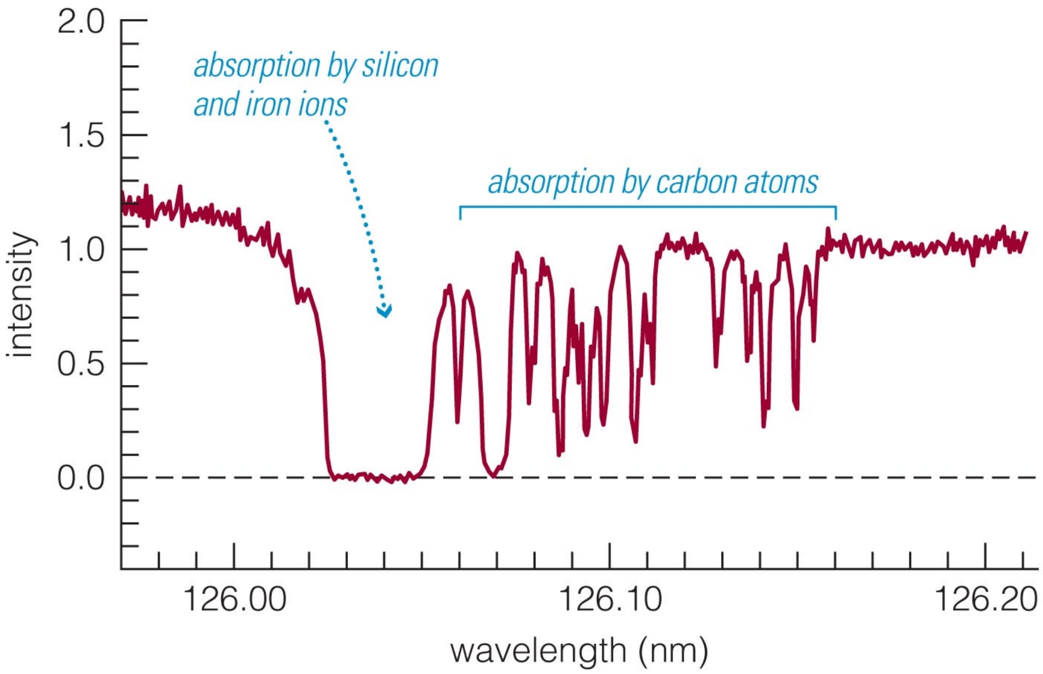
Lecture 16 – Star Birth

Where and how do stars form?

Star-Forming Clouds

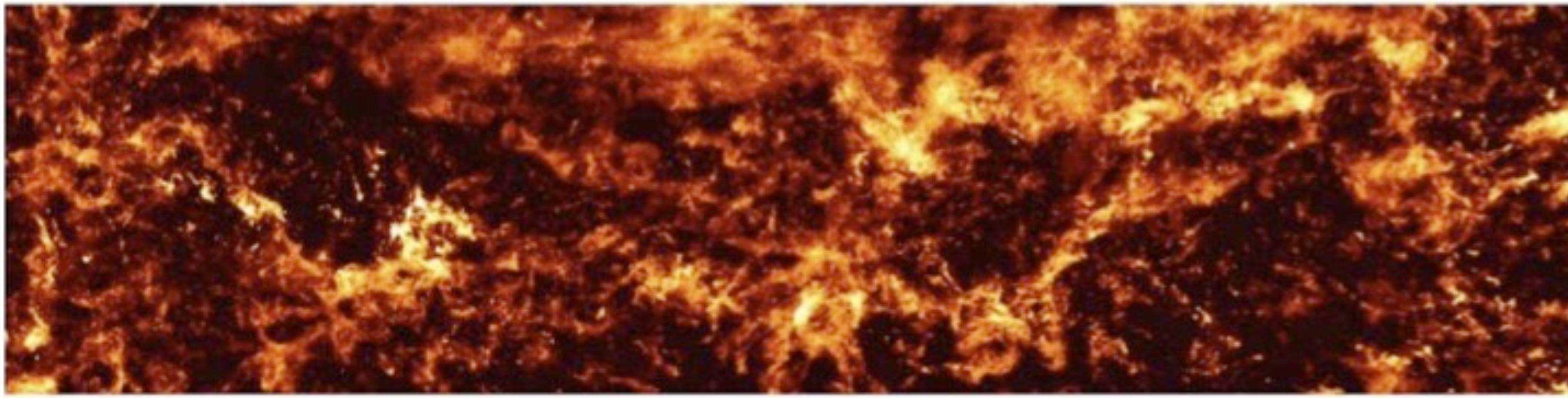
- The gas between the stars is the **interstellar medium.**
- Stars form in a cloud (a **nebula**) of dusty gas.
- Stars form when they contract and become hot enough for fusion in core.

Composition of Clouds



- Composition of interstellar gas found from absorption lines in their spectra.
- 70% H, 28% He, 2% heavier elements

Molecular Clouds



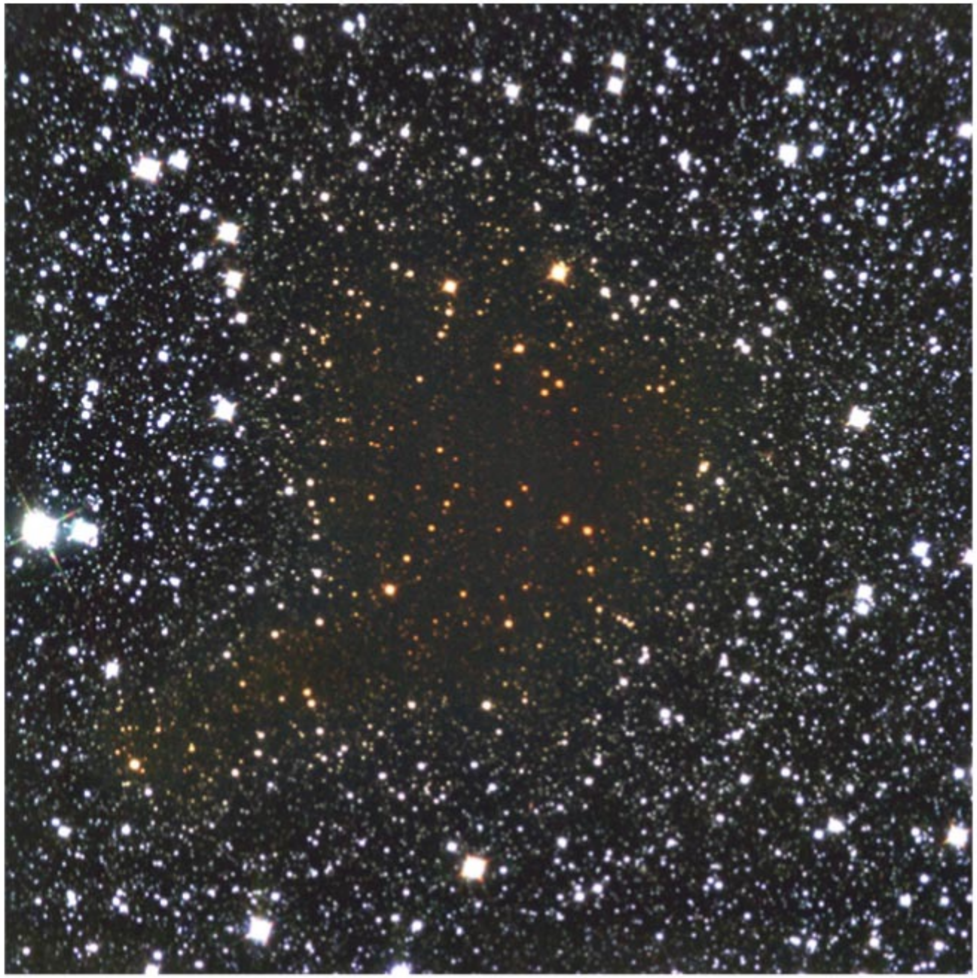
- Most matter in star-forming clouds are molecules (H_2, CO, etc.).
- These *molecular clouds* have a temperature of 10–30 K and a density of 300 molecules cm^3.
- What wavelengths must we observe them in?

Interstellar Dust

- Tiny particles of *interstellar dust* block our view of stars within a **dark nebula**.
- Stars near the edge of the nebula appears **reddened** because blue light is scattered by dust.

Interstellar Reddening

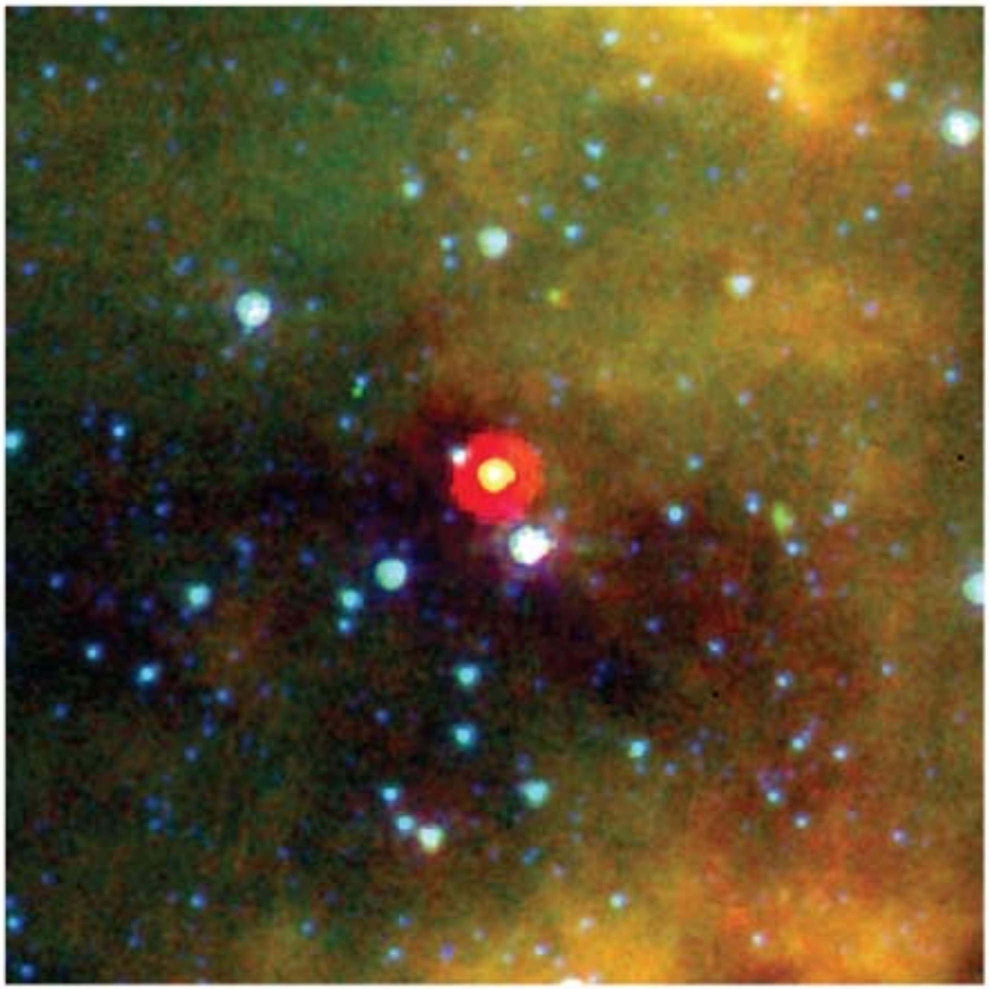
- Long-wavelength infrared light passes through cloud more easily than visible light.
- Infrared observations reveal stars inside the cloud.



Observing Newborn Stars

- Visible light from forming stars is trapped within the dark, dusty gas clouds.

