Chapter 10:
Star Formation & Evolution

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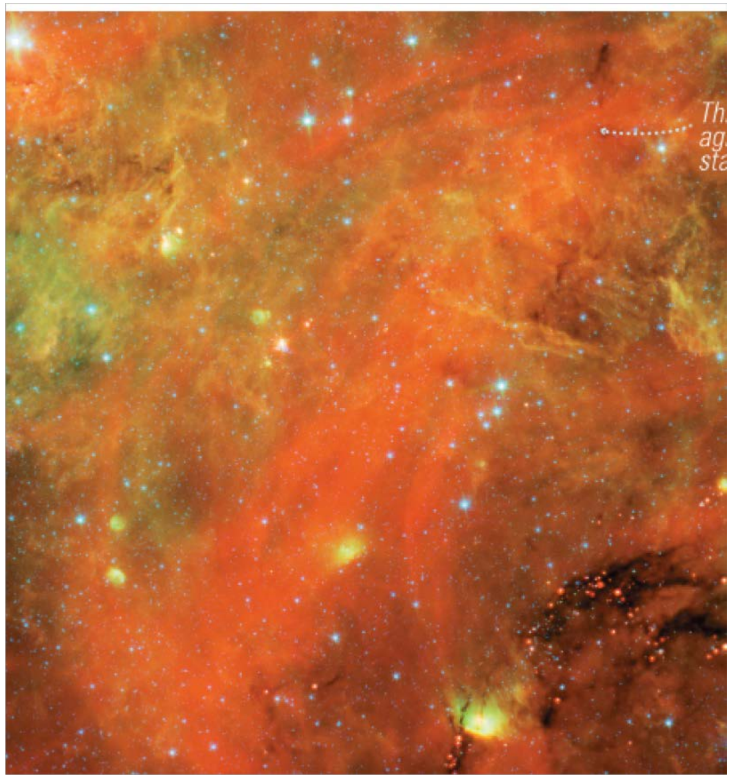
AST 1002

Interstellar Medium

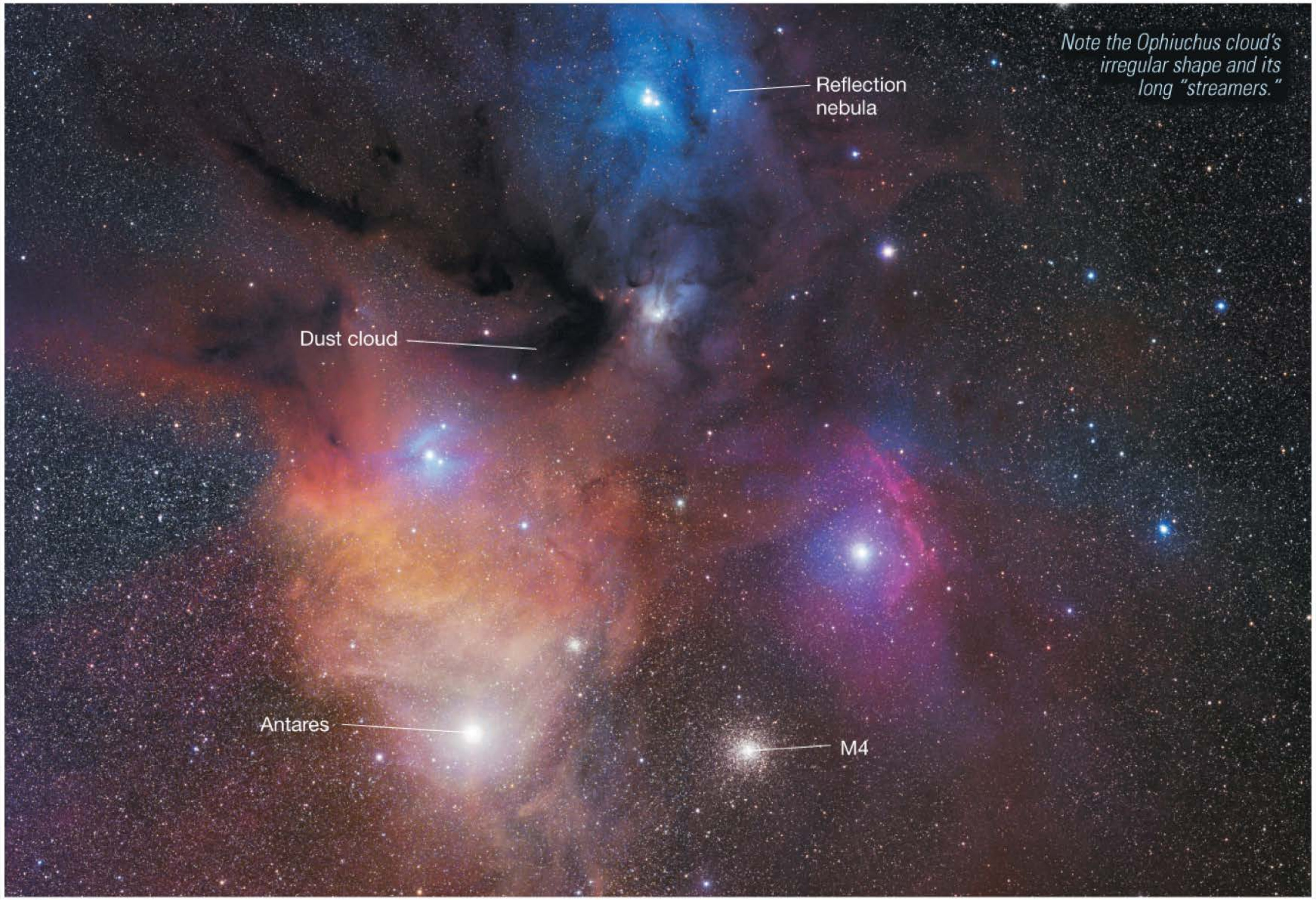
Interstellar medium (ISM) is the matter between stars. It comes in **two types**: gas and dust

Dust

Gas



Matter in Space



Characteristics of ISM

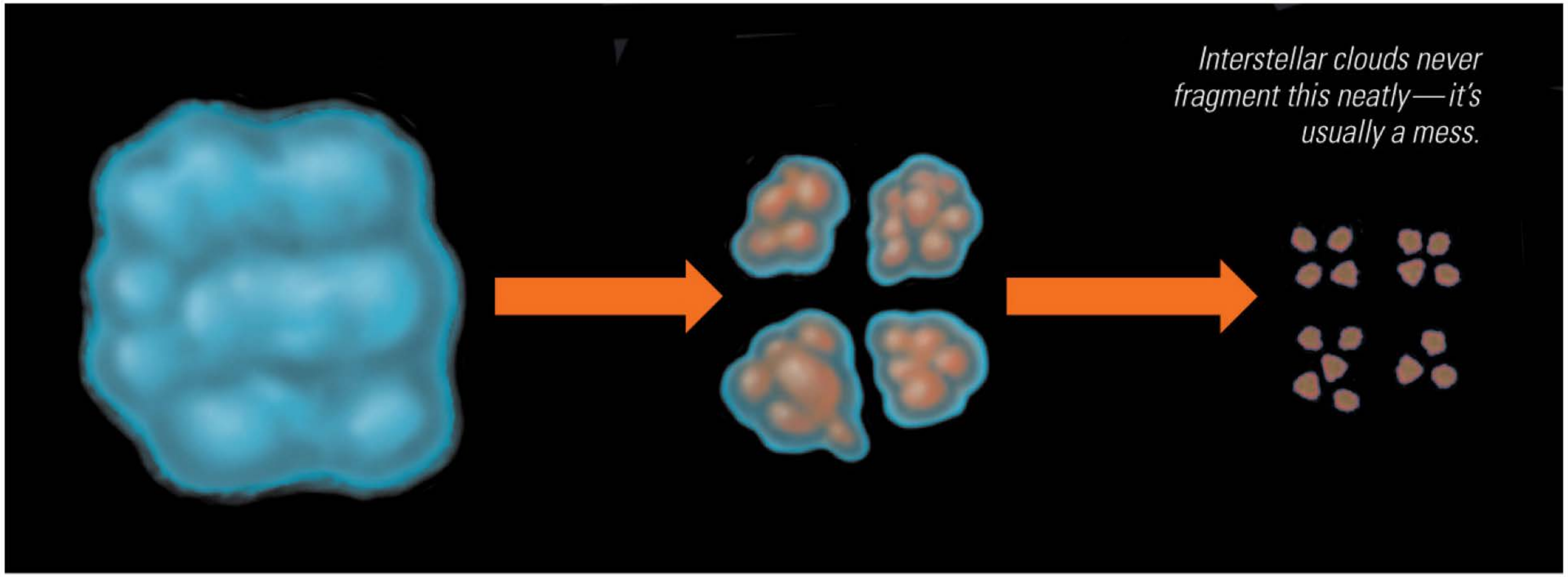
- Temperature:
  - 10 – 20 K (for non-heated ISM)
  - Can be much higher (thousands of K) for heated ISM
- Density:
  - 10^6 atoms/m^3 (for non-heated ISM)
  - Much lower for heated ISM
- Composition:
  - 75% hydrogen, 25% helium
  - There is also a tiny bit of “metals” (much less than 1%)

