Chapter 12
Star Stuff
How do stars form?
Star-Forming Clouds

- Stars form in the interstellar medium
- This contains very cold, dark clouds of dusty “molecular” gas
- To form a star, the gas has to collapse, just like when planets form
- In fact, it is when planets form
Gravity Versus Pressure

- An interstellar gas cloud is supported by *thermal pressure*
- The cloud can collapse and create stars only when *gravity* can overcome the *thermal pressure*
- If the cloud is massive enough (thousands of solar masses or more), this can happen spontaneously
- Otherwise it must be triggered by something (a nearby supernova explosion, collision with another cloud, etc)
Gravity Versus Pressure

• Once the collapse begins, gravity becomes stronger as the gas becomes denser. Why does gravity become stronger?
Gravity Versus Pressure

- Once the collapse begins, gravity becomes stronger as the gas becomes denser.
- But the gas is getting hotter at the same time.

*Why does the gas get hotter?*
Gravity Versus Pressure

- Once the collapse begins, gravity becomes stronger as the gas becomes denser
- But the gas is getting hotter at the same time
- The collapse will continue until the *outward push* of thermal pressure balances the *inward crush* of gravity
- On the way to gravitational equilibrium, the cloud usually fragments into smaller pieces
Fragmentation of a Cloud

- This is a simulation of an interstellar cloud containing 50 solar masses of gas.
Fragmentation of a Cloud

- This is a simulation of an interstellar cloud containing 50 solar masses of gas.
- It is turbulent, and the random motions cause it to become lumpy.
Fragmentation of a Cloud

- This is a simulation of an interstellar cloud containing 50 solar masses of gas
- It is turbulent, and the random motions cause it to become lumpy
- Lumps that are dense enough to collapse go on to become stars
- A large cloud can make a whole cluster of stars
Glowing Dust Grains

- As stars begin to form, dust grains in the cloud absorb visible light.
- This heats them up and causes them to emit infrared light.
- The visible light from forming stars is obscured by dust.
- But not the infrared light.
• Solar-system formation and star formation go hand-in-hand

• Cloud heats up as gravity causes it to contract.

• Contraction can continue as long as the thermal energy it generates is radiated away.

• As gravity forces a cloud to become smaller, it begins to spin faster and faster.

• The spinning cloud flattens as it shrinks

• And in the center, where it is hottest, a star is born
Formation of Jets

- Often, jets of matter shoot out of the star along the rotation axis.
- This gets rid of some of the angular momentum so the star doesn’t spin itself apart.
- It is not well-understood, but almost certainly involves magnetic fields.
- How might magnetic fields explain the jets?
• Jets can be seen coming from the disks around protostars.
• A movie of this jet shows how it removes angular momentum
The Hertzsprung–Russell Diagram

One of the most important tools for astronomers
An H-R diagram plots luminosity versus surface temperature.
**Luminosity**
Amount of energy a star radiates per second in watts (joules/sec)

**Apparent brightness**
Amount of star’s energy that reaches Earth per second in watts per square meter.

*Luminosity is the total amount of power (energy per second) the star radiates into space.*

*Not to scale!*

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Luminosity passing through each sphere is the same.

Area of sphere:

$$4\pi \text{ (radius)}^2$$

Divide luminosity by area to get brightness.
The relationship between apparent brightness and luminosity depends on distance:

\[
\text{Brightness} = \frac{\text{Luminosity}}{4\pi (\text{distance})^2}
\]

We can determine a star’s luminosity if we can measure its distance and apparent brightness:

\[
\text{Luminosity} = 4\pi (\text{distance})^2 (\text{Brightness})
\]

Luminosity cannot be measured by just looking at the star. Surface temperature can, if you look at its spectrum…
Lines in a star’s spectrum correspond to a **spectral type** that reveals its temperature:

(Hottest) O B A F G K M (Coolest)
An H-R diagram plots luminosity versus surface temperature.

- Allows stars to be classified as giants, main sequence, or white dwarfs.
- Also gives information about mass, radius, and main-sequence lifetime.

Most stars are main-sequence stars.

- How long they stay main-sequence depends on their mass.
- Star masses vary greatly but do have limits…
How massive can stars be?
The relative frequency is mostly due to relative lifetimes.

