The Lives of Stars
Understanding how stars evolve requires both observation and ideas from physics

- Because stars shine by thermonuclear reactions, they have a finite life span
  - That is, they fuse lighter elements into heavier elements
    - When the lighter elements are depleted, there is nothing left to fuse

- The theory of stellar evolution (not in the same sense as biological evolution, but more like life cycle development, like growing up) describes how stars form and change during that life span
Interstellar gas and dust is ubiquitous in the Galaxy

- Interstellar gas and dust, which make up the interstellar medium (ISM), are concentrated in the disk of the Galaxy
- Clouds within the interstellar medium are called nebulae
- Dark nebulae are so dense that they are opaque
  - They appear as dark blots against a background of distant stars
- Emission nebulae, or H II regions, are glowing, ionized clouds of gas
  - Emission nebulae are powered by ultraviolet light that they absorb from nearby hot stars
- Reflection nebulae are produced when starlight is reflected from dust grains in the interstellar medium, producing a characteristic bluish glow
As light from a distant object travels through interstellar space...

...short-wavelength blue light is scattered or absorbed by dust grains...

...while red light passes through.

How dust causes interstellar reddening
NGC 3576: A closer nebula

NGC 3603: A distant nebula

Reddening depends on distance
Protostars form in cold, dark nebulae

- Star formation begins in dense, cold nebulae, where gravitational attraction causes a clump of material to condense into a protostar.
- As a protostar grows by the gravitational accretion of gases, Kelvin-Helmholtz contraction causes it to heat and begin glowing.
During the birth process, stars both gain and lose mass

- In the final stages of pre–main-sequence contraction, when thermonuclear reactions are about to begin in its core, a protostar may eject large amounts of gas into space
- Low-mass stars that vigorously eject gas are called T Tauri stars
Protostars evolve into main-sequence stars

- A protostar’s relatively low temperature and high luminosity place it in the upper right region on an H-R diagram.
- Further evolution of a protostar causes it to move toward the main sequence on the H-R diagram.
- When its core temperatures become high enough to ignite steady hydrogen burning, it becomes a main sequence star.
Circumstellar accretion disk

Magnetic field lines thread through the disk
Protostar

As the disk contracts toward the protostar, it pulls the magnetic field lines with it.
Swirling motions in the disk distort the field lines into helical shapes.

Some infalling disk material is channeled outward along the helices.
All main sequence stars produce energy by hydrogen fusion, not in a single step, but in a sequence of thermonuclear reactions in which four hydrogen nuclei combine to produce a single helium nucleus.

(a) Step 1:
- Two protons (hydrogen nuclei, \(^1\text{H}\)) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino (\(\nu\)), and a positively charged electron, or positron (\(e^+\)).
- The proton and neutron form a hydrogen isotope (\(^2\text{H}\)).
- The positron encounters an ordinary electron (\(e^-\)), annihilating both particles and converting them into gamma-ray photons (\(\gamma\)).

(b) Step 2:
- The \(^2\text{H}\) nucleus from the first step collides with a third proton.
- A helium isotope (\(^3\text{He}\)) is formed and another gamma-ray photon is released.

(c) Step 3:
- Two \(^3\text{He}\) nuclei collide.
- A different helium isotope with two protons and two neutrons (\(^4\text{He}\)) is formed and two protons are released.
Stars of different masses have different structures, furthermore, the more massive the star, the more rapidly it evolves.

(a) Mass more than about $4 \, M_\odot$: Energy flows by convection in the inner regions and by radiation in the outer regions.

(b) Mass between about $4 \, M_\odot$ and $0.8 \, M_\odot$: Energy flows by radiation in the inner regions and by convection in the outer regions.

(c) Mass less than $0.8 \, M_\odot$: Energy flows by convection throughout the star’s interior.
Young star clusters give insight into star formation and evolution

- Newborn stars may form an open or galactic cluster.
- Stars are held together in such a cluster by gravity.
- Occasionally a star moving more rapidly than average will escape, or “evaporate,” from such a cluster.
- A stellar association is a group of newborn stars that are moving apart so rapidly that their gravitational attraction for one another cannot pull them into orbit about one another.
1. This emission nebula (about 2200 pc away and about 20 pc across) surrounds the star cluster M16.

