10. The Lives of the Stars

1. Star Formation

2. Low-Mass Stars

3. High-Mass Stars
Stars are born inside giant clouds of cool gas and dust. Such a cloud may contain thousands of dense blobs of gas; some of these blobs collapse under their own weight. Gravitational compression heats the gas until thermonuclear reactions occur. When the production of nuclear energy matches the rate of energy escape into space, the collapse halts and a main-sequence star is born. Eventually, the hydrogen in the star's core is used up, and the star flares up in last burst of brilliance before it dies. If the star is massive enough, it explodes, spewing newly-synthesized elements back into space.
I. STAR FORMATION

a. Star-Forming Clouds

b. Stages of Collapse

c. Stellar Mass Limits
Stars form in cold, dark clouds of dusty gas floating in space. These clouds are called **molecular clouds**.
Gravity Versus Pressure

Gravity can’t form stars unless it can overcome the force of thermal (gas) pressure.

For this to happen, the ‘free-fall’ time, $t_{ff}$, must be less than the ‘sound-crossing’ time, $t_{sc}$.

There is a minimum size (and mass) for clouds which can collapse.
Gravity Versus Pressure

A molecular cloud \((T \approx 30 \text{ K}, n \approx 300 \text{ atoms/cm}^3)\) *must* weigh \(\sim 300 M_\odot\) to collapse.

The cloud can keep cool by emitting radio and infrared photons.

This cooling allows the collapse to continue a long way down.
Dimensions: 82500. AU
Time: 0 yr
Glowing Dust Grains

In a collapsing cloud, dust grains that block visible light heat up and emit infrared light.
Stages of Collapse

1. A gas cloud starts to collapse due to its own gravity.

2. It spins faster and radiates energy as it collapses.

3. Vertical motions die out, leaving a spinning disk.

4. As the center becomes opaque, it starts to heat up.
Collapse: Angular Momentum and Energy

1. Angular momentum conservation causes the cloud to spin faster as it contracts:
   \[(\text{rotation speed}) \propto \frac{1}{(\text{cloud diameter})}\]

   Collapse stops when the cloud spins at orbital speed.

2. Energy conservation causes the cloud to heat up:
   - Potential energy
   - Kinetic energy
   - Thermal energy
     - Gravitational collapse
     - Gas shocks
Disks and Jets

Rotation presents a barrier to star formation; unless most of the original angular momentum is lost, gas can’t reach the center!

It seems that jets — possibly driven by magnetic fields — may slow disk rotation and allow gas to flow in.
Three-Trillion-Mile-Long Jet From a Wobbly Star
Protostar Contraction

Once a protostar becomes opaque, it can continue to radiate from its surface. By doing so, it *heats up!*

An ordinary solid object cools off and fades from blue-hot to red-hot as it radiates energy.

A gas sphere held together by its own gravity contracts as it radiates, growing ever hotter.

*Gravitational energy* released as the protostar contracts powers this increase in temperature.
A Star is Born

As the central temperature reaches $\sim 10^7$ K, hydrogen fusion begins in the core of the protostar.

The protostar continues to contract and heat up until the fusion rate balances the energy radiated away.

When this balance is struck, contraction stops and the star settles onto the main sequence.
Stellar Mass Limits
Upper Limit on a Star’s Mass

- Photons exert a slight amount of pressure when they strike matter.

- Very massive stars are so luminous that the collective pressure of photons drives their matter into space.
Upper Limit on a Star’s Mass

- Models of stars suggest that radiation pressure limits how massive a star can be without blowing itself apart.

- Observations have not found stars more massive than about $150M_{\text{Sun}}$. 
Lower Limit on a Star’s Mass

• Fusion will not begin in a contracting cloud if some sort of force stops contraction before the core temperature rises above $10^7$ K.

• Thermal pressure cannot stop contraction because the star is constantly losing thermal energy from its surface through radiation.

• Is there another form of pressure that can stop contraction?
Degeneracy Pressure:

Laws of quantum mechanics prohibit two electrons from occupying the same state in the same place.
Thermal Pressure:
Depends on heat content
The main form of pressure in most stars

Degeneracy Pressure:
Particles can’t be in same state in same place
Doesn’t depend on heat content
Brown Dwarfs

- Degeneracy pressure halts the contraction of objects with $<0.08M_{\text{Sun}}$ before the core temperature becomes hot enough for fusion.

