)
- Surface temperature (Kelvin)

- 85$M_{\text{Sun}}$
- 40$M_{\text{Sun}}$
- 25$M_{\text{Sun}}$
- 9$M_{\text{Sun}}$

- Sun
Stellar Structure: Pressure vs. Gravity
Stellar Evolution: Burning Phases

NUCLEAR FUEL (H) EXHAUSTED

NUCLEAR FUEL (H) "SWITCHED ON"

$e^a = T^b \ (n \gg 1)$

CONTRACTION

CONTRACTION

CONTRACTION

CONTRACTION

CONTRACTION

SI-MELTING

EXPLOSION

LOCUS-STAR

MAIN SEQUENCE STARS

RED GIANTS

SUPER GIANTS

SUPERNOVAE

CENTRAL TEMPERATURE

LUMINOSITY
Stellar Evolution: Burning Phases

Nuclear fuel (H) exhausted
Nuclear fuel (H) "switched on"
\( \epsilon_n \sim T^n \) (n >> 1)

Proto-stars → Main sequence stars → Red giants → Super giants → Collapse (explosion)

Central temperature
Luminosity

\( \epsilon_{grav} \)

Coulomb barrier

Energy (per baryon)

Distance

Nuclear potential well (binding energy)
H, He, C, O, Si, Fe
Stellar Evolution: Burning Phases
Stellar Evolution: Burning Phases

NUCLEAR FUEL (H) EXHAUSTED

NUCLEAR FUEL (H) "SWITCHED ON"
$e_N = T^n \ (n \gg 1)$

COLLAPSE
(Explosion)

CONTRACTION

H-BURNING

He-BURNING

C/O-BURNING

CONTRACTION

Si-MELTING

SUPERGIANTS

SUPERNOVAE

PROTO-STARS

MAIN SEQUENCE STARS

RED GIANTS

CENTRAL TEMPERATURE

LUMINOSITY
Stellar Evolution: High Mass Stars

- Nonburning hydrogen
- Hydrogen fusion
- Helium fusion
- Carbon fusion
- Oxygen fusion
- Neon fusion
- Magnesium fusion
- Silicon fusion
- Inert iron core
Stellar Evolution: High Mass Stars

**Stellar Collapse and Supernova Explosion**

- Progenitor star with degenerate iron core:
  - \( \rho = 10^9 \text{ g cm}^{-3} \)
  - \( T = 10^{10} \text{ K} \)
  - \( M_{\text{Fe}} = 1.5 M_{\odot} \)
  - \( R_{\text{Fe}} = 8000 \text{ km} \)

- Proto neutron star:
  - \( \rho = \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3} \)
  - \( T = 30 \text{ MeV} \)

- Neutrino Cooling:
  - \( 3 \times 10^{53} \text{ erg in few sec} \)

- Rebound of shock wave ➔ SN Explosion

- \( \approx 50 \text{ km} \)
Formation of a SNR

Birth of a Neutron Star and Supernova Remnant
(not to scale)

red giant

Core Implosion → Supernova Explosion → Supernova Remnant

neutron star
SNR: Expansion & Interaction with ISM

- How fast will the SNR expand, and on which typical timescales?
- What are the dominant physical processes?
- What are typical temperatures and densities?
- How will the SNR interact with the surrounding ISM?
SNR: Free Expansion Phase

Graph a) shows the variation of log ρ (in cm⁻³) with Radius [10¹⁸ cm]. The graph b) displays the variation of u (in km/s) with Radius [10¹⁸ cm]. Graph c) illustrates the variation of log P (in erg cm⁻³ s⁻¹) with Radius [10¹⁸ cm].

The diagram on the right represents the interaction of the SNR with the ISM, indicated by symbols and lines denoting different shock fronts and regions.
SNR: Expansion & Interaction with ISM

blast wave
(energy conserving)

shell formation
(radiative losses $\lesssim E$)

snow plow
(momentum conserving)
SNR: Expansion & Interaction with ISM

- **$\eta = 1$**: Free expansion
- **$\eta = 2/5$**: Sedov
- **$\eta = 2/7$**: Snow plow into ISM
- **$\approx 60 \text{ pc}$**
- **$\approx 20 \text{ pc}$**
- **$\approx 4.5 \text{ pc}$**

Graph showing log $R_s$ vs. log time with key milestones and parameters.
Example: Cas A SNR

- Chandra image (X-rays)
- X-Ray (NASA/CXC/SAO)
- Radio (VLA)
- Infrared (ISO)
Example: Tycho's SNR

SN event observed by T. Brahe in 1572

no stellar remnant:
SN type Ia

Chandra image:
- X-rays
- colours: diff. energies
- blue rim:
  - shock, 20 million K
- fingers: stellar debris, 10 million K
<table>
<thead>
<tr>
<th>Type</th>
<th>Ia</th>
<th>Ib</th>
<th>Ic</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectrum</strong></td>
<td>No Hydrogen</td>
<td>No Silicon</td>
<td>No Helium</td>
<td>Hydrogen</td>
</tr>
<tr>
<td></td>
<td>Silicon</td>
<td></td>
<td>Helium</td>
<td></td>
</tr>
<tr>
<td><strong>Physical mechanism</strong></td>
<td>Nuclear explosion of low mass star</td>
<td>Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Light curve</strong></td>
<td>Reproducible</td>
<td>Large Variations</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Neutrinos</strong></td>
<td>Insignificant</td>
<td></td>
<td>~ 100 x Visible energy</td>
<td>Neutron star (typically appears as pulsar) Sometimes black hole?</td>
</tr>
<tr>
<td><strong>Compact Remnant</strong></td>
<td>None</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rate/h^2SNy</strong></td>
<td>0.36 ± 0.11</td>
<td>0.14 ± 0.07</td>
<td>0.71 ± 0.34</td>
<td></td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>Total ~ 2000 as of today (nowadays ~200/year)</td>
<td></td>
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</tbody>
</table>
The progenitor of a Type Ia supernova

- Two normal stars are in a binary pair.
- The secondary, lighter star and the core of the giant star spiral inward within a common envelope.
- The aging companion star starts swelling, spilling gas onto the white dwarf.
- The common envelope is ejected, while the separation between the core and the secondary star decreases.
- The white dwarf’s mass increases until it reaches a critical mass and explodes...
- The remaining core of the giant collapses and becomes a white dwarf.
- ...which spills gas onto the secondary star, causing it to expand and become engulfed.
- ...causing the companion star to be ejected away.
Example: SN 1987A


HST • WFPC2 • ACS


January 8, 1999  April 21, 1999  February 2, 2000  June 16, 2000  November 14, 2000


NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

STScI-PRC04-09
Example: SN 1987A

Supernova 1987A
Collision Between Explosion
Ejecta and Slower Moving Gas

- Visible gas ring
- Fastest moving ejecta collides with gas
- Slow-moving gas from red giant phase
- Fireball
Example: Cygnus Loop

SN explosion took place about 15,000 years ago.

HST picture shows only a small part of the SNR.

The shock wave (moving left to right) is hitting denser IS gas.

- Blue: O (doubly ionized) hot gas behind shock
- Red: S (singly ionized) cooler gas
- Green: H directly behind shock