2. Star formation is still taking place within this dark, dusty nebula.

3. Hot, luminous stars (beyond the upper edge of the closeup image) emit ultraviolet radiation: This makes the dark nebula evaporate, leaving these pillars.

4. At the tip of each of these “fingers” is a cocoon nebula containing a young star.

5. Eventually the cocoon nebulae evaporate, revealing the stars.
(a) The Pleiades star cluster

(b) An H-R diagram of the stars in the Pleiades

This star cluster is old enough that all of its cool, low-mass stars have arrived at the main sequence: Hydrogen fusion has begun in their cores.
• Star-forming regions appear when a giant molecular cloud is compressed.

• This can be caused by the cloud’s passage through one of the spiral arms of our Galaxy, by a supernova explosion, or by other mechanisms.
Star formation progresses in this direction. Shell of hydrogen that has not yet been ionized.

Older cluster
Old cluster
Expanding region of ionized hydrogen (H II)

Young cluster

New stars being formed

Giant molecular cloud
Shock wave spreads into molecular cloud

Radiation and stellar winds from this massive, luminous star...

...may have triggered the formation of these stars.
Supernovae can compress the interstellar medium and trigger star birth.

A shock wave spreads away from the site of a supernova explosion.

This interstellar gas was compressed and heated by the shock wave, making it glow.
A star’s lifetime on the main sequence is proportional to its mass divided by its luminosity.

Table 21-1: Approximate Main-Sequence Lifetimes

<table>
<thead>
<tr>
<th>Mass ($M_\odot$)</th>
<th>Surface temperature (K)</th>
<th>Spectral class</th>
<th>Luminosity ($L_\odot$)</th>
<th>Main-sequence lifetime ($10^6$ years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>35,000</td>
<td>O</td>
<td>80,000</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>30,000</td>
<td>B</td>
<td>10,000</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>11,000</td>
<td>A</td>
<td>60</td>
<td>800</td>
</tr>
<tr>
<td>1.5</td>
<td>7000</td>
<td>F</td>
<td>5</td>
<td>4500</td>
</tr>
<tr>
<td>1.0</td>
<td>6000</td>
<td>G</td>
<td>1</td>
<td>12,000</td>
</tr>
<tr>
<td>0.75</td>
<td>5000</td>
<td>K</td>
<td>0.5</td>
<td>25,000</td>
</tr>
<tr>
<td>0.50</td>
<td>4000</td>
<td>M</td>
<td>0.03</td>
<td>700,000</td>
</tr>
</tbody>
</table>

The main-sequence lifetimes were estimated using the relationship $t \propto 1/M^{2.5}$ (see Box 21-2).

- The duration of a star’s main sequence lifetime depends on the amount of hydrogen in the star’s core and the rate at which the hydrogen is consumed.
- N.B. - The more massive a star, the shorter is its main-sequence lifetime.
The Sun has been a main-sequence star for about 4.56 billion years and should remain one for about another 7 billion years.
During a star’s main-sequence lifetime, the star expands somewhat and undergoes a modest increase in luminosity.

The Sun 4.56 × 10^9 years ago

The Sun today
When core hydrogen fusion ceases, a main-sequence star becomes a red giant.
Red Giants

- Core hydrogen fusion ceases when the hydrogen has been exhausted in the core of a main-sequence star
- This leaves a core of nearly pure helium surrounded by a shell through which hydrogen fusion works its way outward in the star
- The core shrinks and becomes hotter, while the star’s outer layers expand and cool
- The result is a red giant star
• When the central temperature of a red giant reaches about 100 million K, helium fusion begins in the core.

• A process called the triple alpha process, converts helium to carbon and oxygen.
After the helium flash, a low-mass star moves quickly from the red-giant region of the H-R diagram to the horizontal branch.
H-R diagrams and observations of star clusters reveal how red giants evolve.

