Chap 17: The Evolution of High-Mass Stars
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- CNO Cycles
- Convective cores
- Consecutive fusion shells
- End of fusion - Binding Energy
- Core collapse supernovae

- Neutron stars and Pulsars
- Supernova Remnants (SNR)
- The Origin of Elements: six primary astrophysical sources
- Periodic variables: L-P relations (distance measure)
Chap 17 deals with stars of initial masses greater than $3\ M_{\text{Sun}}$

- A star’s life depends on mass and composition because the rates and types of fusion depend on the star’s mass.
- Stars of different masses evolve differently. There are three categories of stars:
  - **low-mass stars** ($\text{Mass} < 3\ M_{\text{Sun}}$)
  - **intermediate-mass stars** ($\text{Mass}$ between $3\ M_{\text{Sun}}$ and $8\ M_{\text{Sun}}$)
  - **high-mass stars** ($\text{Mass} > 8\ M_{\text{Sun}}$)

<table>
<thead>
<tr>
<th>Name</th>
<th>High-mass stars</th>
<th>Medium-mass stars</th>
<th>Low-mass stars</th>
<th>Very low-mass stars</th>
<th>Brown dwarfs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral type</td>
<td>O, B</td>
<td>B</td>
<td>A, F, G, K</td>
<td>M</td>
<td>M, L, T, Y</td>
</tr>
<tr>
<td>Minimum mass</td>
<td>$8\ M_{\text{Sun}}$</td>
<td>$3\ M_{\text{Sun}}$</td>
<td>$0.5\ M_{\text{Sun}}$</td>
<td>$0.08\ M_{\text{Sun}}$</td>
<td>$\sim0.01\ M_{\text{Sun}}$ ($\sim13\ M_{\text{Jupiter}}$)</td>
</tr>
</tbody>
</table>
Massive stars are rare, not only because of their short lifespan

- *Initial Mass Function* shows the distribution of stellar masses at birth

The vast majority of stars are less luminous than the Sun.

Only a few are at the upper range of luminosities.
The division at $3 \, M_{\text{Sun}}$ marks an rough transition in the shape of the computed evolutionary tracks.
High-mass stars on the main sequence: CNO cycle and convective core
Massive MS stars have higher core temperature but lower core pressure

- Core temperature can be estimated using the **virial theorem**:
  \[ kT_c \approx GM\mu m_H / R \]

- Core pressure can be estimated from a **force balance**:
  \[ 4\pi R^2 P_c \approx GM^2 / R^2 \Rightarrow P_c \approx GM^2 / (4\pi R^4) \]

- Main sequence stars show a **mass-radius relation** of:
  \[ R \propto M^{0.8} \]

- Therefore, \( T_c \propto M^{0.2} \) and \( P_c \propto M^{-1.2} \)
The CNO Cycle: step-by-step

Legend:
- Proton
- Nucleus
- Positron
- Neutrino
- Gamma ray
CNO Cycle

This carbon nucleus goes back to the beginning—it’s a catalyst.

The net result is that four hydrogen nuclei were turned into a helium nucleus, two neutrinos, and seven gamma rays.
Net reaction of the CNO cycle

- In high-mass stars and the midlife Sun, hydrogen burning proceeds in the CNO cycle instead of the pp chain, due to higher core temperatures.
- The net result is the same as the pp chain: 4 H -> 1 He
Net reaction of the Proton-Proton chain

1. In the first step, colliding protons create deuterium ($^2$H).
2. In the second step, protons collide with deuterium nuclei to produce helium-3 ($^3$He).
3. In the final step, helium-3 nuclei collide to create helium-4 ($^4$He).