- Starlike objects not massive enough to start fusion are brown dwarfs.
Brown Dwarfs

- A brown dwarf emits infrared light because of heat left over from contraction.

- Its luminosity gradually declines with time as it loses thermal energy.
Brown Dwarfs in Orion

- Infrared observations can reveal recently formed brown dwarfs because they are still relatively warm and luminous.
Stars more massive than $150M_{\text{Sun}}$ would blow apart.

Stars less massive than $0.08M_{\text{Sun}}$ can’t sustain fusion.
1. Why are there lots of stars in some parts of this picture, and only a few in others?

A. Stars are scattered at random, so some parts of the sky have more than others.
B. This is a window out of the Milky Way and into intergalactic space, where stars are scarce.
C. There is a cloud of dust and gas, which absorbs visible light and hides more distant stars.
2. What is this cloud made of?

A. Very cold dense gas \((T \approx 30 \text{ K}, n \approx 300 \text{ atoms/cm}^3)\). Most of the hydrogen is in the form of molecules.

B. Warm gas \((T \approx 8000 \text{ K}, n \approx 1 \text{ atom/cm}^3)\). Most of the hydrogen is in the form of single atoms.

C. Hot gas \((T \approx 10^5 \text{ K}, n \approx 0.001 \text{ atom/cm}^3)\). Most of the hydrogen is ionized (\(e^-\) and \(p^+\) are separated).
3. Why is there a minimum size and mass for star-forming molecular clouds?

A. Clouds weighing less than one $M_\odot$ can’t form stars.
B. A cloud must contain a few hundred $M_\odot$ for gravity to overcome gas pressure.
C. Small clouds rotate too fast to collapse.
4. What happens to the gravitational energy released as a cloud of molecular gas begins to collapse?

A. It heats the cloud, increasing the gas pressure.
B. It escapes in the form of visible light.
C. It is converted to matter.
D. It escapes in the form of radio and infrared light.
E. It escapes in the form of ultraviolet light.
5. At what point does a spherical protostar begin to form in a collapsing cloud?

A. Before the gas settles into a spinning disk.
B. After the center of the disk becomes opaque to the radio and infrared radiation it has been emitting.
C. When nuclear reactions begin producing energy fast enough to replace the energy lost from the surface.
6. Consider a gas sphere in pressure balance. Suppose we add energy to it (instead of letting energy escape); what will happen?

A. The sphere will contract, and heat up.
B. The sphere will expand, and heat up.
C. The sphere will contract, and cool down.
D. The sphere will expand, and cool down.
E. Nothing will happen.
7. How does a protostar finally reach the temperature of \(~10^7\) K needed to begin hydrogen fusion?

A. Gravitational energy released by planetesimals hitting its surface.
B. Gravitational energy released by slow contraction.
C. Nuclear energy released by fission (splitting) uranium atoms.
D. Chemical energy released by hydrogen combining with oxygen.
8. Why is Jupiter not a star?

A. Gas (thermal) pressure within Jupiter resists gravitational contraction.
B. Degeneracy pressure within Jupiter resists gravitational contraction.
C. Jupiter does not have the hydrogen necessary to support fusion reactions.
D. It’s impossible to have more than one star in a system, and the Sun got there first.
8. Why can’t a large molecular cloud collapse to form a single star weighing a thousand $M_\odot$?

A. Radiation pressure limits the maximum mass of a star to about 150 $M_\odot$.

B. Degeneracy pressure halts the contraction of the cloud before nuclear reactions can take place.

C. Gas (thermal) pressure balances gravity and prevents the cloud from collapsing.
2. LOW-MASS STARS

a. Life on the Main Sequence
b. Red Giants and Beyond
c. Death of a Low-Mass Star
A star’s life is a constant struggle against gravity, which gradually squeezes it core to ever-higher temperatures and densities. This struggle ends when the star ‘dies’.
Main Sequence Lifetimes

A star stays on the main sequence until its core runs out of hydrogen.