The age of a star cluster can be estimated by plotting its stars on an H-R diagram.

H-R diagram of 20,853 stars—note the width of the main sequence.
Post–main-sequence evolutionary tracks of five stars with different mass.
The cluster’s age can be estimated by the age of the main-sequence stars at the turnoff point (the upper end of the remaining main sequence).
All of these stars have joined the main sequence.

The least massive stars evolve the slowest and have not yet joined the main sequence.

This part of the main sequence is now empty: The most massive stars have depleted the hydrogen in their cores...

...and have become red giants.

The least massive stars are finally approaching the main sequence.

More of the main sequence is now empty...

...because with time, lower-mass stars have depleted the hydrogen in their cores and become red giants.
Stars of ever-lower mass have depleted their core hydrogen, so even more of the main sequence is now empty.

Much of the main sequence is now empty.

Only the least massive stars remain on the main sequence.

Age: 100 million years

Age: 4 1/4 billion years
As a cluster ages, the main sequence peels away from the main sequence region as stars of progressively smaller mass evolve into red giants.
Relatively young Population I stars are metal rich; ancient Population II stars are metal poor.

The metals (heavy elements) in Population I stars were manufactured by thermonuclear reactions in an earlier generation of Population II stars, then ejected into space and incorporated into a later stellar generation.

Some scientists now call the oldest of stars Population III stars.
When a star’s evolutionary track carries it through a region in the H-R diagram called the instability strip, the star becomes unstable and begins to pulsate.
• Cepheid variables are high-mass variable stars
• RR Lyrae variables are lower-mass, metal-poor variable stars with short periods
• Long-period variable stars also pulsate but in a fashion that is less well understood
There is a direct relationship between Cepheid periods of pulsation and their luminosities.

The light curve of δ Cephei (a graph of brightness versus time)
When δ Cephei is at maximum brightness, the star is expanding most rapidly.

Radial velocity versus time for δ Cephei
(positive: star is contracting; negative: star is expanding)
When δ Cephei is at maximum brightness, the star is near its maximum surface temperature.

Surface temperature versus time for δ Cephei
When δ Cephei is at maximum brightness, the star is expanding (its diameter is increasing).
Mass transfer can affect the evolution of close binary star systems. Mass transfer in a close binary system occurs when one star in a close binary overflows its Roche lobe.
Gas flowing from one star to the other passes across the inner Lagrangian point.

Mass can flow from the enlarged star to the other across the inner Lagrangian point.

Semi-detached binary: One star fills its Roche lobe.
A semidetached binary

- Large red giant
- More luminous main-sequence star

Algol

<table>
<thead>
<tr>
<th>Apparent visual magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
</tr>
<tr>
<td>2.4</td>
</tr>
<tr>
<td>2.6</td>
</tr>
<tr>
<td>2.8</td>
</tr>
<tr>
<td>3.0</td>
</tr>
<tr>
<td>3.2</td>
</tr>
<tr>
<td>3.4</td>
</tr>
</tbody>
</table>

- Small star eclipses the large one.
- Large star eclipses the small one.

2.87 days
Mass flows from the large star onto the small one, forming an accretion disk.

A semidetached binary with mass transfer

12.9 days

Small star eclipses the large one.

Large star eclipses the small one.
Mass can flow from either star to the other across the inner Lagrangian point

Contact binary: Both stars fill their Roche lobes.
This mass transfer can affect the evolutionary history of the stars that make up the binary system.

Both stars share the same outer atmosphere.

Overcontact binary: Both stars overfill their Roche lobes.
An overcontact binary

W Ursae Majoris

Both stars are about the same size, so all eclipses are roughly the same.

Apparent visual magnitude vs. Phase

8.0 hours
Low-mass stars go through two distinct red-giant stages

- A low-mass star becomes
  - a red giant when shell hydrogen fusion begins
  - a horizontal-branch star when core helium fusion begins
  - an asymptotic giant branch (AGB) star when the helium in the core is exhausted and shell helium fusion begins
1. The star shines by shell hydrogen fusion: The inert core shrinks and the outer layers expand.

