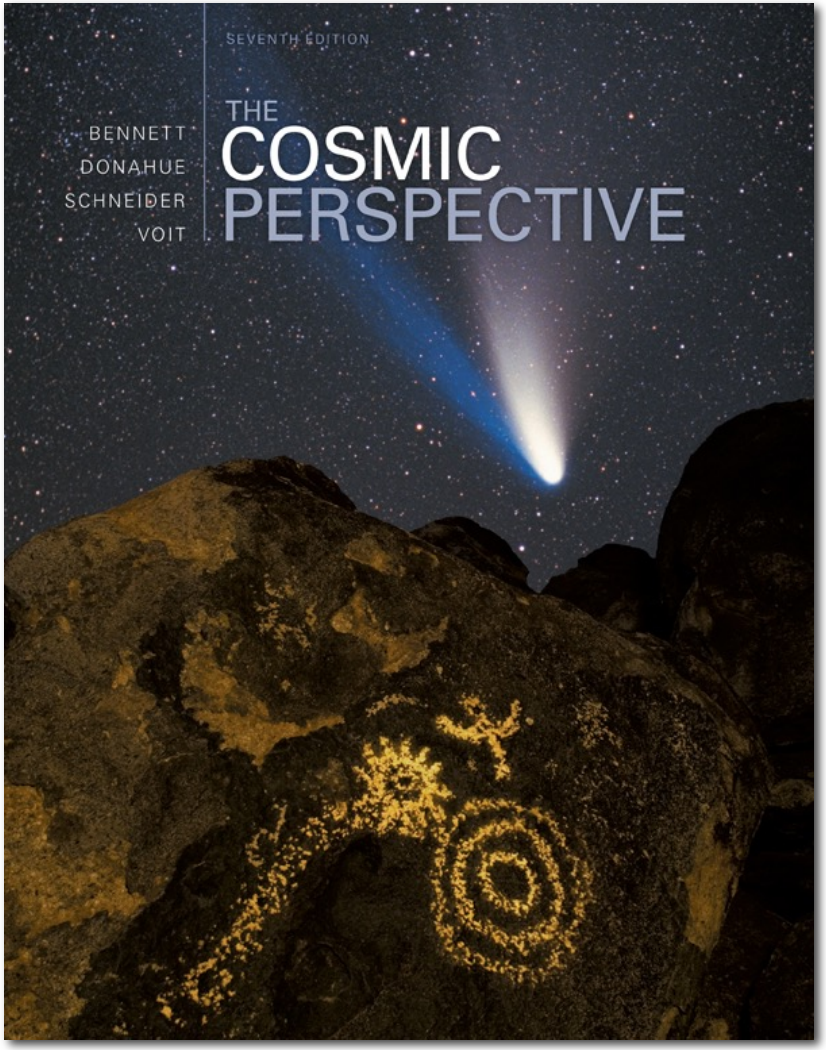
Chapter 16 Lecture

The Cosmic Perspective



Star Birth

Star Birth

The dust and gas between the stars in our galaxy is referred to as the **Interstellar medium (ISM).**

