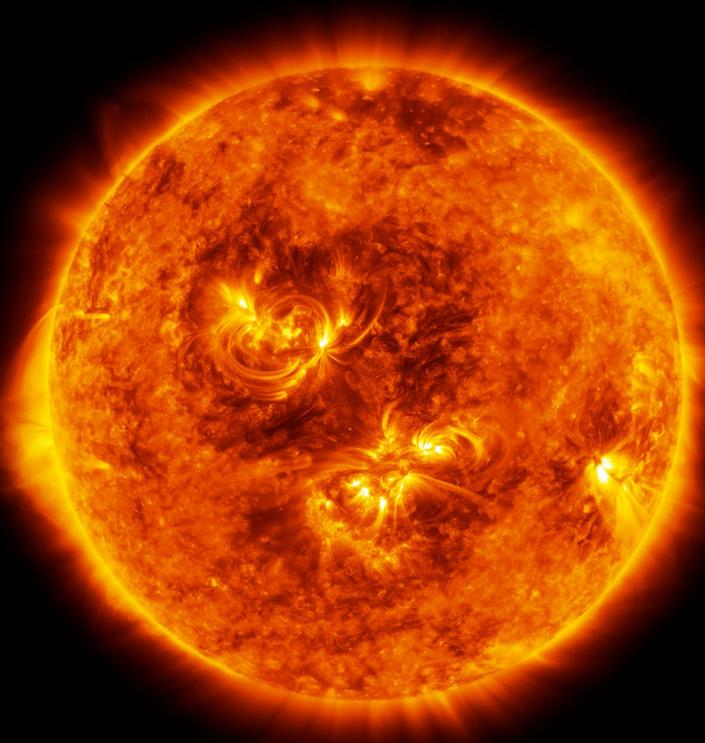




Sun and Stellar Evolution

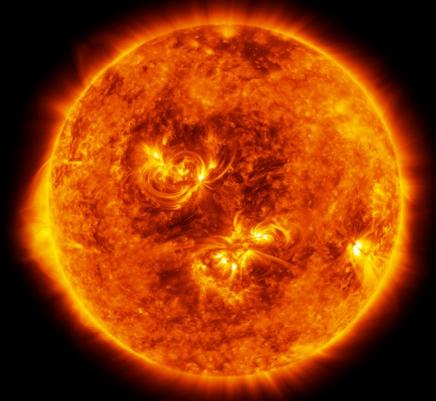
Sun-Composition



The Abundance of Elements in the Sun		
Element	Percentage by Number of Atoms	Percentage By Mass
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.80
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14



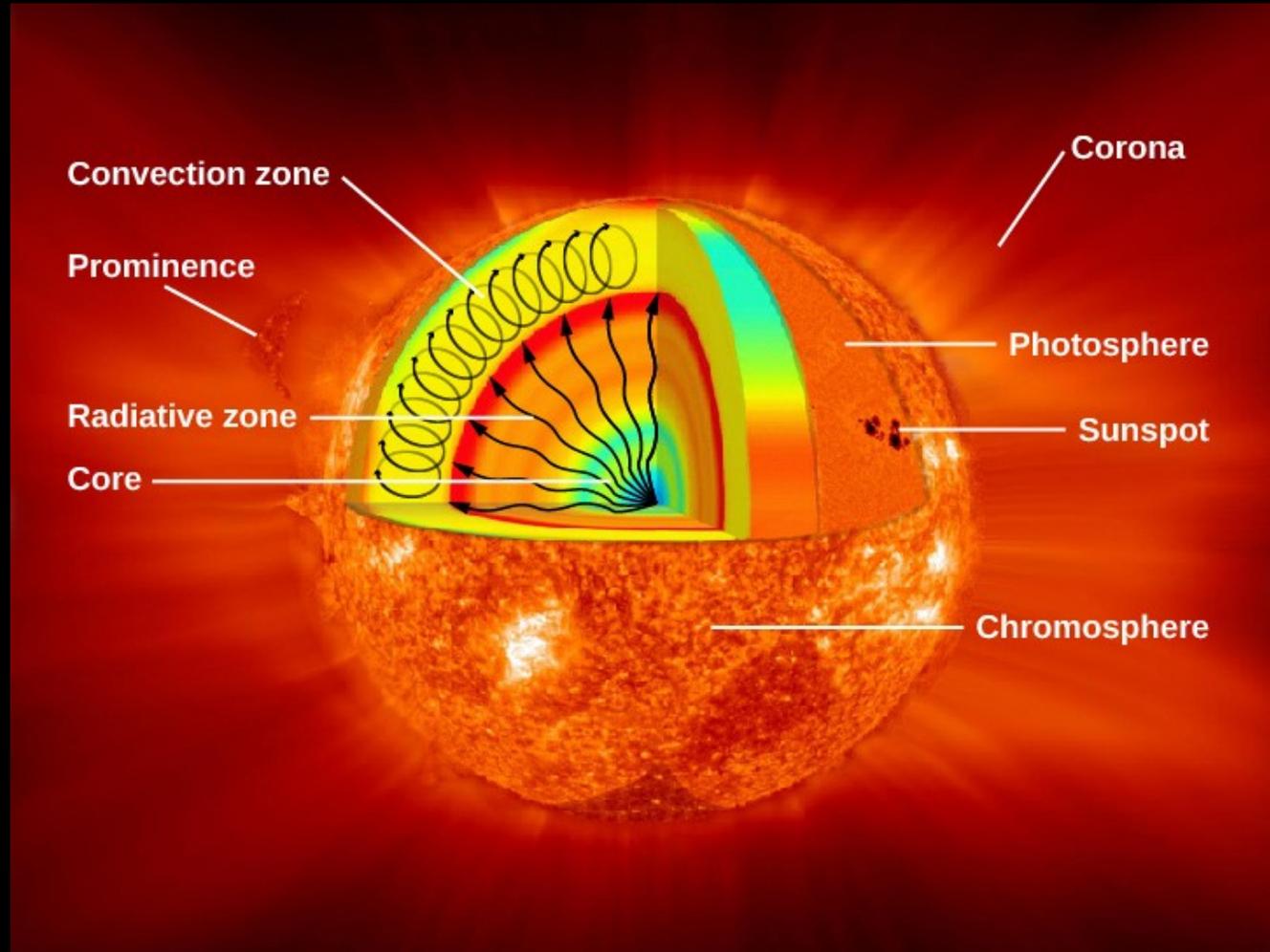
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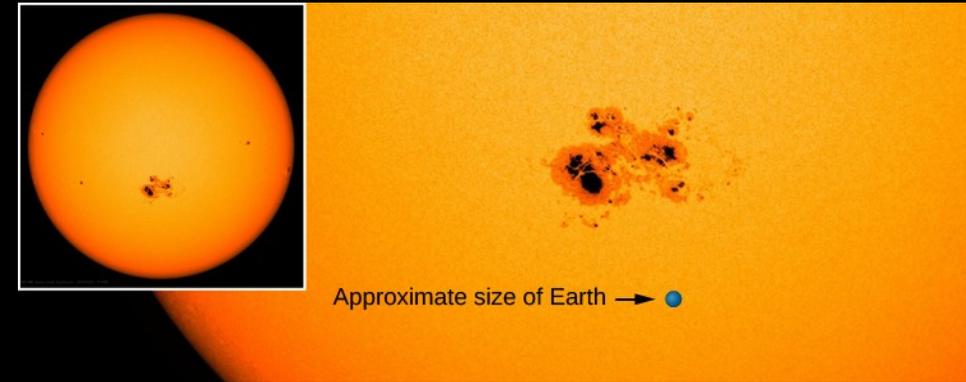
- Early belief: Sun and stars share Earth's composition.
- Cecilia Payne's work revealed the Sun's composition is dominated by hydrogen and helium.
- Sun and stars' composition reflects the broader universe, unlike Earth's heavier elements.
- Most elements exist as atoms with a few molecules, all in gaseous form.
- Extreme Heat: No liquids or solids can exist due to the Sun's intense heat.
- Many atoms are ionized, losing one or more electrons.
- The Sun's environment is electrically charged, unlike Earth's neutral atmosphere. This state is known as plasma.

Sun-Structure



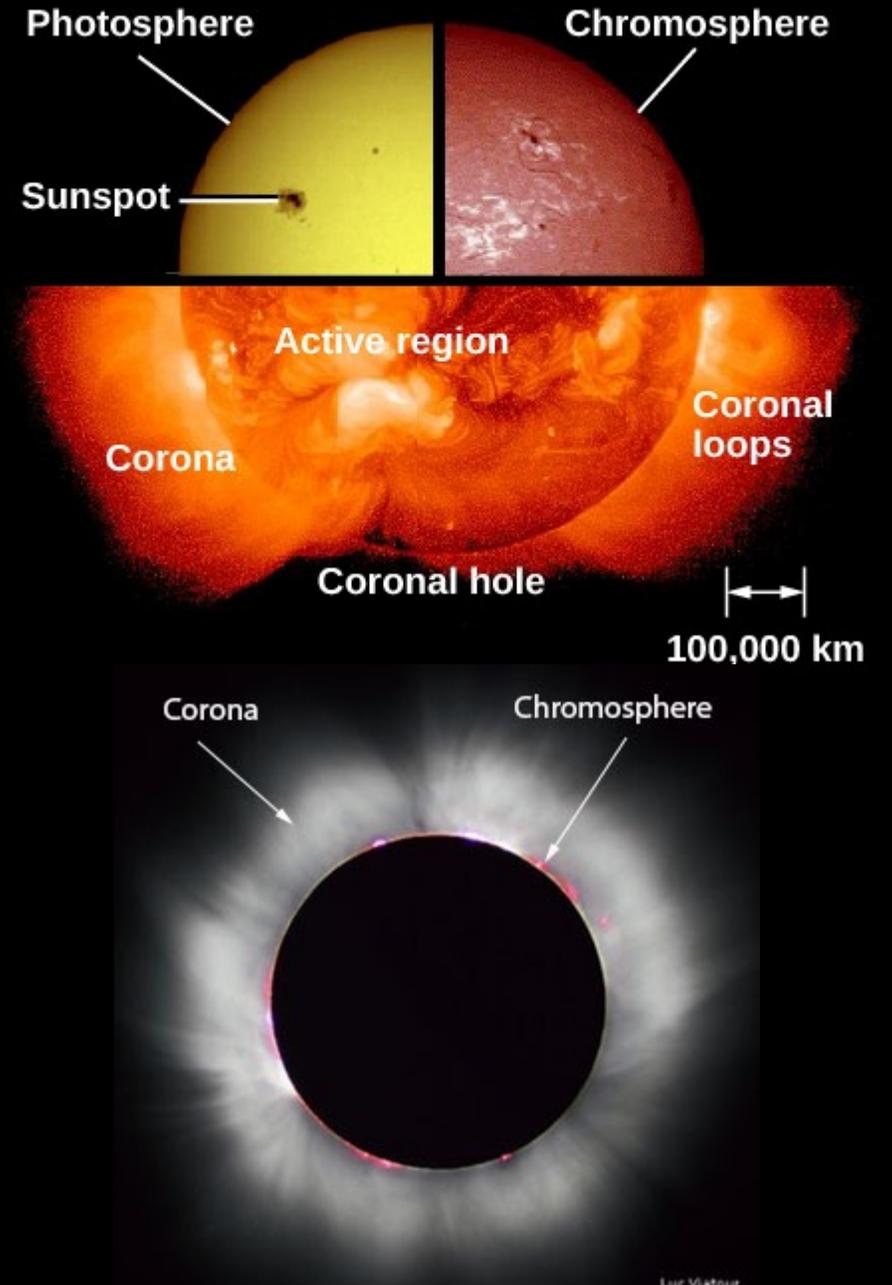
Solar Photosphere

- The photosphere is the layer where the Sun becomes opaque and marks the boundary past which we cannot see
- Energy that emerges from the photosphere was originally generated deep inside the Sun
- This energy is in the form of photons, which make their way slowly toward the solar surface.
- Outside the Sun, we can observe only those photons that are emitted into the solar photosphere, where the density of atoms is sufficiently low and the photons can finally escape from the Sun without colliding with another atom or ion.
- Temperature 4000-6500K



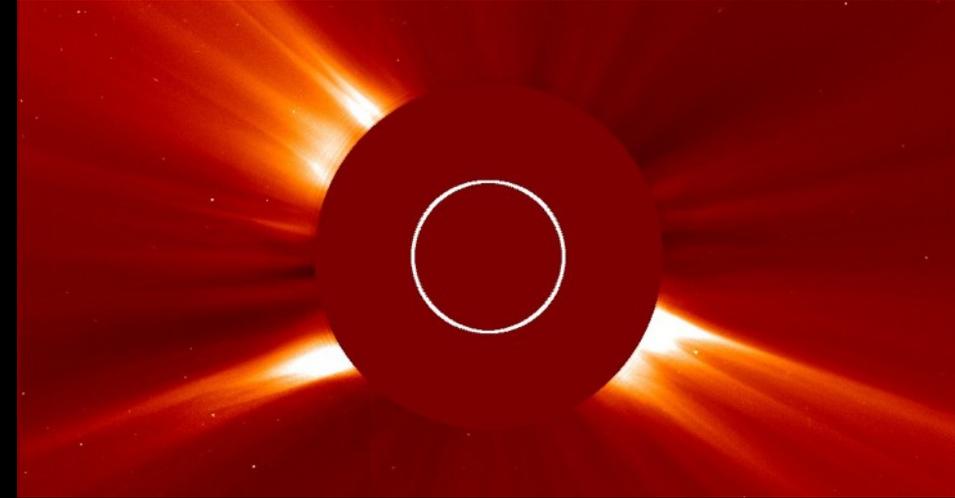
Chromosphere

- The region of the Sun's atmosphere that lies immediately above the photosphere is called the chromosphere.
- Until this century, the chromosphere was visible only when the photosphere was concealed by the Moon during a total solar eclipse
- Chromosphere is about 2000 to 3000 kilometers thick, and its spectrum consists of bright emission lines.
- The reddish color of the chromosphere—the bright red line caused by hydrogen
- In 1868, observations of the chromospheric spectrum revealed a yellow emission line that did not correspond to any previously known element on Earth.
- Scientists quickly realized they had found a new element and named it helium
- The temperature of the chromosphere is about 10,000 K.