2. Luminosity increases and surface temperature decreases, so the star moves up and to the right on the H-R diagram (along the red-giant branch).

3. Core helium fusion begins with the helium flash (*)..

Before the helium flash: A red-giant star
4. The star now shines by shell hydrogen fusion and core helium fusion: The core expands and the outer layers shrink.

5. Luminosity decreases and surface temperature increases, so the star moves down and to the left on the H-R diagram (into the horizontal branch).

6. Eventually all of the core helium is used up.

After the helium flash: A horizontal-branch star
7. The star now shines by shell hydrogen fusion and shell helium fusion. The core shrinks and the outer layers expand.

8. Luminosity increases and surface temperature decreases, so the star moves up and to the right on the H-R diagram (along the asymptotic giant branch).

9. Eventually the star sheds its outer layers to form a planetary nebula.
Bringing the products of nuclear fusion to a giant star’s surface

- As a low-mass star ages, convection occurs over a larger portion of its volume
- This takes heavy elements formed in the star’s interior and distributes them throughout the star

![Diagram of an AGB star with labeled components: Earth’s orbit, Dormant hydrogen-fusing shell, Carbon-oxygen core, Helium-fusing shell, Central regions of an AGB star. The diagram shows a scale of 300 million km.]
Low-mass stars die by gently ejecting their outer layers, creating planetary nebulae

- Helium shell flashes in an old, low-mass star produce thermal pulses during which more than half the star’s mass may be ejected into space.
- This exposes the hot carbon-oxygen core of the star.
- Ultraviolet radiation from the exposed core ionizes and excites the ejected gases, producing a planetary nebula.
Star

Gas ejected from the star
Why do planetary nebulae look so different from one another?

1. The star ejects a doughnut-shaped cloud of gas and dust from its equator.
2. The star then ejects gas from its entire surface.
3. The doughnut channels the ejected gas into two oppositely directed streams.
The burned-out core of a low-mass star cools and contracts until it becomes a white dwarf.

- No further nuclear reactions take place within the exposed core.
- Instead, it becomes a degenerate, dense sphere about the size of the Earth and is called a white dwarf.
- It glows from thermal radiation; as the sphere cools, it becomes dimmer.
High-mass stars create heavy elements in their cores

- Unlike a low-mass star, a high mass star undergoes an extended sequence of thermonuclear reactions in its core and shells
- These include carbon fusion, neon fusion, oxygen fusion, and silicon fusion

<table>
<thead>
<tr>
<th>Stage</th>
<th>Core temperature (K)</th>
<th>Core density (kg/m³)</th>
<th>Duration of stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen fusion</td>
<td>$4 \times 10^7$</td>
<td>$5 \times 10^3$</td>
<td>$7 \times 10^6$ years</td>
</tr>
<tr>
<td>Helium fusion</td>
<td>$2 \times 10^8$</td>
<td>$7 \times 10^5$</td>
<td>$7 \times 10^5$ years</td>
</tr>
<tr>
<td>Carbon fusion</td>
<td>$6 \times 10^8$</td>
<td>$2 \times 10^8$</td>
<td>600 years</td>
</tr>
<tr>
<td>Neon fusion</td>
<td>$1.2 \times 10^9$</td>
<td>$4 \times 10^9$</td>
<td>1 year</td>
</tr>
<tr>
<td>Oxygen fusion</td>
<td>$1.5 \times 10^9$</td>
<td>$10^{10}$</td>
<td>6 months</td>
</tr>
<tr>
<td>Silicon fusion</td>
<td>$2.7 \times 10^9$</td>
<td>$3 \times 10^{10}$</td>
<td>1 day</td>
</tr>
<tr>
<td>Core collapse</td>
<td>$5.4 \times 10^9$</td>
<td>$3 \times 10^{12}$</td>
<td>1/4 second</td>
</tr>
<tr>
<td>Core bounce</td>
<td>$2.3 \times 10^{10}$</td>
<td>$4 \times 10^{15}$</td>
<td>milliseconds</td>
</tr>
<tr>
<td>Explosive (supernova)</td>
<td>about $10^9$</td>
<td>varies</td>
<td>10 seconds</td>
</tr>
</tbody>
</table>
In the last stages of its life, a high-mass star has an iron-rich core surrounded by concentric shells hosting the various thermonuclear reactions.