Very massive stars are rare.

Low-mass stars are common.

The relative frequency is mostly due to relative lifetimes.
Very massive stars are short-lived.
Very massive stars are short-lived

Low-mass stars are long-lived
But there are upper and lower limits to the masses that stars can have.
Upper Limit on a Star’s Mass

- The *upper limit* on star mass is due to luminosity.
- Photons exert a slight amount of pressure when they strike matter.
- Very massive stars are so luminous that the collective pressure of photons blows them apart.
Upper Limit on a Star’s Mass

• The idea of an upper mass limit—around $150M_{\text{Sun}}$—comes from models of star formation.

• But it is supported by observations:
  – Only one star has been observed with a mass larger than $150M_{\text{Sun}}$.
  – It is 265-320$M_{\text{Sun}}$.
  – But it might have formed by several stars merging.
Lower Limit on a Star’s Mass

- The **lower limit** on star mass is due to “degeneracy pressure”
- Degeneracy pressure is a quantum effect—very different from thermal pressure
- Gravitational equilibrium—a balance between gravity and thermal pressure from core fusion—supports main-sequence stars (like the Sun)
- Core compression initially provides the $10^7$ K necessary for fusion
- The degree of compression—and the temperature—depends on mass
- If a protostar is massive enough, the fusion temperature is reached, fusion starts, gravity is balanced, and a star is born
- But heat from compression alone cannot balance gravity
- So if a protostar is not massive enough, it continues to be compressed until degeneracy pressure kicks in
- But what is degeneracy pressure?
• **Degeneracy Pressure** comes from the quantum nature of matter
• Two quantum particles—electrons, nuclei, etc—cannot be in the same place at the same time
• So they can only get so close
• When a protostar has contracted to the point where it can’t contract anymore without particles being in the same place…
• That’s one way of conceptualizing degeneracy pressure
• It keeps the particles from getting any closer together and stops the contraction
Degeneracy Pressure:
• Quantum theory requires that particles can’t be in the same place
• Contraction will continue if fusion doesn’t start
• So if contraction continues until particles “touch”, it stops
• Even if the cloud isn’t compressed enough to be hot enough for fusion

Thermal Pressure:
• Depends on temperature
• Because higher temperature means faster particles
• Temperature in turn depends on degree of compression
• And this depends upon the weight of material above
• If there is enough compression to generate $10^7$ K, fusion will stop contraction
Brown Dwarfs

- So if there is not enough mass to compress the core enough to achieve $10^7$ K before degeneracy pressure kicks in…
- Fusion never starts…
- And the protostar never becomes a hydrogen-fusing star
- Objects with mass $<0.08M_{\text{Sun}}$ will not heat up enough before degeneracy pressure halts their collapse
- And such objects end up as 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.
- And even more numerous than the smallest stars.
- So to summarize...
Stars more massive than $150M_{\text{Sun}}$ would blow apart.

Stars less massive than $0.08M_{\text{Sun}}$ can’t sustain fusion.
What are the life stages of a low-mass star?
A star remains on the main sequence as long as it can fuse hydrogen into helium in its core.
Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over.

The reason is that the “core thermostat” breaks…
After the Main Sequence - Broken Thermostat

On main sequence
“core thermostat”
works
After the Main Sequence - Broken Thermostat

- What happens then?
- With no fusion energy, the core contracts and heats
- As it does, H begins fusing to He in a shell around the core
- But this doesn’t restore the “core thermostat”, because the fusion is outside the core
- The He core continues to contract, even to the point of degeneracy
- Meanwhile the hydrogen-burning shell continues to deposit He “ash” on the core, and it continues to heat up
Eventually helium fusion begins, but not right away, because it requires much higher temperatures (100 million K) than hydrogen fusion.

This is because of the higher electric charge on He.

