Chapter 12: The Life Cycle of Stars
12.1 Star Birth

Our goals for learning:
• How do stars form?
• How massive are newborn stars?
Stars are born in **molecular clouds**

- Consist of molecular hydrogen (H$_2$) gas and dust grains.
- Masses of $\sim 10^5$ to $10^6$ times the Sun’s mass.
- Sizes of $\sim 150$ light years in diameter.
Stars are born in molecular clouds

- Clouds are very cold: ~10-30 K. (273 K = water freezes)
- Stars form when gravity overcomes thermal pressure.
- Then gas clumps begin to collapse.
Earliest stages of star birth: Protostars

- Dense cores of gas in the larger molecular cloud **collapse due to self-gravity.**

- Cloud heats up as it contracts due to conservation of energy: gravitational potential energy is converted to thermal energy (heat).
Rotation is an important factor during the star birth process (part 1)

• As gravity forces a dense core to become smaller, it spins faster and faster.

• This is due to conservation of angular momentum.
  – Dense cores have a small amount of initial rotation.
  – As the cores get smaller, they must spin up to conserve angular momentum.
Rotation (cont’d)

- Collisions between gas particles in cloud gradually reduce
  - random motions and
  - up+down motions.

➔ Collisions flatten the cloud into a disk.

- The result is a rotating protostar with a rotating disk of gas & dust.

- The orderly motions of our solar system today are a direct result of the solar system’s birth in a spinning, flattened cloud of gas.
And sometimes …

- **Outflows of hot gas or Jets** are often driven from young protostars ($<\sim 1$ million yrs old)

Jets can have strong effects on the birth molecular cloud.

[Close-up edge-on view of jets (red) and disk (green) around protostar. Top and bottom surfaces of disk are glowing, but cannot see darker middle layers of disk]

- **Fragmentation** into a binary star if protostar spins very fast
Outflow animation

Jets
Summary of Star Birth Process

• Gravity causes dense cores in molecular clouds to collapse.

• Collapsing cores heat up.

• When core gets hot enough, fusion begins and stops the shrinking.

• New star achieves long-lasting state of balance.

• Sometimes protostars can drive an outflow (jets) of material

• Protostars rotate rapidly, and some may spin so fast that they split to form close binary star systems.
Next step: Protostar to Main-sequence Star

- Protostar contracts and heats until core temperature is sufficient for hydrogen fusion.
- Contraction ends when energy released by hydrogen fusion balances energy radiated from surface.
- Takes 50 million years for star like Sun from birth to reach the main sequence. (Takes less time for more massive stars).
Star birth is a dynamic process

• First generation of stars to form can affect the molecular cloud from which it was born.
• Can trigger birth of a new generation of stars.
• Can lead to destruction of the original molecular cloud.
Star birth is best-studied using long wavelengths

- Much on-going star formation is “invisible”:
  - *Interstellar dust grains in molecular clouds absorb most optical photons.*

- Easiest to study star birth at long wavelengths
  - *Infrared wavelengths*
  - *Millimeter/radio wavelengths*

- These wavelengths are good for 2 reasons:
  - *Less absorption due to dust*
  - *Radiation from young stars can heat up the dust, causing it to emit at IR/millimeter wavelengths.*
Interstellar dust blocks optical light
Interstellar dust blocks optical light
Glowing Dust Grains

As stars begin to form, dust grains that absorb visible light heat up and emit infrared light of even longer wavelength.
Clusters of many stars can form from a single molecular cloud: wide range of stellar masses
Very massive stars are rare.

Low-mass stars are common.
Mass ranges of stars

- Stars more massive than 100 $M_{\text{Sun}}$ would blow themselves apart.
- Stars less massive than 0.08 $M_{\text{Sun}}$ can’t sustain core fusion.
What prevents protostars from continually collapsing ever smaller?

If $M > 0.08 \, M_{\text{Sun}}$, then gravitational contraction heats the core until fusion begins. Energy generated by fusion provides thermal pressure to stop the collapse ("star").

If $M < 0.08 \, M_{\text{Sun}}$, degeneracy pressure stops gravitational contraction before fusion can begin ("brown dwarf").
Degeneracy Pressure:
Laws of quantum mechanics prohibit two electrons from occupying same state in same place

Ten million atoms could fit end to end across this dot.
The nucleus is nearly 100,000 times smaller than the atom but contains nearly all of its mass.

Atom: Electrons are “smeared out” in a cloud around the nucleus.
Nucleus: Contains positively charged protons (red) and neutral neutrons (gray).
**Thermal Pressure:**

Depends on heat content

The main form of pressure in most stars

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**Degeneracy Pressure:**

Electrons can’t be in the same state in the same place.

Doesn’t depend on heat content.
Brown Dwarf

- An object less massive than $0.08 \, M_{\text{Sun}}$ [or $80 \, M_{\text{Jupiter}} (M_{\text{Sun}} = 1000 \, M_{\text{Jupiter}})]$
- Radiates infrared light.
- Has thermal energy from gravitational contraction.
- Cools off after degeneracy pressure stops contraction.
Brown dwarfs:
Between planets and stars

**Brown dwarfs**

**Planets**
- Mass < 15 Mjup
- Cold objects

**Stars**
- Mass > 80 Mjup
- Hot objects

**Brown dwarfs**
- Mass = 15-80 Mjup
- Start hot, get cold
  ("failed stars")
Brown Dwarfs in Orion

- Infrared observations can reveal recently formed brown dwarfs because they are still relatively warm and luminous.
What have we learned?

How massive are newborn stars?