Corona

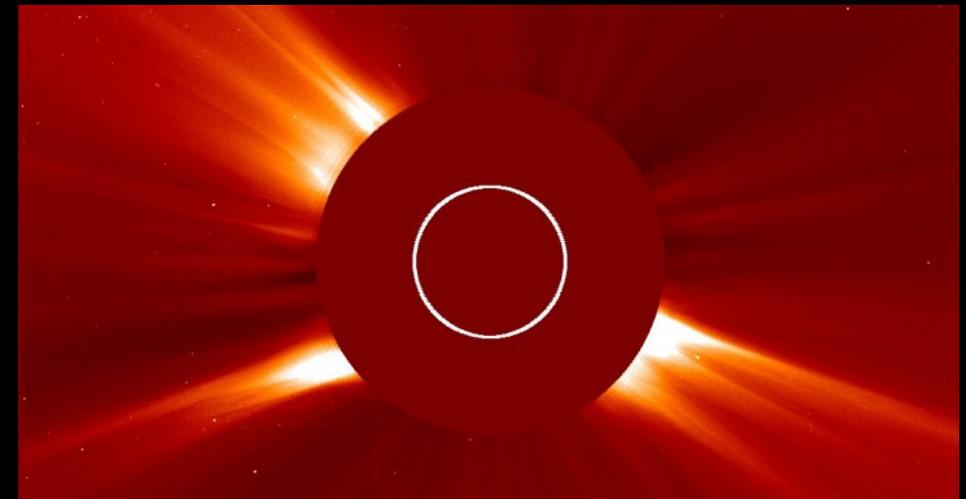
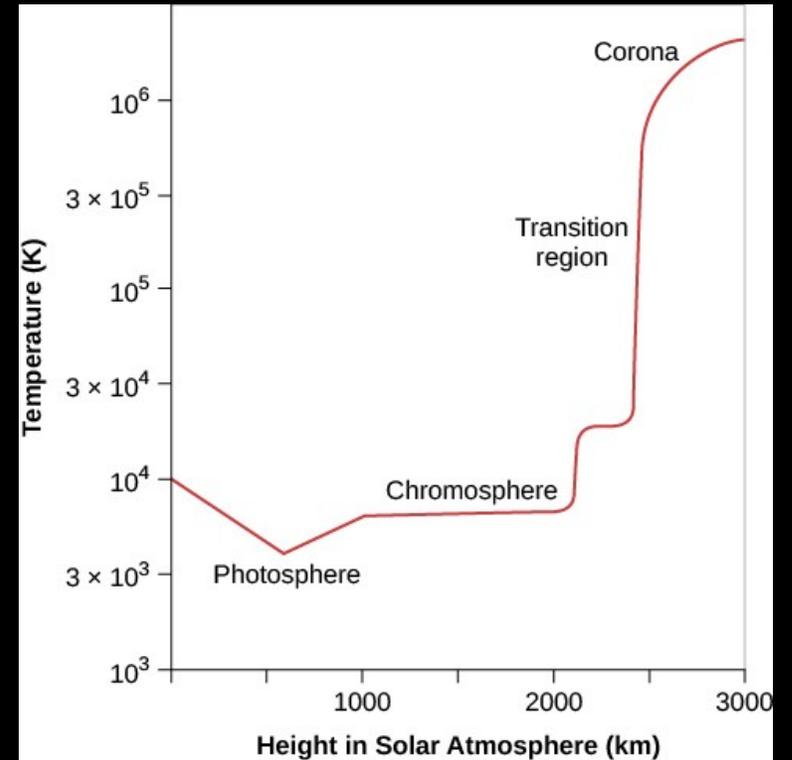
- The outermost part of the Sun's atmosphere is called the corona
- Corona was first observed during total eclipses
- The corona extends millions of kilometers above the photosphere and emits about half as much light as the full moon.
- The reason we don't see this light until an eclipse occurs is the overpowering brilliance of the photosphere.
- Temperature : 3 million Kelvin



Corona

- **Magnetic Heating (Magnetic Reconnection)** -The Sun's magnetic field lines tangle, twist, and reconnect, releasing vast amounts of energy. These reconnection events transfer energy to the corona, heating it significantly.
- **Nanoflares:** Tiny, frequent bursts of magnetic energy (smaller versions of solar flares) occur constantly in the corona. Though individually small, their cumulative effect can generate significant heating.
- **Thermal Conduction Suppression:** Unlike typical heat conduction, the highly ionized plasma in the corona prevents efficient transfer of heat back to the cooler layers. This helps maintain the high temperatures in the corona.

Despite these theories, the exact mechanism behind coronal heating remains an active area of research in solar physics.



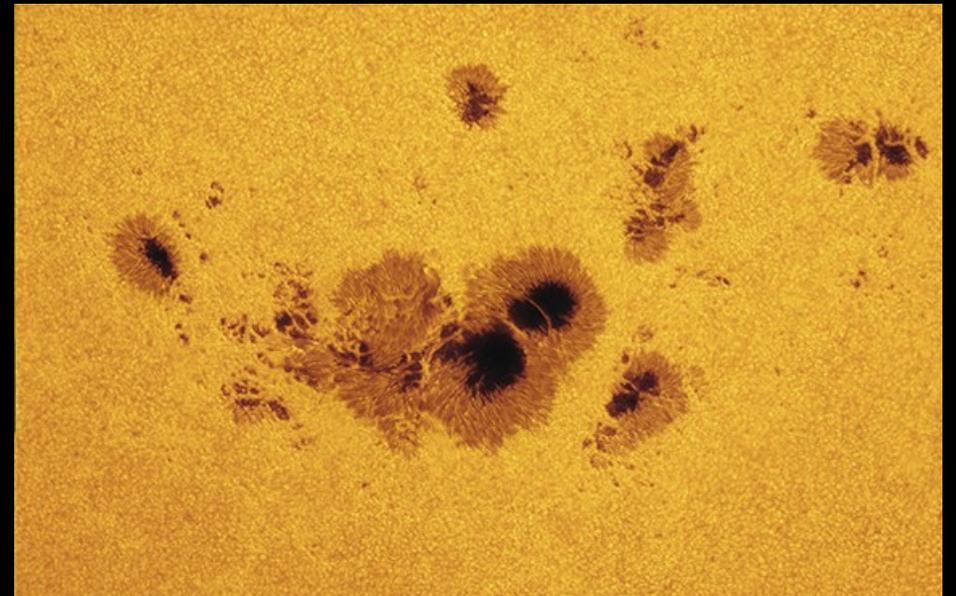
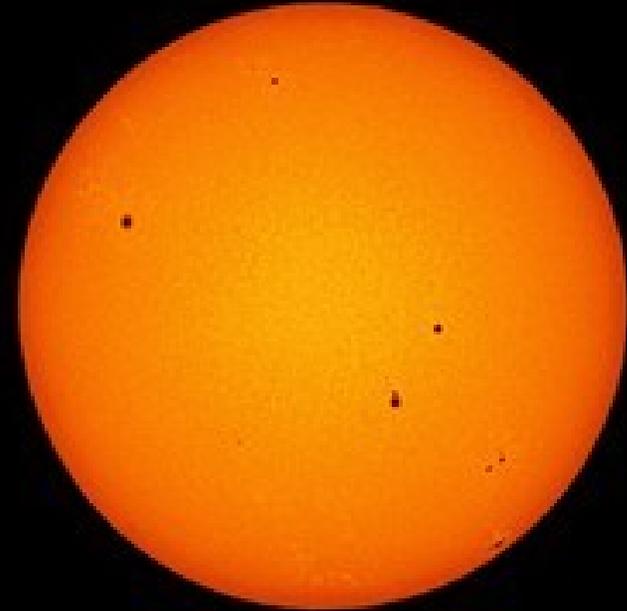
Solar Wind

- Sun's atmosphere produces a stream of charged particles (mainly protons and electrons) - solar wind.
- These particles flow outward from the Sun into the solar system at a speed of about 400 kilometers per second. Although the solar wind material is very, very rarified, the Sun has an enormous surface area. Astronomers estimate that the Sun is losing about 1–2 million tons of material each second through this wind.
- *At the surface of Earth, we are protected to some degree from the solar wind by our atmosphere and Earth's magnetic field*
- *However, the magnetic field lines come into Earth at the north and south magnetic poles.*
- *Here, charged particles accelerated by the solar wind can follow the field down into our atmosphere. As the particles strike molecules of air, they cause them to glow, called the auroras, or the northern and southern lights*



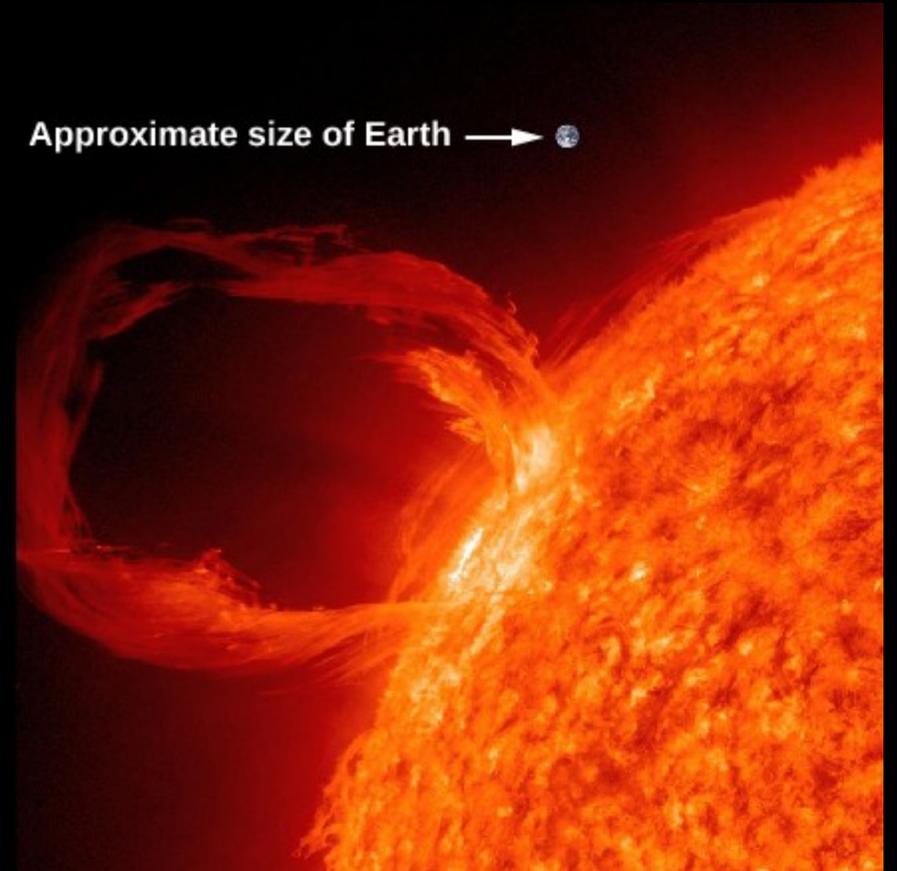
Sunspots

- Sunspots are large, dark features seen on the surface of the Sun caused by increased magnetic activity.
- They look darker because the spots are typically at a temperature of about 3800 K, whereas the bright regions that surround them are at about 5800 K
- *Lifetimes range from a few hours to a few months.*
- *Consists of two parts: an inner darker core, the umbra, and a surrounding less dark region, the penumbra.*
- *By recording the apparent motions of the sunspots as the turning Sun carried them across its disk Galileo, in 1612, demonstrated that the Sun rotates on its axis with a rotation period of approximately 1 month.*
- *Speed of rotation of the Sun varies according to latitude.*
- *The rotation period is about 25 days at the equator, 28 days at latitude 40°, and 36 days at latitude 80°. We call this behavior differential rotation.*



Prominences

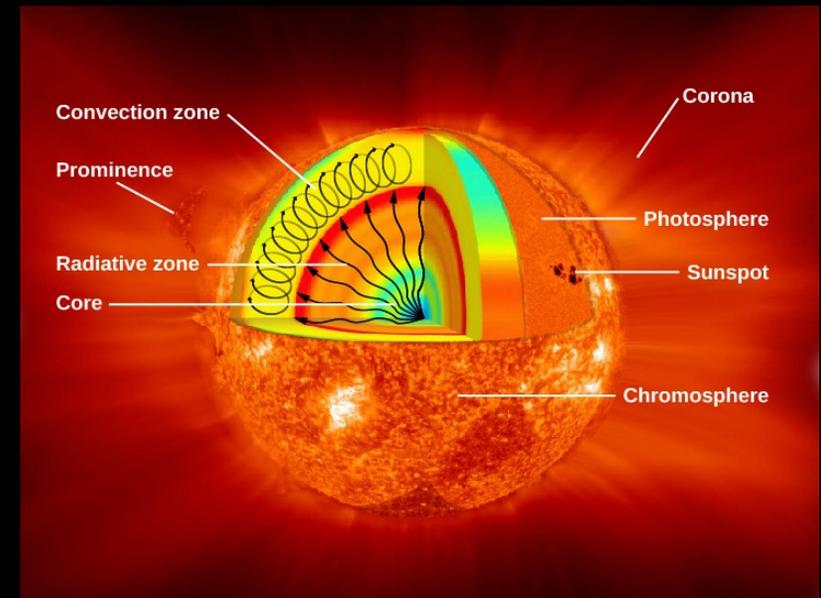
- Prominence, sometimes referred to as a filament, is a large plasma and magnetic field structure extending outward from the Sun's surface,] often in a loop shape.
- Prominences are anchored to the Sun's surface in the much brighter photosphere, and extend outwards into the solar corona.
- While the corona consists of extremely hot plasma, prominences contain much cooler plasma, similar in composition to that of the chromosphere.
- Eclipse observers often see prominences as red features rising above the eclipsed Sun and reaching high into the corona.
- The relatively rare eruptive prominences appear to send matter upward into the corona at high speeds, and the most active surge prominences may move as fast as 1300 kilometers per second
- Some eruptive prominences have reached heights of more than 1 million kilometers above the photosphere.



Heat Transfer in a Star

- **Conduction**, atoms or molecules pass on their energy by colliding with others nearby. For example, when the handle of a metal spoon heats up as you stir a cup of hot coffee.
- **Convection**, currents of warm material rise, carrying their energy with them to cooler layers. A good example is hot air rising from a fireplace.
- **Radiation**, energetic photons move away from hot material and are absorbed by some material to which they convey some or all of their energy. You can feel this when you put your hand close to the coils of an electric heater, allowing infrared photons to heat up your hand.

In stars, which are much more transparent, radiation and convection are important, whereas conduction can usually be ignored.