- **1 $M_\odot$ star:** $L = L_\odot$
  - lifetime: $T_\odot \approx 10^{10}$ yr

- **10 $M_\odot$ star:** $L \approx 10^4 L_\odot$
  \[ \Rightarrow T \approx (10/10^4) T_\odot \approx 10^7 \text{ yr} \]

- **0.1 $M_\odot$ star:** $L \approx 0.003 L_\odot$
  \[ \Rightarrow T \approx (0.1/0.003) T_\odot \approx 3 \times 10^{11} \text{ yr} \]
Main Sequence Evolution

As the hydrogen in its core is slowly used up, a star’s ‘thermostat’ gradually raises the core’s temperature.

With a higher temperature, more energy flows out, and the star gets brighter.

For example, the Sun is getting about 6% brighter every billion years.
9. What happens when a main-sequence star’s core runs out of hydrogen?

A. The core cools off.  
B. The core shrinks and heats up.  
C. The core expands and heats up.  
D. Helium fusion begins immediately.
H begins fusing to He in a *shell* around the contracting He core — but this can’t stop the contraction, so the core gets *hotter* and the star gets even more luminous.
After the Main Sequence

Once hydrogen starts burning in a shell, a star becomes larger, redder, and much more luminous — at least for a while...
Helium Fusion

When the core temperature hits $10^8$ K, helium nuclei can overcome their repulsion and fuse to make carbon.

Compared to hydrogen fusion, this is not very efficient; $3\, ^4\text{He} \rightarrow ^{12}\text{C}$ converts just 0.07% of the mass to energy.
The central thermostat once again stabilizes the star’s energy production, and the total luminosity decreases.
Models predict that stars get smaller, hotter, and less luminous after He ignition. HR diagrams of old star clusters reveal stars with the predicted properties.
How does a low-mass star die?
Thought Question

What happens when a star’s core runs out of helium?

A. The star explodes.
B. Carbon fusion begins.
C. The core cools off.
D. Helium fuses in a shell around the core.
Double Shell Burning

- After core helium fusion stops, He fuses into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer.

- This double shell–burning stage never reaches equilibrium—the fusion rate periodically spikes upward in a series of thermal pulses.

- With each spike, convection dredges carbon up from the core and transports it to the surface.
Thought Question

What happens when a star’s core runs out of helium?

A. The star explodes.
B. Carbon fusion begins.
C. The core cools off.
D. Helium fuses in a shell around the core.
Planetary Nebulae

- Double shell–burning ends with a pulse that ejects the H and He into space as a planetary nebula.
- The core left behind becomes a white dwarf.
Planetary Nebulae

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Planetary Nebulae

- Double shell–burning ends with a pulse that ejects the H and He into space as a *planetary nebula*.

- The core left behind becomes a white dwarf.
End of Fusion

• Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen).

• Degeneracy pressure supports the white dwarf against gravity.
Life Track of a Sun-Like Star

[Diagram showing the life cycle of a sun-like star, including stages such as the main sequence, red giant, and planetary nebula.]
3. HIGH-MASS STARS

a. Evolution of High-Mass Stars

b. The Origin of the Elements

c. Steps to a Supernova
Life of a High-Mass Star ($M > 8 \, M_\odot$)

- Protostar
- Main-Sequence Star
- Helium-burning Star
- Red Supergiant
- Multi-Shell Supergiant
- Supernova
High temperatures in main-sequence stars with masses $M > 1.5 M_\odot$ allow a *faster* form of hydrogen fusion:

- $^1\text{H} + ^{12}\text{C} \rightarrow ^{13}\text{N} + \gamma$
- $^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu$
- $^1\text{H} + ^{13}\text{C} \rightarrow ^{14}\text{N} + \gamma$
- $^1\text{H} + ^{14}\text{N} \rightarrow ^{15}\text{O} + \gamma$
- $^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu$
- $^1\text{H} + ^{15}\text{N} \rightarrow ^{12}\text{C} + ^4\text{He}$

0.7% of mass $\Rightarrow$ energy
Evolution of High-Mass Star . . .