Net reaction:

$$6 \ ^1\text{H} + 2 \ e^- \rightarrow \ ^4\text{He} + 2 \ ^1\text{H} + 2 \ \nu + 6 \ \gamma$$
Changes on the Main Sequence due to Fuel Exhaustion

- The chemical composition inside a star changes over time as hydrogen is fused into helium.
- The Sun started with 70 percent hydrogen by mass, but now contains only 35 percent hydrogen in the core.
- What will happen when the hydrogen is exhausted in the core?
Condition for Convection: Large Temperature Gradients

- When **adiabatic expansion** of a gas pocket causes its temperature to drop **less** than that of the ambient gas, **convection** ensues:
  \[
  \frac{1}{\gamma} \frac{T}{P} \frac{dT}{dr} < - \frac{1 - \frac{\delta}{\gamma}}{P} \frac{dP}{dr}
  \]

- **Why?** \( P = nkT \), warmer gas at the same pressure as colder gas will have lower density. So the pocket will continue to rise due to buoyancy.
Convective Cores

- High-mass stars have large $T$ gradient, so convection mixes the core effectively.

- Increases the amount available for fusion, but still cannot sustain the high luminosity very long.

- High-mass stars live faster lives ($3$ Myr for $25$ $M_{\text{sun}}$).

- Once H is exhausted from the core, the star leaves the MS and expands and cools.
High-mass stars’ post-MS evolution:

Onion layers of burning shells, nearly horizontal evolution on the HRD
Fusion Shells

- The compression of the core ignite **He-burning** before it becomes degenerate, unlike low-mass stars.

- The fusion shells build up like the layers of an onion.

- The more massive the star, the heavier the elements that can fuse.

- Cores of high-mass stars will fuse elements up until iron (Fe).
# Burning Stages in High-Mass Stars

<table>
<thead>
<tr>
<th>Core Burning Stage</th>
<th>9-$M_\odot$ Star</th>
<th>25-$M_\odot$ Star</th>
<th>Typical Core Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (H) burning</td>
<td>20 million years</td>
<td>7 million years</td>
<td>$(3-10) \times 10^7$ K</td>
</tr>
<tr>
<td>Helium (He) burning</td>
<td>2 million years</td>
<td>700,000 years</td>
<td>$(1-7.5) \times 10^8$ K</td>
</tr>
<tr>
<td>Carbon (C) burning</td>
<td>380 years</td>
<td>160 years</td>
<td>$(0.8-1.4) \times 10^9$ K</td>
</tr>
<tr>
<td>Neon (Ne) burning</td>
<td>1.1 years</td>
<td>1 year</td>
<td>$(1.4-1.7) \times 10^9$ K</td>
</tr>
<tr>
<td>Oxygen (O) burning</td>
<td>8 months</td>
<td>6 months</td>
<td>$(1.8-2.8) \times 10^9$ K</td>
</tr>
<tr>
<td>Silicon (Si) burning</td>
<td>4 days</td>
<td>1 day</td>
<td>$(2.8-4) \times 10^9$ K</td>
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3 The ash of one reaction becomes the fuel for the next as the star evolves a layered structure.
Evolution Tracks on H-R Diagram

Once leaving the main sequence, the star starts to expand to a supergiant, while keeping almost constant luminosity.

The reason of the expansion is the same as the red giant stars — the fusion shell.
The mirror principle of a fusion shell: when one side contracts, the other side expands

- While the **gravitational thermostat** works well to control the **burning core**’s temperature, it cannot control the temperature of a **burning shell**.
- When fusion stops in the **core**, it **contracts**. Gravitational potential energy heats up the core and it conducts its heat to the surrounding shell.
- As the **shell’s temperature rises**, its fusion reaction rate increases rapidly.
- To avoid a thermonuclear runaway, the shell must decrease its temperature by dumping its energy to the **non-burning envelope**, causing the star to expand to a giant.