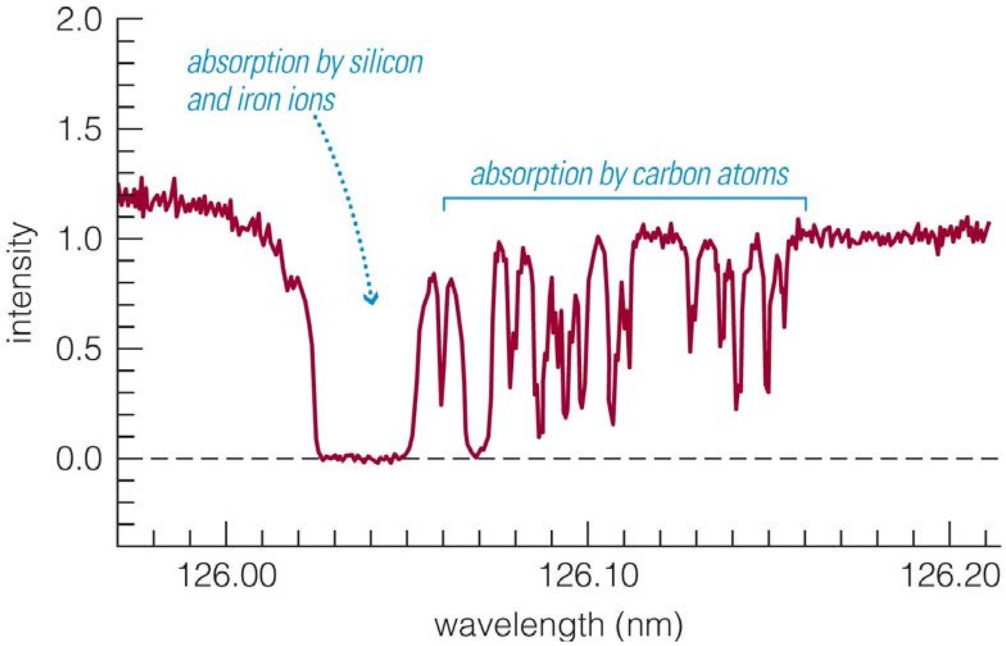
16.1 Stellar Nurseries

- Our goals for learning:
  - **Where do stars form?**
  - **How do stars form?**

Where do stars form?

Stars form in dark clouds of dusty gas in the interstellar medium.

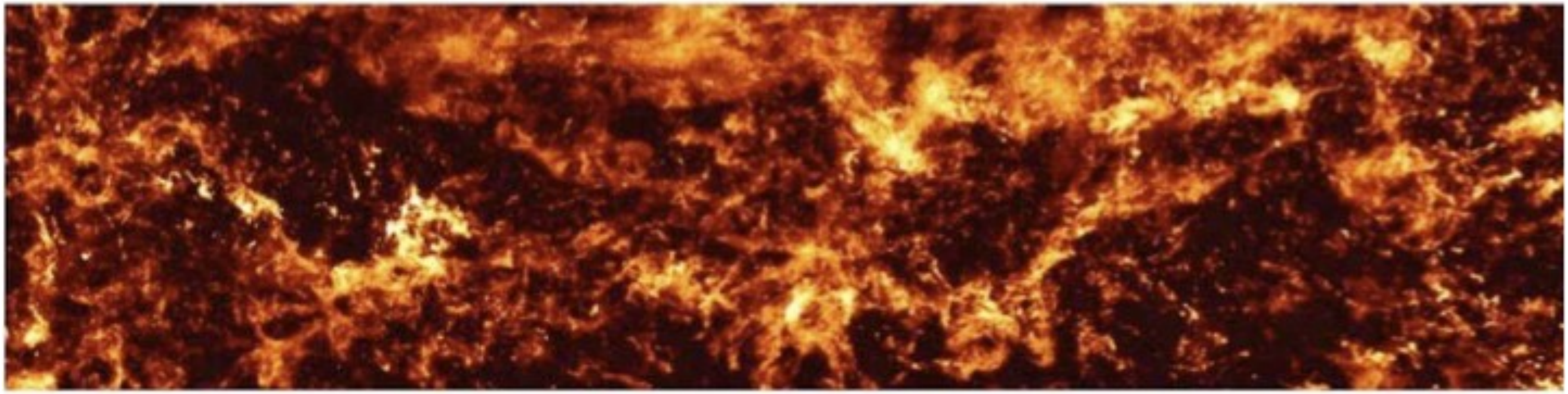
Composition of Clouds



- We can determine the **composition** of interstellar gas **from its absorption lines** in the spectra of stars.

