Stellar Evolution

The Birth, Evolution and Death of Stars

Stellar Evolution / Main Stages

- The Collapse of an Interstellar Cloud
- Fragmentation into smaller clumps → Stars
- Hydrogen Burning - Main Sequence
- Helium Burning - Red Giant
- Higher “nuclear” fuels (depending on mass)
- Death, depending on mass:
  - Planetary Nebula → White Dwarf
  - Supernova → Neutron Star
  - Supernova → Black Hole

Collapse of Interstellar Cloud

- Interstellar Medium Contains Clouds.
- $T \approx 10-100^\circ K$, $M \approx 10^\text{’s}-1000^\text{’s}$ of $M_\text{sun}$
- If gravitational pull exceeds gas (and B) pressure, gas collapses.

Numerical Simulation of Cloud Interstellar Cloud Collapse

- Cloud Gravitationally unstable and starts collapsing. Flow limited by formation of shock waves

Gravity

Gas pressure
- At some point, gravitational collapse forms dense cores

- Cores accrete through accretion disks
- Simulation by Matthew Bate
  http://www.ukaff.ac.uk/starcluster/

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**Star Formation Region in Orion**

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**Star Formation Region in Orion**

Hubble Space Telescope
Wide Field Planetary Camera 2
### Formation of Disks, why?

- It is easy for the gas to **cool** and lose **energy**.
- It is **hard** for gas to lose **angular momentum** as it contracts.
- \( L \sim M r v \) \( \Rightarrow \) \( v \sim L/(M r) \)
- Forces: \( F_{\text{centrifugal}} \sim v^2/r \sim L^2/r^3 \) & \( F_{\text{grav}} \sim M/r^2 \)
- Force ratio: \( F_{\text{centrifugal}} / F_{\text{grav}} \sim L^2/r \)
- As collapse proceeds, \( F_{\text{centrifugal}} / F_{\text{grav}} \) increases. Impossible to form star with too much angular momentum.
- **Result:**
  - 2/3 of stellar systems are **double stars**!
  - 1/3 of stellar systems should have planets.
  - (e.g., 99% of \( L \) in solar system, is in Jupiter!)

### Disks are ubiquitous to nature.

\( \text{Disks of Be stars form from stellar winds, not accretion disks} \)

**Be stars**

- Hot, bright, & rapidly rotating stars.
- Discovered by Father Secchi in 1868
- The “\( \pi \)” stands for emission lines in the star’s spectrum
- Detailed spectra show emission intensity is split into peaks to blue and red of line-center.
- This is from Doppler shift of gas moving **toward and away** from the observer.

- Indicates a disk of gas orbits the star.
Loss of angular momentum:
- Probably using magnetic fields
- Magnetic field is probably responsible for the acceleration of jets

The disk loses its mass by accretion and outflow
At the same time, condensations take place inside the disk
The clumps collide with one another and merge to form planets

Strong winds from the young star can form jets!

The clumps that did not merge to planets form the asteroids belt, the Kuiper belt and the Oort cloud.
Largest Kuiper belt object: Pluto!
Oort Cloud: Reservoir of Comets
Most observed Jupiters are significantly closer to their Sun
Need “planet migration”
Fuels burnt in stars:

Evolution of Stars / Gross Features:
- $M < 0.08 \, M_{\odot}$ – Brown Dwarf (no nuclear burning)
- $0.08 \, M_{\odot} < M < 0.5 \, M_{\odot}$ – Central hydrogen burning. Formation of a degenerate core. No helium ignition. End as a He white dwarf.
- $0.5 \, M_{\odot} < M < 2 \, M_{\odot}$ – Central Hydrogen burning, Helium flash, Helium burning. End as CO White dwarf.
- $2 \, M_{\odot} < M < 8 \, M_{\odot}$ – Central Hydrogen burning, Helium ignites non degenerately. End as CO White dwarf.
- $8 \, M_{\odot} < M < 20 \, M_{\odot}$ – Numerous burning stages after Helium burning. Type II Supernova ends as Neutron Star.
- $20 \, M_{\odot} < M$ – As above, but ends as a Black Hole.
- Note: High masses are inaccurately known due to large wind mass loss during evolution.

Hydrogen Burning
- Low mass stars: Outer convection because $T$ is low (opacity, ionization).
- High mass stars: Core convection because CNO H-burning (high $T$ dependence).