Sources of Sunshine

- Burning of hydrocarbons or hydrogen, release energy of about **10^7 joules per kilogram**.
- Let's assume the entire Sun's mass (**1.989×10^{30} kg**) is available for chemical burning.

$$\begin{aligned}\text{Total chemical energy} &= \text{mass} \times \text{energy per kg} \\ &= 1.989 \times 10^{30} \text{ kg} \times 10^7 \text{ J/kg} \\ &= 1.989 \times 10^{37} \text{ joules}\end{aligned}$$

$$\begin{aligned}\text{Time} &= \frac{1.989 \times 10^{37} \text{ joules}}{3.8 \times 10^{26} \text{ watts}} \\ &\approx 5.24 \times 10^{10} \text{ seconds} \\ &\approx 1,660 \text{ years}\end{aligned}$$



Sources of Sunshine

$$E_{\text{gravitational}} = \frac{GM^2}{R}$$

Where:

- G = Gravitational constant = $6.674 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$
- M = Mass of the Sun = $1.989 \times 10^{30} \text{ kg}$
- R = Radius of the Sun = $6.96 \times 10^8 \text{ m}$

$$E_{\text{gravitational}} = \frac{(6.674 \times 10^{-11})(1.989 \times 10^{30})^2}{6.96 \times 10^8}$$
$$\approx 2.3 \times 10^{41} \text{ joules}$$

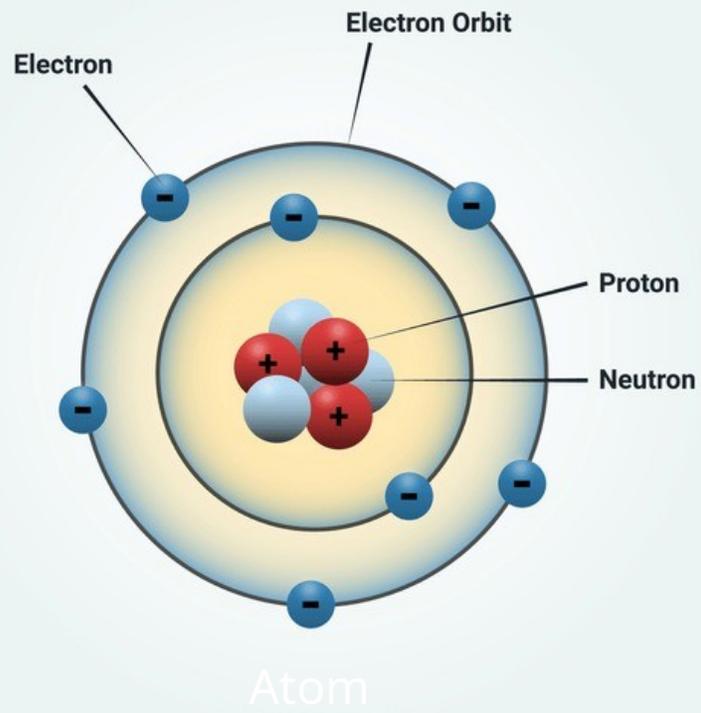
$$\text{Time} = \frac{2.3 \times 10^{41} \text{ joules}}{3.8 \times 10^{26} \text{ joules/second}}$$
$$\approx 6.1 \times 10^{14} \text{ seconds}$$
$$\approx 20 \text{ million years}$$

$$E = mc^2$$

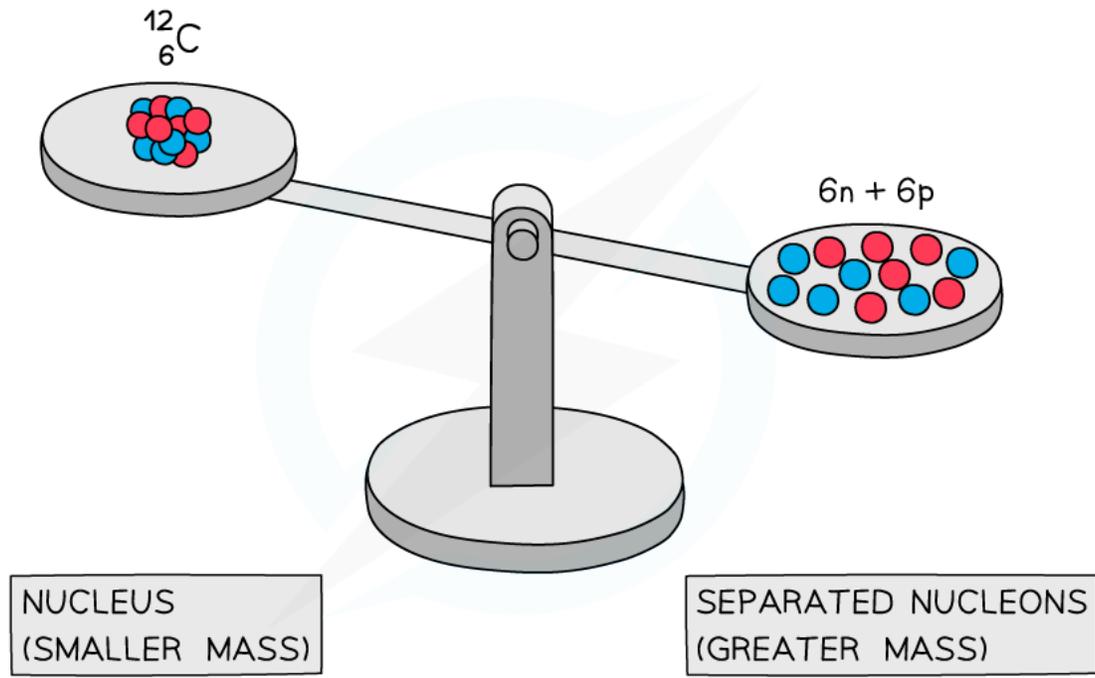


Into the World of Atoms

[Video Link](#)



Nucleus



Hydrogen
Nucleus

P 1.007825 u

+

P 1.007825 u

+

P 1.007825 u

+

P 1.007825 u

=



He

4.031300 u -
4.002603 u

0.0287 u

4.0313 u

4.002603u

Hydrogen
Nucleus

P 1.007825 u

+

P 1.007825 u

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P 1.007825 u

+

P 1.007825 u

4.0313 u

=



He

4.002603u

4.031300 u -

4.002603 u

0.0287 u

1u = 1.66×10^{-27} kg

$$\Delta m = 0.0287 \text{ u} \times 1.66054 \times 10^{-27} \text{ kg/u}$$

$$\Delta m \approx 4.76 \times 10^{-29} \text{ kg}$$

Using $E = \Delta mc^2$:

$$E = (4.76 \times 10^{-29} \text{ kg}) \times (3 \times 10^8 \text{ m/s})^2$$

$$\underline{E \approx 4.28 \times 10^{-12} \text{ joules}}$$

Sources of Sunshine

Fusion Reaction:

The Sun generates energy by fusing **hydrogen nuclei (protons)** into **helium** in its core. The overall reaction is:



For each reaction:

- **Mass converted to energy:** About 0.7% of the initial mass of hydrogen.
- **Energy released:** Using $E = mc^2$, about 4.3×10^{-12} joules is released per fusion reaction.

Sources of Sunshine

a) Total Mass of Hydrogen in the Sun:

- Approximately 75% of the Sun's mass is hydrogen.
- Total mass of hydrogen:

$$M_{\text{H}} = 0.75 \times 1.989 \times 10^{30} \text{ kg} \approx 1.49 \times 10^{30} \text{ kg}$$

- Each hydrogen atom has a mass of about 1.67×10^{-27} kg.

b) Number of Hydrogen Atoms in the Sun:

$$N_{\text{H}} = \frac{1.49 \times 10^{30}}{1.67 \times 10^{-27}} \approx 8.92 \times 10^{56} \text{ atoms}$$

c) Total Energy Produced by Fusion:

- Each fusion reaction consumes 4 protons (hydrogen nuclei), so:

$$\frac{8.92 \times 10^{56}}{4} = 2.23 \times 10^{56} \text{ fusion reactions}$$

- Total energy released per reaction is 4.3×10^{-12} joules:

$$E_{\text{total}} = 2.23 \times 10^{56} \times 4.3 \times 10^{-12}$$

$$E_{\text{total}} \approx 9.6 \times 10^{44} \text{ joules}$$

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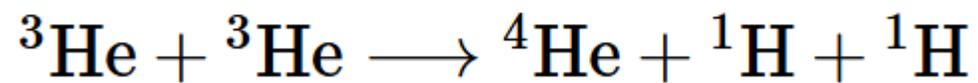
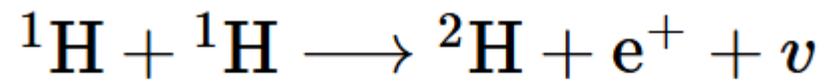
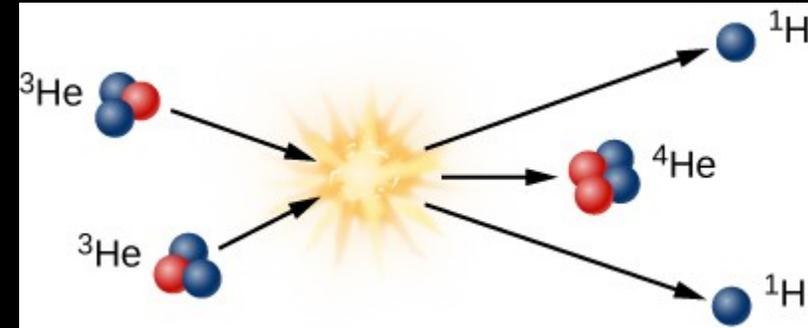
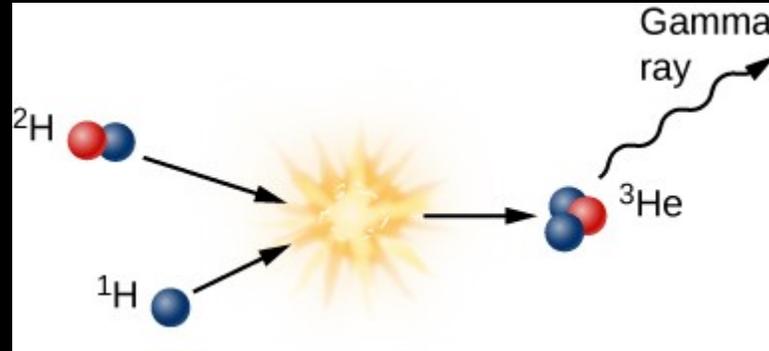
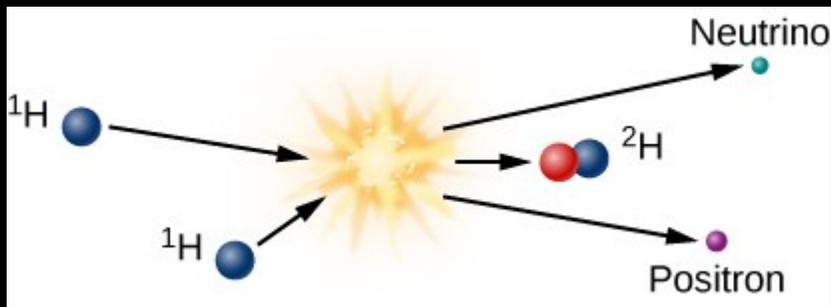
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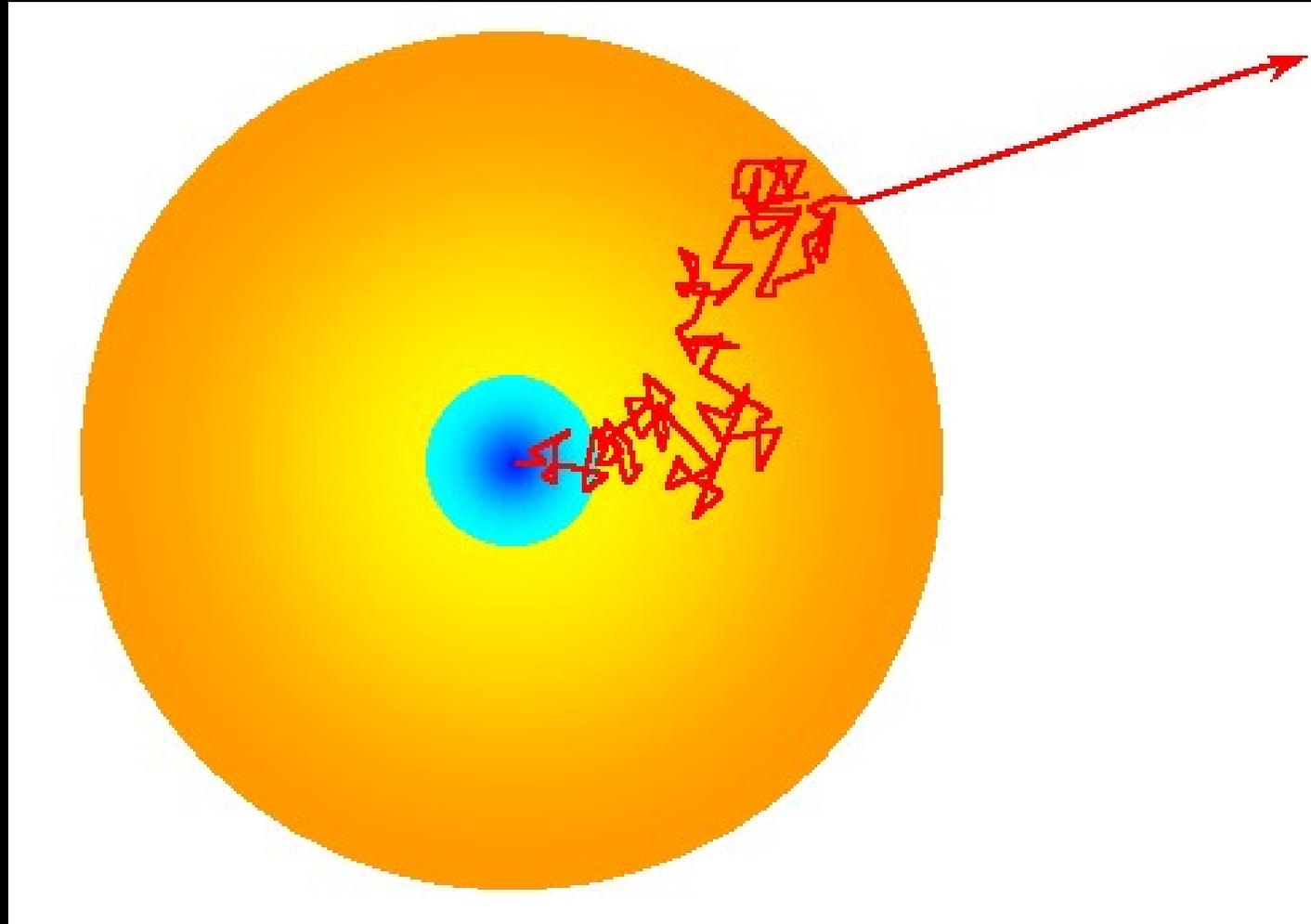
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Journey of a Photon from Core