Observing Newborn Stars

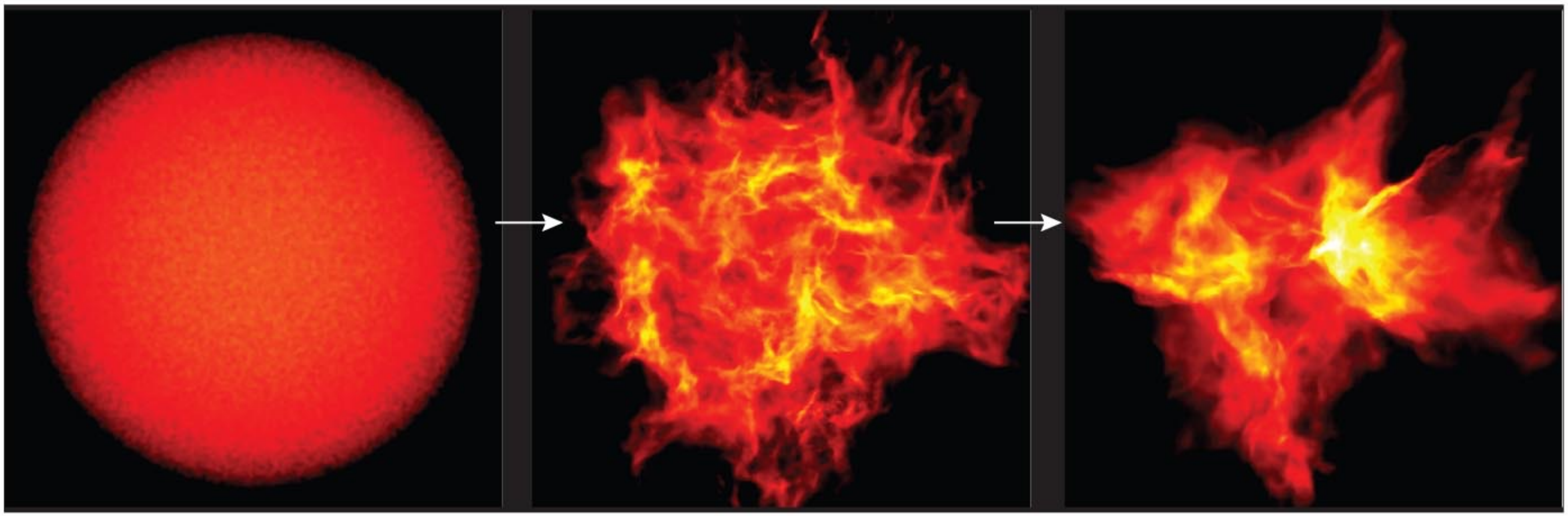


- But observing infrared light from a cloud can reveal the newborn star inside it!

Glowing Dust Grains

- Dust grains absorb visible light, heat up and emit infrared light of even longer wavelength.
- Long-wavelength infrared light is brightest where stars are forming (**bright nebula**)

How do stars form?



*It's all about **gravity!***

Gravity versus Pressure

- Gravity creates stars only if it overcomes the **thermal pressure** of a cloud.
- The cloud must have:

  1. high enough **density** (stronger gravity)
  2. low enough **temperature** (lower pressure)

- Star forming clouds must be **colder** and **denser** than the interstellar medium.
- The cloud can reduce pressure by emitting thermal energy as infrared photons.

Mass of a Star-Forming Cloud

- Balance point between gravity and thermal pressure depends on mass.
- A typical **molecular cloud** of $T \sim$ 30 K, $n \sim 300$ particles/cm^3 must contain > **200 solar masses** for gravity to overcome pressure.
- As density increases, less mass is needed to form stars so cloud fragments into smaller objects.
- Most clouds form numerous stars.

$$M_{bal} = 18 M_{Sun} \, (T^3 / n)^{1/2}$$

The formula to calculate the minimum mass of a cloud that will collapse to form stars.

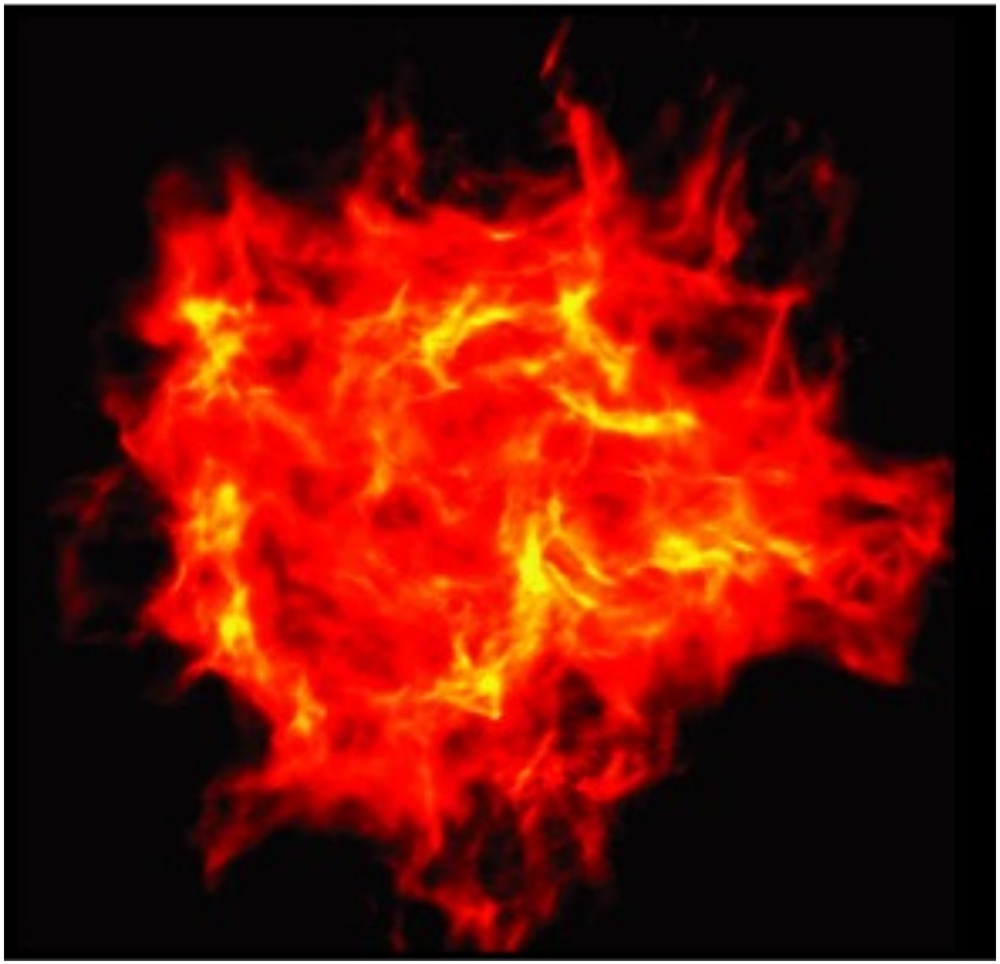
Trapping of Thermal Energy

- As density increases (particles closer together), it is harder for photons to escape (increased **opacity**).
- Thermal energy builds up inside, increasing pressure.
- Contraction slows; as density increases the cloud fragments into **protostars.**

From cloud to protostar

1. Gravity pulls material to center of cloud, increasing temperature and density.
2. Early in collapse, heat is radiated away easily.
3. Increasing density (opacity) traps heat; its harder to radiate heat away.
4. Temperature & pressure rise, resist gravity, slowing collapse.
5. Cloud fragments and denser pieces continue contracting.
6. Gas is pulled onto new **protostar**, increasing its mass.

Fragmentation of a Cloud



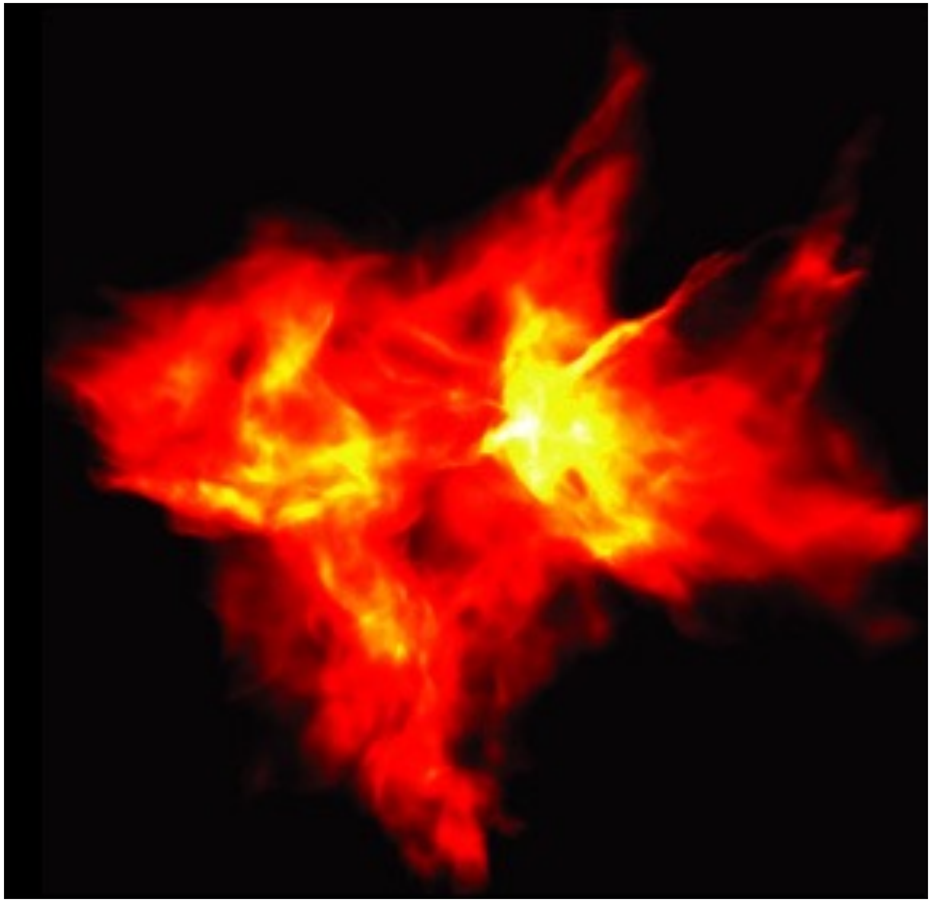
- Star birth begins with a cloud containing enough mass (gravity) to overcome pressure.
- The random motions of different sections of the cloud make it clumpy.

Fragmentation of a Cloud

• Each clump in which gravity can overcome pressure can become a star.

• A large cloud makes a whole cluster of stars.

• Gravity overcomes pressure in a small knot if it is very dense, making a star.



Think/Pair/Share

What characteristics of an interstellar nebula are most important in star formation?

A. Its composition, density, radius
B. Its radius, temperature, and mass
C. Its radius, and composition, and temperature
D. Its mass, temperature and density

Think/Pair/Share

What characteristics of an interstellar nebula are most important in star formation?

A. Its composition, density, and radius.
B. Its radius, temperature, and mass.
C. Its radius, and composition, and temperature.
D. Its mass, temperature and density.

$$M_{min} = 18M_{Sun}\,(T^3 / n)^{1/2}$$

Think/Pair/Share

What would happen to a contracting cloud fragment if it were not able to radiate away its thermal energy?

A. It would continue contracting, but its temperature would not change.
B. Its mass would increase.
C. Its temperature would decrease.
D. Its internal pressure would increase, opposing the contraction.

Think/Pair/Share

What would happen to a contracting cloud fragment if it were not able to radiate away its thermal energy?

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What have we learned?

Begin 3 minute review

What have we learned?

Where do stars form?

Stars form in dark, dusty clouds (a **nebula**) of molecular gas with temperatures of 10–30 K.

These clouds contain molecular hydrogen (H_2) carbon monoxide (CO), and other molecules.