Initial evolution follows same sequence as a low-mass star.
After the helium in the core is gone, burning continues in two shells. Until the core contracts enough to ignite carbon.
Origin of the Elements

The Big Bang made 75% H and 25% He.
Origin of the Elements

Helium fusion makes carbon in most stars.
Origin of the Elements

The CNO cycle changes C into N and O.
Helium Capture Reactions

High core temperatures enable helium to fuse with other nuclei, producing $^{16}\text{O}$, $^{20}\text{Ne}$, $^{24}\text{Mg}$, ...
Origin of the Elements

He capture makes C into O, Ne, Mg — atoms with even numbers of protons.
Evidence for Helium Capture

Even-number elements are more common than odd-number elements!
Advanced Nuclear Burning

Nuclei up to the iron group (Fe, Co, Ni) can be produced by fusion reactions.
Origin of the Elements

Advanced burning makes a variety of elements.

Lanthanide Series

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<th>Mass Number</th>
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Actinide Series

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Late Stages of Evolution

By the end of its life, a high-mass star has multiple shells of nuclear burning, making a wide range of elements.

<table>
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<th>Reactants</th>
<th>Temperature</th>
<th>Products</th>
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<tr>
<td>$^{12}\text{C} + ^{12}\text{C}$</td>
<td>$6 \times 10^8 \text{ K}$</td>
<td>$^{24}\text{Mg}, ^{23}\text{Mg} + n, ^{23}\text{Na} + ^1\text{H}, ^{20}\text{Ne} + ^4\text{He}, ^{16}\text{O} + 2 ^4\text{He}$</td>
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<tr>
<td>$^{20}\text{Ne} + ^4\text{He}$</td>
<td>$1.2 \times 10^9 \text{ K}$</td>
<td>$^{24}\text{Mg}$</td>
</tr>
<tr>
<td>$^{16}\text{O} + ^{16}\text{O}$</td>
<td>$1.5 \times 10^9 \text{ K}$</td>
<td>$^{32}\text{S}, ^{31}\text{S} + n, ^{31}\text{P} + ^1\text{H}, ^{28}\text{Si} + ^4\text{He}, ^{24}\text{Mg} + 2 ^4\text{He}$</td>
</tr>
<tr>
<td>$^{32}\text{S}, ^{28}\text{Si}, ^{\text{He}}$</td>
<td>$\sim 3 \times 10^9 \text{ K}$</td>
<td>$^{56}\text{Fe}, ^{56}\text{Co}, ^{56}\text{Ni}$</td>
</tr>
</tbody>
</table>

However, the iron-group elements represent the end of this process.
The Limits of Fusion

No more energy is released by fusing iron-group elements — making heavier elements *takes* energy.
Prelude to a Supernova

With no nuclear energy available, the iron core contracts until it becomes degenerate.

As S and Si continue to burn, the mass of the degenerate iron core keeps growing.

When the iron core’s mass reaches $1.4 \, M_\odot$, something catastrophic happens . . .
Degeneracy Pressure

Like photons, electrons are both particles and waves. The wavelength of an electron is

$$\lambda = \frac{h}{m_e v}$$

Electrons in a box obey rules:

1. Each electron must have a different state (ie, wavelength).
2. Only waves which fit evenly are allowed.
Degeneracy Pressure

Like photons, electrons are both particles and waves. The wavelength of an electron is

\[ \lambda = \frac{h}{m_e \nu} \]

By these rules, each electron added to the box must have a shorter wavelength (and higher velocity) than any electron already in the box.
Prelude to a Supernova

Within the degenerate core, electrons are moving at nearly the speed of light.

In effect, the electrons start to behave a bit like light, creating radiation pressure.

But a star supported by radiation pressure is unstable, and the core collapses inward . . .
Core Collapse

The core collapses in less than a second, releasing a huge amount of gravitational energy.

In the core, nuclei are smashed into protons & neutrons; the protons combine with electrons to make neutrons & neutrinos.

Some neutrinos are absorbed by the rest of the star, which is blasted outward . . .
### Origin of the Elements

Neutron capture & decay build rare heavy elements.

#### Key
- Atomic number
- Element's symbol
- Element's name
- Atomic mass

#### Periodic Table

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<th>Symbol</th>
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<td>Ar</td>
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#### Lanthanide Series

- Elements: Rf, Db, Sg, Bh, Hs, Mt, Uun, Uuu, Uub
- Mass range: 138.906 to 277.025

#### Actinide Series

- Elements: Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr
- Mass range: 227.028 to 260.051
Origin of the Elements

Neutron capture & decay build rare heavy elements.
The first nearby supernova in modern times was detected by neutrinos — supporting core collapse.