Stellar Evolution

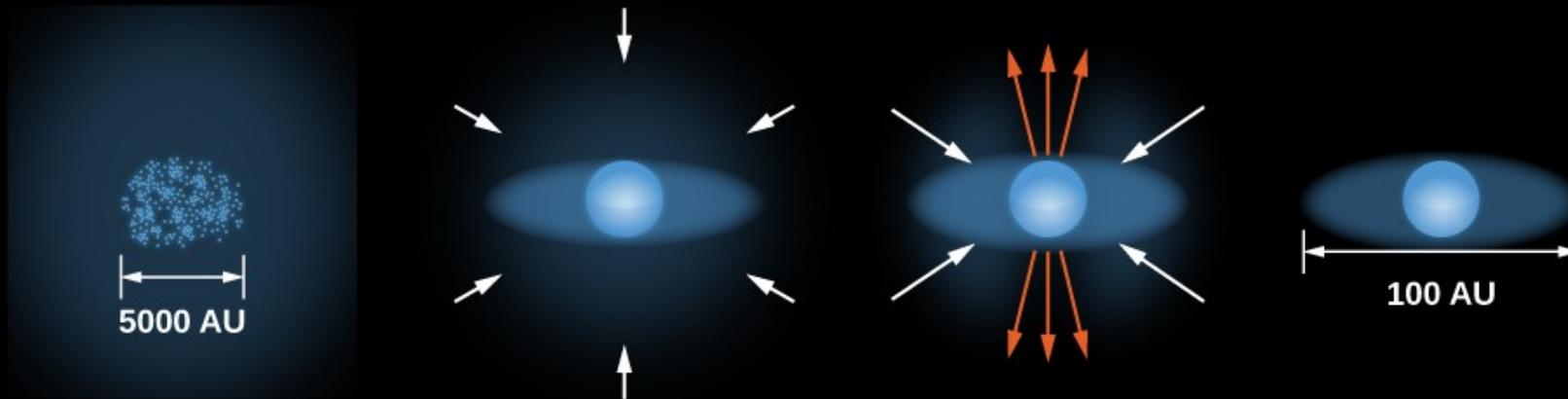
Credit:
ESO/M. Kornmesser

Molecular Clouds: Stellar Nurseries

- Masses of molecular clouds range from a thousand times the mass of the Sun to about 3 million solar masses.
- Molecular clouds have a complex filamentary structure, similar to cirrus clouds in Earth's atmosphere, but much less dense.
- The molecular cloud filaments can be up to 1000 light-years long.
- cold, dense regions with typical masses of 50 to 500 times the mass of the Sun- clumps. Within even denser, smaller regions called cores-embryos of stars.
- Air – 10^{25} Partcles / m³
- Nebula 10^5 Partcles/m³



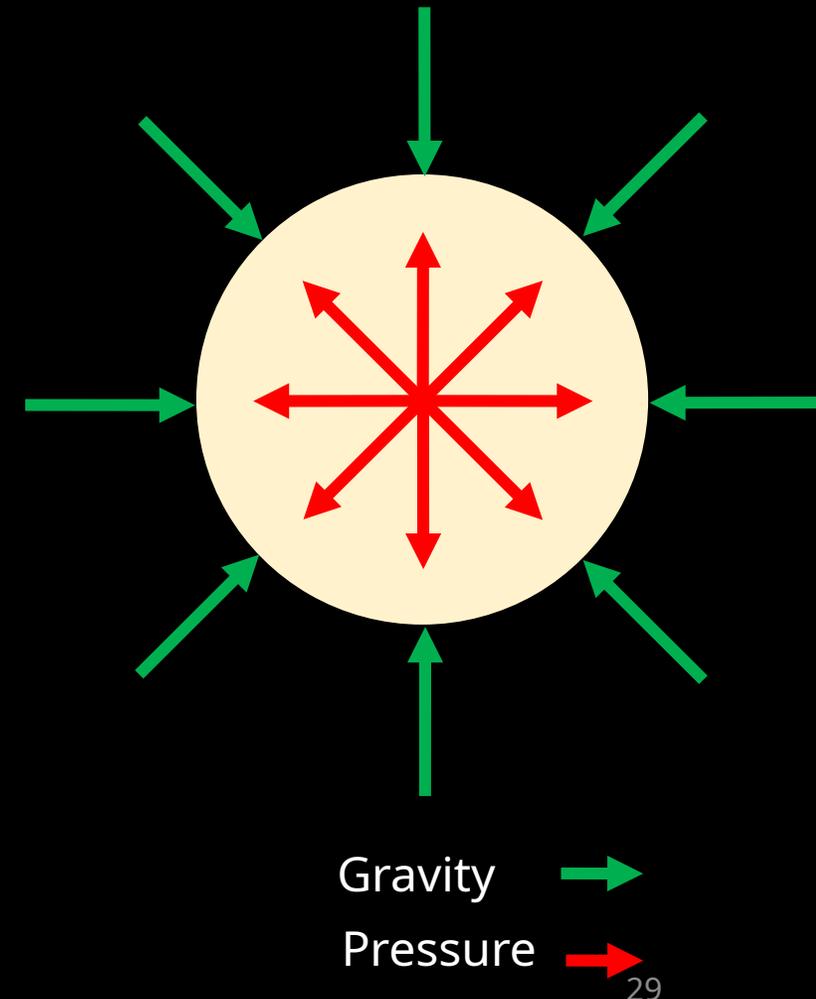
Birth of a proto-Star



Stage	Key Events	Outcome
1. Nebula	Cold gas and dust	Gravitational collapse begins
2. Collapse	Gravity pulls particles inward	Dense core forms
3. Core Formation	Central core heats up	Accretion disk forms
4. Disk Formation	Rotation accelerates	Accretion continues
5. Heating	Temperature rises	Infrared radiation emitted
6. Protostar Stage	No fusion yet, core heats	Protostar glows

Birth of Star

- Energy Source: Initially, gravitational contraction supplies energy as the protostar collapses.
- As the protostar contracts, gravitational potential energy is converted into heat, raising the core temperature.
- Problem: Protons (hydrogen nuclei) are positively charged, so they repel each other due to the Coulomb force.
- Coulomb Barrier: For fusion to occur, protons must overcome the electrostatic repulsion.
- Quantum mechanics allows particles to "tunnel" through the barrier
- At around 10 million K, the protons' kinetic energy and quantum tunnelling enable fusion despite the Coulomb barrier.
- **Hydrostatic Equilibrium** is achieved when the outward radiation pressure from fusion balances the inward gravitational pull.



Mass Criteria

- **Jeans Mass**

- The minimum mass required for a gas cloud to collapse under its own gravity and form a protostar.
- If a cloud's mass is less than the Jeans mass, it will not collapse; instead, it will disperse due to thermal pressure.

- **Hydrogen Burning Limit**

- The minimum mass a protostar needs to sustain hydrogen fusion in its core.
- Value : $\approx 0.08 M_{\odot} \approx 80 M_{\text{Jupiter}}$
- Above this limit: The object becomes a main-sequence star.
- Below this limit: The object becomes a brown dwarf, which cannot sustain continuous hydrogen fusion.

- **Eddington Limit**

- The maximum mass a star can have before radiation pressure overcomes gravitational pull, causing the star to lose mass.
- Value: Generally estimated at ~ 100 to 150 solar masses.
- Stars exceeding this mass limit become unstable due to intense radiation pressure and may lose mass rapidly or explode as supernovae.

Main-Sequence Stars

1. Core:

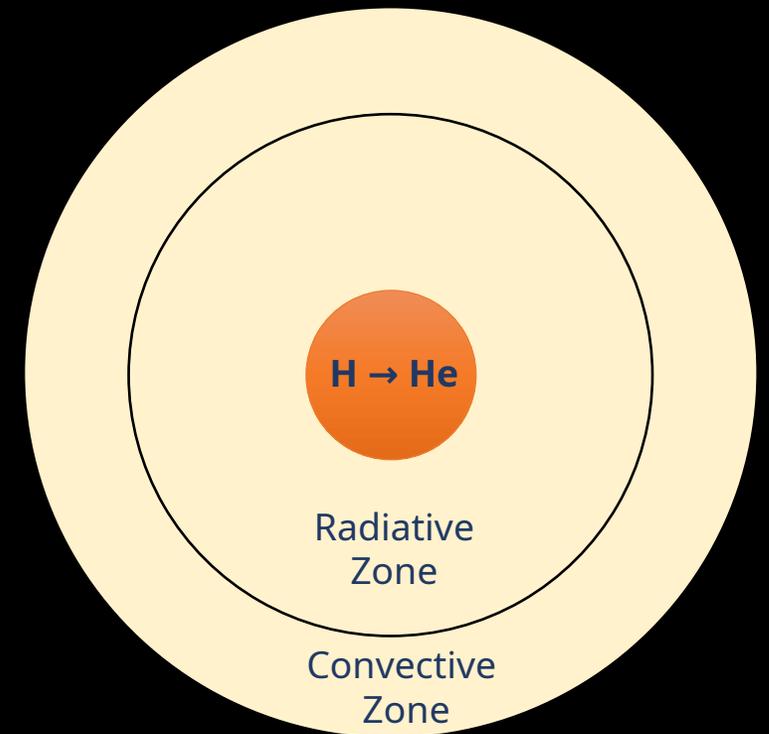
- Site of hydrogen fusion.
- Temperature: ~10 million to 40 million K
- Very high, with ionized hydrogen and helium.

2. Radiative Zone:

- Energy is transported outward by radiation.
- Photons are absorbed and re-emitted multiple times, taking thousands to millions of years to reach the surface.

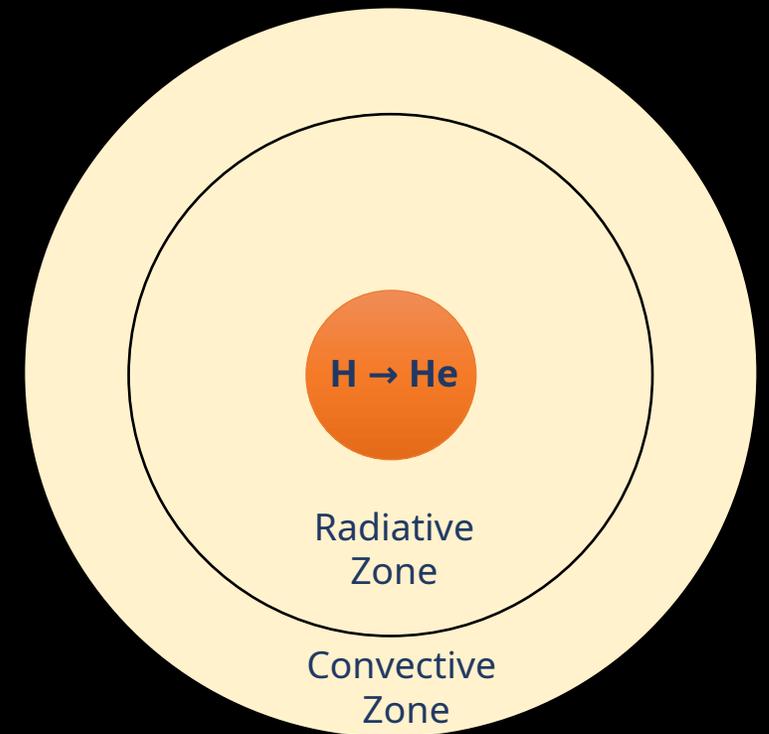
3. Convective Zone:

1. Energy is transported by convection currents
More prominent in low-mass stars like the Sun.



Main-Sequence Stars

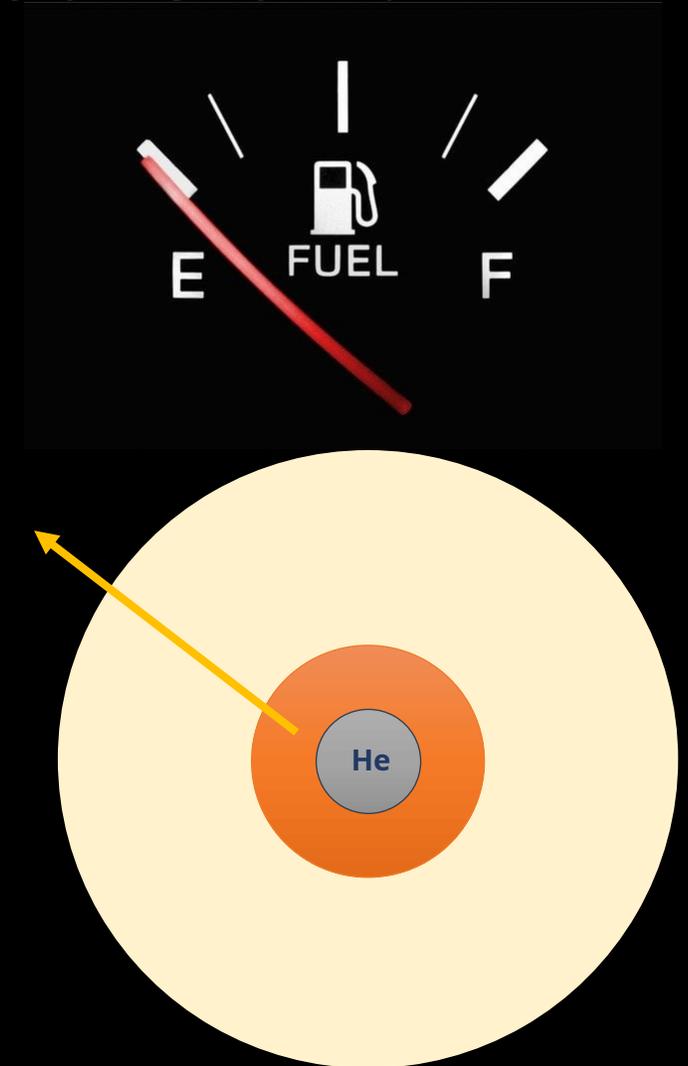
Mass M_s	Surface Temperature (K)	Lifetime on Main Sequence (years)
40	54,000	1 million
16	29,200	10 million
3.3	9600	500 million
1.7	7350	2.7 billion
1.1	6050	9 billion
0.8	5240	14 billion
0.4	3750	200 billion