- **70% H, 28% He**, 2% **heavier elements** in our region of Milky Way

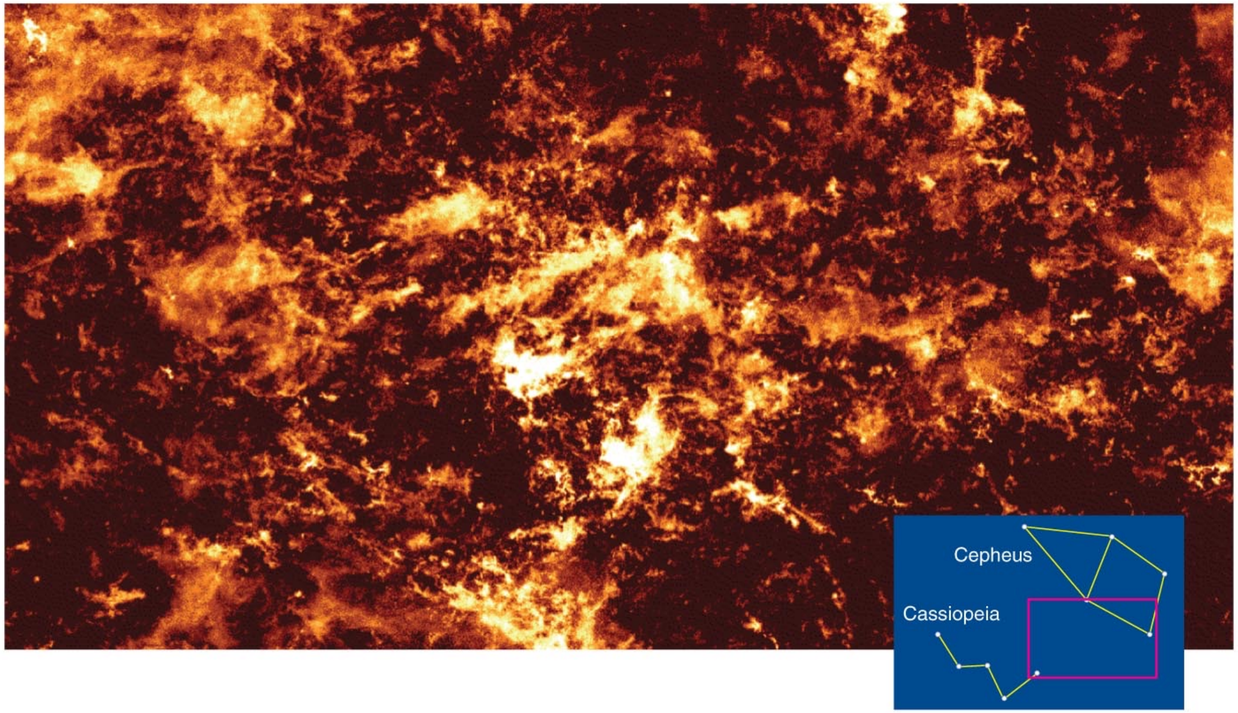
Molecular Clouds



- Stars are born in interstellar clouds that are **cold and dense**. These clouds are called **molecular clouds** because their low temperature and high density allows for the formation of molecules (H_2, CO, etc.).

- These **molecular clouds** have a temperature of 10–30 K and a density of about 300 molecules per cubic centimeter.

Molecular Clouds



- The most common molecule in molecular clouds is H_2. **Emission from hydrogen molecules in the mm band is very weak (symmetric molecule) while mm emission from CO molecules is much stronger.**

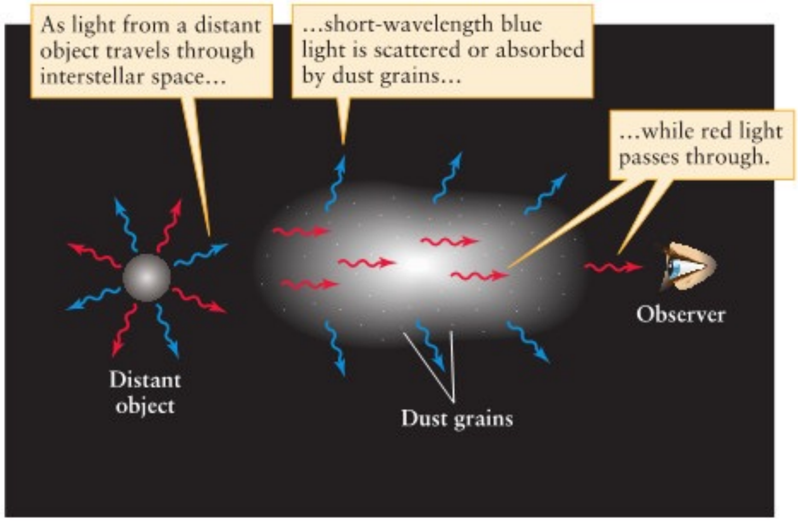
- In interstellar space for every CO molecule there are about a 10,000 H_2 molecules so one can use the **CO as a tracer for H_2**.