![Diagram of Red Giant Star](image)
Betelgeuse

The familiar red star in Orion constellation. Betelgeuse is a red supergiant.

distance = 640 light years, \( M = 7.7 \, M_{\text{sun}} \), \( R = 1,200 \, R_{\text{sun}} \)
Severe Mass Loss of High Mass Stars

- Stars with 20 M$_{\text{sun}}$ could lose $> 50\%$ of their mass.
- Mass loss rates are large: $10^{-7}$ to $10^{-5}$ M$_{\text{sun}}$/yr because of low gravity and radiation pressure, and occasional eruptions.
- Eta Carinae: $150 \, M_{\text{sun}}$ primary + $80 \, M_{\text{sun}}$ secondary
- The primary may have already lost $30 \, M_{\text{sun}}$ by now.
Recap: Massive Star Post-Main-Sequence Evolution
Evolution Tracks on H-R Diagram

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*The ash of one reaction becomes the fuel for the next as the star evolves a layered structure.*

*As in a low-
The End of Nuclear Fusion:
Nuclear Binding Energy
Fusion Energy: the mass per nucleon decreases from H to Fe

- Nuclear fusion produces energy from the mass loss occurred when fusing lighter elements into heavier elements ($E = \Delta m \cdot c^2$). This works from Hydrogen (H), to Helium (He-4), up to Iron (Fe-56), which has the lowest mass per nucleon.
An alternative way to understand fusion energy: nuclear binding energy

- **Binding Energy** is the minimum energy required to **disassemble** the nucleus of an atom into its constituent nucleons.
- **Fusion energy** is produced from **the difference in binding energy** between products and reactants.
- **Fe-56** has the highest binding energy per nucleon, so it marks **the end of both fusion and fission**.

Energy is absorbed when elements more massive than iron fuse.

Energy is released when elements less massive than iron fuse.
The net energy released by a nuclear reaction is the difference between the binding energy of the products and the binding energy of the reactants.

For the triple-alpha process:

\[
\text{(Net energy from fusing 1 kg of He)} = \left( \text{Binding energy of C formed} \right) - \left( \text{Binding energy of He fused} \right)
\]

\[
= (7.402 \times 10^{14} \text{ J}) - (6.824 \times 10^{14} \text{ J})
\]

\[
= 5.780 \times 10^{13} \text{ J}
\]

For the fusion of iron, the binding energy of the products is less than that of the reactants, so the net energy is negative.
Core-Collapse Supernovae

Type II SNe
Core-Collapse SN

1. Not even electron degeneracy pressure can stop the collapse of an iron ash core.

Why does the Fe core collapse? It reaches Chandrasekhar limit.

2. As the core collapses, the core temperature climbs so high that thermal gamma-ray photons photodisintegrate iron...

How did iron become mostly neutrons? Inverse beta decay.

3. ...and the core becomes so dense that electrons are absorbed by protons in atomic nuclei, forming neutrons and releasing energetic neutrinos.

4. Photodisintegration and electron absorption rob the core of pressure support. The collapse accelerates...

Neutrinos streaming from collapsing core

Iron core of evolved massive star

Gamma rays

Iron nucleus

Electron (−) Neutron
Proton (+)
Neutrino (ν)
Core Bounce and Explosion
leaving behind a blast nebula and a neutron star

5...until nuclear forces suddenly become repulsive. The overcompressed core bounces, driving its outer layers outward through the star.

6 The expanding shock is strengthened by the pressure of a hot bubble of trapped neutrinos from the core.

7 The shock continues through the outer layers of the star...

8...blasting forth in a Type II supernova...

9...and leaving behind the collapsed remains of the core, a neutron star.
Simulation of a Core-Collapse SN explosion

- e- degenerate iron core collapses
- $P$ surpasses $e^-$ degenerate
- Fe -> He, \textit{photodisintegration}
- $p^+ + e^- = n + \nu$
- core collapse accelerates
- strong nuclear force becomes repulsive
- core \textbf{bounces} and send shock waves outwards
- trapped \textbf{neutrinos} further accelerate shock waves
- 0.1$c$ shocks reach surface and heat it to 500,000 K
HOW TO BLOW UP A STAR
1. **CORE BOUNCE**

The growing iron core collapses under gravity, forming a neutron star. Infalling material bounces off the neutron star, creating a shock wave.