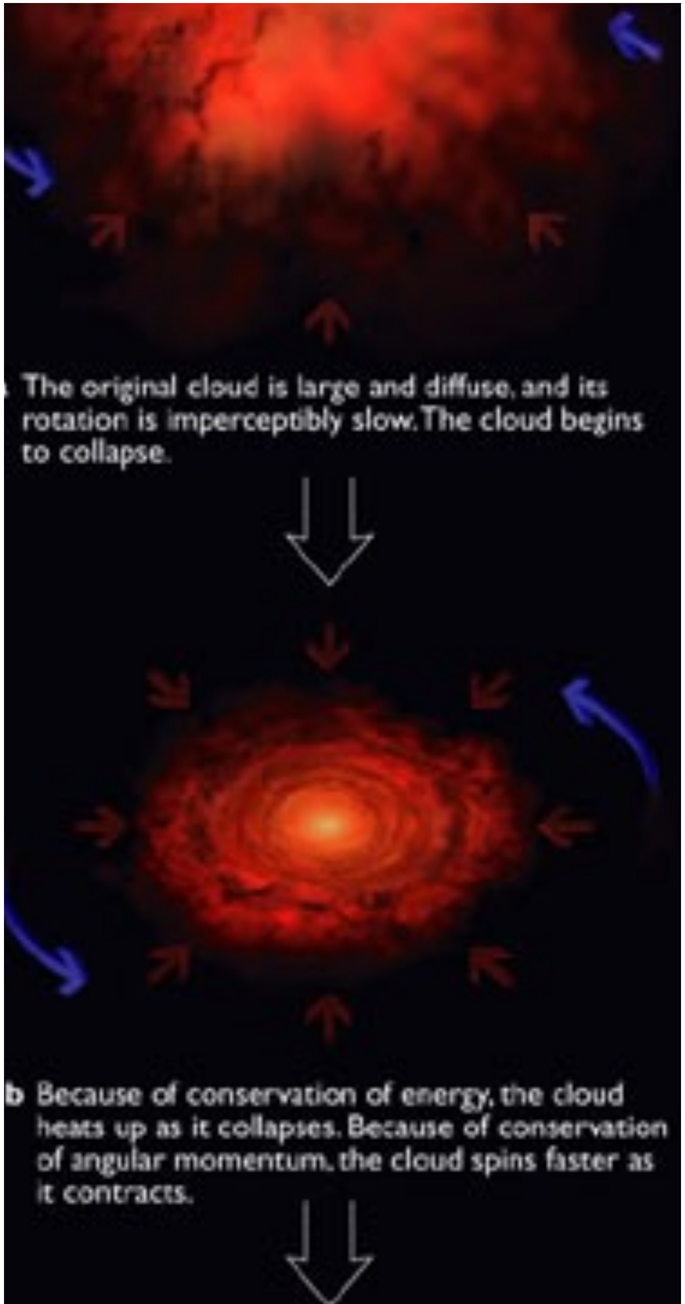
How do stars form?

Stars form in clouds massive enough for gravity to overcome thermal pressure.

A cloud contracts and fragments into pieces that go on to form stars.

How does star birth begin?

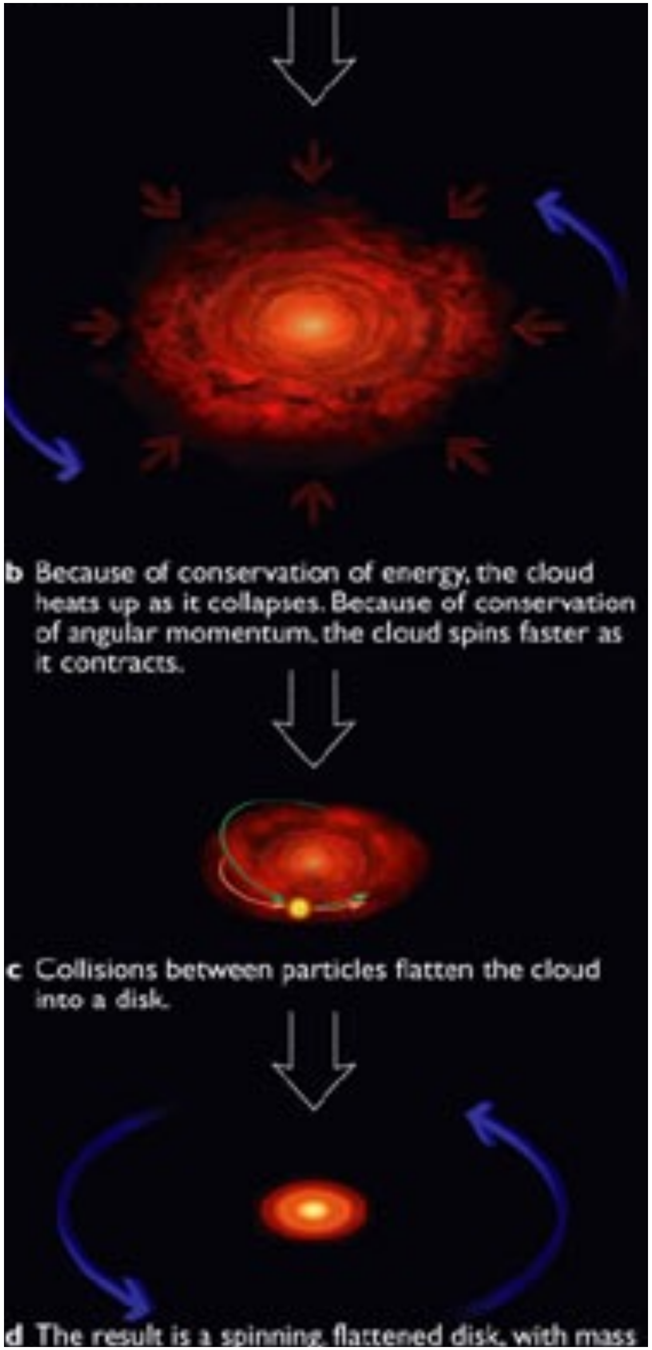
- **Conservation of energy** must be obeyed.
- **Conservation of angular momentum** must be obeyed.



How does star birth begin?

- Cloud **heats up** as gravity causes it to contract *(conservation of energy)*.

- Contraction can continue only if thermal energy is radiated away (why?)

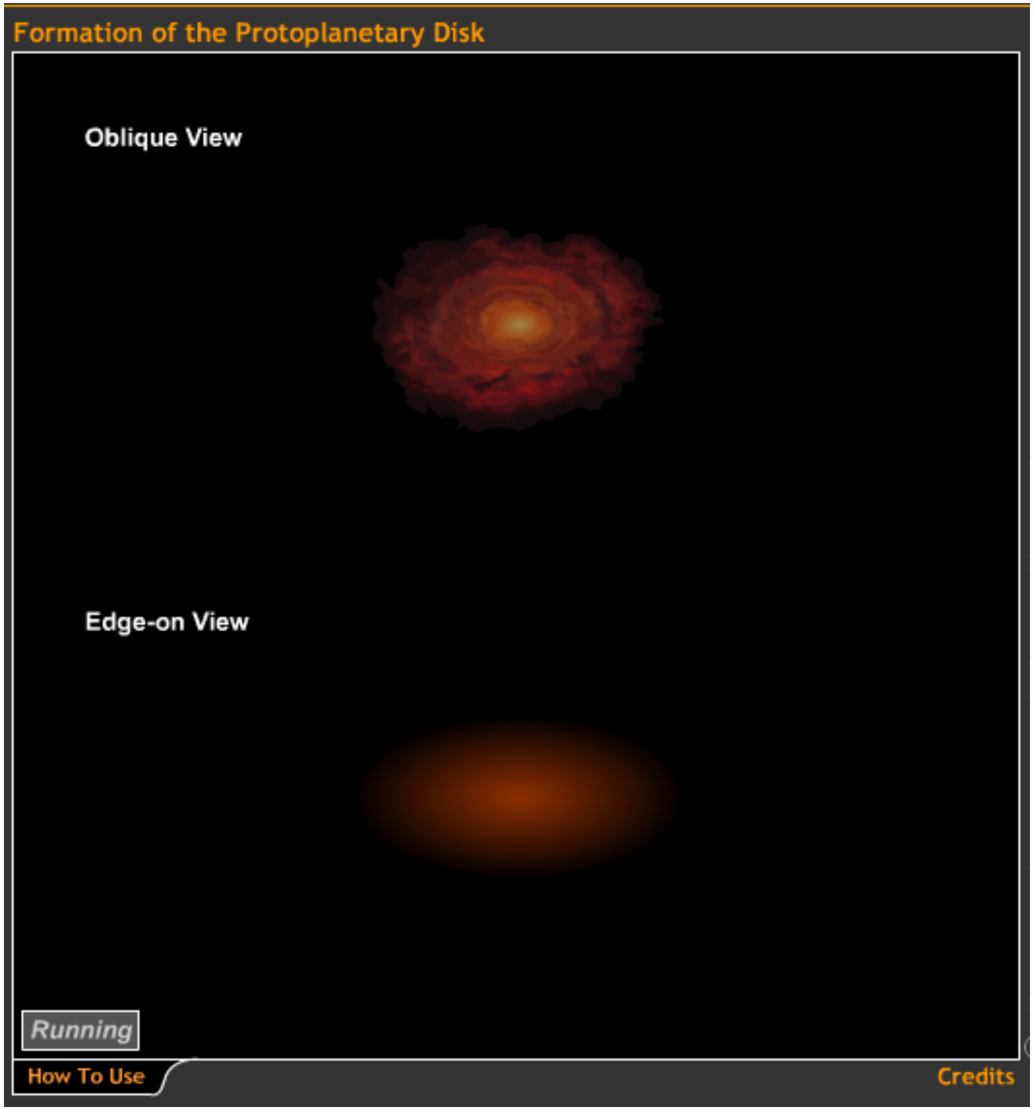


How does star birth begin?

- As gravity forces a cloud to become smaller, it begins to **spin faster** *(conservation of angular momentum)*.

- Gas **flattens** into a spinning disk because spin hampers collapse perpendicular to the spin axis.

Cloud collapse



Formation of the Protoplanetary Disk

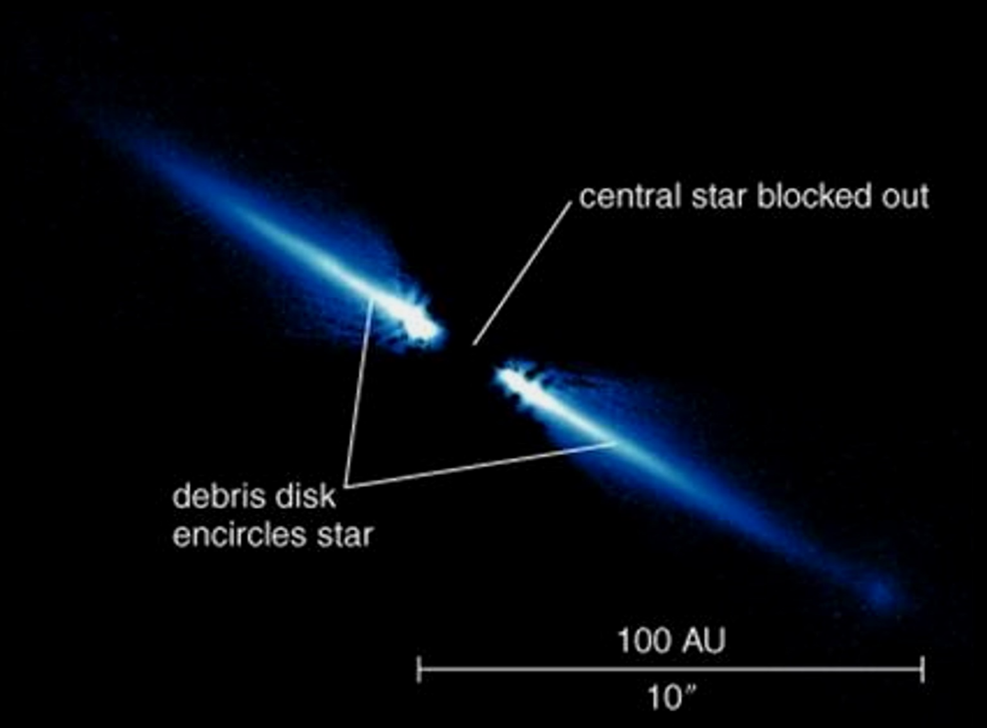
The spinning cloud **heats up**, **flattens** and **spins faster** as it shrinks.