Stages of Stellar Evolution

1. **Gas cloud**: at this point, what will eventually become our star is just a cloud of gaseous interstellar medium.
2. **Protostar**: this is a gas cloud that has started pulling itself together, accumulating more and more mass
3. **Pre-main sequence star**: a star that has stopped accumulating mass and has reached equilibrium and begins to burn hydrogen
4. **Main sequence star**: a “healthy” star
5. **Post-main sequence stars**: when “healthy” stars run out of hydrogen to burn, they depart the main sequence (typically as giants), and undergo further evolution dictated by their mass

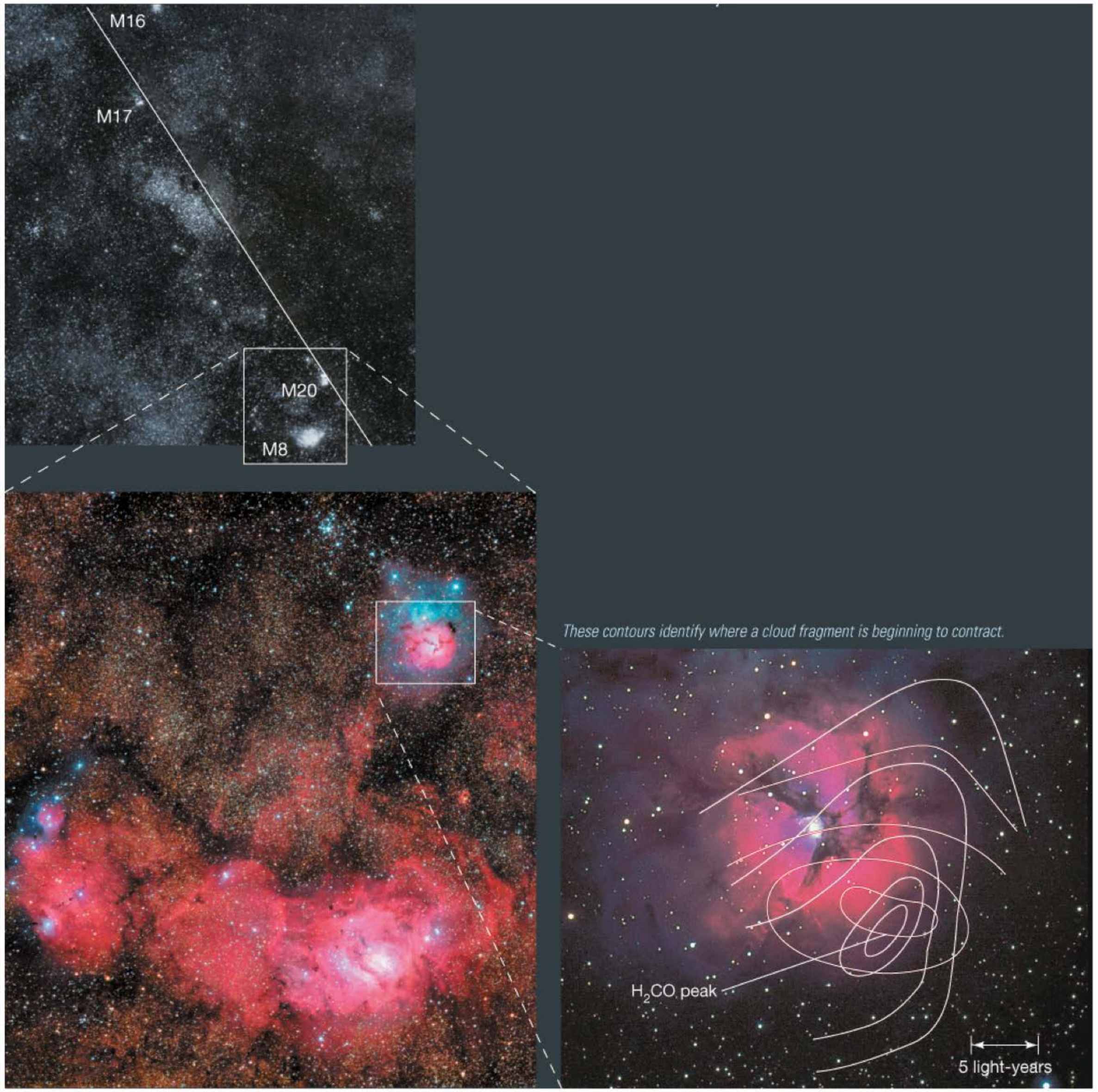
Gas Clouds and Fragmentation

Gas clouds are huge, producing many, many individual stars through the process of **fragmentation**. These fragments become protostars.