The sequence of thermonuclear reactions stops here, because the formation of elements heavier than iron requires an input of energy rather than causing energy to be released.
High-mass stars violently blow apart in supernova explosions

• A high-mass star dies in a violent cataclysm in which its core collapses and most of its matter is ejected into space at high speeds
• The luminosity of the star increases suddenly by a factor of around $10^8$ during this explosion, producing a supernova
• The matter ejected from the supernova, moving at supersonic speeds through interstellar gases and dust, glows as a nebula called a supernova remnant
(a) 10 milliseconds after the core “bounce”

Star’s core

Shock wave spreads outward from the core

(b) 20 milliseconds after the core “bounce”

Instabilities generate turbulent eddies
Material was ejected in “blobs” from the supernova that produced the Cassiopeia A supernova remnant.
In 1987 a nearby supernova gave us a close-up look at the death of a massive star.
Supernova 1987A seen in 1996

- SN 1987A
- Outer rings
- Inner ring, about 1.3 ly (0.4 pc) in diameter
Outer ring — at edge of swept-up gas from earlier mass loss

Inner ring — of swept-up red-supergiant gas

Supernova remnant. A dark, invisible outer portion surrounds the brighter inner region lit by radioactive decay.

An explanation of the rings
Neutrinos emanate from supernovae like SN 1987A.

More than 99% of the energy from such a supernova is emitted in the form of neutrinos from the collapsing core.
White dwarfs in close binary systems can also become supernovae.

- An accreting white dwarf in a close binary system may become a supernova when carbon fusion ignites explosively throughout the degenerate star.
Type Ia supernovae are those produced by accreting white dwarfs in close binaries.

(a) Type Ia supernova

- The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).
- Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).
(b) Type Ib supernova

- The spectrum has no hydrogen lines, but does have a strong absorption line of un-ionized helium (He I).
- Produced by core collapse in a massive star that lost the hydrogen from its outer layers.
(c) Type Ic supernova

- The spectrum has no hydrogen lines or helium lines.
- Produced by core collapse in a massive star that lost the hydrogen and the helium from its outer layers.
Type II supernovae are created by the deaths of massive stars

(d) Type II supernova
- The spectrum has prominent hydrogen lines such as $H_\alpha$
- Produced by core collapse in a massive star whose outer layers were largely intact.
REMEMBER THIS!?
Scientists first proposed the existence of neutron stars in the 1930s

- A neutron star is a dense stellar corpse consisting primarily of closely packed degenerate neutrons
- A neutron star typically has a diameter of about 20 km, a mass less than 3 times the mass of the Sun, a magnetic field $10^{12}$ times stronger than that of the Sun, and a rotation period of roughly 1 second
- Zwicky and Baade proposed that a highly compact ball of neutrons would produce a degenerate neutron pressure in star remnants too large to become white dwarfs
  - Not verified until 1960’s
The discovery of pulsars in the 1960s stimulated interest in neutron stars.

Pulsar PSR 0329+54
Interval between pulses: 0.714 second
Pulsars are rapidly rotating neutron stars with intense magnetic fields

- A pulsar is a source of periodic pulses of radio radiation
- These pulses are produced as beams of radio waves from a neutron star’s magnetic poles sweep past the Earth
• Intense beams of radiation emanate from regions near the north and south magnetic poles of a neutron star.
• These beams are produced by streams of charged particles moving in the star’s intense magnetic field.
The Crab pulsar in visible light

The Crab pulsar in X rays

Pulsar in "on" state

Pulsar in "off" state

10 arcsec

1 arcmin
Fast-moving material from the pulsar creates shock waves, forming X-ray-emitting rings.

The Crab pulsar

The pulsar’s magnetic field funnels outgoing material into two oppositely directed jets.