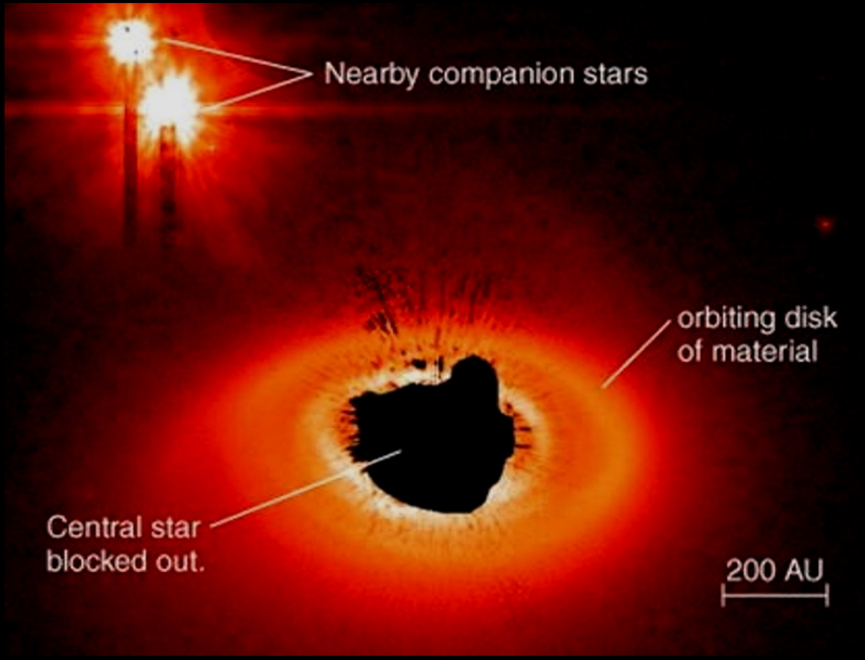
Evidence from Other Gas Clouds

- An **emission nebula** is a cloud of gas glowing from the light of young stars.
- Stars and disks are forming in huge clouds, supporting nebular theory.
- *Can we see these disks?*

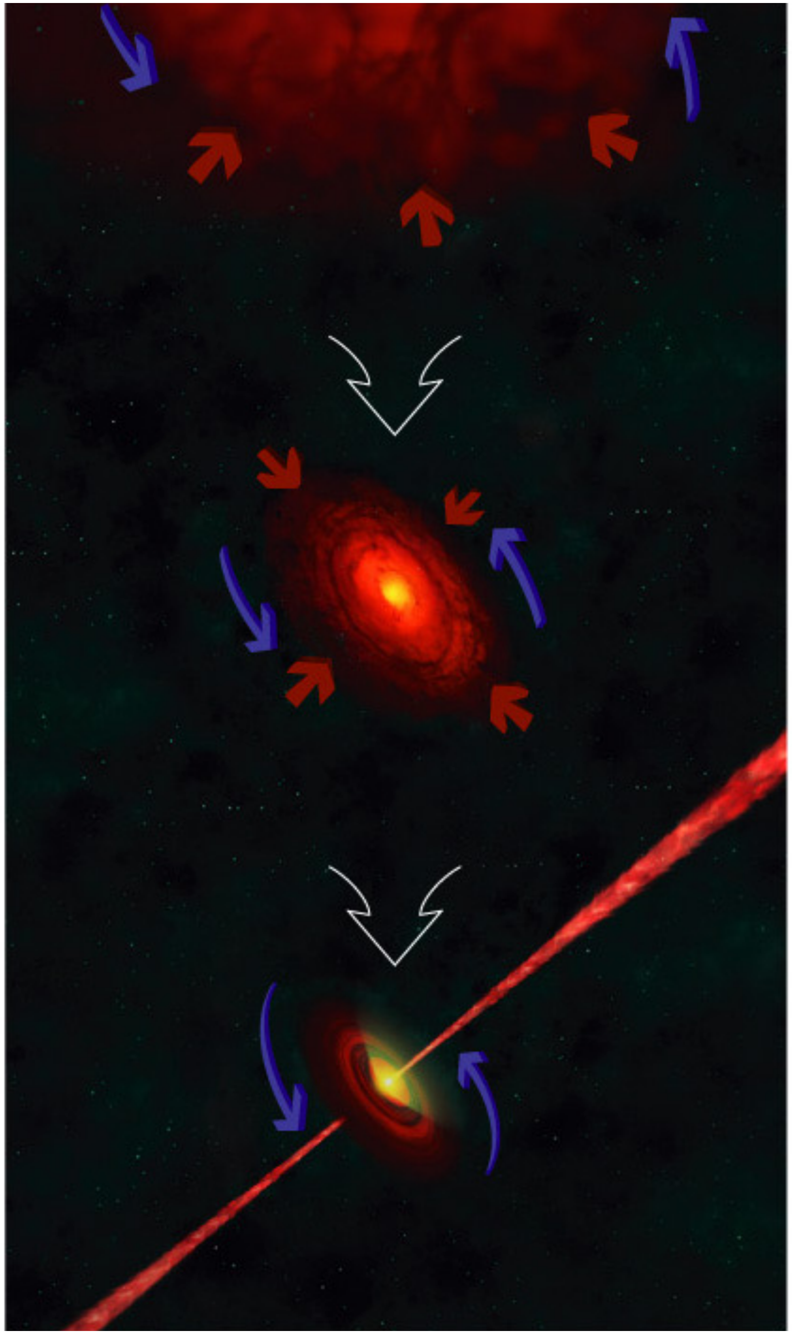
The Orion Nebula with “proplyds” (protoplanetary disks).

Disks Around Other Stars





We see disks around other stars which support the nebular hypothesis!

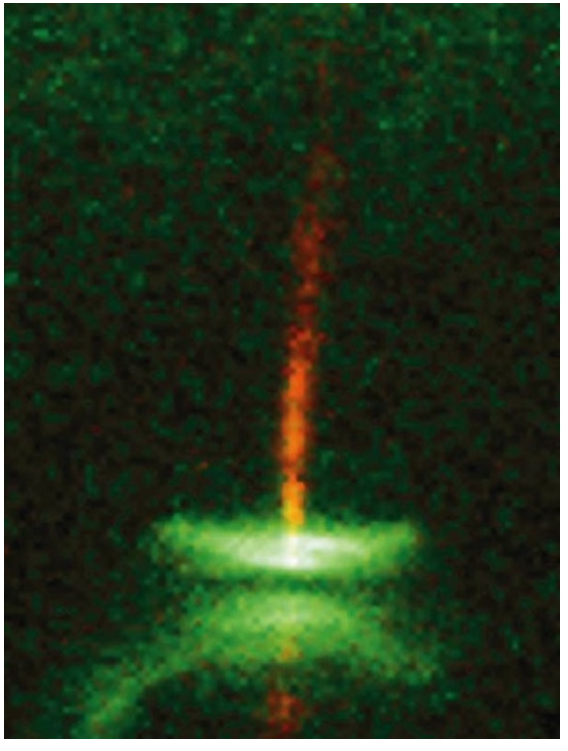


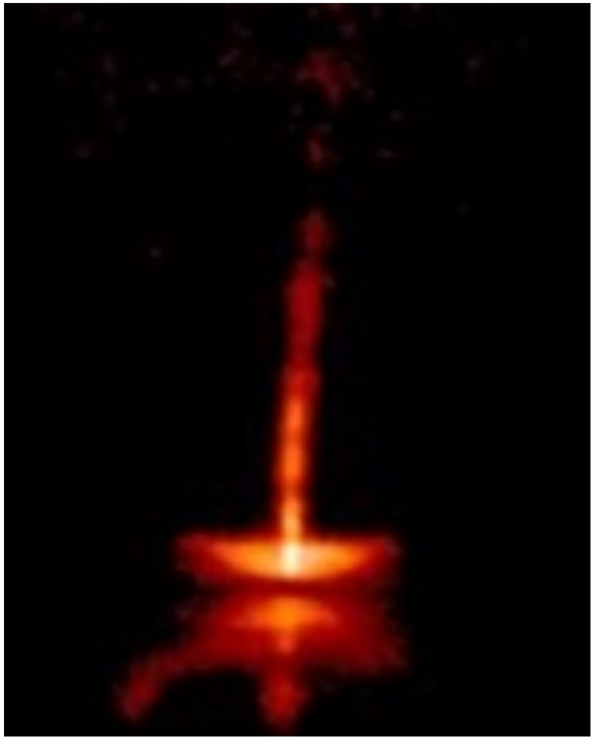
Formation of jets

- Concentration of weak **magnetic field** during contraction produces a strong field around protostar.
- Rapid rotation of field channels matter along rotation axis.
- This causes jets of matter to shoot out along the rotation axis.

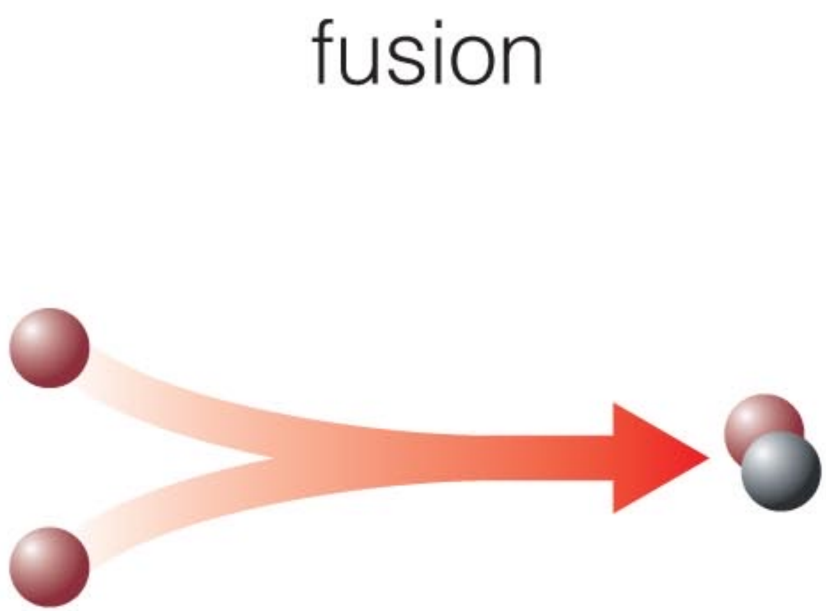
Proto-stellar jets

• Jets are observed coming from the centers of disks around protostars!
• Remaining gas gradually dissipates.



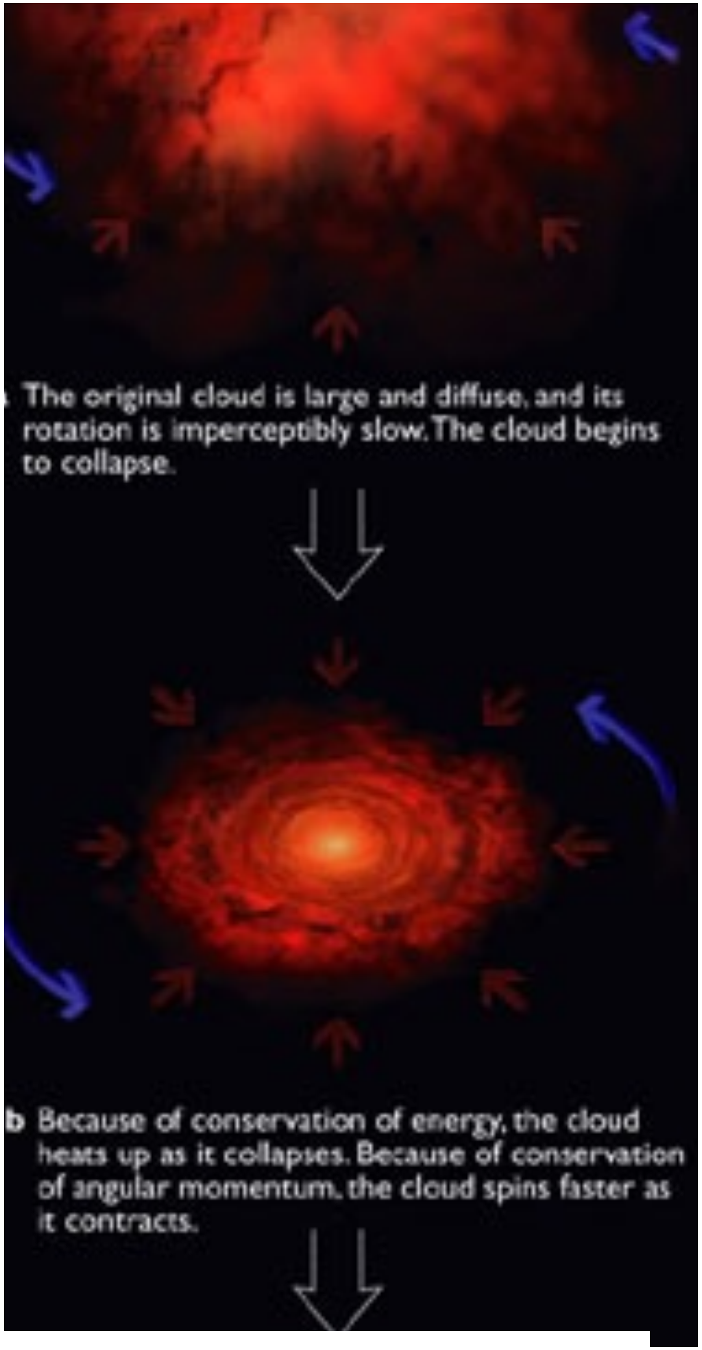


So how do we get a new star?