When helium fusion does begin, three He nuclei fuse to carbon through the “triple alpha” reaction pictured above.
The Helium Flash

- The thermostat is broken in a low-mass red giant
- Degeneracy pressure supports the core
- The core heats as the hydrogen-burning shell drops helium ash onto it
- Helium begins to fuse when the temperature reaches the helium fusion point
- But it fuses faster than the thermal pressure it produces can cool the core by expanding it
- So the temperature rises sharply, and helium fusion spreads rapidly throughout the core:
- This is the **helium flash**
- Eventually thermal pressure expands and stabilizes the core at a somewhat cooler temperature
Helium burning stars neither shrink nor grow because the core thermostat is temporarily fixed.
Life Track After Helium Flash

- Models show that a red giant should shrink and become less luminous after helium fusion begins in the core.
Life Track After Helium Flash

- Observations of star clusters agree with those models.
- Helium-burning stars are found in a horizontal branch on the H-R diagram.
- An H-R diagram like this provides a way of figuring out the age of the star cluster.
A cluster of many stars can form out of a single cloud.
Here is such a cluster...
Here is such a cluster…the Pleaides
Do you see the similarity?
Combining models of stars of similar age but different mass helps us to age-date star clusters.

Using the H-R Diagram to Determine the Age of a Star Cluster
How does a low-mass star die?
The diagram illustrates the evolution of a star's luminosity and surface temperature over time, depicting the life track of a star that lost considerable mass during the red giant phase. The helium flash is also indicated on the diagram.
Double-Shell Burning

• After core helium fusion stops, the carbon core collapses and heats
• Meanwhile hydrogen continues to burn in a shell around the carbon core, depositing a shell of helium on the core
• The shell of helium begins fusing to carbon while the hydrogen shell above it fuses to helium
• The star has become a red giant called a “double-shell burning star”
• This double-shell-burning stage is unsteady, and the fusion rate periodically spikes upward in a series of thermal pulses.
• With each pulse, carbon gets dredged up from the core and transported into the overlying “envelope”
• Soon that carbon will enrich the interstellar medium…
Planetary Nebulalae and White Dwarfs

- Double-shell burning ends with a pulse (or pulses) that ejects the gas envelope into space as a *planetary nebula*. 

[Image of a planetary nebula]
Planetary Nebulae and White Dwarfs

- Double-shell burning ends with a pulse that ejects the gas envelope into space as a planetary nebula
- The core left behind becomes a white dwarf
- White dwarfs are inert balls of carbon and oxygen (from fusion of helium and carbon)
- They might also have a little residual H/He atmosphere
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Planetary Nebulae and White Dwarfs

- Double-shell burning ends with a pulse that ejects the gas envelope into space as a *planetary nebula*.
- The core left behind becomes a white dwarf.
- White dwarfs are inert balls of carbon and oxygen (from fusion of helium and carbon).
- They might also have a little residual H/He atmosphere.
- They are about the size of Earth.
- Some even contain gigantic diamonds!

For more information about the diamond star, see [http://www.cfa.harvard.edu/news/archive/pr0407.html](http://www.cfa.harvard.edu/news/archive/pr0407.html)
Planetary Nebulae and White Dwarfs

- The planetary nebulae surrounding white dwarfs come in all shapes and sizes.
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End of Fusion

- In low-mass stars, fusion goes no further than the triple-alpha reaction \(3\text{He} \rightarrow \text{C}\)
- The core temperature doesn’t get hot enough for fusion of heavier elements (though some He fuses with C to make O).
- The dying core of the star collapsed whenever it used up a fusion fuel.
- The white dwarf does not collapse because it is supported by degeneracy pressure.
Life stages of a low-mass star like the Sun
Life Track of a Sun-Like (“Low Mass”) Star
What are the life stages of a high-mass star?
Life Stages of High-Mass Stars

- Main-sequence life of high-mass stars is similar to low-mass stars:
  - Hydrogen core fusion (main sequence)
High-mass main-sequence stars fuse H to He at much higher rates than low-mass stars. This is partly because their higher mass means higher core temperatures. But it’s also because they use carbon, nitrogen, and oxygen as catalysts. The “CNO cycle” is shown at left. Why doesn’t this happen in low-mass stars? In low-mass stars the core temperature isn’t high enough to overcome repulsion between protons and the larger nuclei.
Life Stages of High-Mass Stars

• Main-sequence life of high-mass stars is similar to low-mass stars:
  — Hydrogen core fusion (main sequence)

• Early stages after main sequence are similar for high-mass stars and low-mass stars:
  — Hydrogen shell burning (supergiant)
  — Helium core fusion (supergiant)
  — But high-mass stars can go beyond that
Multiple-Shell Burning