From Main-Sequence Star to Red Giant

Hydrogen Depletion in the Core

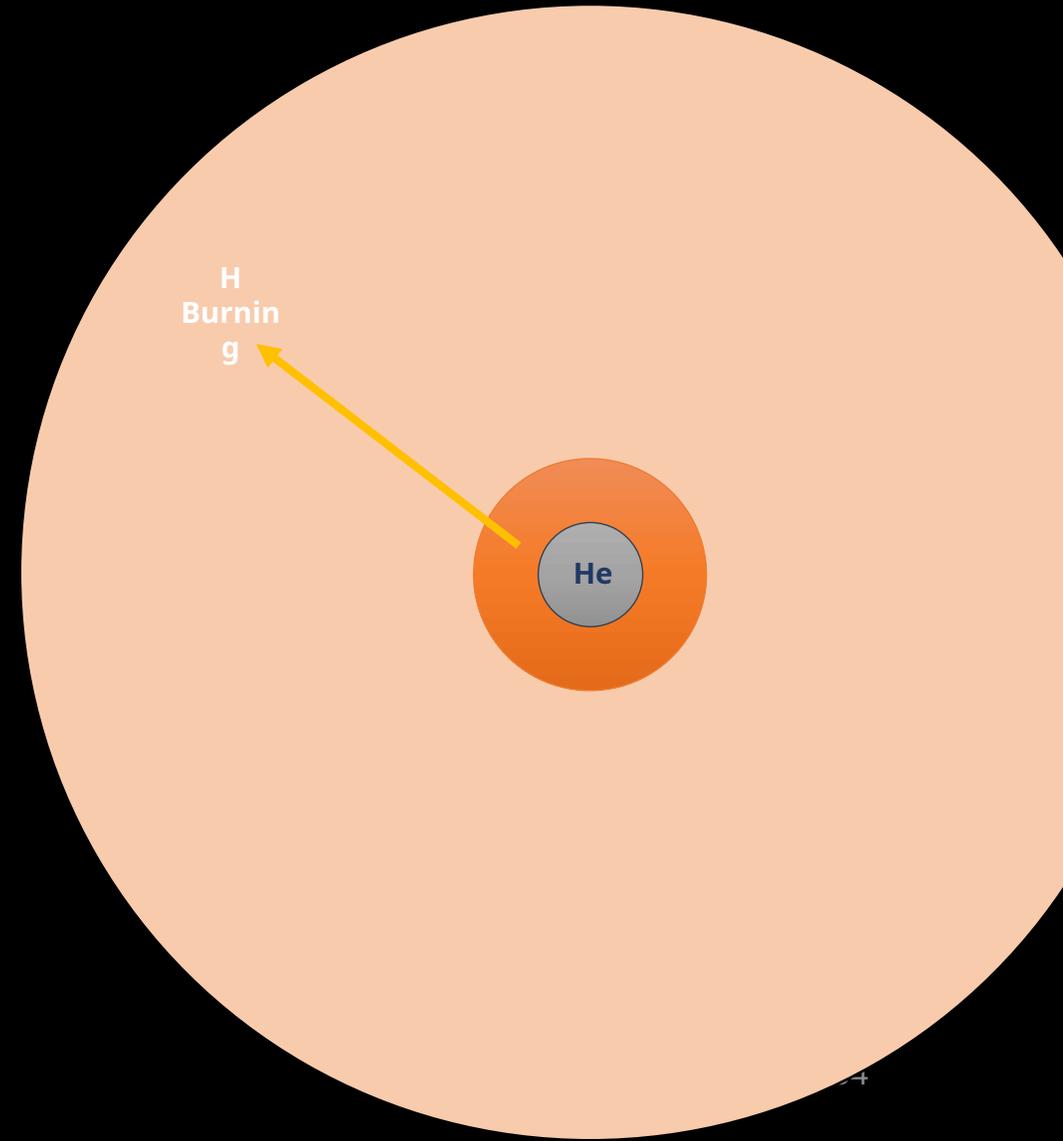
- Core Contraction: As hydrogen is depleted in the core, fusion slows, and the core starts to collapse under gravity.
- Helium Core Formation: Core consists mostly of inert helium, unable to fuse (helium fusion requires ~100 million K).
- Hydrogen Shell Burning: Hydrogen fusion continues in a shell surrounding the helium core, causing the core to heat up further.



From Main-Sequence Star to Red Giant

Core Contraction and Shell Expansion

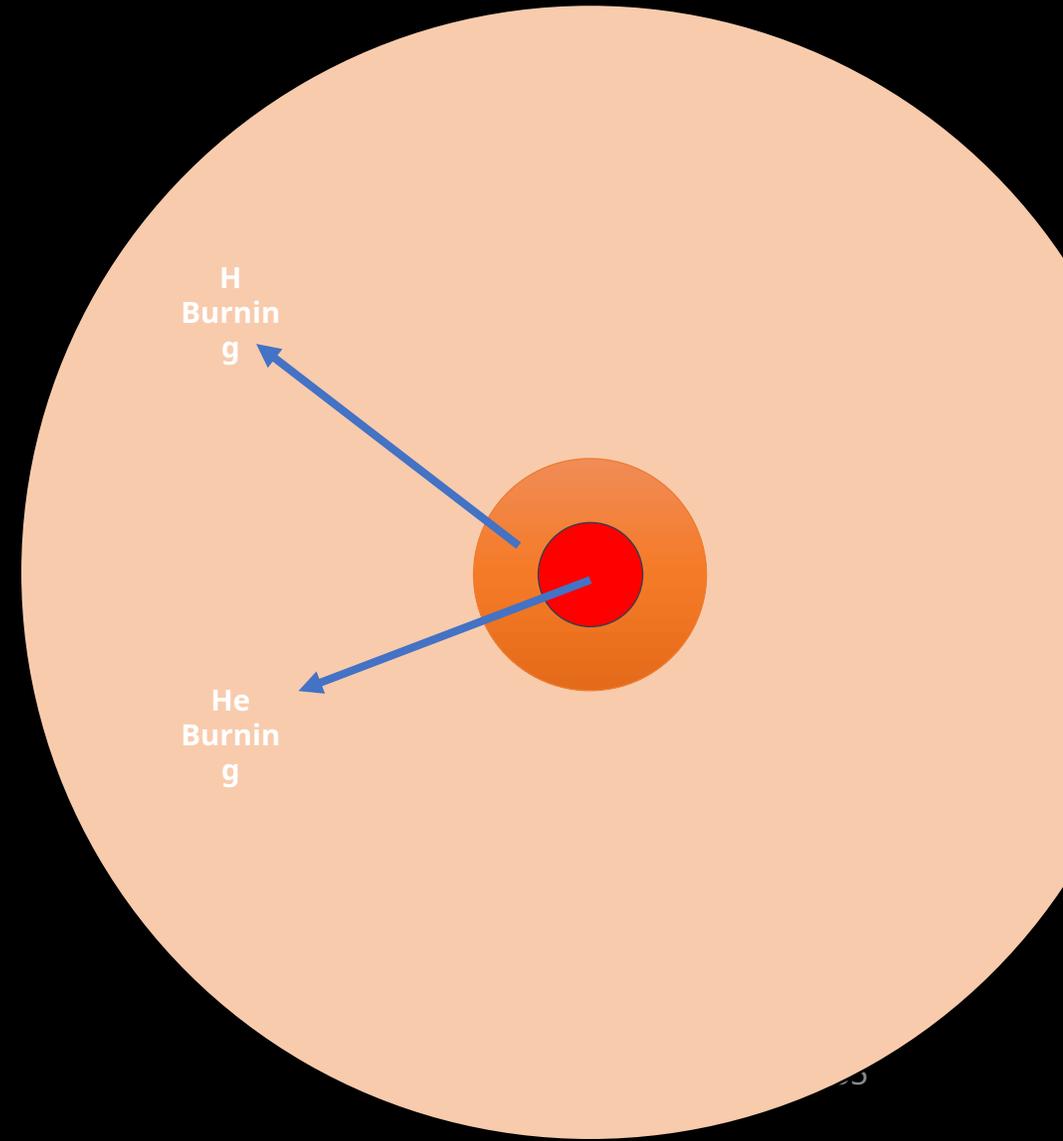
- **Energy Increase:** As the core contracts, gravitational potential energy is converted into thermal energy, heating the core and shell.
- **Outer Layers Expand:** The increased energy from the hydrogen shell burning causes the star's outer layers to expand significantly.
- **Surface Cooling:** As the star's radius increases, its surface temperature decreases, making the star appear cooler and redder.



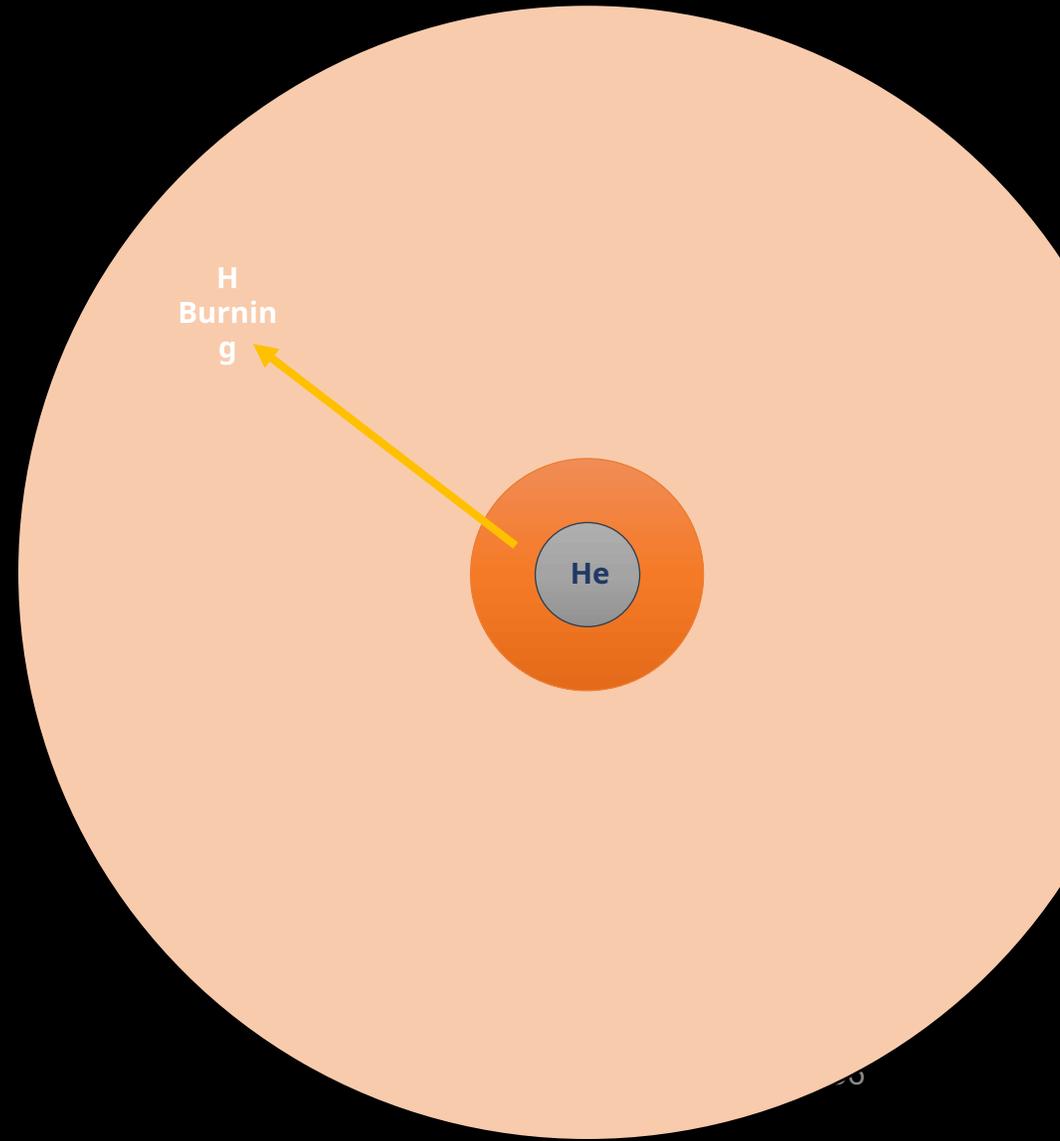
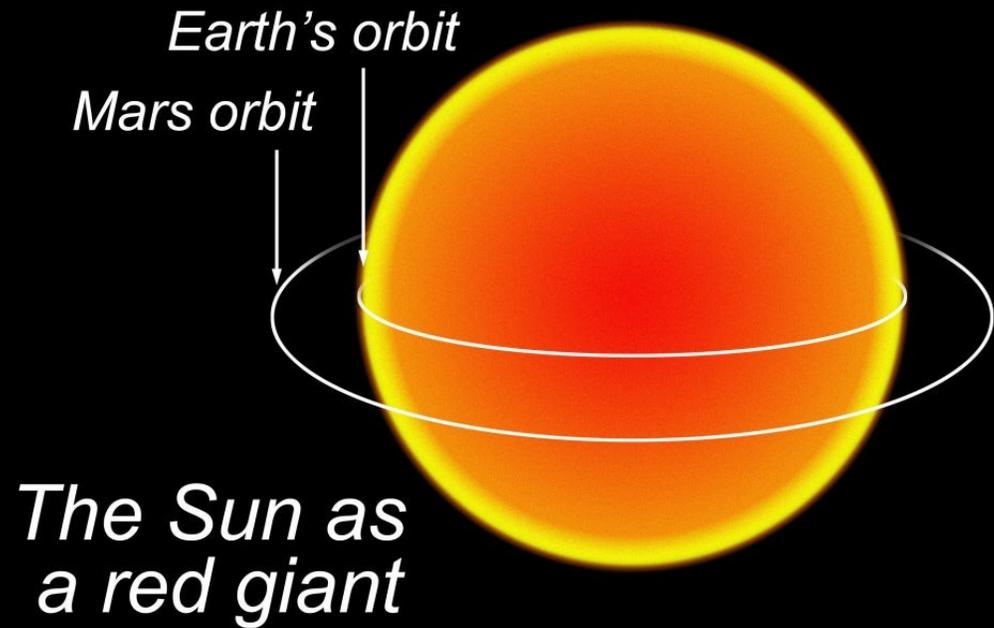
From Main-Sequence Star to Red Giant

Helium Flash (for Low- and Medium-Mass Stars)

- In stars like the Sun:
 - Core Ignition: When the core temperature reaches ~ 100 million K, helium fusion begins in a sudden, explosive event called the helium flash.
 - Helium Fusion: Helium nuclei fuse to form carbon and oxygen via the triple-alpha process
- High-mass stars smoothly ignite helium fusion without a helium flash.