2. **SHOCK STAGNATION**

The outward-travelling shock wave collides with still-falling iron in the outer layers of the iron core and stalls.

3. **NEUTRINO HEATING**

Neutrinos emerge from the neutron star and heat up surrounding matter. The heat creates violent sloshing motions and bubbling convection.

4. **SHOCK REVIVAL**

The ferocious motions in the hot core create a pressure that helps to revive the shock wave and drive it out.
Just a few hundred milliseconds after the shock wave first forms, it accelerates out of the core — although it can take as long as a day to reach the star’s surface. The energy of the shock wave creates new elements, such as radioactive nickel. In the neutrino-heated, inner part of the explosion, nuclei also capture free neutrons or protons to form elements heavier than iron.
Light Curves & Energy Output: Type Ia vs. Type II Supernovae

Total Energy Release \( \sim \) Neutrino Energy \( \sim \) \( f \ M_{\text{chandra}} \ c^2 \)

Neutrino Energy \( \sim \) 100x Kinetic Energy \( \sim \) 10,000x EM Energy

\( f \sim 10\% \) for core-collapse SNe, \( f \sim 1\% \) for Type Ia SNe

\((\sim 10^{44} \text{ Joules in kinetic energy})\)

\((\sim 10^{43} \text{ Joules in kinetic energy})\)
Spectra: Type I (No Hydrogen lines) vs. Type II (Hydrogen lines)

Sketches of supernova spectra near maximum light (about 1 week)

White dwarf thermonuclear runaway

Core collapse of massive stars

Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.
Properties of Neutron Stars: Theoretical Models
Sirius B - the white dwarf companion of the Dog Star

- Inferred properties of Sirius B:
  - 1 Solar Mass
  - 0.03 Solar Luminosity
  - 27,000 K surface temperature
  - 5500 km radius (Earth-size)

Sirius B represent a class of objects called **White Dwarfs (WDs)**

- The physical conditions of WDs are extreme:
  - extreme density \( \rho \approx 3e9 \text{ kg/m}^3 \)
  - \( n_e \approx 1e36 /\text{m}^3 \)
  - extreme surface gravity (HW)
  - extreme pressure at the center
Neutron stars are extremely compact and dense, even compared to white dwarfs.

- packing a solar mass into a ball of ~10 km in radius results in a density of ~$10^9$ tons per teaspoon (compared to ~10 tons on a white dwarf)
- surface gravitational field – 300,000 times that of Earth ($g = GM/R^2$)
- To escape from a neutron star, an object would have to reach 50% the speed of light!

**Neutron Star**

- Mass ~ 1.5 times the Sun
- ~12 miles in diameter

**Solid crust**

- ~1 mile thick

**Heavy liquid interior**

- Mostly neutrons, with other particles
Outer crust
Atomic nuclei, free electrons

Inner crust
Heavier atomic nuclei, free neutrons and electrons

Outer core
Quantum liquid where neutrons, protons and electrons exist in a soup

Inner core
Unknown ultra-dense matter. Neutrons and protons may remain as particles, break down into their constituent quarks, or even become ‘hyperons’.

Atmosphere
Hydrogen, helium, carbon

Beam of X-rays coming from the neutron star’s poles, which sweeps around as the star rotates.
Core scenarios
A number of possibilities have been suggested for the inner core, including these three options.

- Up quark
- Strange quark
- Down quark
- Anti-down quark

Quarks
The constituents of protons and neutrons — up and down quarks — roam freely.

Bose–Einstein condensate
Particles such as pions containing an up quark and an anti-down quark combine to form a single quantum-mechanical entity.

Hyperons
Particles called hyperons form. Like protons and neutrons, they contain three quarks but include 'strange' quarks.
X-ray hotspots rotate in two scenarios for the pulsar J0030+0451, based on analysis of NICER data (Neutron Star Interior Composition Explorer)
Observable Neutron Stars I:
Pulsars
Neutron star has a size of a small city - How can we find them?
What are the unique observational properties of neutron stars?