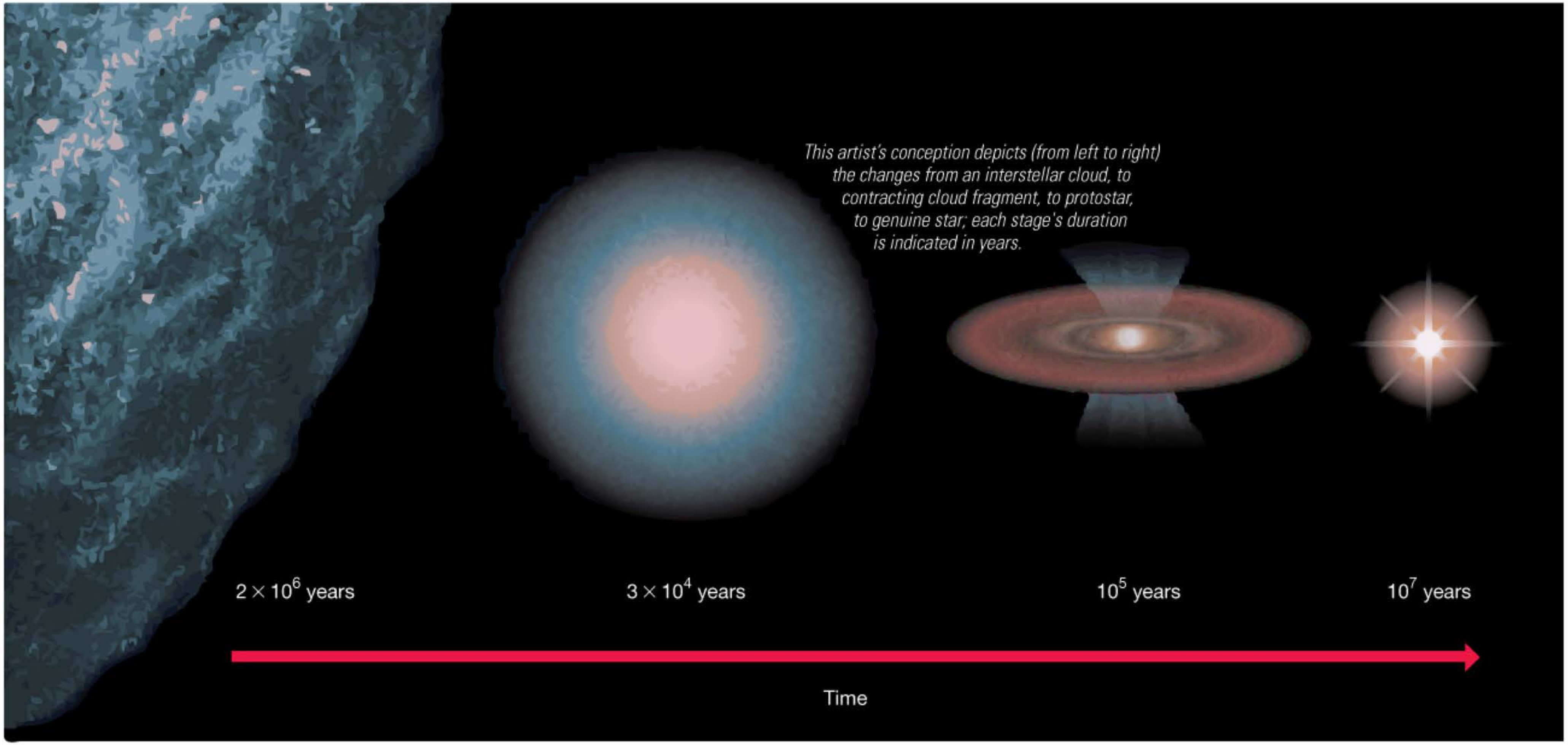


Trifid Nebulae

The contours in the figure to the lower-right are called “velocity contours.” When they are closer together, gas is moving faster. These contours show gas collapsing to the point labeled “H_2CO peak” in the figure, where the contours start to close and get very close together. This gas will form into a fragment, which will become a protostar.



Protostar Formation



Protostar Structure

Jet

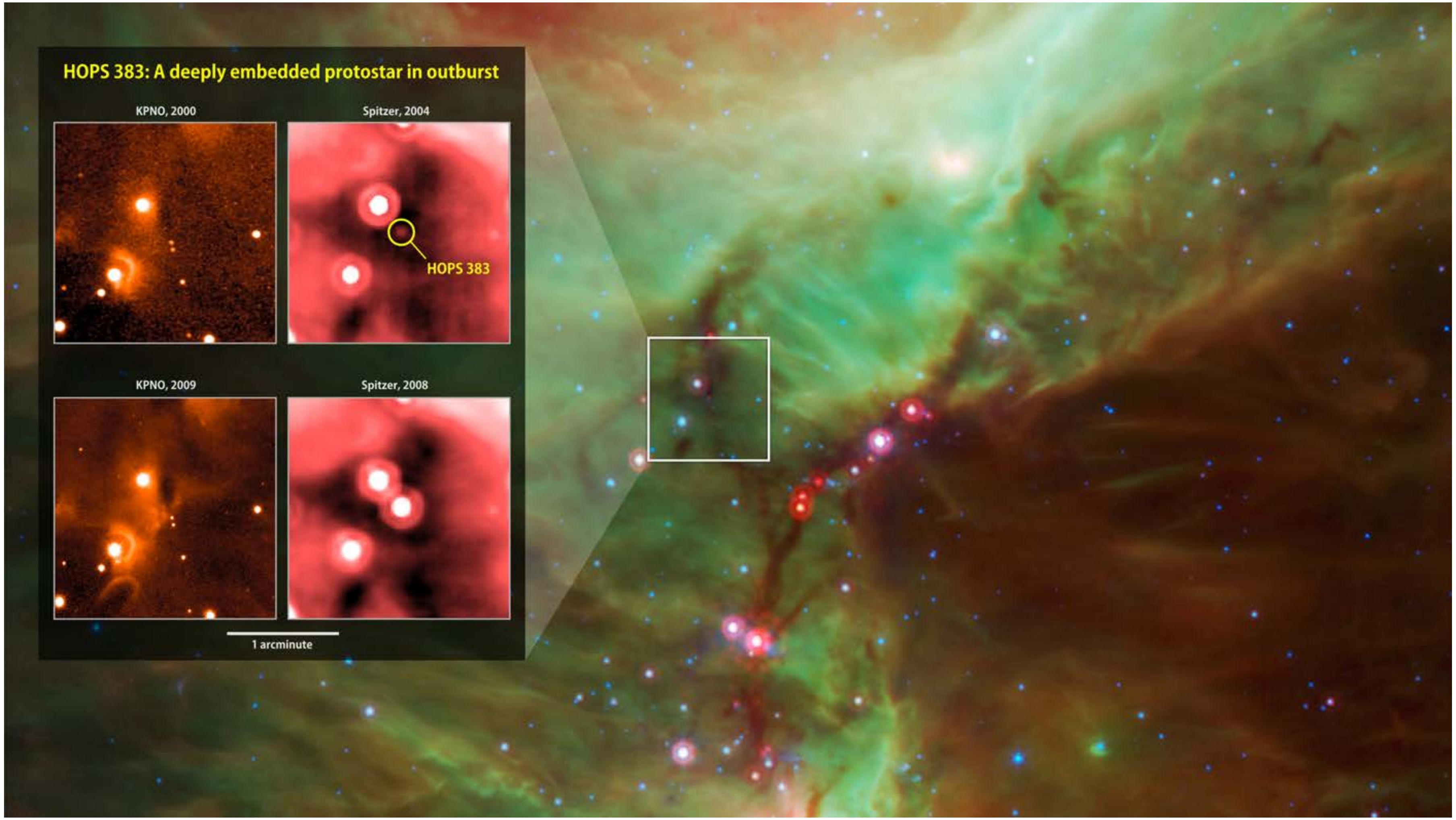
(Protostars are very unstable, and tend to produce much more powerful stellar winds. These form jets. The jet itself can trigger more star formation.)

Accretion disk

(The gas nearest the core falls in very fast, but gas farther away falls in much more slowly. This is known as accretion. Planets often form in the accretion disk.)

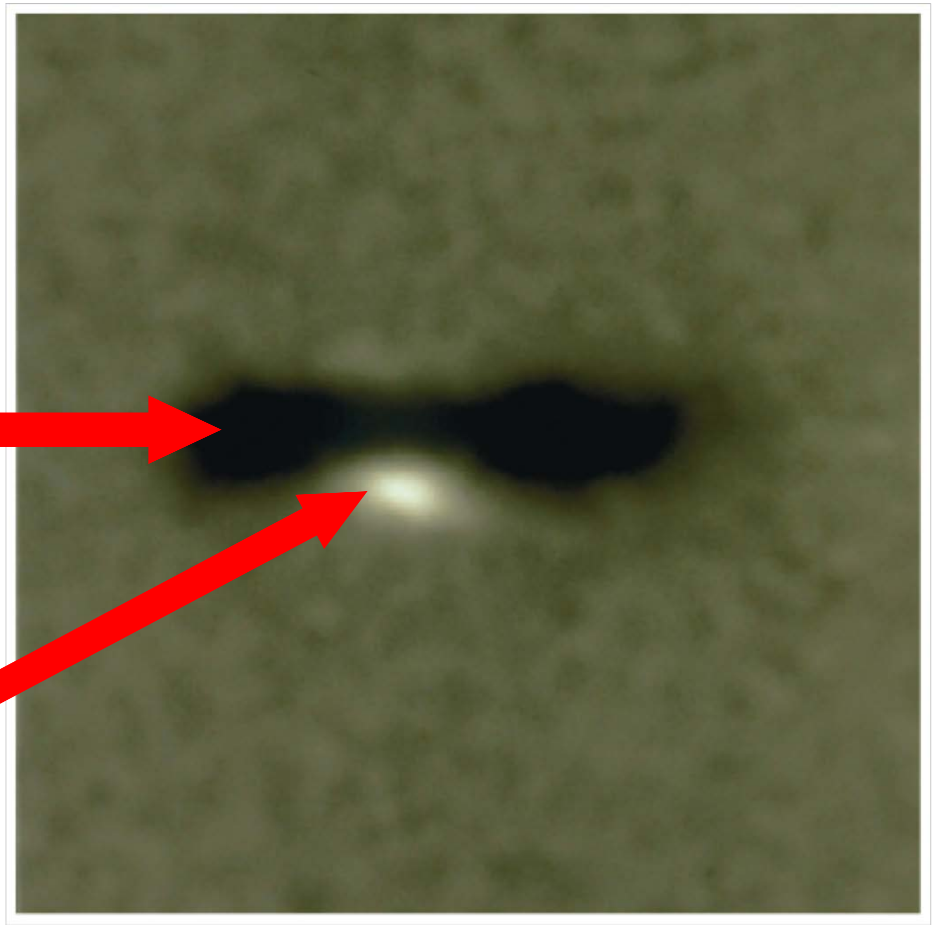
Protostar

Direct Observation of Protostar Formation



Direct Observation of Protostar (?)