Protostar to Main Sequence

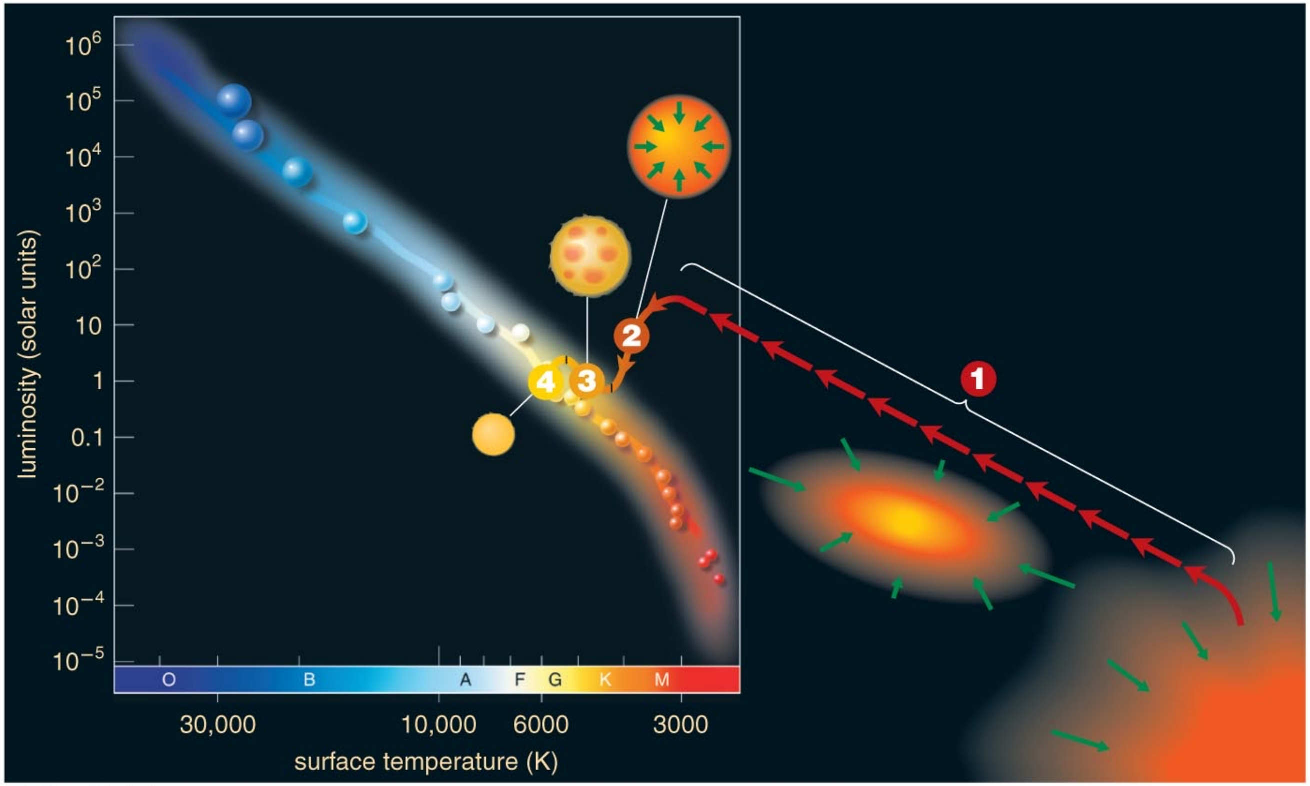
- A protostar's thermal energy is from gravitational contraction.
- A protostar must contract and heat until **the core temperature is sufficient for hydrogen fusion** (~ 10^7 K).
- *Contraction ends when energy released by hydrogen fusion balances inward pull of gravity;*
- *Energy produced = energy radiated from the surface – a star is born on the main sequence!*



Summary of Star Birth

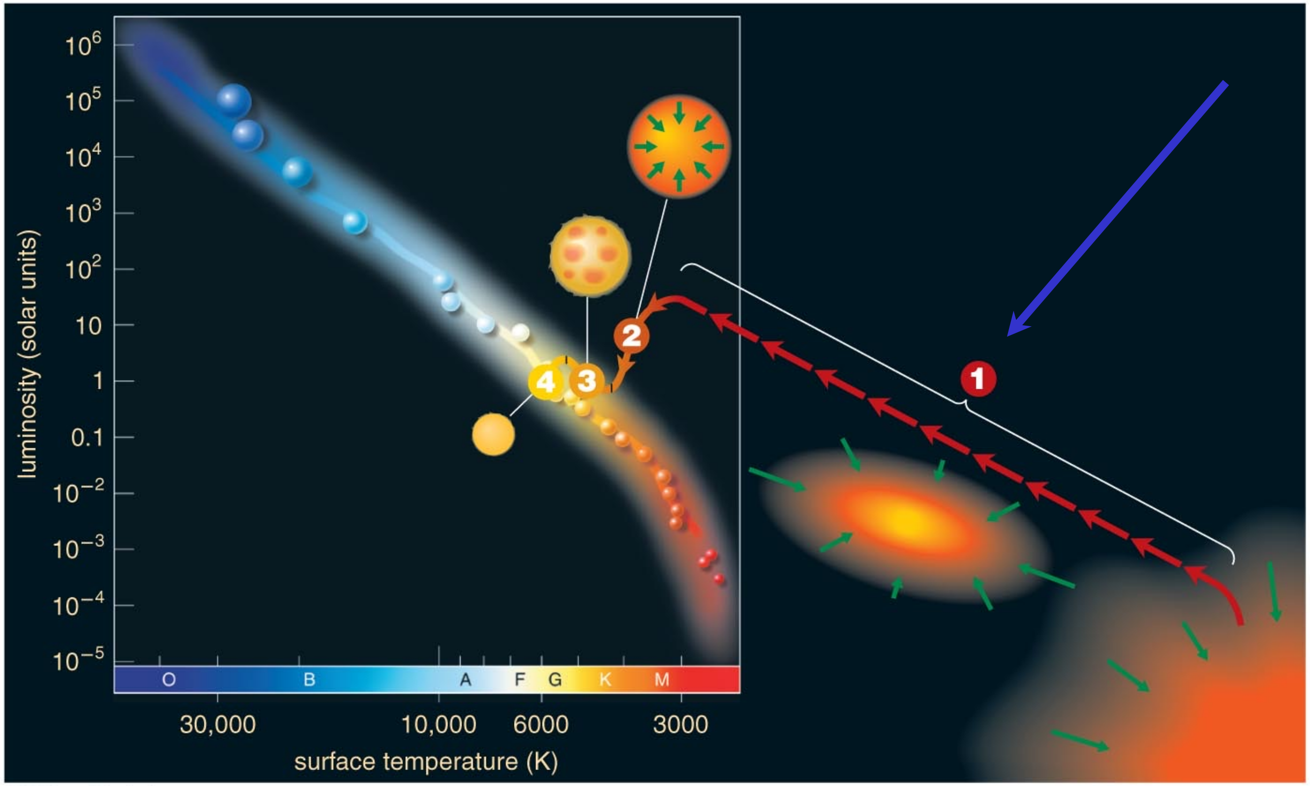
1. Gravity causes gas cloud to shrink and fragment
2. Core of shrinking protostar heats up
3. When core gets hot enough, fusion begins and stops the shrinking
4. New star achieves long-lasting state of balance

Birth Stages on a Life Track



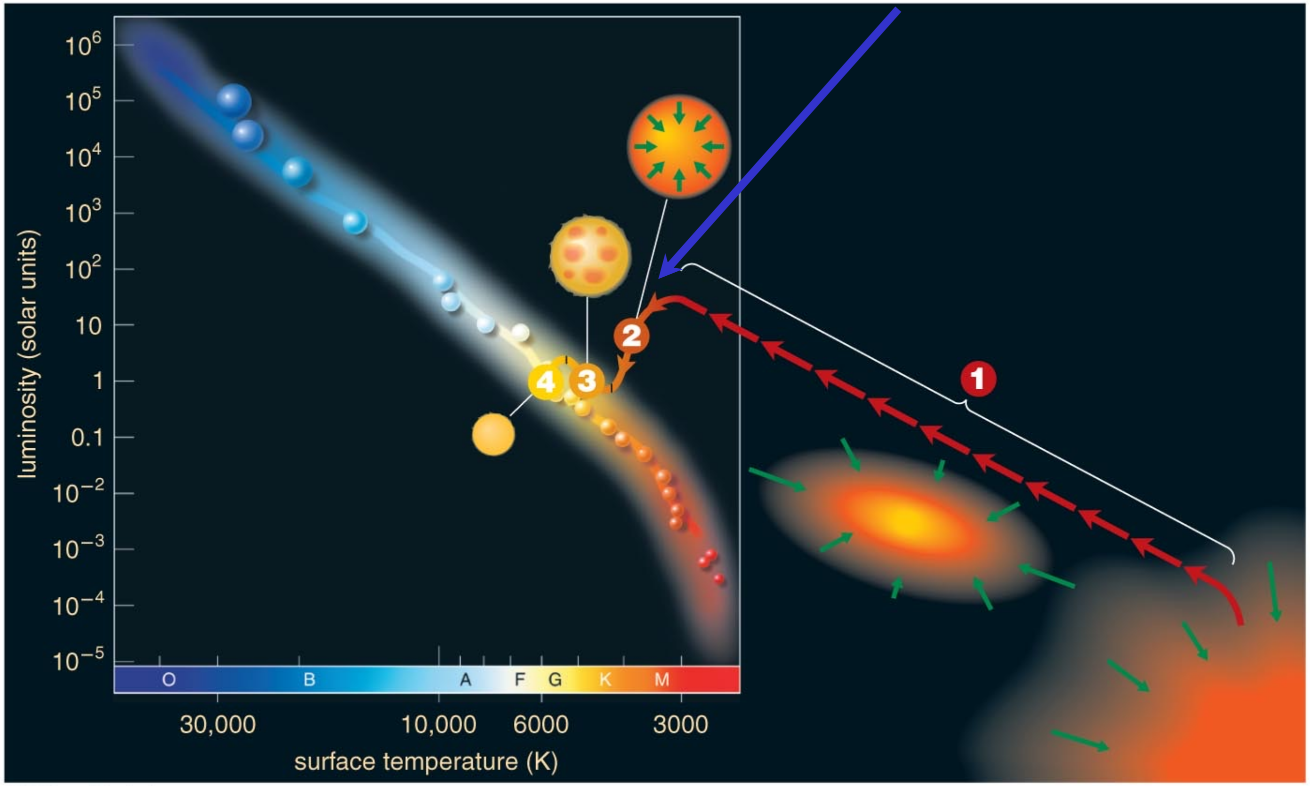
- A **life track** illustrates a star's surface temperature and luminosity at different moments in time.