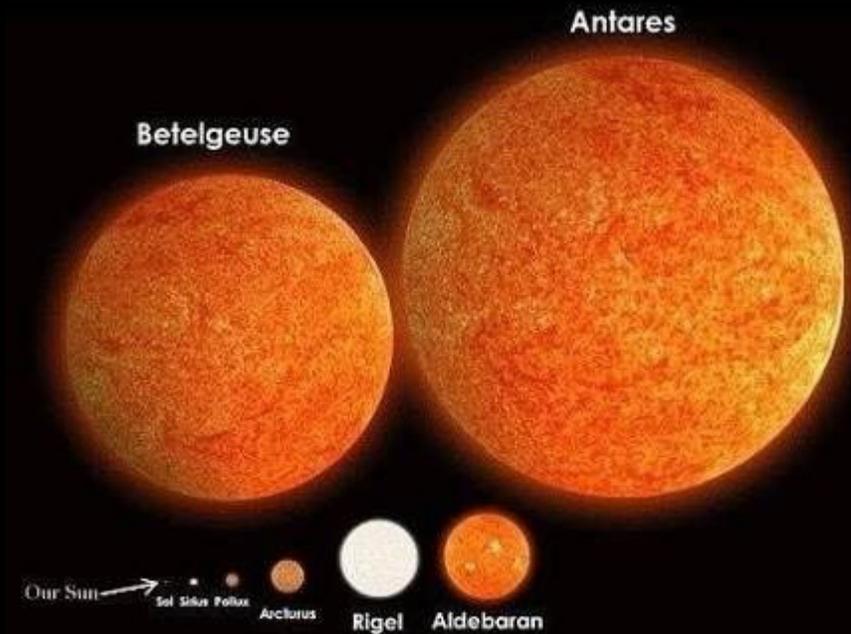
From Main-Sequence Star to Red Giant



From Main-Sequence Star to Red Giant

Red Giant Characteristics

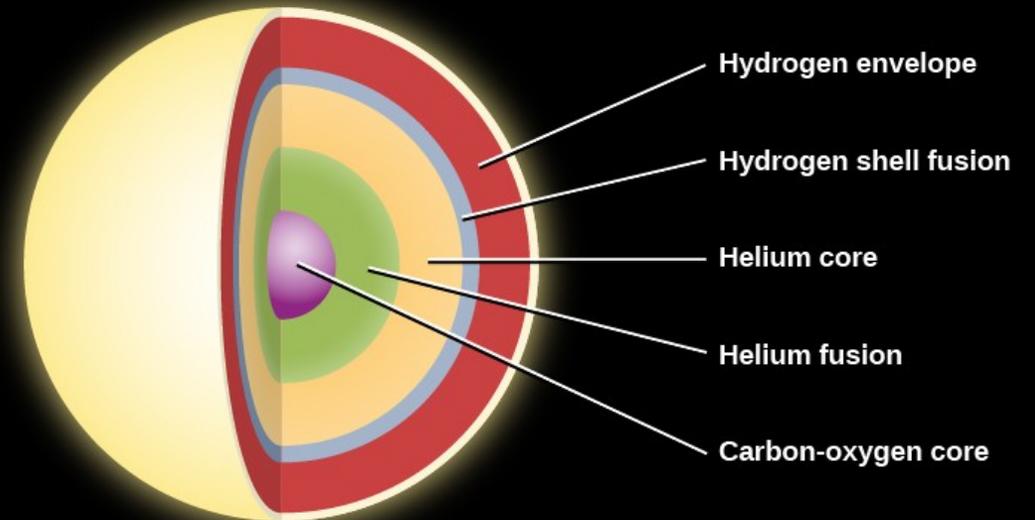
- Increased Luminosity
 - Despite cooling, the star becomes much more luminous due to its enormous size.
- Radius Expansion
 - The star can expand to tens or hundreds of times its original radius.
- Surface Temperature Drop
 - The surface temperature decreases, leading to a reddish appearance.



Evolution of a Low-Mass Star ($M < 8$ Solar Masses)

Asymptotic Giant Branch (AGB)

- Helium Exhaustion in the Core
 - Helium in the core is depleted, leaving a core made mostly of carbon and oxygen.
- Double Shell Burning:
 - Helium Shell Burning: Helium fusion occurs in a shell around the core.
 - Hydrogen Shell Burning: Hydrogen fusion continues in an outer shell.
- Pulsations and Mass Loss: The star undergoes thermal pulses, and powerful stellar winds drive away its outer layers, enriching the interstellar medium with heavier elements.



Evolution of a Low-Mass Star ($M < 8$ Solar Masses)

Stage	Time in This Stage (years)	Surface Temperature (K)	Luminosity (L_{sun})	Diameter (Sun = 1)
Main sequence	11 billion	6000	1	1
Becomes red giant	1.3 billion	3100 at minimum	2300 at maximum	165
Helium fusion	100 million	4800	50	10
Giant again	20 million	3100	5200	180

Evolution of a Low-Mass Star ($M < 8$ Solar Masses)

Planetary Nebula Formation

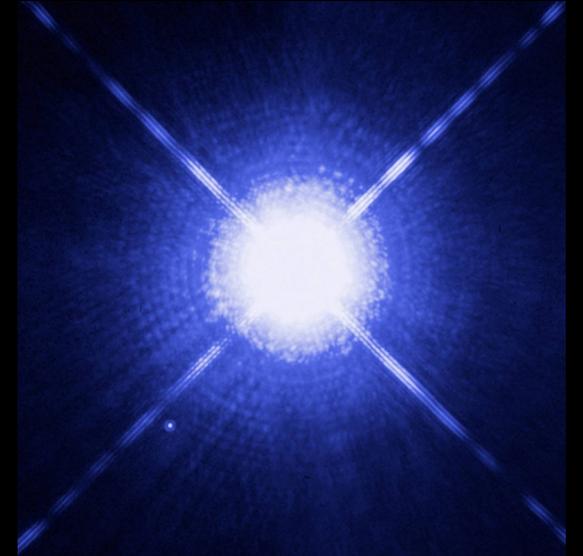
- Ejection of Outer Layers: The outer layers are expelled due to strong stellar winds, forming a planetary nebula.
- Core Exposure: The hot, dense core is exposed at the center of the nebula.
- Illumination: Ultraviolet radiation from the core ionizes the surrounding gas, causing the nebula to glow.



Evolution of a Low-Mass Star ($M < 8$ Solar Masses)

White Dwarf Formation

- **Core Cooling and Collapse:** The remaining core, composed of carbon and oxygen, collapses into a white dwarf.
- **Degenerate Matter:** The core is supported by electron degeneracy pressure, not fusion.
- **Mass Limit:** If the mass is below the **Chandrasekhar limit** (~ 1.4 solar masses), it becomes a stable white dwarf.
- **Temperature and Size:** Extremely hot initially (up to 100,000 K), but small (about the size of Earth).
- **No Fusion:** The white dwarf slowly cools and fades over billions of years.
- **After trillions of years,** the white dwarf will cool to become a black dwarf

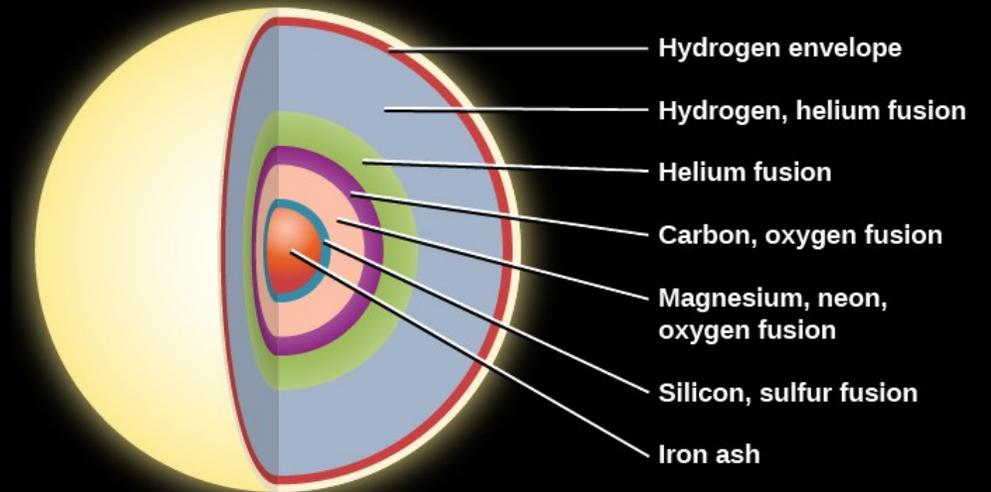


A teaspoon of
white dwarf star =
9000kg

Evolution of High-Mass Stars ($M > 8$ Solar Masses)

Helium Fusion and the Supergiant Phase

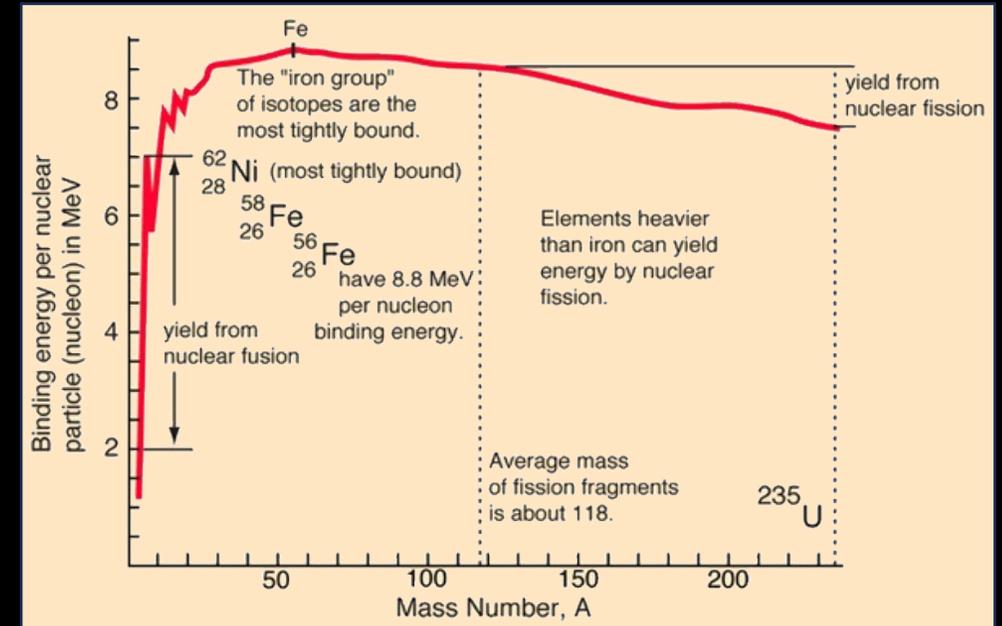
- After helium fusion begins, the high-mass star progresses into the supergiant phase.
 - Helium Core Fusion: In the supergiant phase, helium is fused into heavier elements like carbon and oxygen.
 - Multi-shell Fusion: As helium is depleted, the core contracts further, and the star starts to fuse heavier elements, such as carbon, neon, oxygen, and silicon, in multiple shells surrounding the core.
- Layered Fusion
 - Each element requires progressively higher temperatures for fusion, so the star creates successive "shells" of fusion.
- The inner core may be fusing iron and nickel toward the end.



Evolution of High-Mass Stars ($M > 8$ Solar Masses)

Iron Core Formation and the End of Fusion

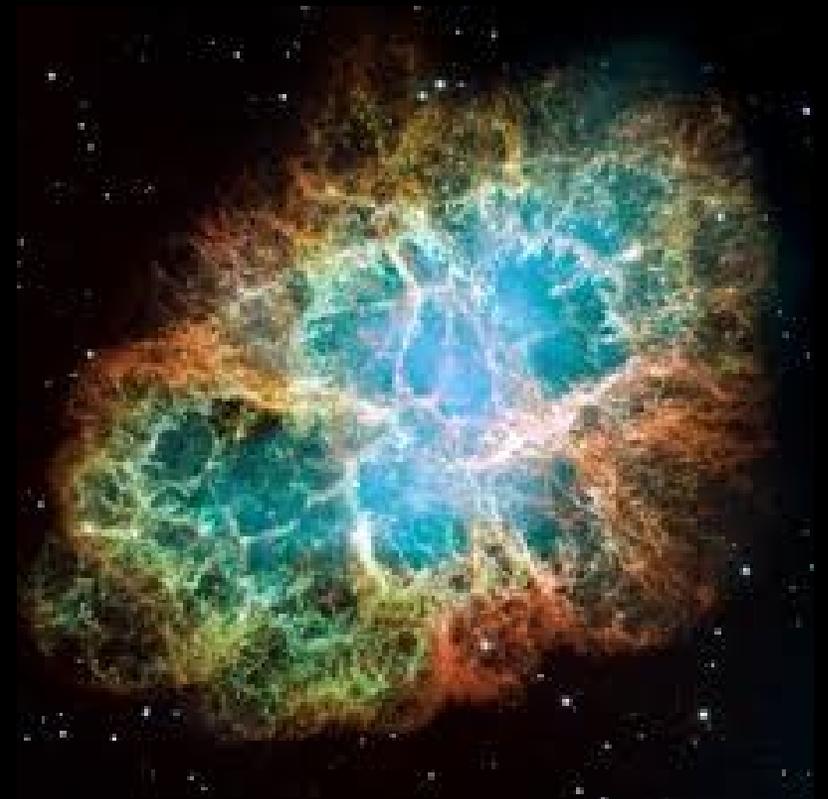
- As fusion continues, the core accumulates heavier elements, eventually forming an iron core.
- Iron cannot be fused into heavier elements with the release of energy
- Fusion Stops : Star can no longer sustain fusion to counterbalance gravity.
- Core Collapse: Without the outward pressure from fusion, gravity causes the iron core to collapse inward, increasing its density and temperature dramatically.



Evolution of High-Mass Stars ($M > 8$ Solar Masses)

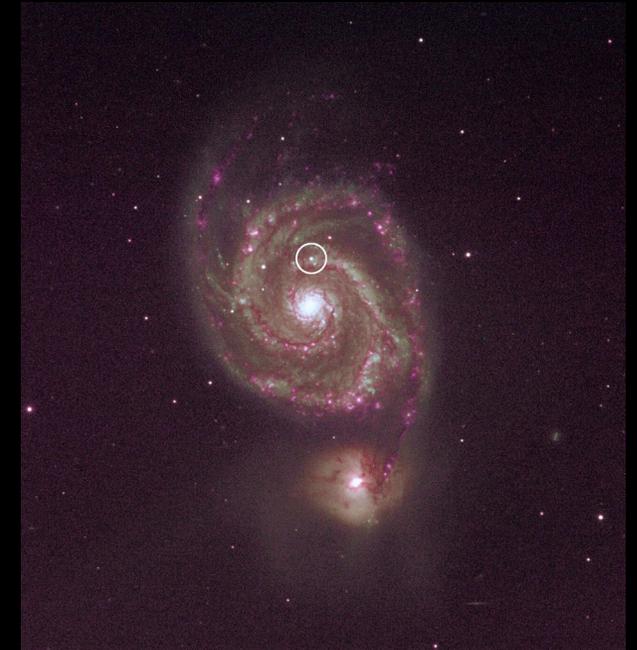
Supernova Explosion

- Iron core reaches a mass $>$ Chandrasekhar limit (1.4 solar mass), core collapses violently.
- This triggers a supernova explosion, which is one of the most energetic events in the universe.
- Core Collapse: The core's collapse causes the outer layers to be ejected at high velocities.
- Shock Wave: The collapse sends out a shockwave that blasts the outer layers into space, creating the spectacular light and energy output of a Type II Supernova.
- Heavy Element Synthesis: The intense energy of the supernova can fuse even heavier elements beyond iron