It is thought, but not known for certain, that this is an image of a protostar.

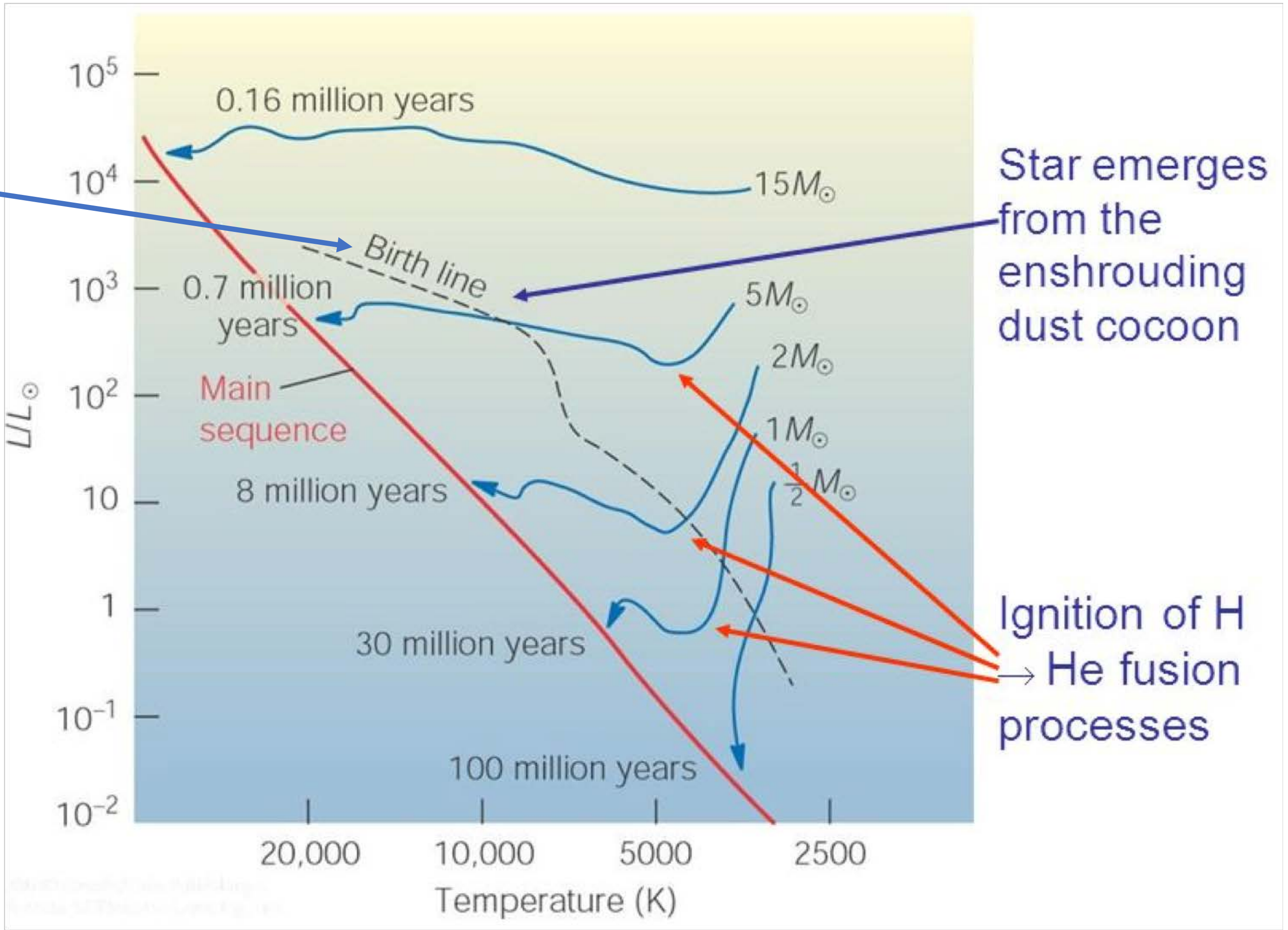


Protostar to Pre-Main Sequence Star

- Protostars are still accreting mass, and are unstable, rapidly changing size and temperature with the added mass.
- As the protostar compresses to a small enough size, the temperature becomes large enough to burn hydrogen. The protostar has now become a pre-main sequence star.
- However, now that hydrogen is burning, there is a “fight” between gravitational pressure inward and thermal pressure outward, causing the star to (more slowly) adjust its size and temperature.
- Once it’s “happy,” it becomes a main sequence star.

HR Diagram of Stellar Birth

The birth line marks the point at which the star stops accumulating gas. This is where protostars become pre-main sequence stars.



Brown Dwarfs

- A pre-main sequence star whose mass is too small (less than $0.1M_{\odot}$) don't have enough gravitational pull to compress itself enough to reach that 14 MK temperature needed for fusion.
- These stars remain cold and very dim, thus hard to see. They weren't first observed until the late-1980s/early-1990s.
- They are "planet-like," with stable amounts of hydrogen and helium.

Life on the Main Sequence

TABLE 17.6 Key Properties of Some Well-Known Main-Sequence Stars

Star	Spectral Type	Mass, M (Solar Masses)	Central Temperature (10^6 K)	Luminosity, L (Solar Luminosities)	Estimated Lifetime (M/L) (10^6 years)
Spica B*	B2V	6.8	25	800	90
Vega	A0V	2.6	21	50	500
Sirius	A1V	2.1	20	22	1000
Alpha Centauri	G2V	1.1	17	1.6	7000
Sun	G2V	1.0	15	1.0	10,000
Proxima Centauri	M5V	0.1	0.6	0.00006	16,000,000