Assembly of a Protostar



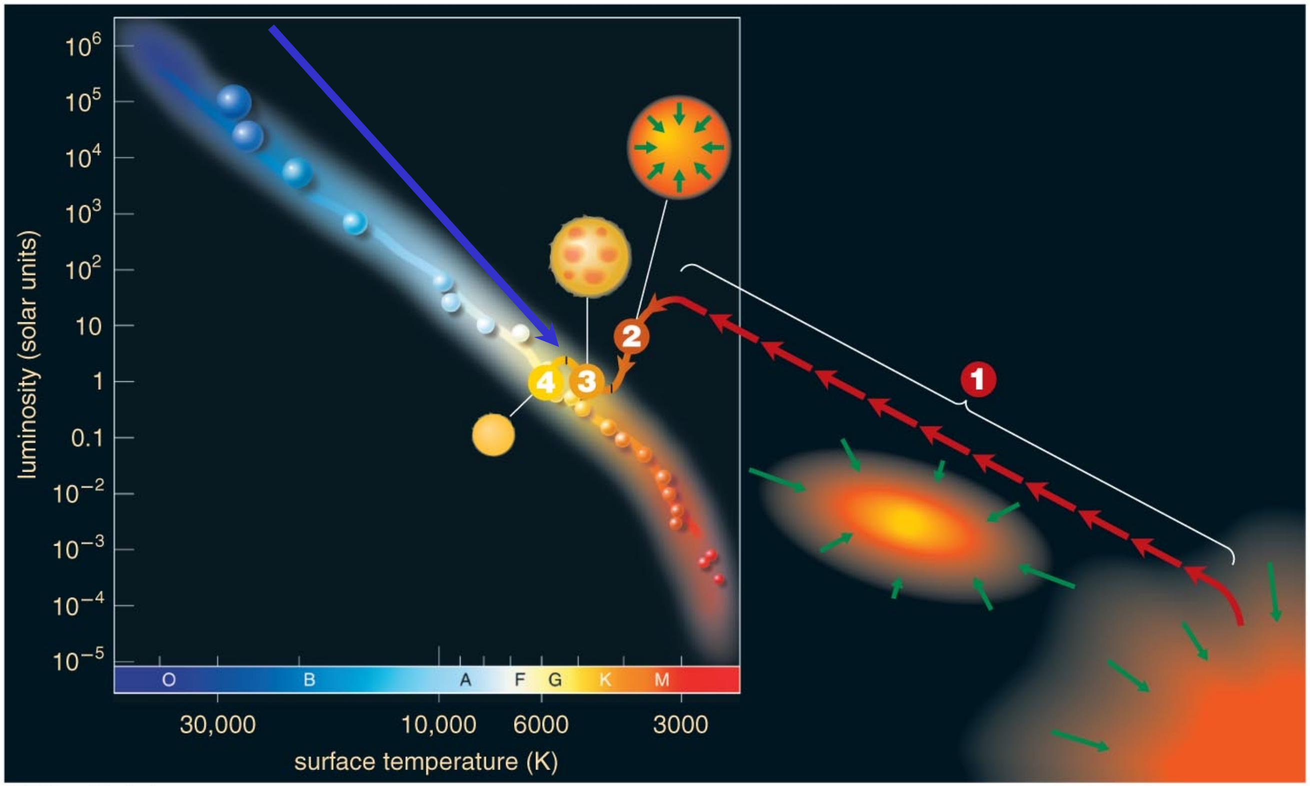
- Luminosity and temperature grow as protostars contract.

Convective Contraction



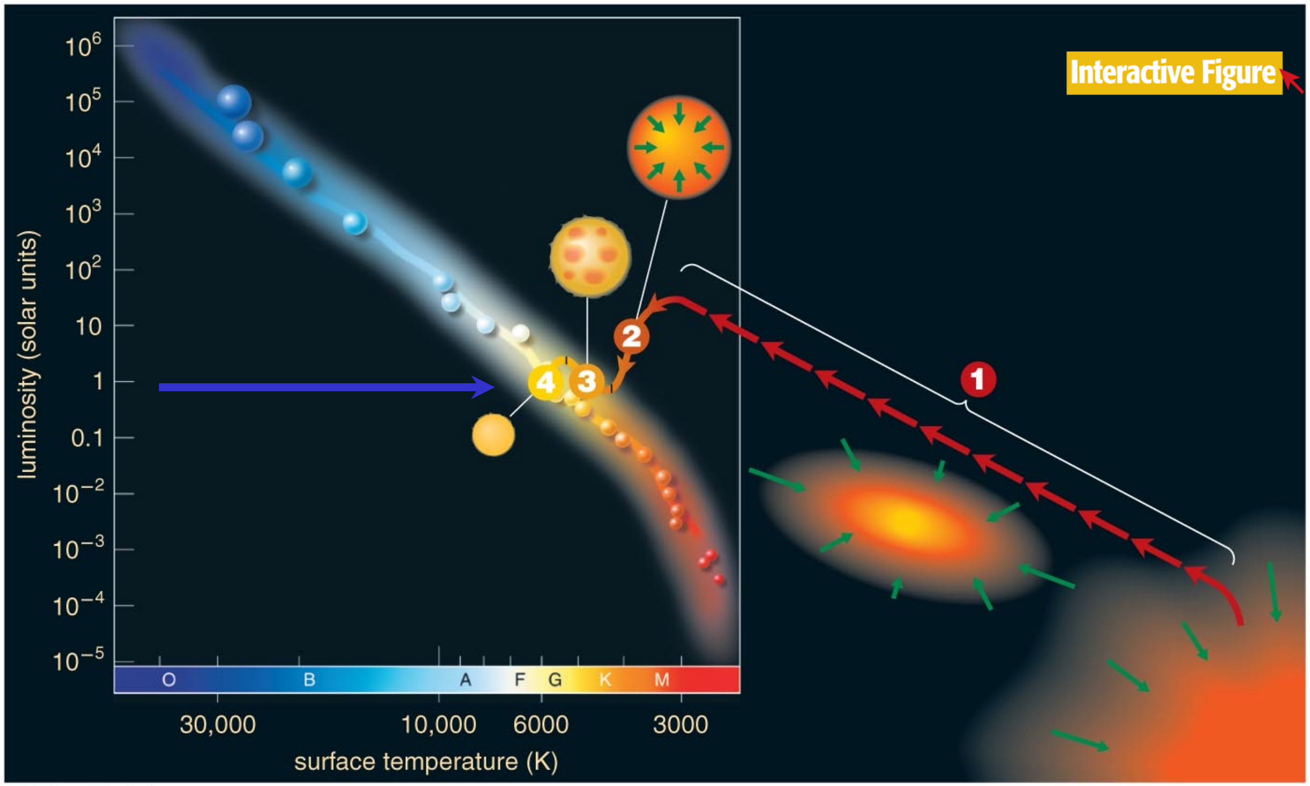
- Surface temperature remains near 3000 K while **convection** is main energy transport mechanism.

Radiative Contraction



- Luminosity remains nearly constant during late stages of contraction, while **radiation transport** moves energy thru star.

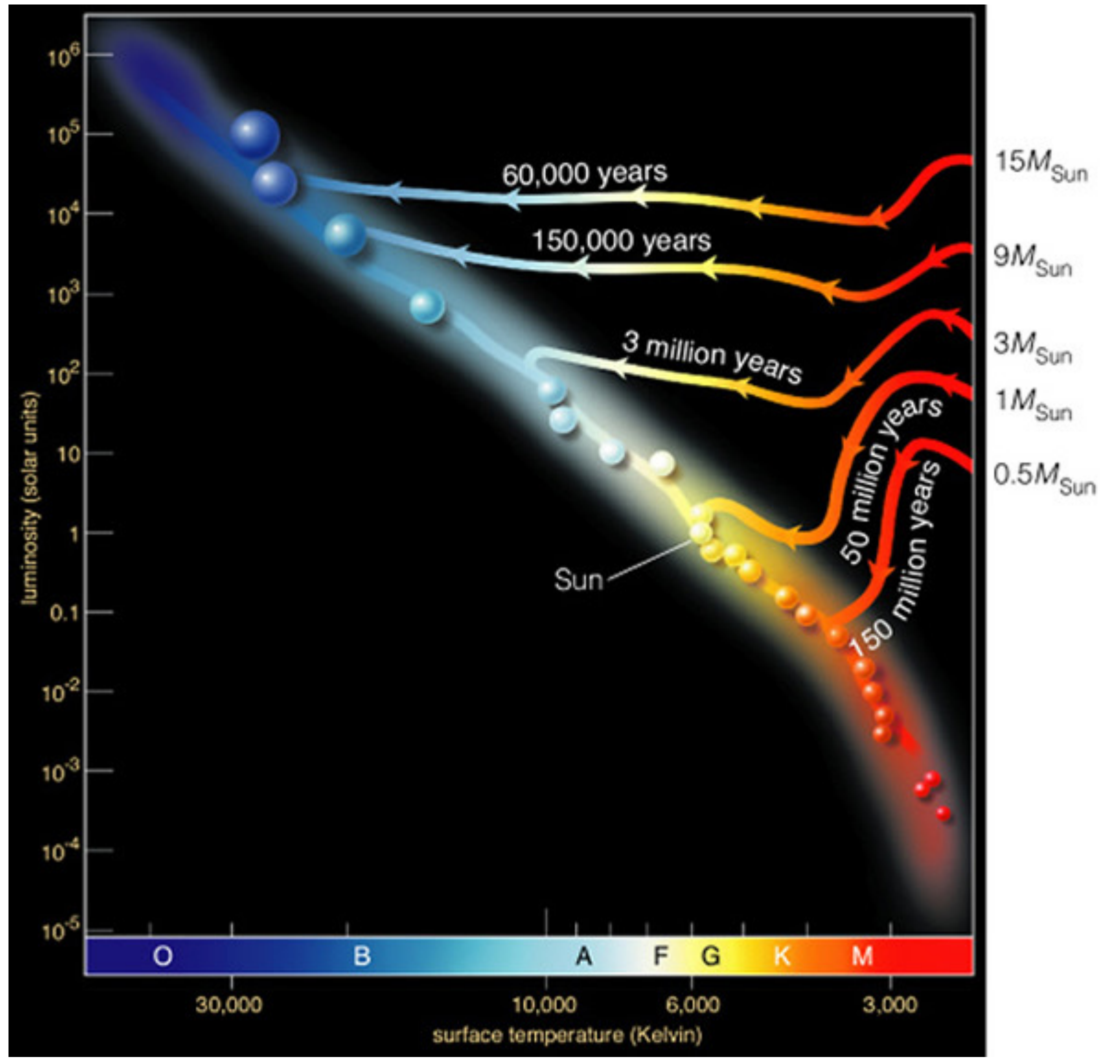
Self-Sustaining Fusion!



- Core temperature continues to rise until star begins **fusion** and arrives on the main sequence.

Time for stellar formation

- The time for stars of different masses to form varies greatly.
- High mass stars form quickly.
- Low mass stars form slowly



What have we learned?

Begin 3 minute review

What have we learned?

What slows the contraction of a star-forming cloud?

The contraction of a cloud fragment slows when thermal pressure builds up because photons can no longer escape.

What is the role of rotation in star birth?

Conservation of energy and angular momentum leads to the formation of **disks** around protostars.

How does nuclear fusion begin in a newborn star?

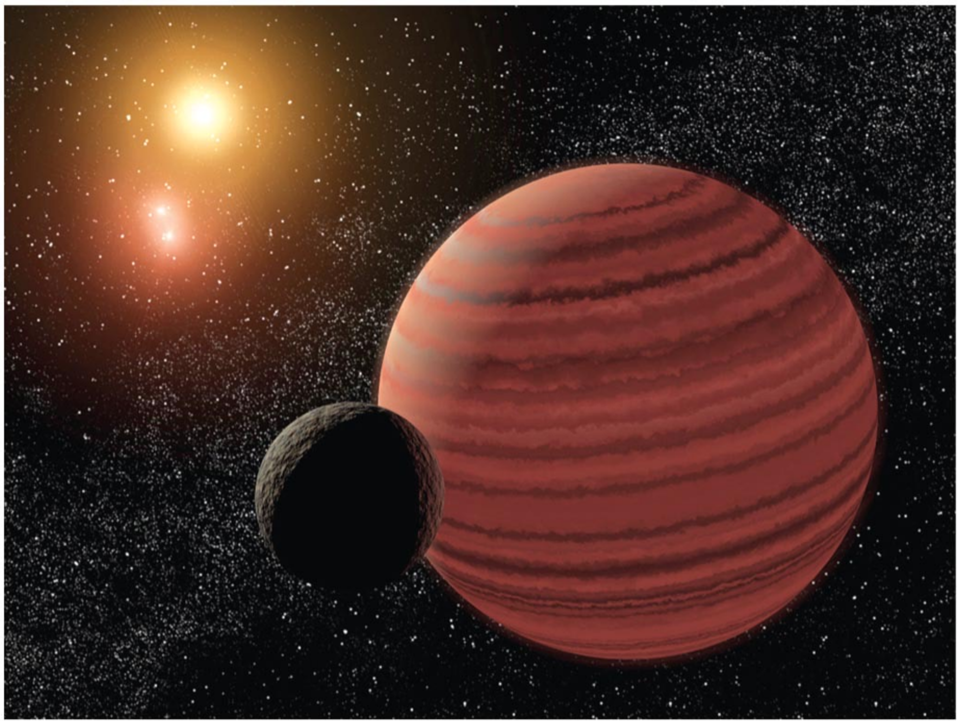
Nuclear fusion begins when contraction causes the star's core to grow hot enough for fusion.