1 light-year
Superfluidity and superconductivity are among the strange properties of neutron stars

• A neutron star consists of a superfluid, superconducting core surrounded by a superfluid mantle and a thin, brittle crust
• There is evidence for an “atmosphere”
The dashed curve shows the expected X-ray spectrum of neutron star 1E 1207.4-5209.

The solid curve shows the observed spectrum: The dips are caused by absorption of X-ray photons by the neutron star’s atmosphere.
Pulsars gradually slow down as they radiate energy into space

- The pulse rate of many pulsars is slowing down steadily
- This reflects the gradual slowing of the neutron star’s rotation as it radiates energy into space
- Sudden speedups of the pulse rate, called glitches, may be caused by interactions between the neutron star’s crust and its superfluid interior or material falling onto the crust
The neutron star’s rotation is gradually slowing down, so the pulsar period increases.

Pulsar glitch: The neutron star’s rotation suddenly speeds up and the period decreases.

After the glitch, the neutron star’s rotation resumes its slowdown and the period again increases.
The fastest pulsars were probably created by mass transfer in close binary systems

• If a neutron star is in a close binary system with an ordinary star, tidal forces will draw gas from the ordinary star onto the neutron star

• The transfer of material onto the neutron star can make it rotate extremely rapidly, giving rise to a millisecond pulsar
X rays are emitted when high-energy particles in the pulsar “wind” run into the interstellar medium.
1. The Black Widow pulsar emits intense X-radiation and a strong wind of matter and antimatter.

2. The radiation and wind from the pulsar cause the companion star to evaporate.

3. A wind of evaporated material streams from the companion star.

4. Interactions between the two stars’ winds form a shock wave that emits even more X rays.

An illustration of the pulsar and its companion
Pulsating X-ray sources are also neutron stars in close binary systems

- Magnetic forces can funnel the gas onto the neutron star’s magnetic poles, producing hot spots
- These hot spots then radiate intense beams of X rays
- As the neutron star rotates, the X-ray beams appear to flash on and off
- Such a system is called a pulsating X-ray variable
X-ray pulses from Cen X-3 occur at intervals of only 4.84 s.

The measured intensity of the pulses changed as the spacecraft’s detectors rotated toward and away from Cen X-3.
1. The ordinary star has expanded to become a giant or supergiant, filling its Roche lobe. Some of its gas escapes.

2. Some gas from the ordinary star crosses the inner Lagrangian point and forms an accretion disk around the neutron star.

3. The neutron star’s magnetic field funnels gas onto the magnetic poles, forming hot spots.

4. As the neutron star rotates, beams of X rays from the hot spots sweep around the sky.
Explosive thermonuclear processes on white dwarfs and neutron stars produce novae and bursters

- Material from an ordinary star in a close binary can fall onto the surface of the companion white dwarf or neutron star to produce a surface layer in which thermonuclear reactions can explosively ignite.

- Explosive hydrogen fusion may occur in the surface layer of a companion white dwarf, producing the sudden increase in luminosity that we call a nova.

- The peak luminosity of a nova is only $10^{-4}$ of that observed in a supernova.

- Explosive helium fusion may occur in the surface layer of a companion neutron star.

- This produces a sudden increase in X-ray radiation, which we call a burster.
(a) Nova Herculis 1934 shortly after peak brightness  
(b) Two months later
1. Material from a star accretes onto a companion white dwarf.

2. When enough accreted material builds up, thermonuclear reactions occur on the white dwarf’s surface, creating a burst of visible light.

3. The nova fades over several weeks.
1. Material from a star accretes onto a companion neutron star.

2. When enough accreted material builds up, thermonuclear reactions occur on the neutron star’s surface, creating a burst of X rays.

3. The X-ray burster fades within seconds.
Like a white dwarf, a neutron star has an upper limit on its mass

- The pressure within a neutron star comes from two sources
  - One is the degenerate nature of the neutrons, and the other is the strong nuclear force that acts between the neutrons themselves
- The discovery of neutron stars inspired astrophysicists to examine seriously one of the most bizarre objects ever predicted by modern science, the black hole