Interstellar Dust

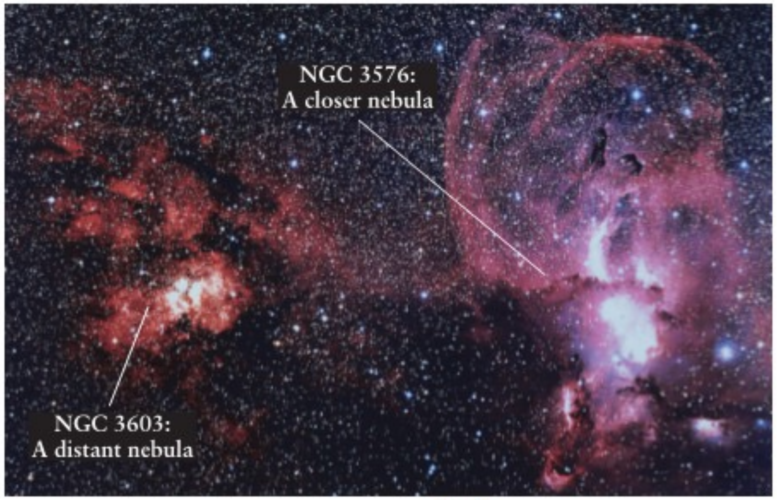
Observation is in the **visible band**. Light from stars behind the dust cloud is absorbed.

- Tiny solid particles of ***interstellar dust*** **block our view of stars** on the other side of a cloud.
- Dust particles are < 1 micrometer (10^{-6} m) in size and made of elements like C, O, Si, and Fe.
- 70% of the ISM is H, 28% is He and 2% is heavier elements. Out of those 2% half the heavier elements are found in **tiny solid grains of interstellar dust.**

Interstellar Extinction and Reddening



(a) How dust causes interstellar reddening



(b) Reddening depends on distance R I **V** U X G

Interstellar extinction is the dimming of light as it passes through the interstellar medium.