How massive are newborn stars?

A cluster of many stars forms out of a single cloud - so there must be hundreds of solar masses of matter (remember minimum cloud size?)

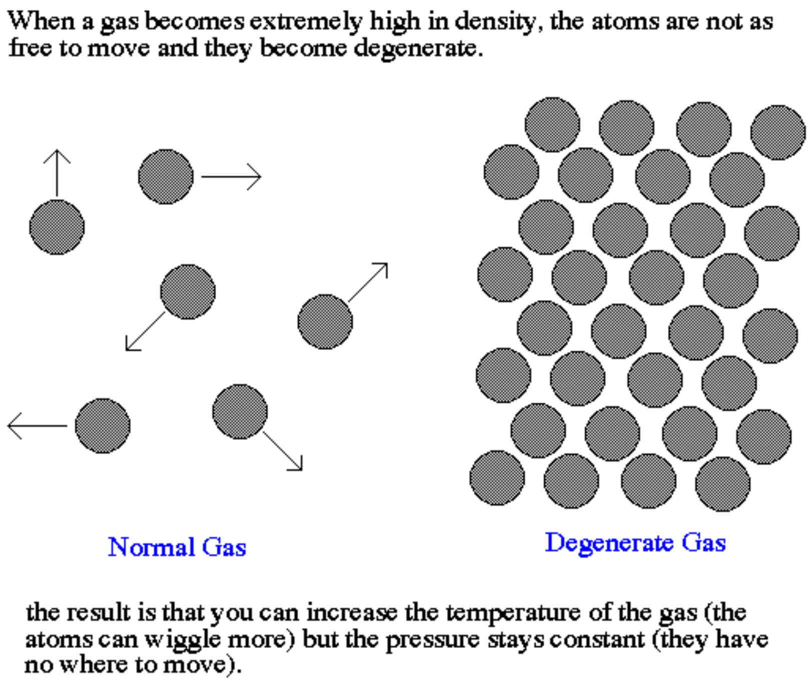
What mass (smallest, largest) stars form?

What is the **smallest** mass a star can have?



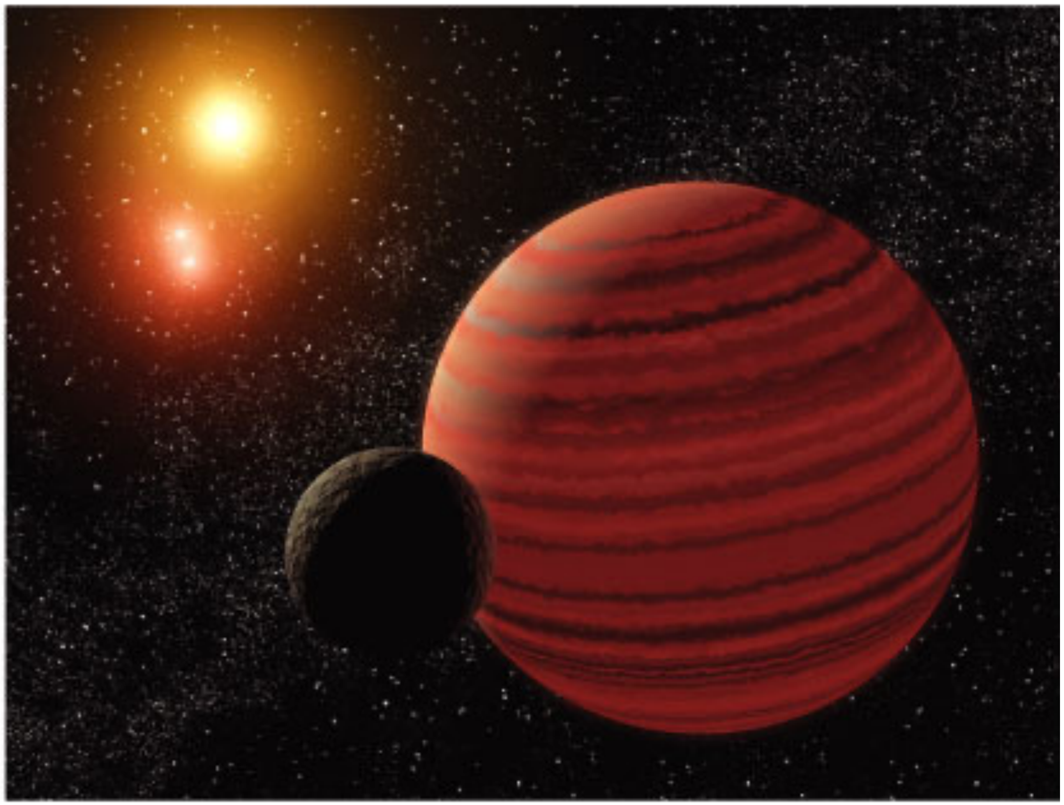
- Fusion will not begin in a protostar if some force stops contraction before core temperature reaches 10^7 K.
- **Thermal pressure** cannot stop contraction because the star is losing thermal energy through radiation.
- Is there another form of pressure that can stop contraction?

Degeneracy Pressure:



- Electrons can't be in same state in same place
- When crowded together they repel each other and resist further contraction
- Doesn't depend on heat content – *<u>can</u> stop contraction!*

Brown Dwarfs

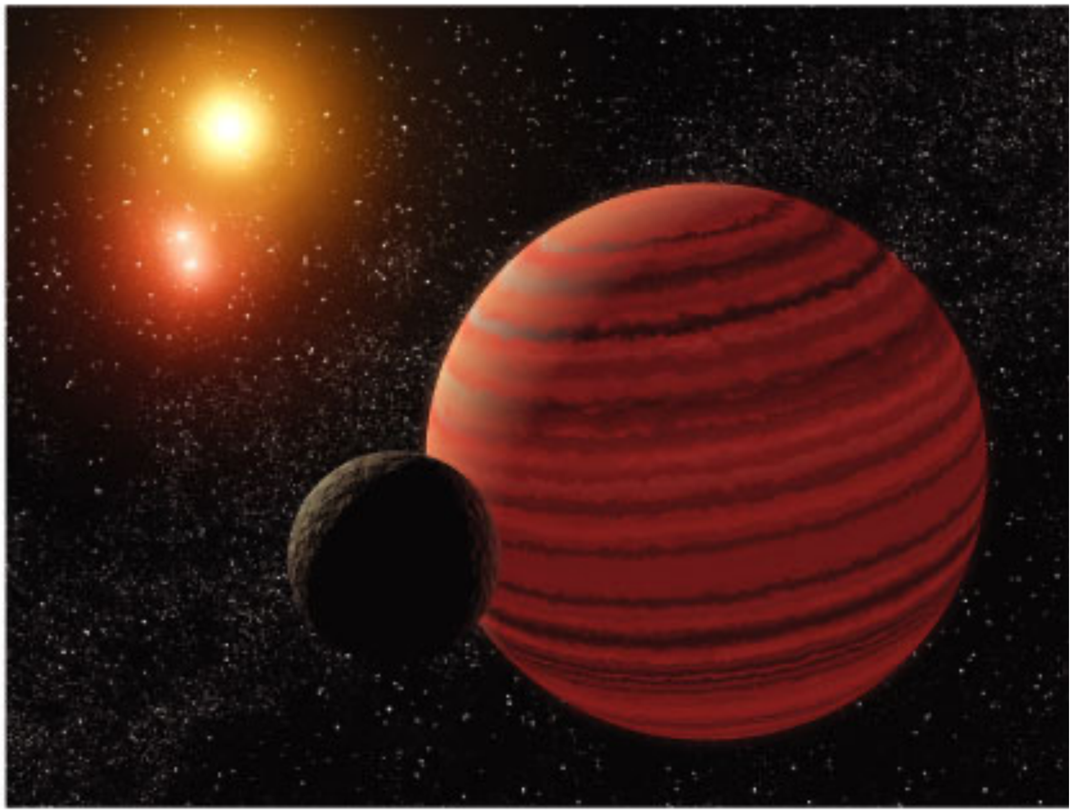


- Degeneracy pressure halts the contraction of objects with **<0.08$\boldsymbol{M}_{\mathbf{Sun}}$** before core temperature becomes hot enough for fusion.

- Lowest mass stars are 2100K, 8.7% solar radius, 1/8000 solar luminosity.

- *What about lower mass objects?*

Brown Dwarfs



- Objects not massive enough to start fusion are **brown dwarfs.**

- A brown dwarf emits infrared light because of heat from contraction.

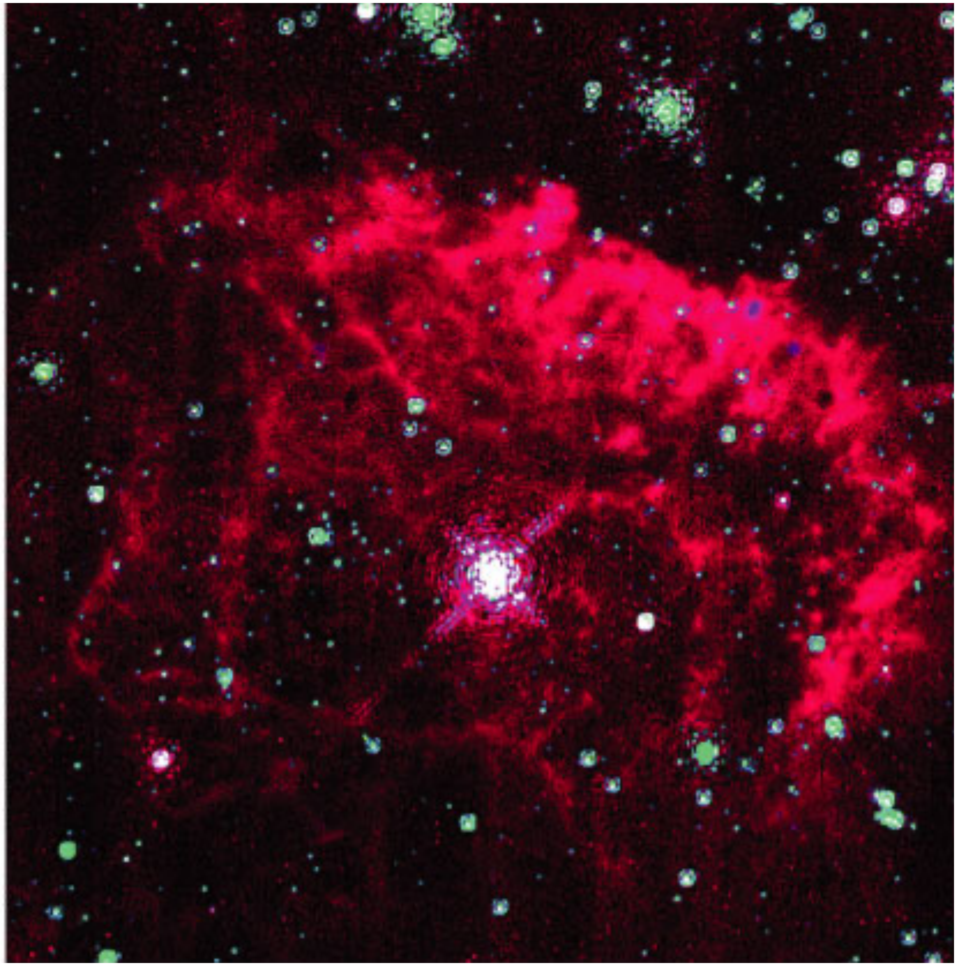
- Its luminosity gradually declines with time as it loses thermal energy.