• How can we tell if any of the objects in the image is a neutron star?
Contact (1997): Jodie Foster - Detecting the signal at the VLA
The Discovery of Pulsars in 1967

1967: Jocelyn Bell Burnell
PhD student of Anthony Hewish
at Cambridge University, England

Helped build a radio telescope to study the solar wind by looking at “twinkling” of background radio sources as their emission passes through the solar wind

In Nov 1967, she discovered a repeating radio signal with $P \sim 1\text{s}$

Thought it could be detection of ET – “LGM1” extraterrestrial (ET) little green men (LGM)

Now known as PSR 1919+21
- Charged particles around rapidly rotating, highly magnetized object produce beam of synchrotron radiation

- The beams sweep by Earth like a lighthouse beam.
Neutron stars are expected to spin very fast!

Angular momentum of a uniform sphere, and $L$ is conserved during collapse

\[ L = I \omega = \frac{2}{5} Mr^2 \omega \Rightarrow \omega \propto r^{-2} \Rightarrow P \propto r^2 \]
When the Sun ($R = 7e5$ km) collapses into a neutron star ($R = 10$ km):

What’s the current angular velocity?  
What will be the rotating period?  

$$\omega_\odot = \frac{2\pi}{P} = 14 \text{ deg/day for } P = 25 \text{ days}$$

When it collapses to 10 km radius, its rotation period will be $P = 0.44$ milliseconds.
Conservation of magnetic flux: Neutron stars are expected to have strong magnetic fields

The collapse of a star concentrates the magnetic field on the surface

Similar to angular velocity, $B \propto R^{-2}$

shrinking to a radius of 10 km, the Sun’s magnetic field would be $10^{10}$ times as strong!

Magnetic field for normal star (e.g. Sun): a few Gauss (G)
Magnetic field for neutron star: up to $10^{15}$ G
Strongest magnetic field produced in a laboratory (for a few seconds): $10^6$ G
Optical Pulsars and Primary vs. Secondary Pulses

The pulsar near the center of the Crab Nebula

a slow-motion optical video
Witnessing the formation of a Supernova Remnant (SNR)

SN 1987A
SN 1987A

LMC
\(d = 50 \text{ kpc}\)
\(\text{Dec} = -70\text{d}\)
\(M^* = 1 \times 10^{10} \text{ M}_{\odot}\)
Zoom in onto SN 1987A

Hubble Space Telescope
The firework after the explosion

SN ejecta catching up with the mass loss from stellar winds
The firework after the explosion

SN ejecta catching up with the mass loss from stellar winds
Neutrinos from SN 1987A

19 neutrinos were detected (in Japan & Ohio) the day *before* the optical explosion was seen.

Detection of neutrinos supports the core-collapse model: neutrinos are released when protons and electrons combine to form neutrons.
How to Measure the Age and Distance of a Supernova Remnant?

e.g., the Crab SNR’s association w/ SN 1054
Zoom into Veil Nebula (a SN remnant formed 10,000 yrs ago)
When you see a SN remnant, how would you measure the age of it and thus estimate when the SN exploded?
The Crab SN remnant is still *visibly* expanding

*How to associate a remnant with a supernova in the past?*

Expansion of the Crab Nebula

Years 1999 and 2012
Crab Nebula
- age = angular size / angular expansion rate
- assumes constant expansion rate
- In 1928, Hubble estimated that the supernova exploded in the year of 1054 CE
• The supernova was seen by the entire world in July 1054 CE.
• Peak magnitude between -7 and -4.5 (brighter than Venus)
• The event was documented by astronomers in Song Dynasty
• There is also some drawing evidence in Native American ruins in New Mexico, Chaco Canyon

SN 1054
• 4x brighter than Venus
• visible in daytime for 23 days!
The Sky in the morning of July 4, 1054

Location of the SN

Capella
Cocher
Vesta
Gémeaux
Mercury
Pollux
Mars
Sun
Moon
Taureau
Aldebaran
Betelgeuse
Orion
Rigel
When you see a SN remnant, how would you measure its distance? So that we know how large it is in physical units (e.g., AU)?