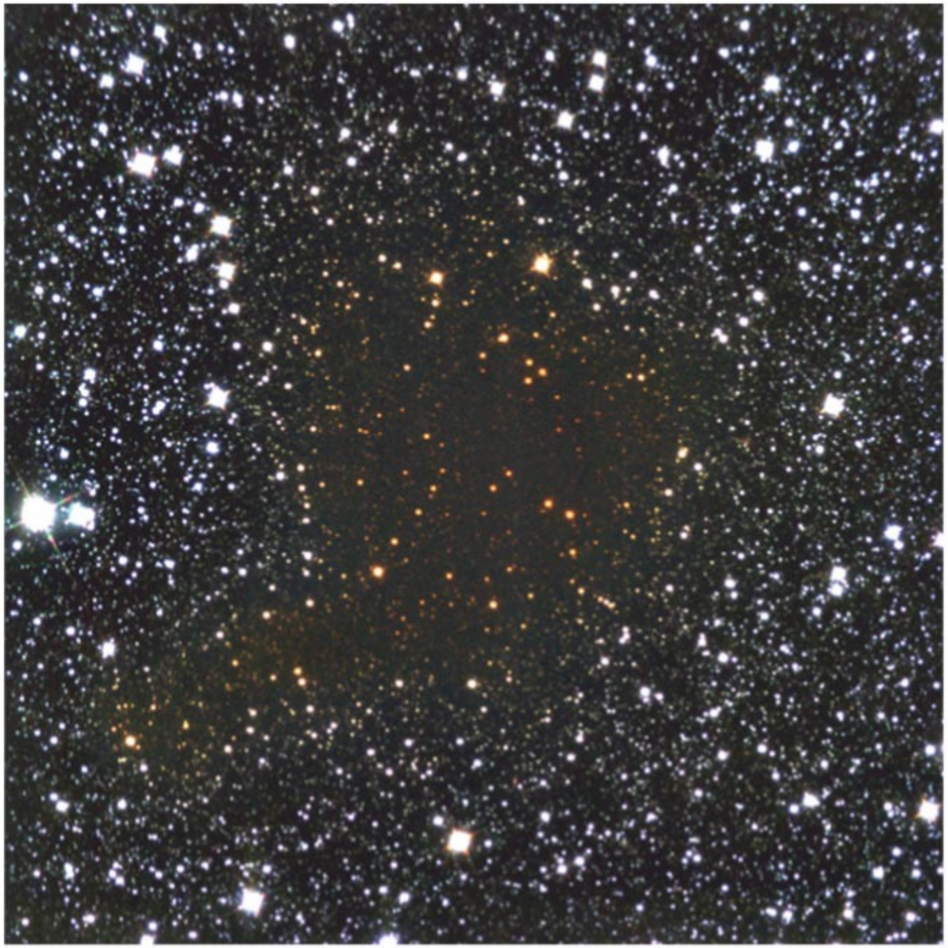
If you look at a source through a cloud of dust grains more blue than red light will be scattered out of your line of sight. Such sources are said to be **reddened**.

Interstellar Reddening

Observation is in the **visible band**. Light from stars behind the dust cloud is absorbed.

- Stars viewed through the edges of the cloud look redder because dust blocks (shorter-wavelength) blue light more effectively than (longer-wavelength) red light.

Interstellar Reddening



Observation is in the **near infrared** band. Light from stars behind the dust cloud passes through the absorber more easily.

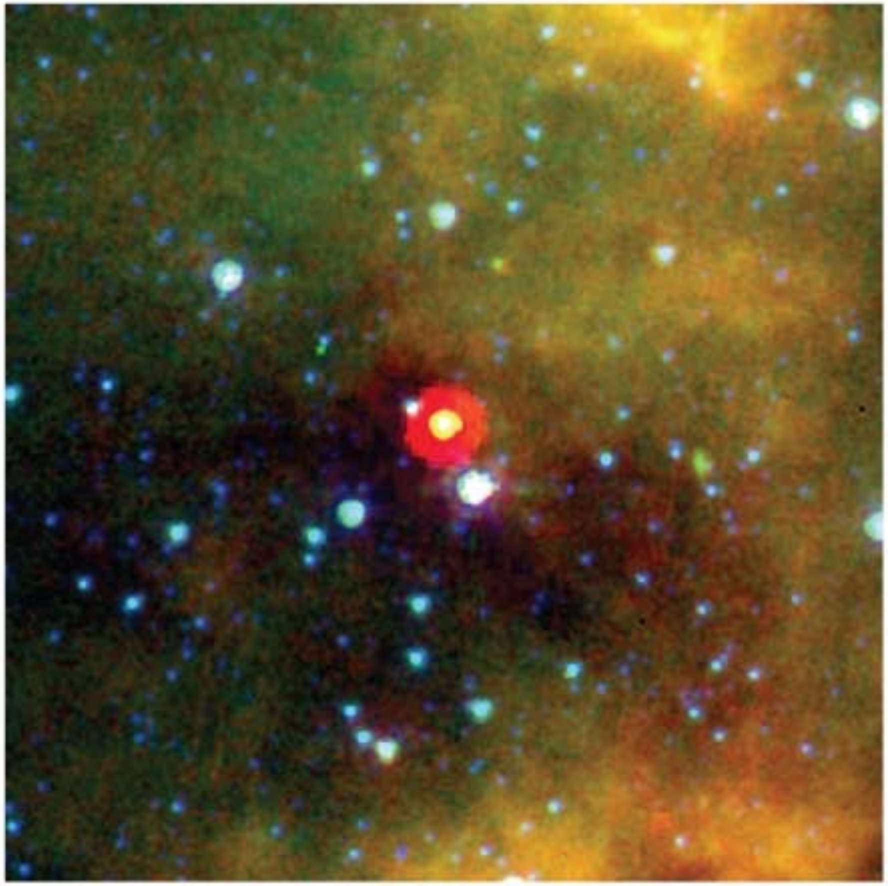
- Long-wavelength near infrared light passes through a cloud more easily than visible light.