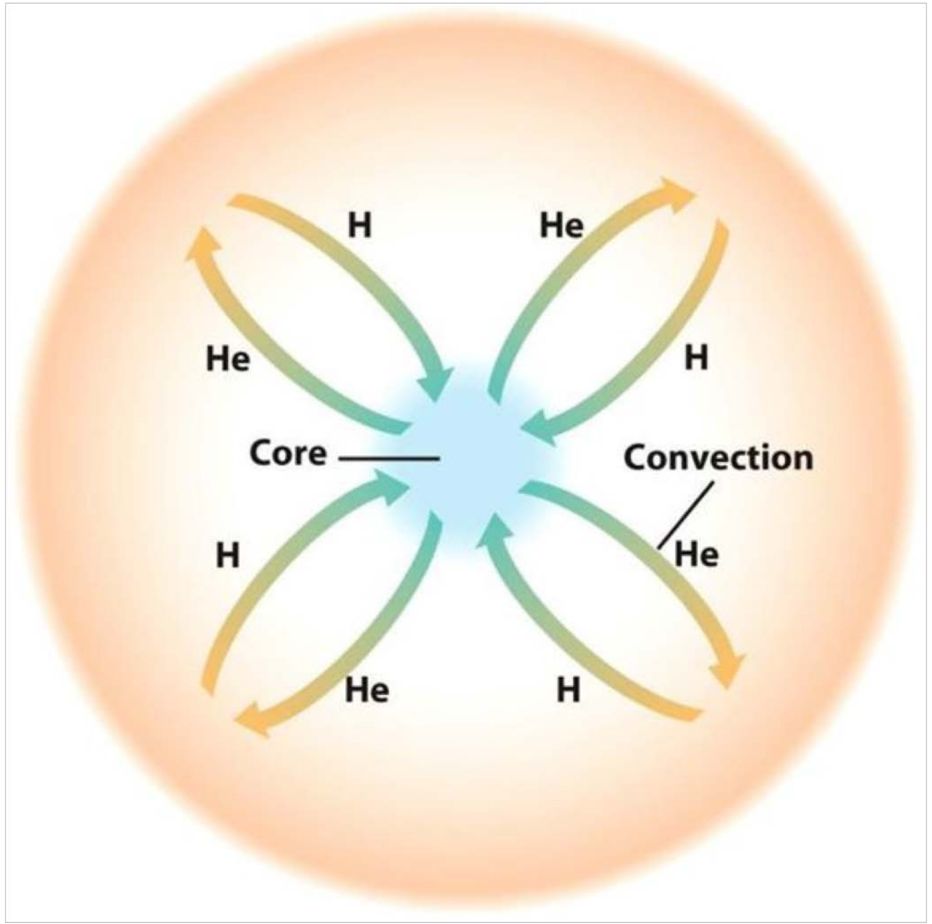
The "star" Spica is, in fact, a binary system comprising a B1III giant primary (Spica A) and a B2V main-sequence secondary (Spica B).

Leaving the Main Sequence

- After a star runs out of hydrogen in its core, it will exit the main sequence.
- What a star does after in its evolution is dramatically different based on its mass.
- We can typically separate stars into two groups: those with a mass less than $0.4M_{\odot}$, and those with a mass greater than $0.4M_{\odot}$.
- Some people say "low mass stars die gently while large mass stars die violently."

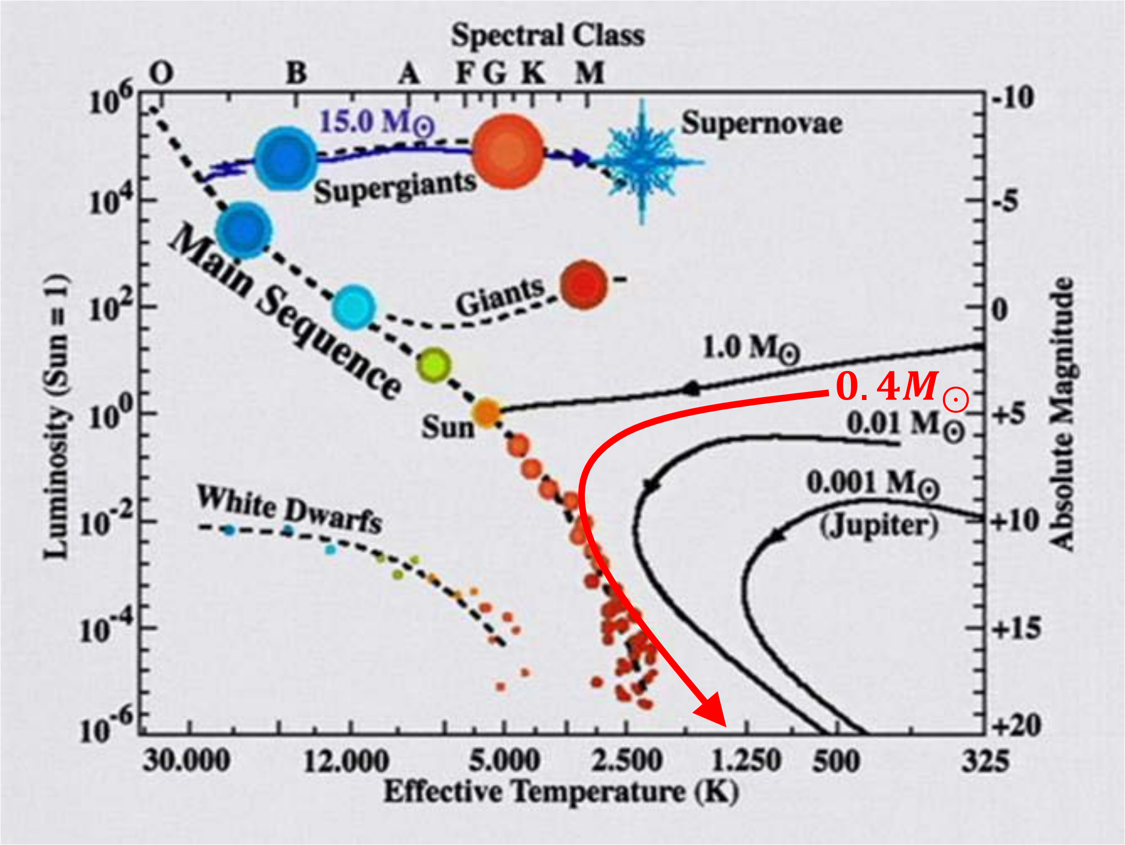
Low Mass Stars (Less Than $0.4M_\odot$)

- These stars are all called **red dwarfs**, and behave completely differently than heavier stars like the Sun
- Red dwarfs do not have a radiation zone, they only have a convection zone.
- Convection continuously resupplies hydrogen to the core to burn.



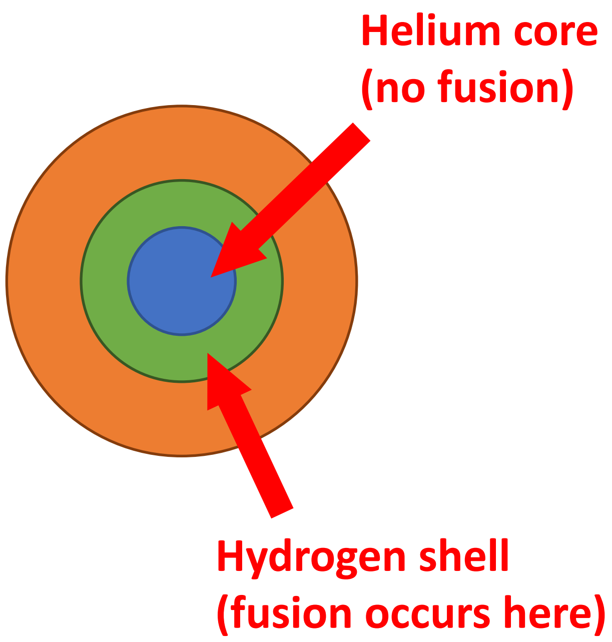
Death of Low Mass Stars

- Eventually, a red dwarf will convert all its mass to helium, and fusion will stop because it can't increase its temperature to burn that helium.
- Slowly, they will radiate their heat, becoming cooler and dimmer.
- Red dwarfs die a "gentle death."