• Newborn stars come in a range of masses, but cannot be less massive than \( 0.08 M_{\text{Sun}} \).
• Below this mass, degeneracy pressure prevents gravity from making the core hot enough for efficient hydrogen fusion, and the object becomes a “failed star” known as a brown dwarf.
12.2 Life as a Low-Mass Star

Learning goals

• What are the life stages of a low-mass star?
• How does a low-mass star die?
Different classes of stars

High-Mass Stars
\( > 8 \, M_{\odot} \)

Intermediate-Mass Stars
(\( \sim 2-8 \, M_{\odot} \))

Low-Mass Stars
\( < 2 \, M_{\odot} \)

Brown Dwarfs
(no H-burning)
\( < 0.08 \, M_{\odot} \)
Overview of stellar evolution

• In general, the story of stellar evolution is the ongoing struggle of stars to generate internal energy in order to resist collapsing under their own self-gravity.

• A star remains on the main sequence as long as it can fuse hydrogen into helium in its core.
  – About 90% of total lifetime spent on main sequence
  – Stable energy generation during this phase.

• Once the core H fuel is gone, the star evolves rapidly off the main-sequence, spending much of the remaining time as a cooler & more luminous star.
  – Exact fate will depend on its original mass.
  – In the end, gravity always wins.
Life & death of a low-mass star (like the Sun)

- Main sequence star
- Red giant star
- Helium-burning star
- Double-shell burning star
- Planetary nebula
- White dwarf
Stage #1: Main sequence phase

- Sun is in gravitational equilibrium during main sequence.

  Inward pull of gravity balanced by outward pressure from energy produced fusion of hydrogen in the core.
Stage #2: Red giant phase
H-burning shell with inert He core

- After 10 billion years, Sun’s core H is used up.
- Left with inert He core: not hot enough to burn (yet).
- He core shrinks in size along with inner layers.
- Surrounding shell of hydrogen gets hot enough to begin fusion.
- H-burning shell produces more energy than main-sequence phase.
- Star expands and cools: red giant phase.
Stage #2: Red giant phase
H-burning shell with inert He core

Main sequence star
(core H burning)

Red giant star
(H-shell burning)
Stage #2: Red giant phase
the “broken thermostat”

- During main sequence, fusion controlled by “solar thermostat”.
- During H-shell burning phase, no such thermostat working.
- H-burning shell makes more He, which is dumped on inert core.
- Core contracts further due to added weight, increasing the pressure.
- H-shell burning accelerates with time.
- Sun grows to 100x in size.
The Sun today

The Sun in 5 billion years:
- 2000x more heat
- 100x larger
Why doesn’t Helium begin nuclear reactions after H is exhausted?

- Helium fusion requires higher temperatures than hydrogen fusion because greater electrical charge leads to greater repulsion (100 million K vs 15 million K).

⇒ Helium core remains inert and shrinks
Stage #2, QUESTION: What happens when a star can no longer fuse hydrogen to helium in its core?

A. Core cools off.
B. Core shrinks and heats up.
C. Core expands and heats up.
D. Helium fusion immediately begins.
Stage #2, QUESTION: What happens when a star can no longer fuse hydrogen to helium in its core?

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*Remember gravitational equilibrium: outward pressure from core energy generation balances the inward push of gravity. W/o the energy generation, the core will be compressed and will heat up.*
Step #2, QUESTION: What happens as a star’s inert helium core starts to shrink?

A. Hydrogen fuses in shell around core
B. Helium fusion slowly begins
C. Helium fusion rate rapidly rises
D. Core pressure sharply drops
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The pressure from the outer portion of the star compresses the interior enough that H-burning starts in a narrow shell around the (inert) helium core.

H-burning shell generates much more energy than during the main sequence. The star swells up due to this energy generation.
Stage #3: Helium-burning star

- He-burning in core (making carbon) with a surrounding hydrogen-burning shell.
- Energy generation in this phase is steady, b/c the internal thermostat is (temporarily) fixed.
- Star becomes smaller and hotter.
Stage #3: Helium fusion

- Helium fusion requires higher temperatures than hydrogen fusion because greater electrical charge leads to greater repulsion (100 million K, compared to 15 million K).

- Eventually, after red giant stage, the core becomes hot enough to burn He.
Helium Flash

• Ignition of the He core happens very quickly ("helium flash")

• Thermostat is broken in low-mass red giant because degeneracy pressure supports core

• Core temperature rises rapidly when helium fusion begins

• Helium fusion rate skyrockets until thermal pressure takes over and expands core again
**QUESTION:** What happens when the 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
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*Analogous to the end of the main sequence, the core shrinks and the surrounding layers get denser.*
Stage #4: Double-shell burning star

- Similar to the red giant phase
  - Inert core of carbon
  - Surrounding shells: burning H and He
- Star becomes very cool & luminous, expanding in size.
- Gravity is very weak at stellar surface, leading to mass loss through a strong stellar wind (Phase #5).
- Continuing contraction of the core leads to greater & greater luminosity. However, never gets hot enough to burn carbon core: end of the line.
- Star collapses to a dense, small, hot object: white dwarf.
Stage #4, QUESTION: What happens when the 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
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A. The star explodes
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The core is not hot enough to burn the produced carbon. So analogous to the red giant phase, the core shrinks and the surrounding layers get denser. Get double-shell burning:

1. H-burning outer shell, and
2. He-burning inner shell.
Phase #5: **Planetary nebula.**

A low-mass star dies by puffing off its outer layers.
Central remaining core is a white dwarf: its very high temperature leads to very ionized gas shell.
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