Zones of Convection

The extent of convective zones (shaded areas) in main-sequence star models as a function of the stellar mass (adapted from R. Kippenhahn & A. Weigert (1990), Stellar Structure and Evolution, Springer-Verlag).
**Depletion of Hydrogen in Core**

- In low mass stars (solar mass or less), pp-chain, and no convection in core.
- In high mass stars (higher than solar mass), CNO cycle, convection in core:

![Graph showing depletion of hydrogen in low and high mass stars](image)

**Evolution of low mass star**

- End of Hydrogen in Core while core is contracting (7)
- Burning of H → He in thick shell (“shell burning”) (7-8)
- Burning of H → He in thin shell (“shell burning”) (8-9)
- Helium ignition in degenerate core → Helium Flash (9)

![Graph showing evolution of a low mass star](image)

**Red Giant Expansion**

- Iben, ApJ, 415, 767 (1990), ‘the transition from main sequence to giant branch involves a complicated interplay between a core, an envelope, and a nuclear-burning shell’.

**An Example of a Red Giant**

![Image of a red giant star](image)
Stable Burning of Helium in Core

- In low mass (< 2 M\(_{\odot}\)), Helium Flash \[\xrightarrow{\text{Stable Helium burning after core expansion.}}\] (10)
- In High Mass (> 2 M\(_{\odot}\)), Stable Core burning without Helium Flash.
- Burning through 3\(\alpha\) \(\rightarrow\) 12C reaction, at T \(\sim\) 10\(^8\)°K
- O formed through \[\text{capture.}\]

Evolution of various masses

- Below 2 M\(_{\odot}\), no Hydrogen Flash.
- Below 8 M\(_{\odot}\), no ignition of C, O
- Above 8 M\(_{\odot}\), burn heavier and heavier fuels

Final evolution of low mass stars

- Low mass stars (< 2 M\(_{\odot}\)) cannot ignite C & O
- Shell burning of Helium (AGB = Asymptotic Giant Branch). (10-11)
- Envelope is very “lose” and shed through instabilities. (11)

Asymptotic Giant Branch Stars & Planetary Nebulae

- Once He is exhausted in core, core continues to contract, He & H burn in shells, envelope expands.
- At some point, envelope becomes unstable, and starts to pulsates, each time shedding some material.
- Envelope ejected at \(\sim\) 30 km/s, and core contracts and cools
- Envelope becomes planetary nebula
- Core becomes white dwarf
Leftover: White Dwarf
- Held by degeneracy pressure of electrons
Advanced burning in massive stars

Shells:

Major nuclear burning processes

<table>
<thead>
<tr>
<th>Nucleus Fuel</th>
<th>Process</th>
<th>Temp (10^8 K)</th>
<th>Products</th>
<th>Energy per Nucleon (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>p-p</td>
<td>~4</td>
<td>HX</td>
<td>6.55</td>
</tr>
<tr>
<td>H</td>
<td>CNO</td>
<td>15</td>
<td>HX</td>
<td>6.28</td>
</tr>
<tr>
<td>He</td>
<td>3He</td>
<td>4.0</td>
<td>C, O</td>
<td>0.51</td>
</tr>
<tr>
<td>C</td>
<td>C+C</td>
<td>600</td>
<td>O, Ne, M, Mg</td>
<td>0.34</td>
</tr>
<tr>
<td>O</td>
<td>O+O</td>
<td>1000</td>
<td>Ne, Mg, Si</td>
<td>~0.3</td>
</tr>
<tr>
<td>Si</td>
<td>Ne+Ne</td>
<td>3000</td>
<td>Ca, Fe, Ni</td>
<td>~0.18</td>
</tr>
</tbody>
</table>

Reactions Proceed up to Iron

- $^{56}\text{Fe}$ is the most stable isotope. Reactions can release energy only below $^{56}\text{Fe}$.
- When temperature in core $\sim 7 \times 10^9$ K, $^{56}\text{Fe}$ photodisintegrates: $^{56}\text{Fe} \rightarrow 13 \text{He} + 4n$ taking 100 MeV of energy! (At higher temperature, higher $S$ is favored)
- This cools the core very quickly and it collapses.

Supernovae

- One Iron photodisintegration takes place, core collapses on time scale of 10’s of ms.
- At “Low” masses, Neutron star is formed, and shock appears.
- As long as there is large fluxes of infalling material, shock cannot “leave” the core. Once shock does propagates outwards (perhaps using heating) it:
  - Heats the envelope (fast nuclear processes take place making Trans-Iron isotopes).
  - Accelerates the envelope, and it is ejected with speeds of order 10,000’s km/s.

Ejecta velocities of $\sim 10000$ km/s
**Left overs of massive stars**

- The remnant left can be either a Neutron Star or a Black Hole!
- Neutron stars are held by degeneracy pressure of neutrons (and not electrons)

**Neutron Stars can be active!**

- Rotation + magnetic field can power objects called pulsars.
- Acceleration of high energy particles along magnetic poles.
- If magnetic axis passes close enough to observer’s line of sight, we see a pulsar. (a lighthouse of high energy particles, radiation)