Imagine the spherical expansion of a shell of gas.
Chemical Abundances in the Solar System

Data from meteorites and models of the Sun
Asplund et al. 2009

C, N, and O are winners in He burning.

Fe, the most stable element, is the end point of nuclear burning.

More massive elements are formed by neutron capture.

Li, Be, and B are destroyed, not formed, in stars.

Sawtooth pattern
The Origin of Elements: from H to Fe

Nucleosynthesis in the Big Bang, stellar cores, and supernovae explosions
The Primary Origin of Each Element
(up to two main contributors are shown for each element)

- The **hydrogen** atoms in water were created 13.7 billion years ago in the **Big Bang** ($t = 3 \text{ min}, T = 1e9 \text{ K}, \text{density} = 1e5 \text{ kg/m}^3$).
- The **oxygen** atoms in the air you breathe and the water you drink were created by nucleosynthesis in the cores of high mass stars and released into the ISM via **type II SNe**.
- The **carbon** atoms were formed in the cores of low mass stars and released into the ISM in the **Post-AGB phase**.
- The **iron** atoms that are a key element of hemoglobin, which makes up the red blood cells that carry oxygen from your lungs to the rest of your body, formed in the explosion of white dwarfs (**type Ia SNe**).
The Origin of Elements: Li, Be, and B

Classical Nova, AGB stars, and Cosmic Ray Spallation
Notice the deficit of Li/Be/B

C, N, and O are winners in He burning.

Fe, the most stable element, is the end point of nuclear burning.

More massive elements are formed by neutron capture.

Li, Be, and B are destroyed, not formed, in stars.

Sawtooth pattern
As part of the triple-alpha process in Helium burning, Beryllium forms:

- $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \text{photon}$

If Be is transported to cooler regions ($10^6 \text{ K}$) by convection, it can form Lithium:

- $^7\text{Be} + e^- \rightarrow ^7\text{Li} + \text{neutrino}$

Otherwise, Beryllium fuses with hydrogen to form Boron:

- $^7\text{Be} + p \rightarrow ^8\text{B} + \text{photon}$

Classical Novae are powered by thermonuclear runaway on the surface of C/O White Dwarfs.
Cosmic Ray Spallation (x-process): Be and B

- **Cosmic rays** are high energy particles emitted by astrophysical sources like our Sun, supernovae, and active galactic nuclei (1936 Nobel Prize)
- Cosmic rays can hit other nuclei and cause them to split. This process is called **Cosmic Ray Spallation** or **x-process**
- Lithium, Beryllium, and Boron are *destroyed* in stars, the x-process is responsible for their abundances: e.g., \( n + ^{14}N \rightarrow p + ^{4}He + ^{10}Be \), then \(^{10}Be \rightarrow ^{10}B + e^-\) (beta decay)
The Origin of Elements: beyond Fe

Neutron star mergers and AGB Stars
Rapid and Slow Neutron Capture Processes (r- / s-process)

- **Rapid** neutron capture: the nuclei can capture multiple neutrons before the beta decay (emission of an electron)
  - Important in **neutron star mergers (short GRB)**, given the high neutron fluxes
  - Makes half of the nuclei heavier than iron (mostly **neutron-rich isotopes**)
- **Slow** neutron capture: the nuclei undergo beta decay before another neutron can be captured.
  - Important in **AGB stars**, neutron flux comes from $^{13}\text{C}(\alpha, n)^{16}\text{O}$ & $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$
  - Together with proton capture (**p-process**), makes the other half of the nuclei heavier than iron
Neutron Star Merger: Gravitational Wave & Gamma-Ray Burst
The Proton Capture Process (p-process)

- makes **neutron-deficit** isotopes from selenium (Se-34) to mercury (Hg-80)
Summary: The Six Astrophysical Sources of Elements