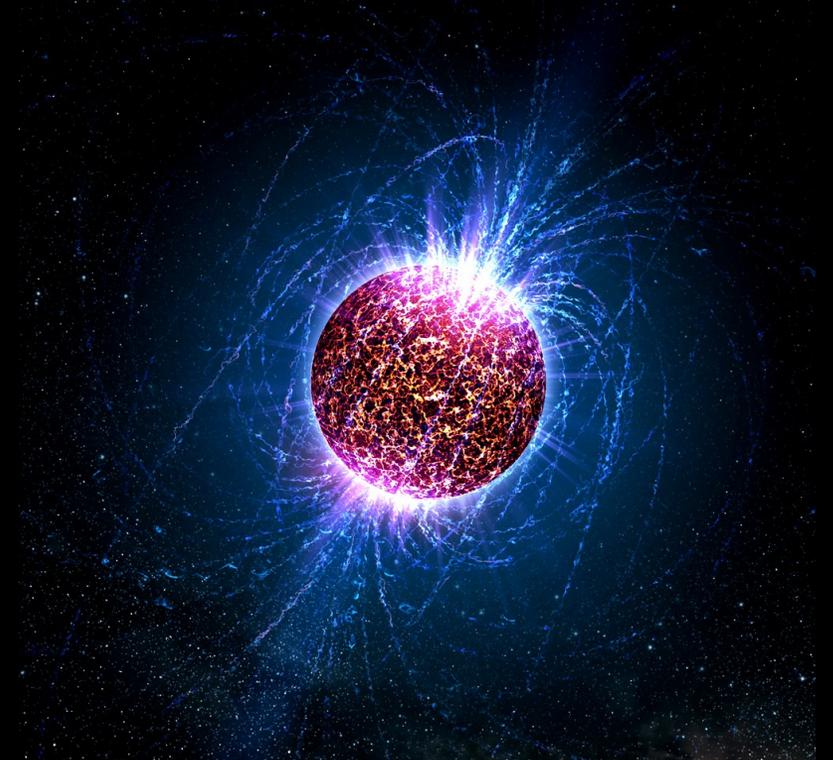
Supernova

- Energy released is approximately 10^{44} joules. 10^9 times the total energy output of the Sun over its entire 10-billion-year lifetime.
- Supernova can outshine an entire galaxy for a brief period, becoming as bright as 10^9 Suns.
- Temperature in the core of the exploding star can reach up to 10 billion Kelvin. Sun's core temperature is around 15 million Kelvin
- Supernova: The material ejected from a supernova can travel at speeds of up to 10,000 to 30,000 km/s. Solar wind about 400 to 800 km/s



Evolution of High-Mass Stars ($M > 8$ Solar Masses)

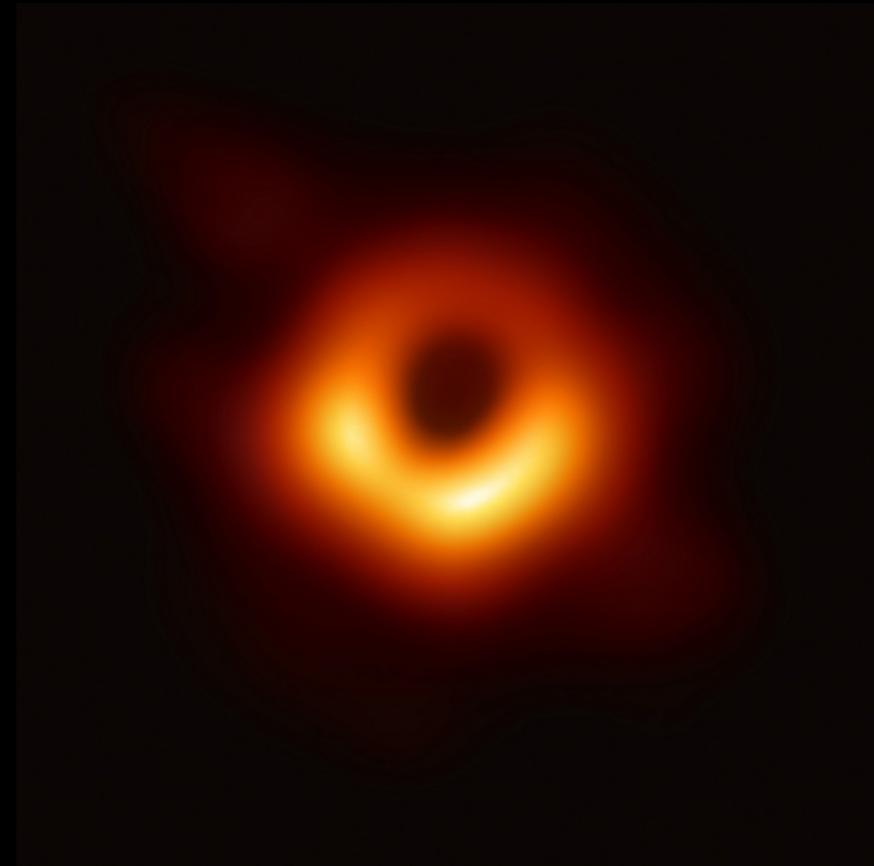
- Neutron Star
 - If the remaining core is between 1.4 and about 3 solar masses, the pressure from neutrons halts further collapse, and a neutron star is formed.
 - Neutron stars are incredibly small (~10–20 km in radius)
 - A neutron star's density is such that a teaspoon of its matter would weigh billions of tons.
 - Neutron stars often have extremely strong magnetic fields and can emit beams of radiation, sometimes observed as pulsars.



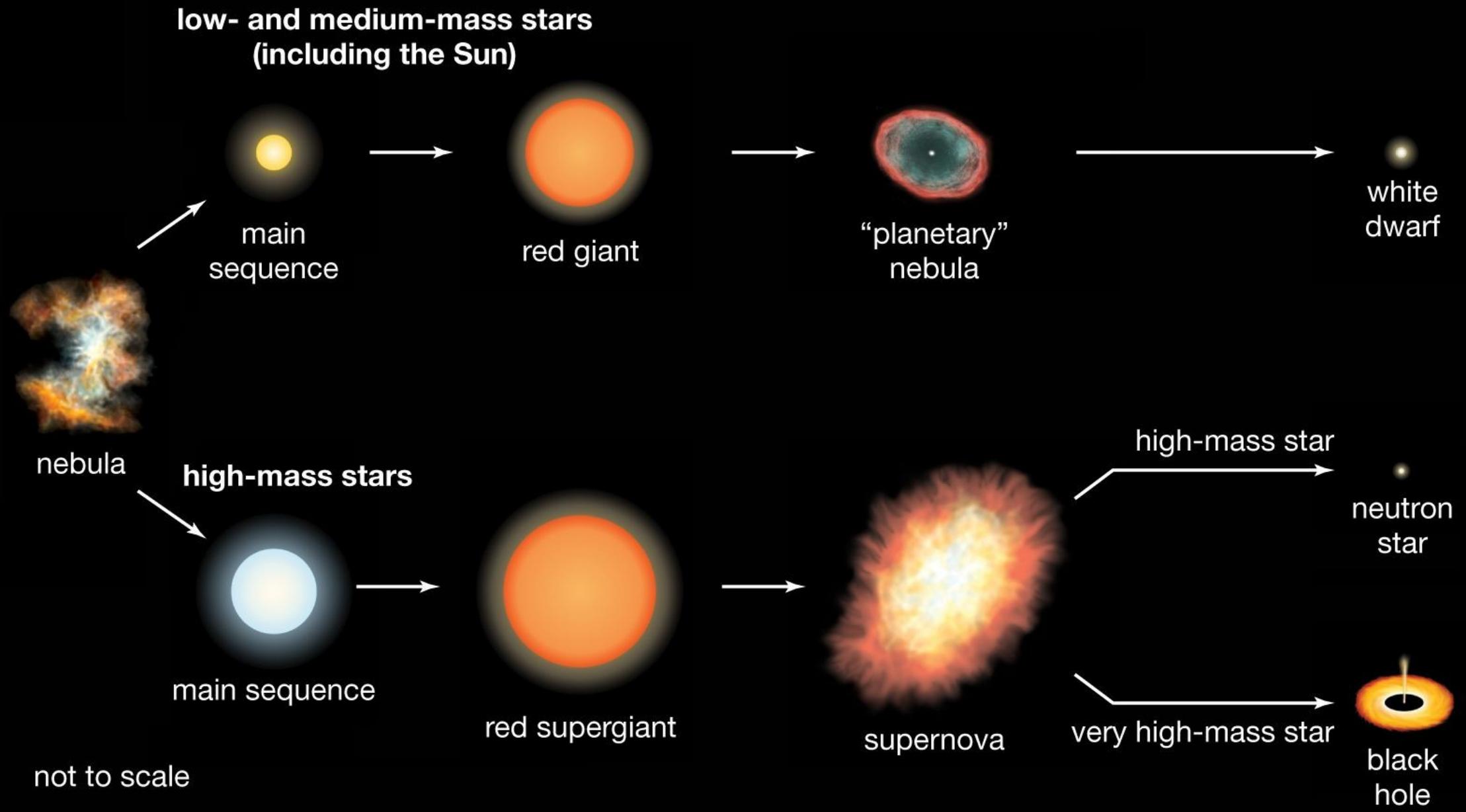
Evolution of High-Mass Stars ($M > 8$ Solar Masses)

Black Hole

- If the core mass exceeds approximately 3 solar masses, **Tolman–Oppenheimer–Volkoff Limit**, not even neutron degeneracy pressure can support the core against gravitational collapse.
- The core continues to collapse into a black hole, where gravity is so strong that not even light can escape.
- Event Horizon: The boundary around a black hole beyond which nothing can escape is called the event horizon.
- Singularity: At the center of a black hole, all mass is compressed into an infinitely small point, known as the singularity.



Stellar evolution



Evolution of a Low-Mass Star ($M < 8$ Solar Masses)

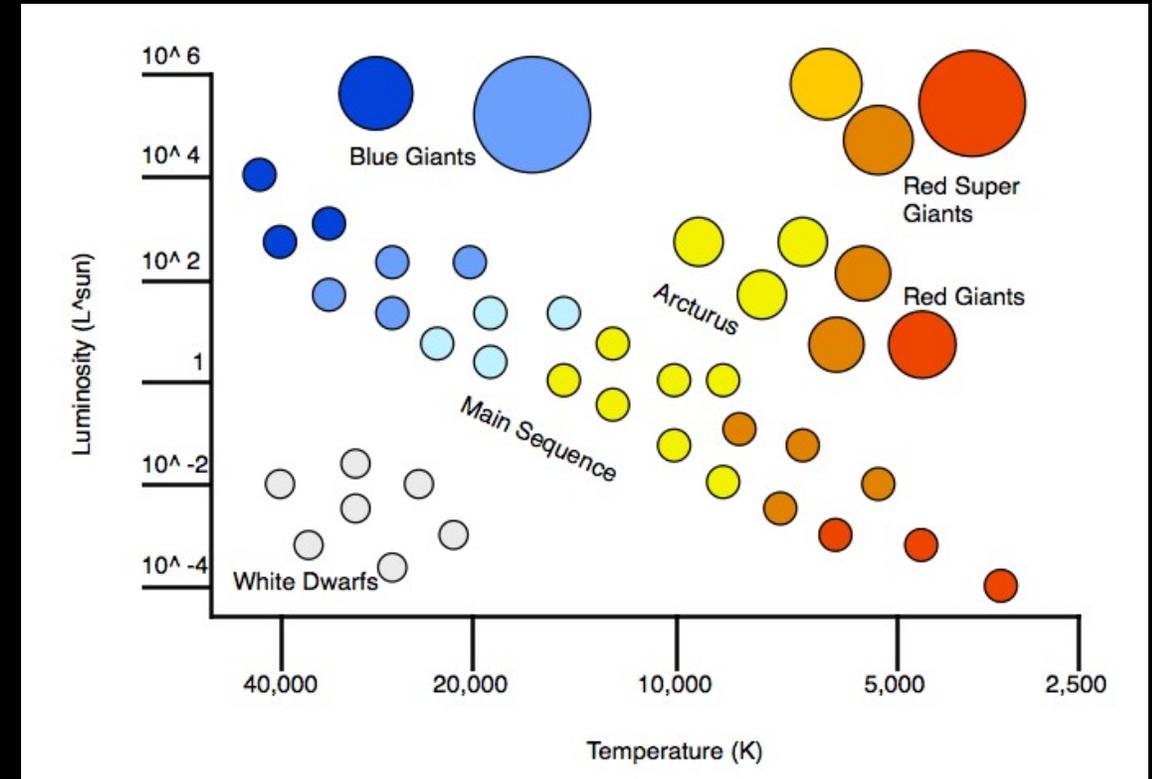
Phase	Core Composition	Energy Source	Outcome
Main Sequence	Hydrogen	Hydrogen fusion	Stable star
Red Giant	Helium (inert)	Hydrogen shell burning	Expands and cools
Horizontal Branch	Helium	Helium core fusion	Stable, smaller
Asymptotic Giant Branch	Carbon, Oxygen	Hydrogen & helium shell fusion	Pulsations, mass loss
Planetary Nebula	Carbon, Oxygen	No fusion (core remnant)	Expelled outer layers
White Dwarf	Carbon, Oxygen	No fusion, degenerate core	Slowly cools and fades

Evolution of High-Mass Stars ($M > 8$ Solar Masses)

Phase	Core Composition	Fusion Process	Outcome
Main Sequence	Hydrogen	Hydrogen fusion	Stable, large star
Red Supergiant	Helium, Carbon, Oxygen	Helium, Carbon fusion	Expands and cools
Supergiant	Carbon, Oxygen, Silicon	Fusion of heavier elements	Expands further, multiple fusion shells
Iron Core	Iron	No fusion (no energy release)	Core collapse begins
Supernova Explosion	Iron, Heavy Elements	No fusion (core collapse)	Shockwave blasts outer layers
Neutron Star or Black Hole	Neutron-rich or Singularity	No fusion (degeneracy pressure)	Neutron star or black hole

Hertzsprung-Russell (H-R) Diagram

1. Main Sequence
 - Stars fuse hydrogen into helium in their cores.
 - Hot, luminous stars on the upper left; cool, dim stars on the lower right.
2. Red Giant Branch
 - Stars in this region have exhausted core hydrogen.
 - Expanded outer layers; cooler but very luminous.
3. White Dwarfs
 - Remnants of low- to medium-mass stars after the red giant phase.
 - Very hot but faint due to small size.
4. Supergiants
 - Massive stars near the end of their lives.
 - Very large and extremely luminous.
5. Blue Supergiants
 - Massive, hot, and extremely luminous stars.



Hertzsprung-Russell (H-R) Diagram

Stars move through the H-R diagram during their life cycle:

1. Protostar Phase:

- Begins off the main sequence (cool and faint).
- Moves towards the main sequence as it contracts and heats up.