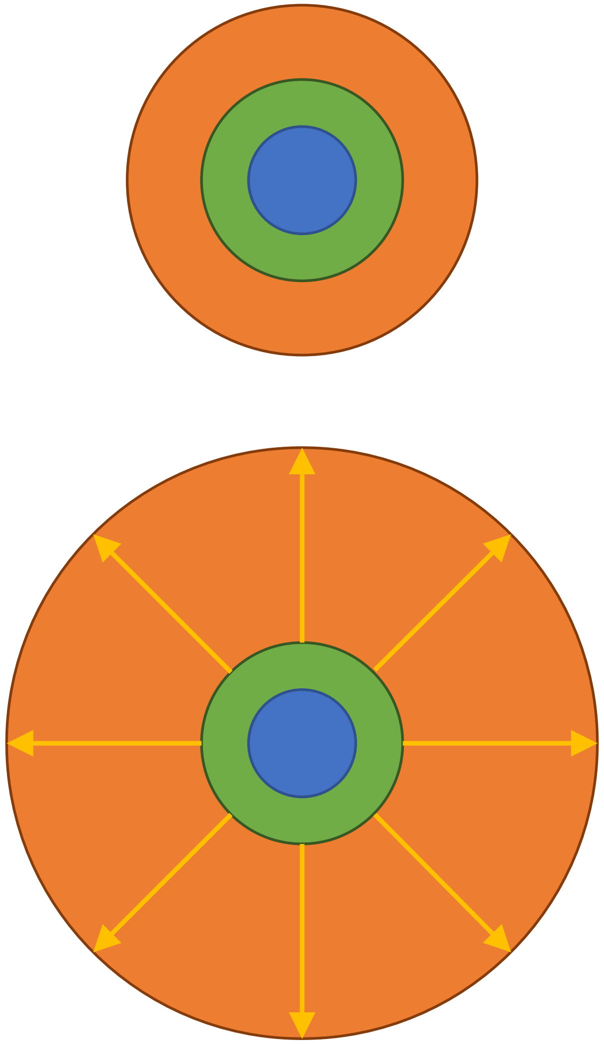
Initial Stage of Red Giant Formation

- Large mass stars form **red giants** when they run out of hydrogen.
- When the core is out of hydrogen, thermal pressure drops and gravitational pressure crushes the helium core. No fusion occurs here yet.
- A **hydrogen shell** around the core is also compressed by the gravitational pressure, increasing its temperature and starting fusion in the shell.



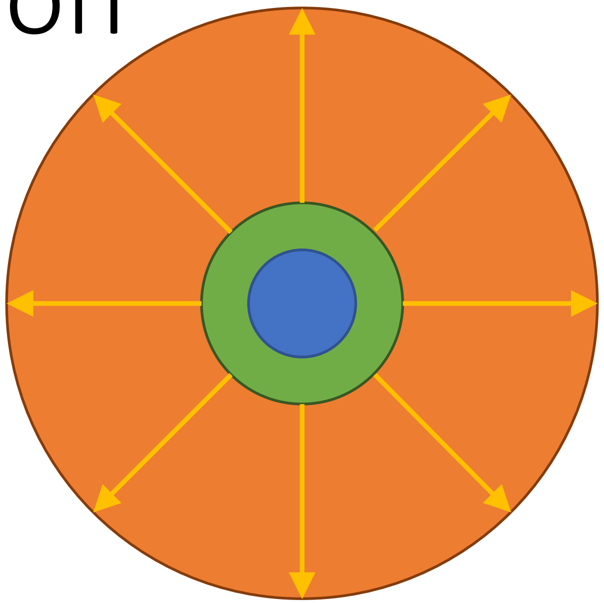
Intermediate Stage of Red Giant Formation

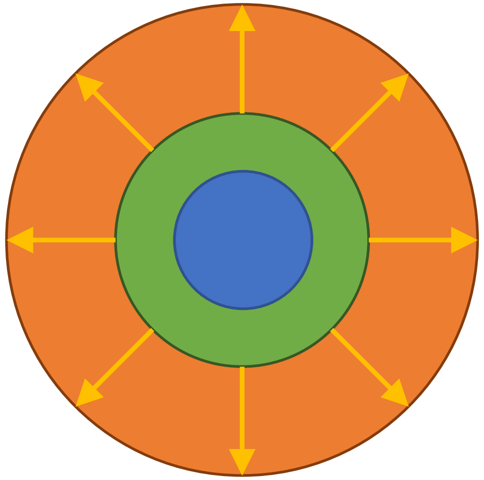
- Photons produced by the hydrogen shell have more energy when they reach the outer layers of the star because they travel shorter distances. This expands the star (hence the term “giant”).
- Helium from the hydrogen shell falls into the core, increasing the temperature of the core. After enough time, the temperature of the core will be high enough to star burning helium.



Final Stage of Red Giant Formation

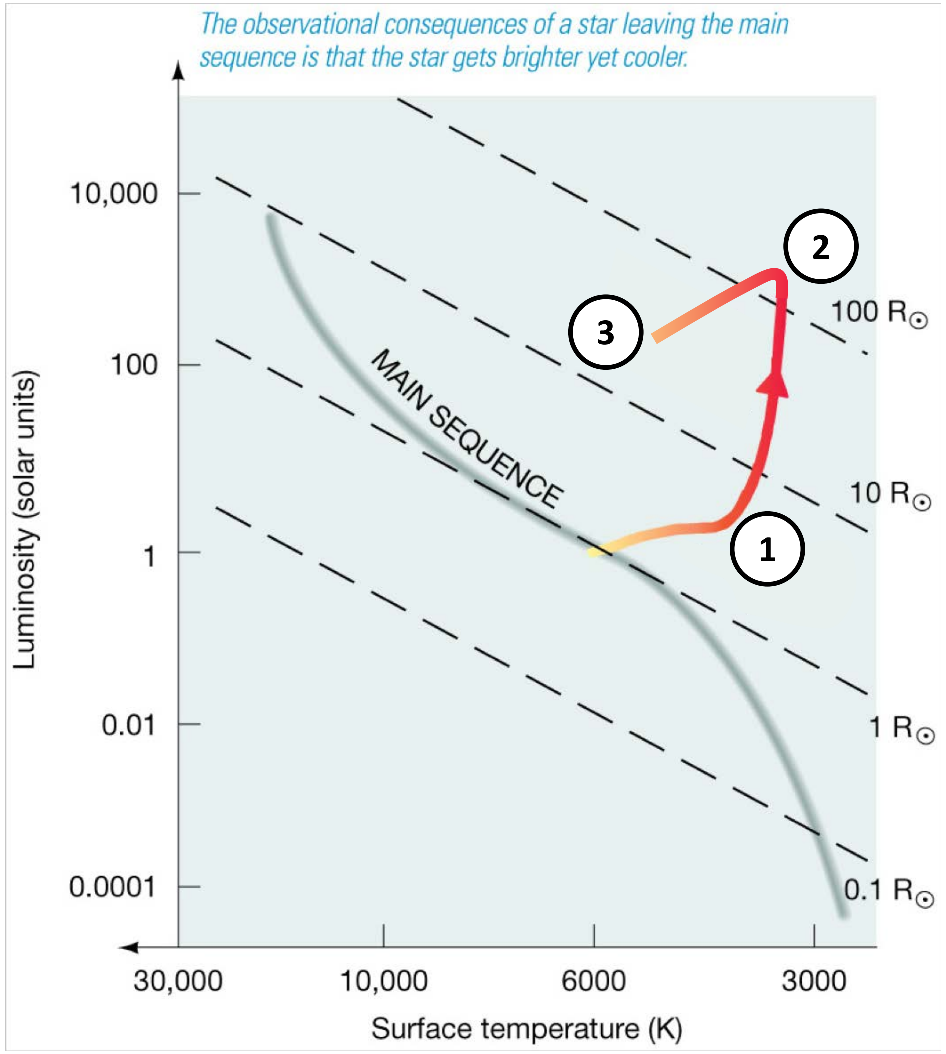
- As helium is burned at the core, the thermal pressure of the core causes it to expand and cool. It also causes the hydrogen shell to expand and cool, as well.
- Since the hydrogen shell is now much cooler than it was in the intermediate stage, it's outputting a lot less energy, which causes the outer layers of gas to pull back in, reducing the radius. The result is a mature red giant, burning helium.





Red Giant Evolution on the HR Diagram

1. Fusion in hydrogen shell, no fusion in core. Rapid expansion of star. Increase in luminosity because the larger hydrogen shell can produce more photons.
2. Start of core helium burning, and decrease in radius.
3. Final equilibrium state of mature red giant.