- Advanced nuclear burning proceeds in a series of nested shells.
- It’s during this process and afterwards that stars synthesize most of the chemical elements.
Synthesis of the elements

\[
\begin{align*}
{^{12}\text{C}} & \rightarrow {^{16}\text{O}} \quad (8\text{p}, 8\text{n}) \\
{^{16}\text{O}} & \rightarrow {^{20}\text{Ne}} \quad (10\text{p}, 10\text{n}) \\
{^{20}\text{Ne}} & \rightarrow {^{24}\text{Mg}} \quad (12\text{p}, 12\text{n}) \\
{^{4}\text{He}} & \quad \quad \quad \quad \\
{^{4}\text{He}} & \quad \quad \quad \quad \\
{^{4}\text{He}} & \quad \quad \quad \quad
\end{align*}
\]
Big Bang made 75% H, 25% He—stars make everything else
Hydrogen fusion on the main sequence produces additional He
**Helium fusion produces carbon**
The CNO cycle can change C into N.
High core temperatures allow helium to fuse with heavier elements.
Helium Capture

- Oxygen is particularly important to “life as we know it” because it is 89% of the mass of water
- Of course some “life as we know it” breathes it too…
So helium capture builds C into O, Ne, Mg ...
• There is evidence for helium capture in the relative abundance of the chemical elements

• Higher abundances of elements with even numbers of protons
Advanced Nuclear Burning

• Core temperatures in stars with $>8M_{\text{Sun}}$ allow fusion of elements as heavy as iron
Advanced reactions in high-mass stars make elements like Si, S, Ca,… and Fe (iron)
• How are these statements related?
• Through the equivalence of mass and energy:
  \[ E = mc^2 \]

But iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

This is because iron has the lowest mass per nuclear particle of all elements.
- Iron cannot fuse to anything larger
- Iron cannot fission to anything smaller
- So iron cannot generate any energy to support the core
- So when iron appears, the star’s death is imminent
How does a high-mass star die?
Multiple-Shell Burning

- The star begins to die as soon as core H is gone
- Advanced nuclear burning proceeds in a series of nested shells until iron appears
- Once iron appears, the dying star’s fate is sealed
- The iron can’t fuse, so the core collapses in a matter of msec
Supernova Explosion

- Why does this cause a supernova?
- The collapse heats the core to the point that the iron nuclei dissociate into protons and neutrons
- The protons then combine with free electrons to produce more neutrons and neutrinos
- With the loss of the electrons, electron degeneracy pressure disappears
- The core collapses to a ball of neutrons, supported by neutron degeneracy pressure
Supernova Remnant

- The energy released by the collapse of the core and the “bounce” when neutron degeneracy pressure kicks in drives outer layers into space
- Left behind is either a neutron star or, if the core is massive enough to “break” the neutron degeneracy pressure, a black hole
- The outer envelope of the star moves out into space, forming a nebula
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054
The energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au and U.
How does a star’s mass determine its life story?
Role of Mass

- A star’s mass determines its entire life story because it determines its core temperature.
- High-mass stars have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
- Low-mass stars have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs.
How are the lives of stars with close companions different?
• Algol is a binary star system consisting of a $0.8 \, M_\text{sun}$ red giant and a $3.7 \, M_\text{sun}$ main-sequence star
• What’s wrong with that?...
• Binary stars formed from the same cloud and should be the same age
• The more massive star should have become a red giant first
• This is the “Algol paradox”
The stars in the Algol system are separated by less than 20% of the distance between Mercury and the Sun, about 0.05 AU.

This is close enough that matter can be pulled by gravity off of the subgiant onto the main-sequence star.

And this “mass transfer” explains the Algol paradox…
The star that is now a subgiant was originally the most massive.

As it reached the end of its life and expanded into a red giant, it began to transfer mass to its companion.