2. Main Sequence Phase:

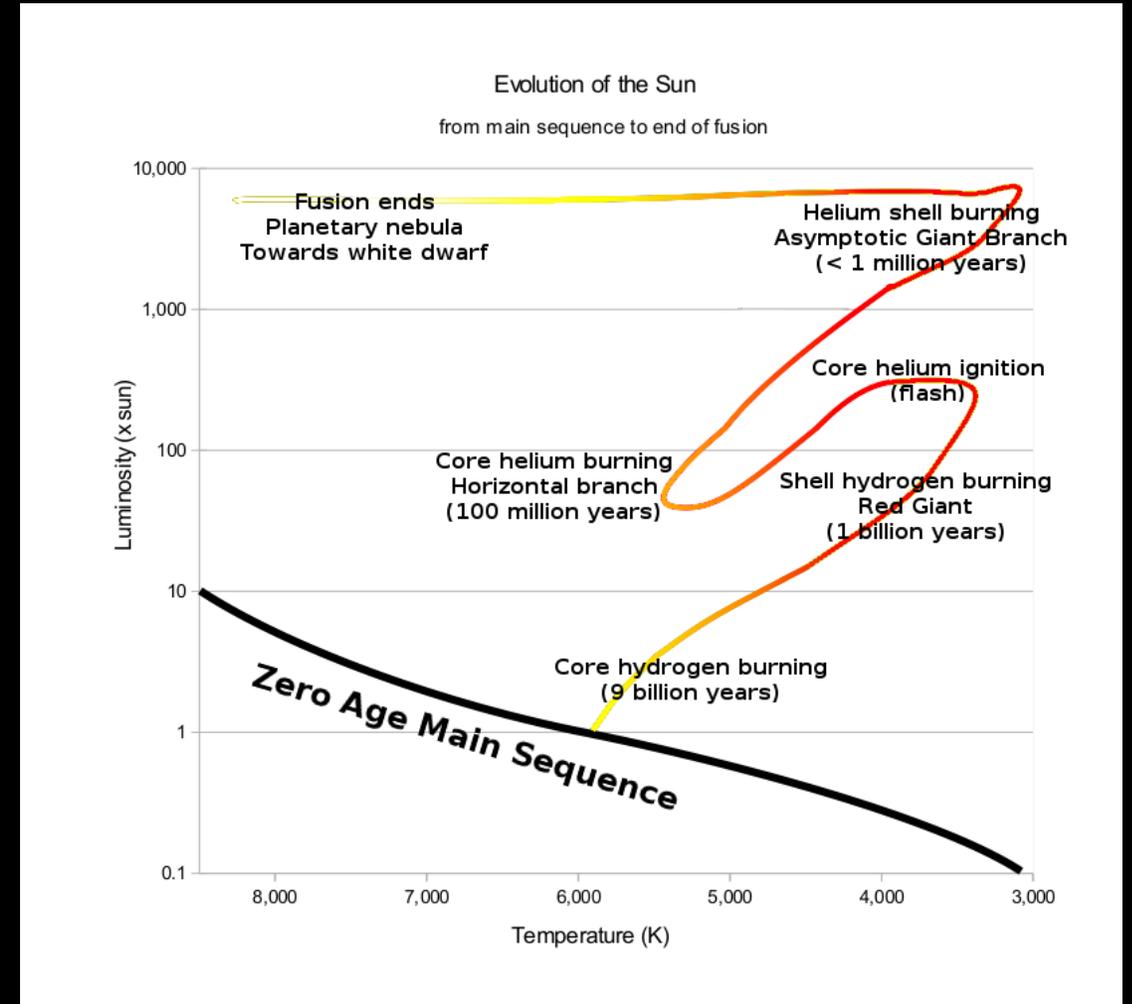
- Stars remain in hydrostatic equilibrium, burning hydrogen into helium.
- Mass determines position:
 - Massive stars: upper left.
 - Low-mass stars: lower right.

3. Red Giant/Supergiant Phase:

- Core contracts; outer layers expand.
- Star becomes cooler but more luminous.

4. Post-Main Sequence:

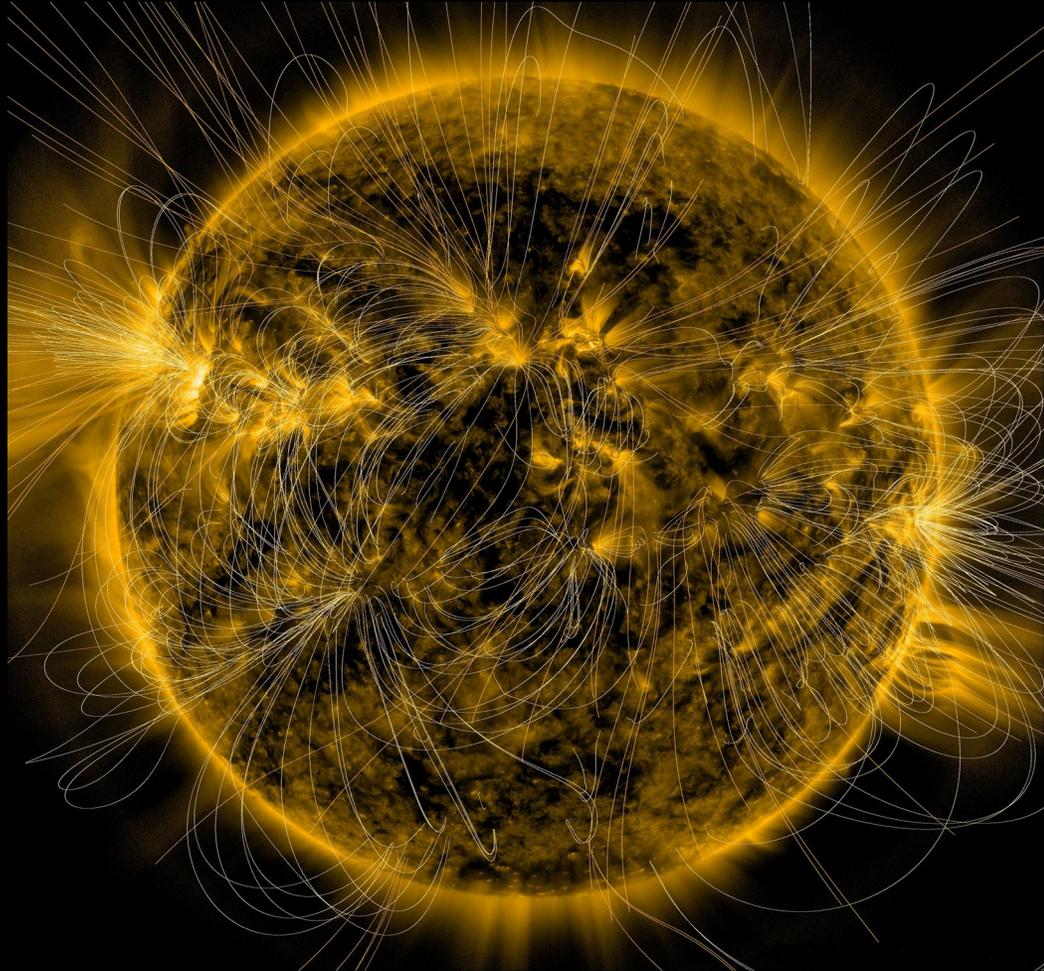
- Low-mass stars evolve into white dwarfs.
- High-mass stars may go supernova and become neutron stars or black holes.



Thank You

Time for Questions....

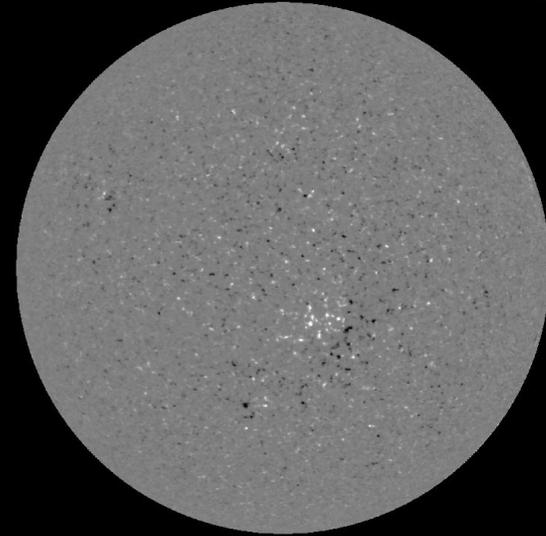
Sun's Magnetic Field



Credits: NASA/SDO/AIA/LMSAL

NSO/SOLIS-VSM
Scale: [-100,100] G

630.2 nm
LOS B

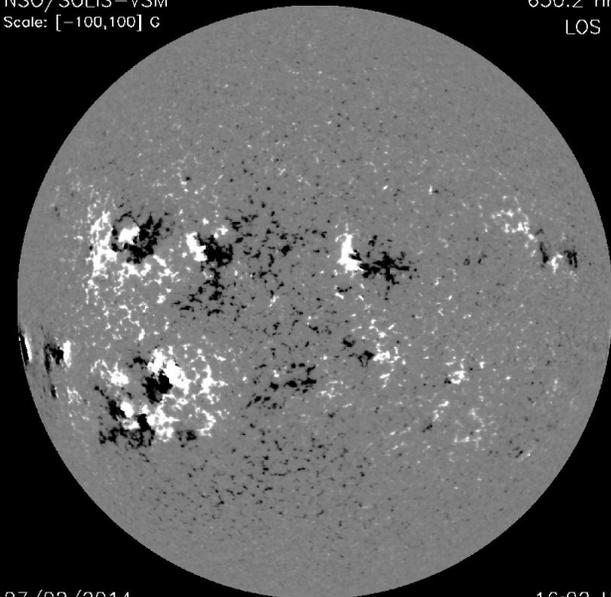


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NSO/SOLIS-VSM
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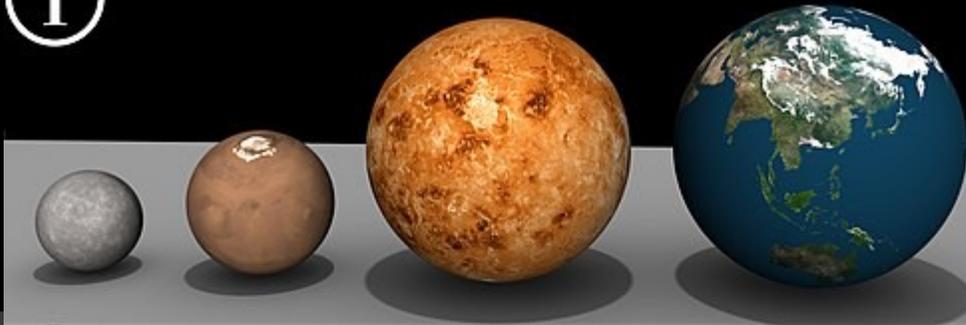
630.2 nm
LOS B



07/02/2014

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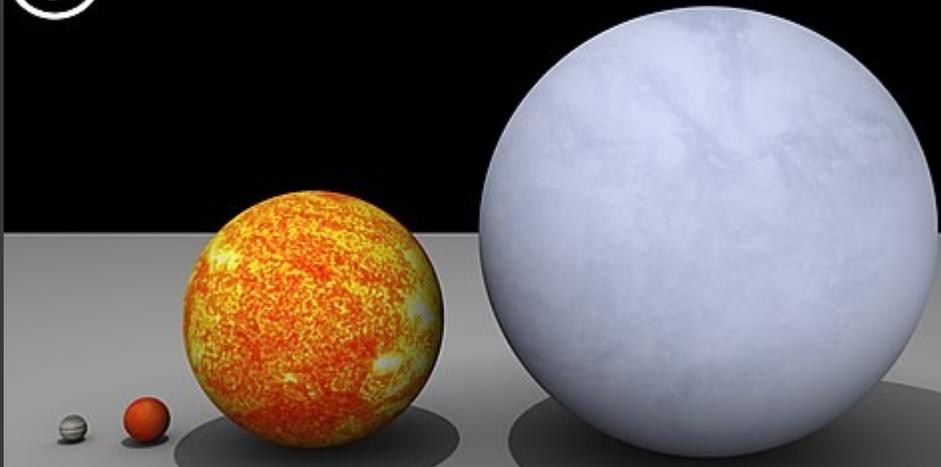
① Mercury < Mars < Venus < Earth



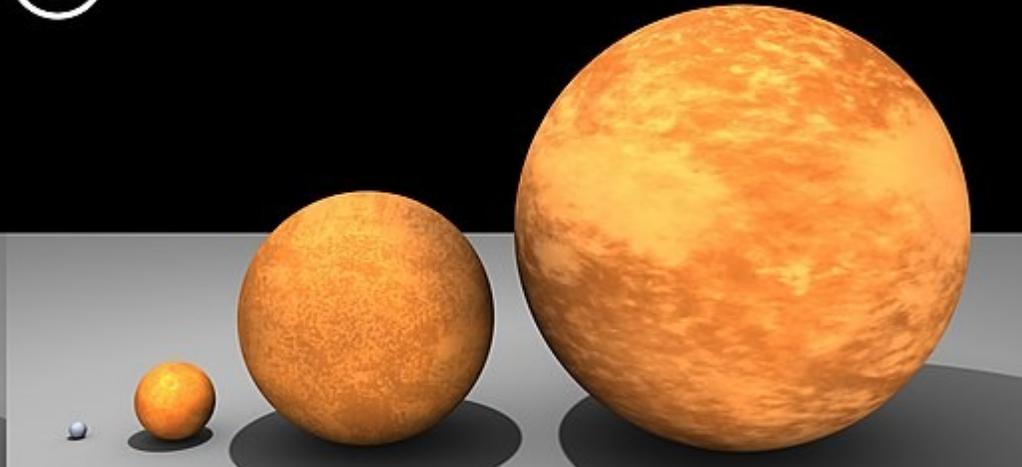
② Earth < Neptune < Uranus < Saturn < Jupiter



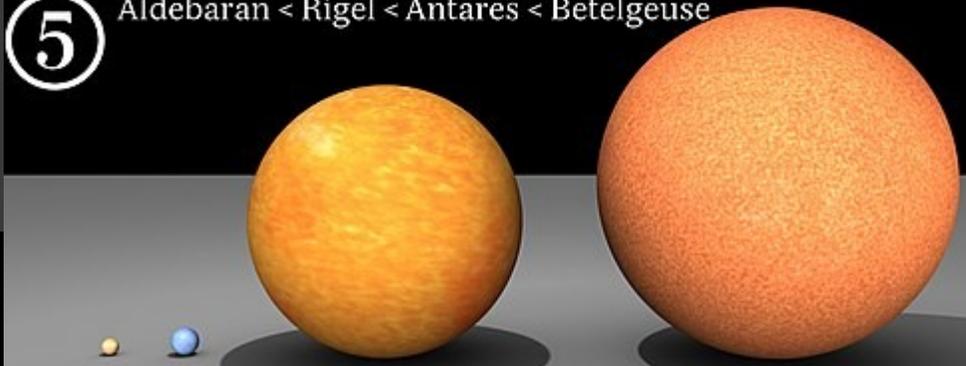
③ Jupiter < Wolf 359 < Sun < Sirius



④ Sirius < Pollux < Arcturus < Aldebaran



⑤ Aldebaran < Rigel < Antares < Betelgeuse



⑥ Betelgeuse < Mu Cephei < VV Cephei A < VY Canis Majoris