Carbon Cores and "Dead" Stars

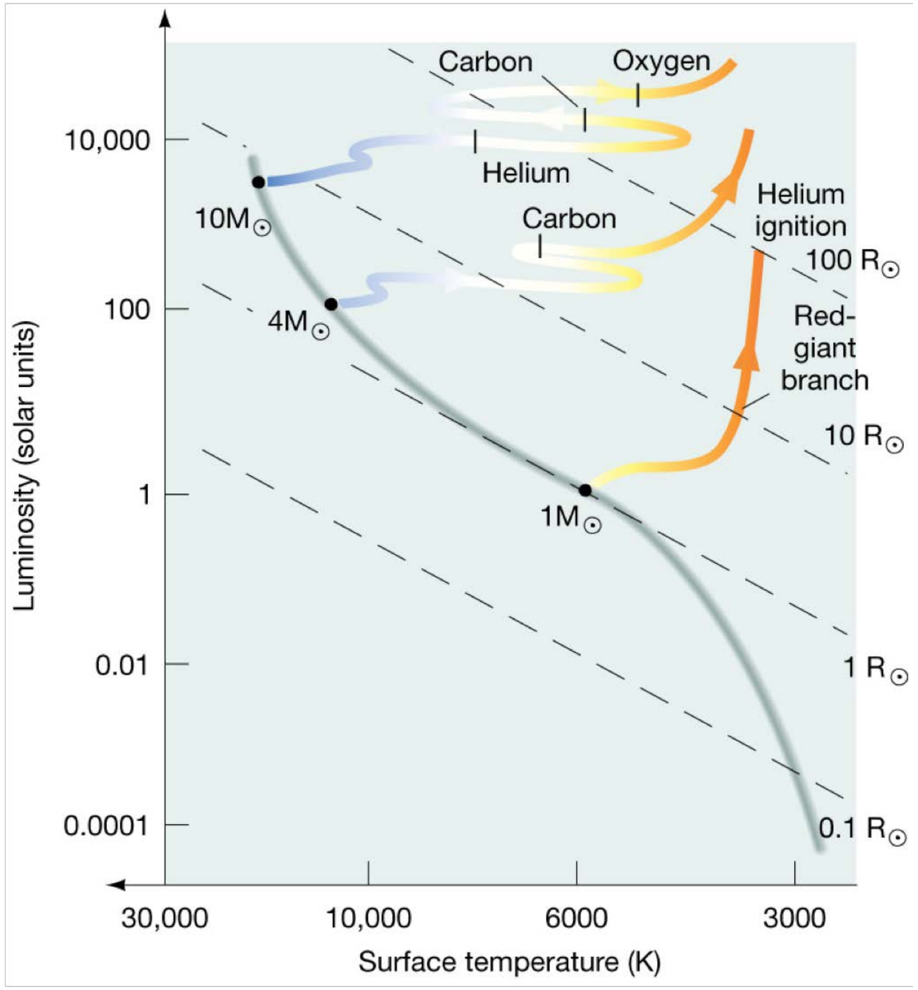
- Helium fusion occurs like:

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C}$$

- Some hydrogen can fuse with carbon, to produce oxygen

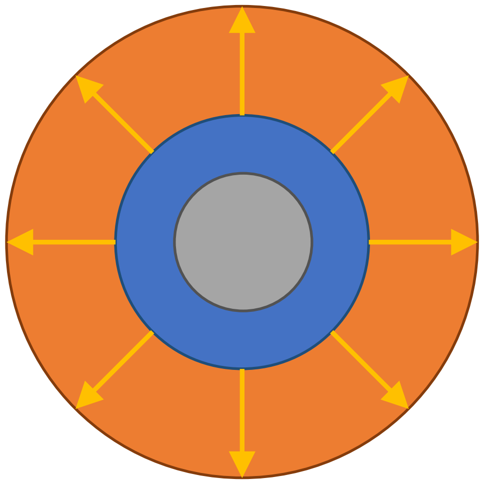
$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O}$$

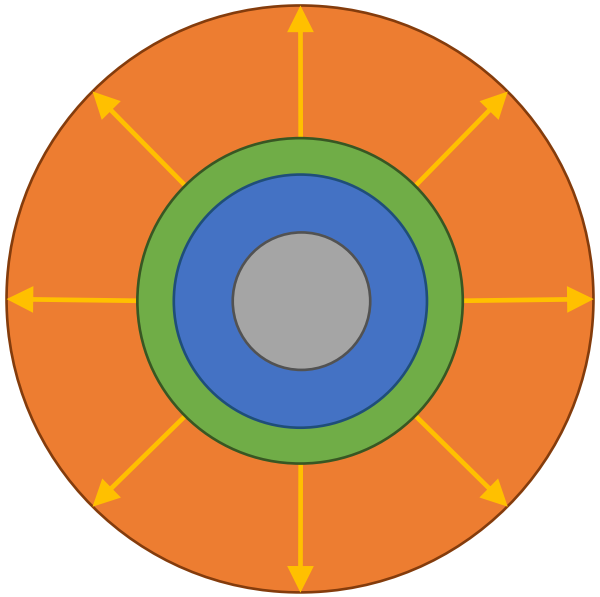
- When a giant reaches the "carbon core" or "carbon-oxygen core" stage, it is effectively "dead".



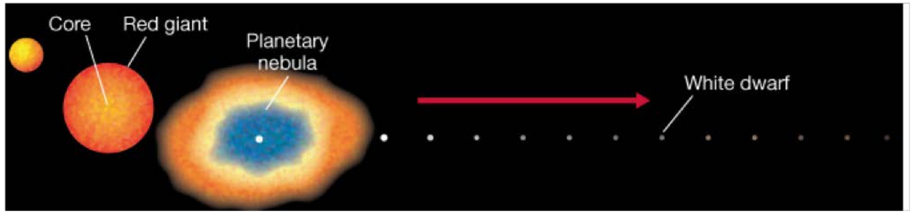
Evolution of Carbon Core Giants

- When the core converts entirely to carbon/oxygen, and becomes inert, fusion moves out to the shell, which is now mainly helium. A new hydrogen shell forms around the helium shell.
- Since helium burns at a higher temperature than hydrogen, the star once again expands.
- As the star expands, its surface cools.
- This star is now known as a double-shell giant.