And the companion star, originally less massive, grew to be more massive.
Close Binaries and White Dwarf Supernovae

- If the giant star in a system like Algol has a low enough mass, it will eventually become a white dwarf.
- When this happens, the direction of mass transfer can be reversed.
- And this can lead to a “white dwarf supernova” (also known as a “type 1a supernova”).
- These were instrumental in the discovery in the 1990s that the expansion of the universe is accelerating.
- Here’s how a white dwarf supernova happens…
Close Binaries and White Dwarf Supernovae

- Once the white dwarf forms, the main-sequence companion can no longer siphon away hydrogen and helium.

- So the main-sequence companion lives out its main-sequence lifetime, and becomes a red giant.

- And now it’s the white dwarf’s turn to siphon…
Hydrogen and helium siphoned from the red giant swirls in an “accretion disk” around the white dwarf.

H and He falls onto the surface of the white dwarf, which is still very, very hot.

A layer of hydrogen and helium builds up over time.

And this leads, not to a supernova, but to a “nova”…
Close Binaries and White Dwarf Supernovae

- The layer of hydrogen and helium on the surface of the white dwarf gets more and more compressed as material continues to rain down.
- And the compression heats it.
- Eventually it reaches the hydrogen fusion temperature.
- Fusion begins suddenly and explosively throughout the layer.
- The white dwarf temporarily appears much brighter.
- This is a “nova”
Close Binaries and White Dwarf Supernovae

- Nova explosions typically recur every few thousands or tens of thousands of years.
- Each time, much of the surface material is blown into space.
- But not all of it.
- So after each nova, the white dwarf is a little more massive.
- This continues until the white dwarf’s mass approaches 1.4 solar masses.
- Electron degeneracy pressure, which prevents white dwarfs from collapsing, can support no more than 1.4 solar masses.
- Let’s delve a little deeper into that…
White dwarfs with the same mass as the Sun are about the same size as Earth.

Higher-mass white dwarfs are smaller.

This is because of the greater compression of the interior.
Size of a White Dwarf

• Electron degeneracy pressure supports them, but it’s “squishy”
• They can still contract as more mass is added
• But due to the quantum nature of matter, not indefinitely
The White Dwarf Limit

• Quantum mechanics says that electrons must move faster as they are squeezed into a very small space
  – This is the “Heisenberg Uncertainty Principle”

• As a white dwarf’s mass approaches $1.4M_{\text{Sun}}$, its electrons must move at nearly the speed of light

• Because nothing can move faster than light, a white dwarf cannot be more massive than $1.4M_{\text{Sun}}$, the white dwarf limit (also known as the Chandrasekhar limit)
So when the mass of the white dwarf reaches 1.4 solar masses, electron degeneracy pressure fails, and the white dwarf collapses.

The resulting compression heats the white dwarf to the carbon fusion temperature.

And the whole white dwarf explodes in a frenzy of carbon fusion.

A white dwarf supernova is even brighter than a massive star’s core-collapse or “type 2 supernova”.

The white dwarf is obliterated.

Nothing is left behind.
• Since white dwarf supernovae always occur when the 1.4-solar-mass limit is reached…
• …the luminosities of different white dwarf supernovae are almost the same
• This is not true for massive star supernovae, whose energies depend on the mass of the star that produces them
• But because white dwarf supernovae are very bright and have a known luminosity, they can be used as “standard candles” to measure very large cosmic distances
• White dwarf supernovae can be distinguished from massive star supernovae by their light curves.
• And also by the presence (m.s.) or absence (w.d.) of H/He absorption lines.
In the 1990s, scientists measured the distances to a number of white dwarf supernovae in galaxies billions of light years away.

Because a white dwarf supernova occurs at a mass of $1.4 \, M_{\text{Sun}}$, they have a known luminosity.

The apparent brightness is easily measured.

And the distance can then be calculated using the “inverse square law for light”:

$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi \times (\text{distance})^2}$$

$$\text{distance} = \sqrt{\frac{\text{luminosity}}{4\pi \times (\text{apparent brightness})}}$$
The scientists compared the distances from the white dwarf supernovae to those predicted by various models of how the universe is expanding. The supernova data was only consistent with a model where the universe is expanding at an accelerating rate. This was a surprise, because the general view was that the expansion rate was constant or even slowing down. This is still somewhat controversial, but it might turn out to be one of the greatest scientific discoveries of all time. Among other things, it led to the proposal of “dark energy” as the reason for the acceleration, and greatly expanded our understanding of the cosmos.