Brown Dwarfs in Orion

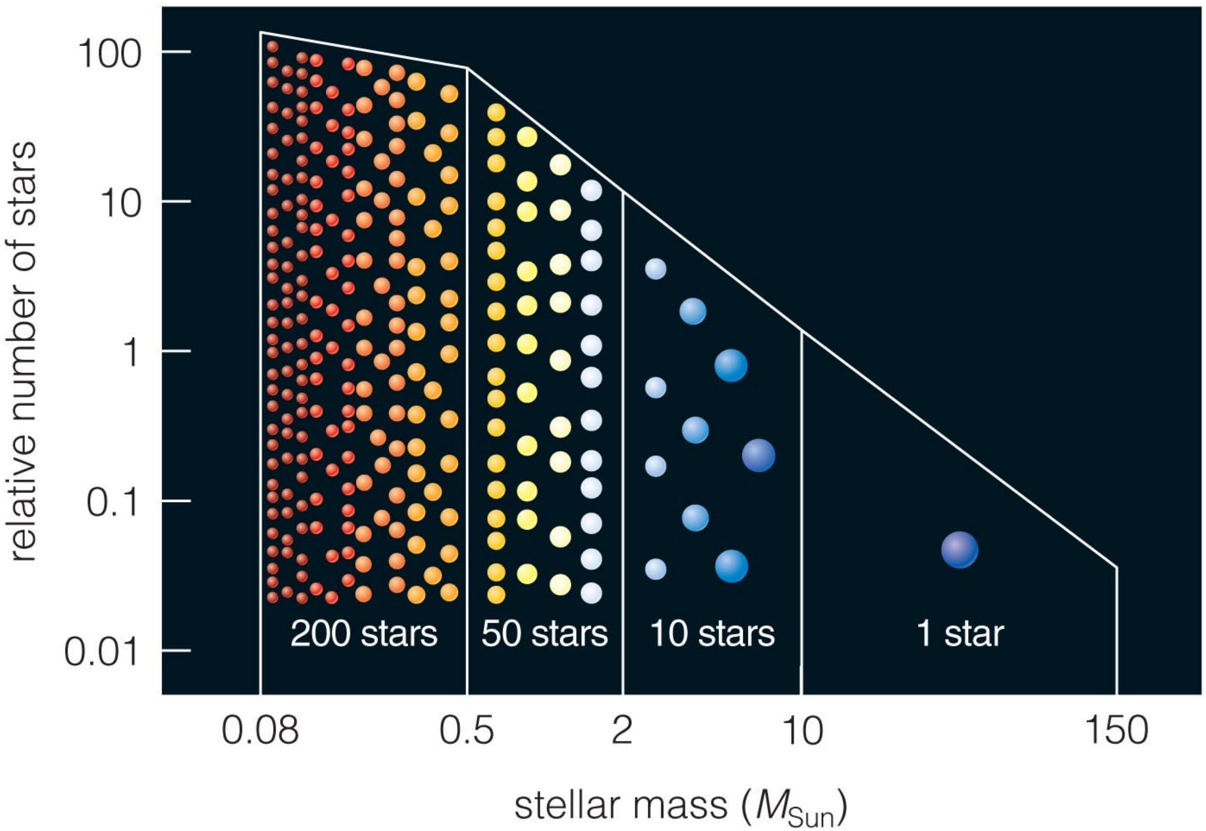
- Infrared observations reveal recently formed brown dwarfs because they are still relatively warm and luminous.

What is the **greatest** mass a star can have?

- Massive stars are so luminous that their radiation pressure drives outer layers into space.
- Radiation pressure limits how massive a star can be without blowing itself apart.
- Theory and observations say no stars more massive than $150M_{Sun}$.

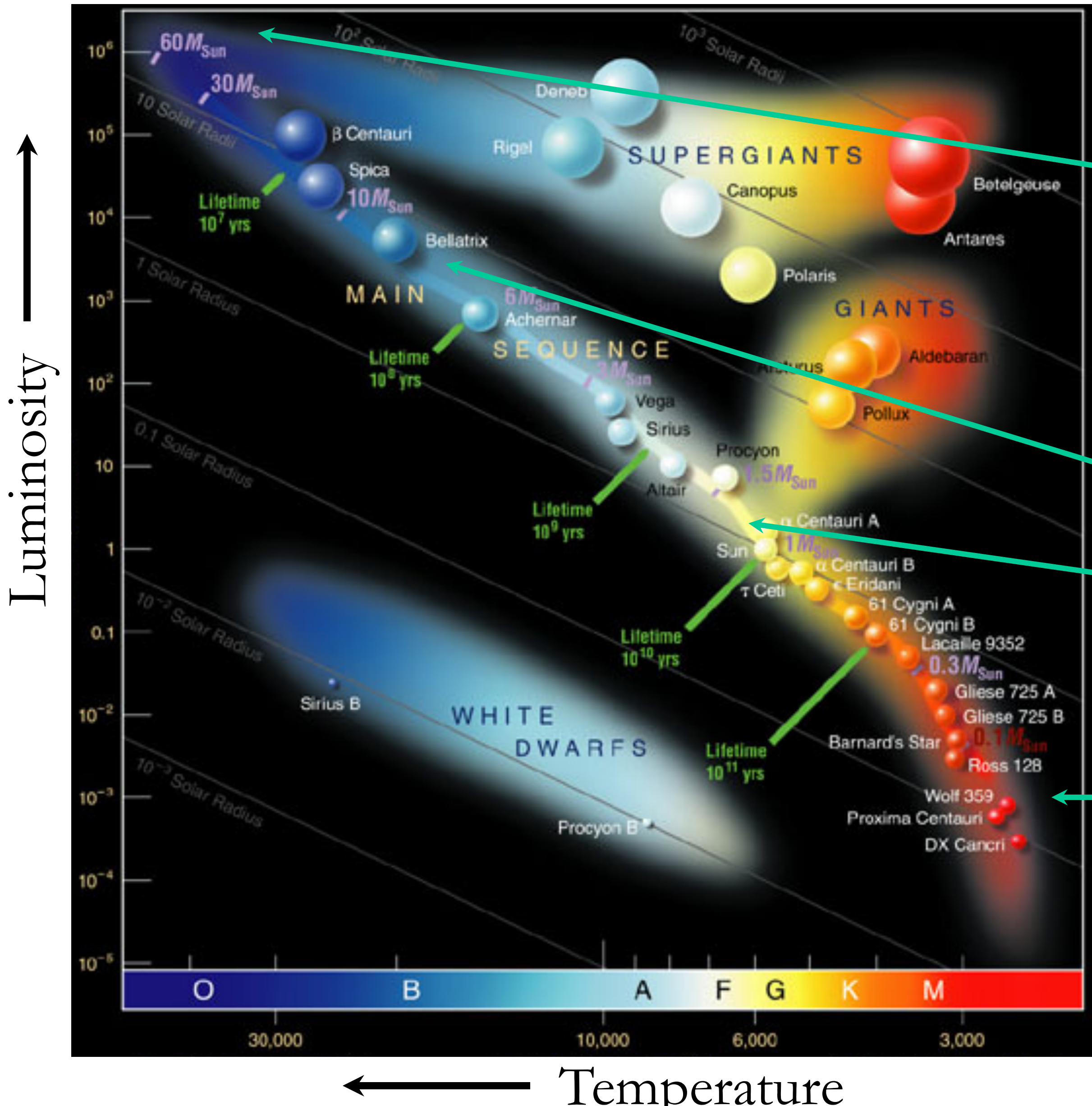


What are the typical masses of newborn stars?



- Star formation makes many more low-mass stars than high-mass stars.

Stellar masses

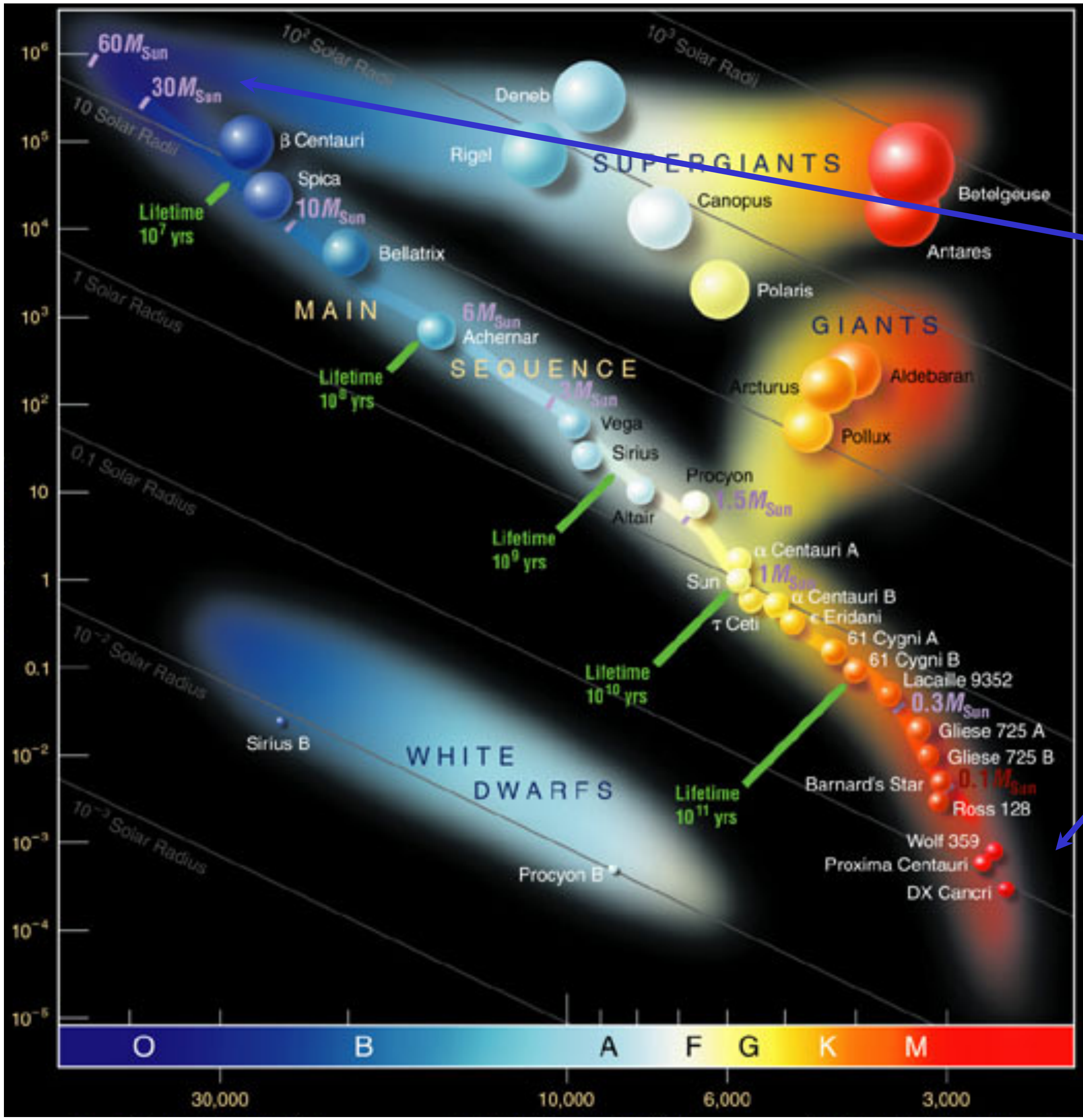


Very massive stars are very rare.

Number of stars increases as mass decreases

Low-mass stars are very common.

Stellar masses



Luminosity

Temperature

Stars more massive than $150M_{\text{Sun}}$ would blow apart.

Stars less massive than $0.08M_{\text{Sun}}$ can't sustain fusion.

Brown dwarfs never make it onto the MS (T<1800K, L<10^{-5} Sun)

What have we learned?

Begin 3 minute review

What have we learned?

What is the smallest mass a newborn star can have?

Degeneracy pressure stops the contraction of objects **<0.08**$\boldsymbol{M_{\mathrm{Sun}}}$ before fusion starts.

What is the greatest mass a newborn star can have?

Stars greater than about **150**$\boldsymbol{M_{\mathrm{Sun}}}$ would be so luminous that radiation pressure would blow them apart.

What are the typical masses of newborn stars?

Star formation makes many more low-mass stars than high-mass stars.