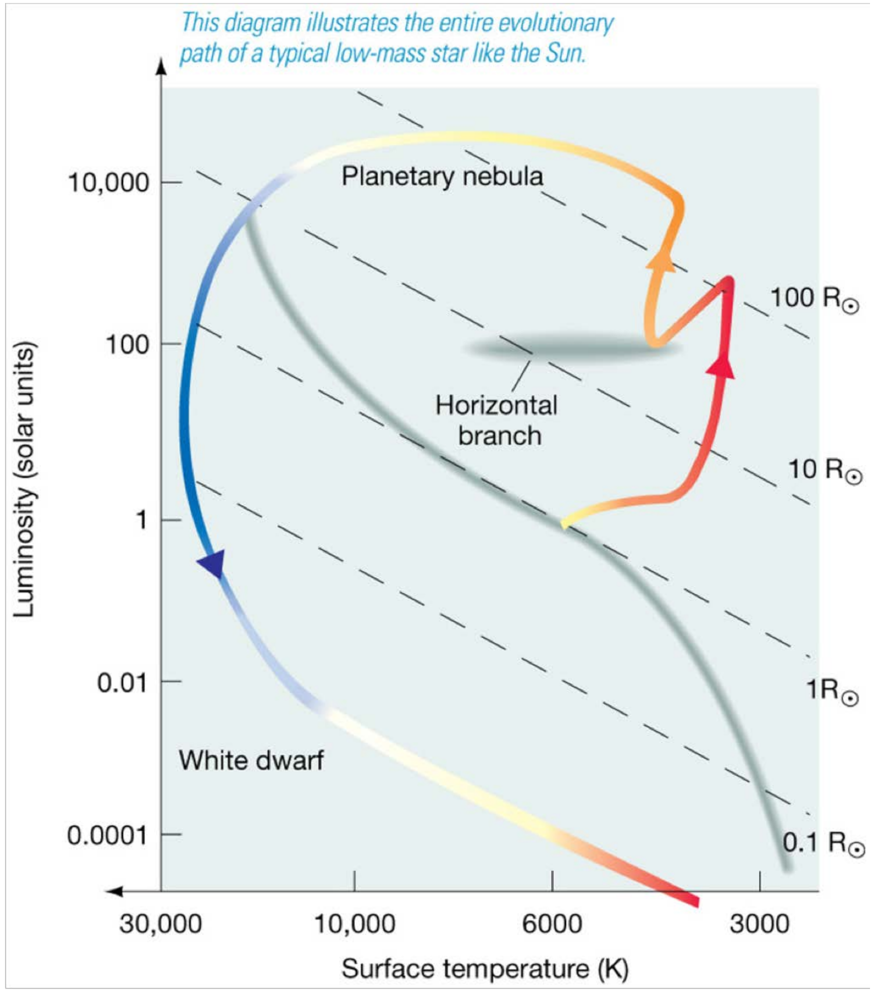




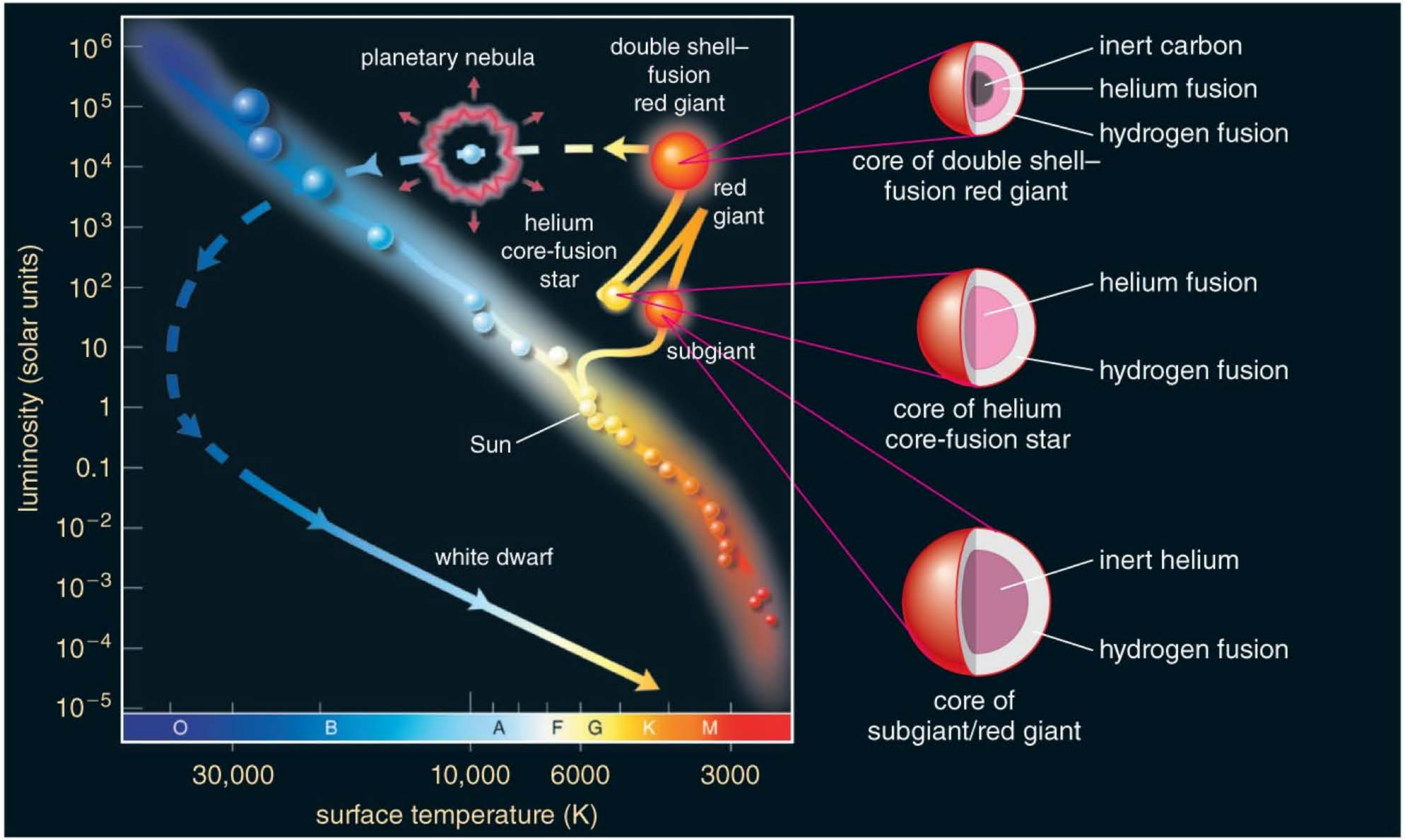
White Dwarfs



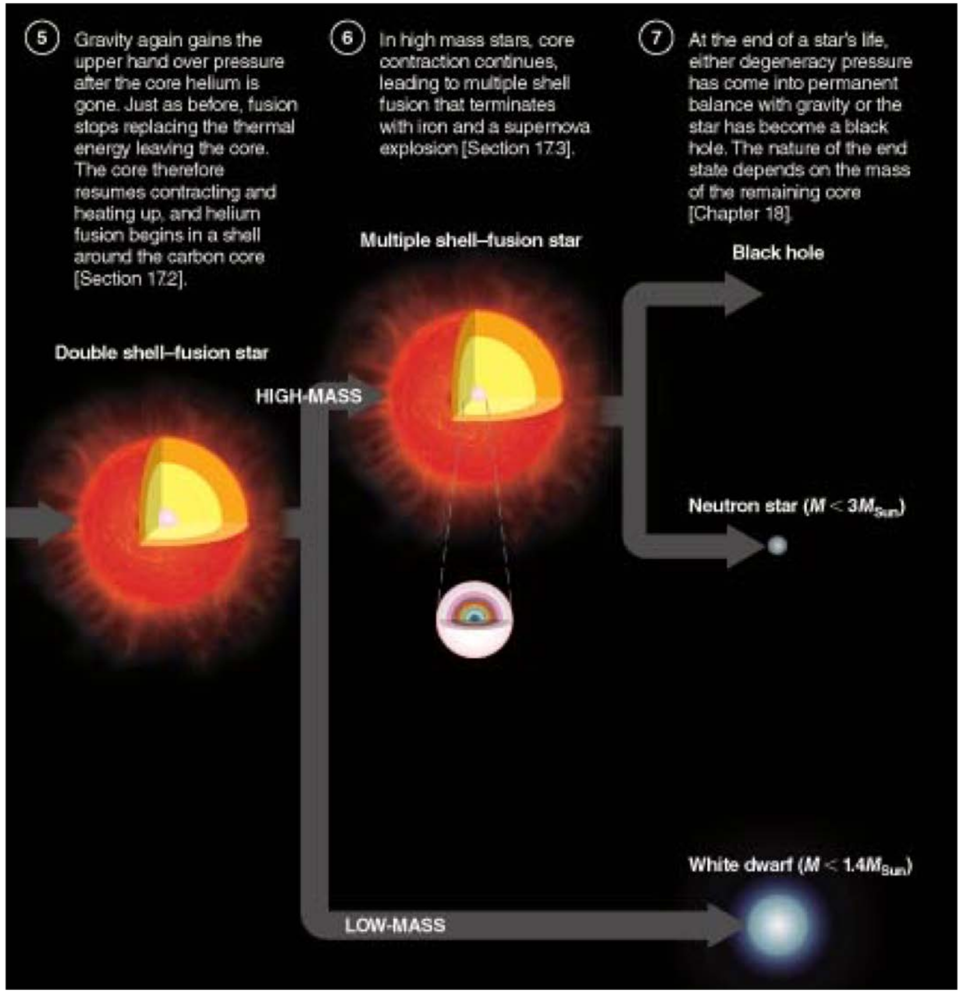
- If a star has a moderate mass, less than $8M_{\odot}$, its outer layers will continue burning hydrogen and helium and just float away.
- This forms what is known as a **planetary nebula**.
- The carbon core that's left becomes a **white dwarf**.



White Dwarfs



Alternatives to White Dwarfs



Summary of Stellar Evolution