(top two/three main contributors are shown for each element)
<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Symbol</th>
<th>Color</th>
<th>Reaction Type</th>
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<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>H</td>
<td>blue</td>
<td>big bang fusion</td>
</tr>
<tr>
<td>O</td>
<td>8</td>
<td>O</td>
<td>red</td>
<td>cosmic ray fission</td>
</tr>
<tr>
<td>N</td>
<td>7</td>
<td>N</td>
<td>purple</td>
<td>merging neutron stars</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>C</td>
<td>green</td>
<td>exploding massive stars</td>
</tr>
<tr>
<td>P</td>
<td>15</td>
<td>P</td>
<td>yellow</td>
<td>exploding white dwarfs</td>
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- **Hydrogen**
- **Oxygen**
- **Nitrogen**
- **Carbon**
- **Phosphorus**
Even through your hardest days, remember we are all made of stardust.

Carl Sagan
The Instability Strip on the H-R Diagram: Pulsating Variable Stars and P-L Relations
Pulsating Variable Stars

- A star can evolve into a **pulsating variable star** when its interior fails to achieve a steady balance between pressure and gravity (i.e., it overshoots).
- The star’s **luminosity** changes as their **radius** and **temperature** changes at a regular period. Note that although the amount of emitted light changes, the **nuclear fusion rate** is unaffected.
**Pulsation Caused by Gas Ionization and Recombination**

- **Pulsations** are caused by the atmosphere oscillating between *ionized* (more opaque) and *neutral* (more transparent) phases.

  - Photons go through gas
  - Gravity condenses star
  - Temperature increases
  - He is ionized
  - Gas becomes opaque
  - Opacity blocks photon flow
  - Pressure increases
  - Less ionization means less blocked photons
  - Decreases pressure
  - Pressure expands star
  - He cools and becomes less ionized
GAIA data release 2: Variable Stars on the HR Diagram

Motion in the colour-magnitude diagram

Source density
$10^3$
$10^4$
$10^5$

Star type
- α2 Canum Venaticorum
- Be Cepheids
- Cateyndrome Variables
- δ Sct
- Eclipsing Binaries
- γ Casocopiae
- Long Period Variables
- RR Lyrae (ab)
- RR Lyrae (c)
- SX Phoenicis
- Type II Cepheids
- U Geminorum

No extinction correction

Day: 542
The Instability Strip on the HR Diagram

- Pulsating variables populate the instability strip on the HR diagram.
Delta Cephei - the Prototype Cepheid Variable Star
Period-Luminosity Relations (Leavitt 1912)

- $M_V = -2.43 \log(P_{\text{day}}) - 1.62$ (Classical Cepheids, Fritz et al. 2007)

- This period-luminosity relationship is important for determining distances to other galaxies: Measuring period gives luminosity (absolute magnitude), which combined with apparent magnitude, gives the distance modulus (thus distance): $m - M = 5 \log(d_{\text{pc}}) - 5$
How to Tell Apart the Different Types of Pulsating Variable Stars?

• Type I Cepheid variables
  - Cepheid variables are high-mass stars becoming supergiants.
  - They have periods from 1 to 100 days.
  - More luminous stars have longer periods.

• RR Lyrae variables and Type II Cepheid variables
  - These are low-mass stars on the horizontal branch.
  - They are less luminous than Cepheid variables.
Cepheids Light Curves - Type I vs. Type II Cepheids

Classical (or Type I) Cepheids

Type II Cepheids

https://arxiv.org/abs/1112.1406
RR Lyrae - Shorter Periods

• RR Lyrae variables have periods shorter than one day.
• Like Cepheids, their light curves show a variety shapes.
• They are low-mass stars in the horizontal branch phase.

Chap 17: The Evolution of High-Mass Stars

- CNO Cycles
- Convective cores
- Consecutive fusion shells
- End of fusion - Binding Energy
- Core collapse supernovae

- Neutron stars and Pulsars
- Supernova Remnants (SNR)
- The Origin of Elements: six primary astrophysical sources
- Periodic variables: L-P relations (distance measure)