- Observations of near infrared light reveal stars on the other side of the cloud.

Observing Newborn Stars

- Visible light from a newborn star is often trapped within the dark, dusty gas clouds where the star formed.

Observing Newborn Stars



- Newborn stars within a cloud are not observable with visible light because it is absorbed by the surrounding dust.
- When the surrounding dust grains absorb visible light they become heated and emit in the Far IR (25 – 1000 μm) and microwave bands.
- The dust surrounding a newborn star can be detected with observations in the Far IR or microwave.

Observing Newborn Stars

A visible-light image shows immense pillars of dark molecular gas.

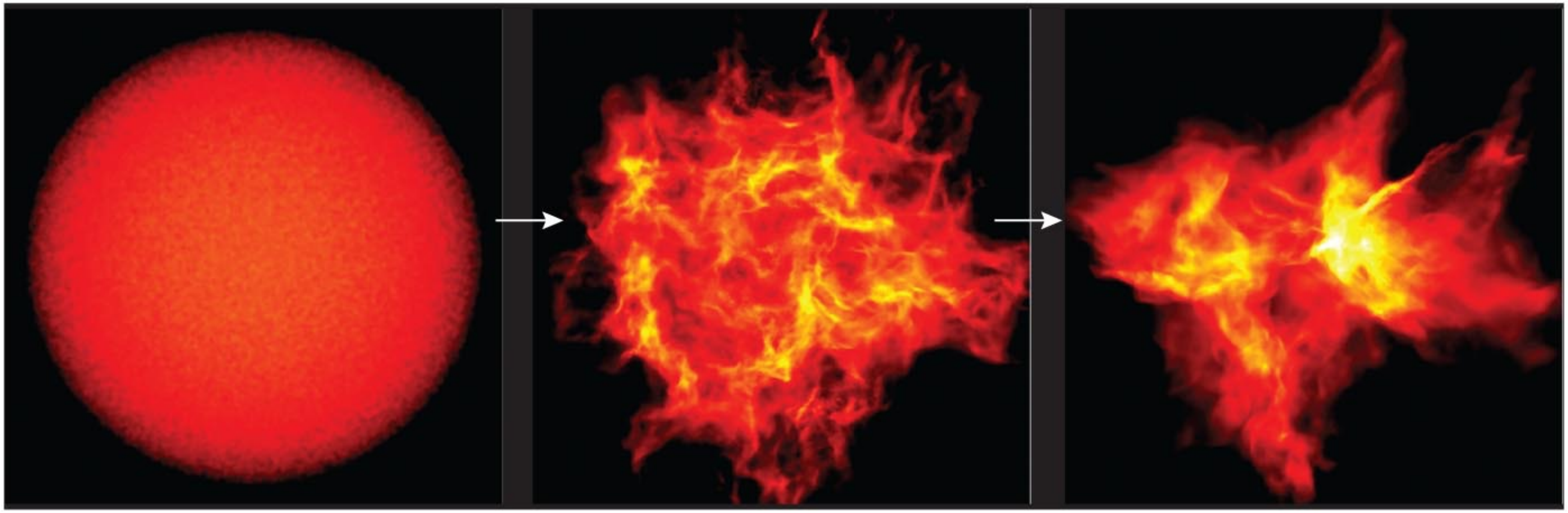
The pillars are being sculpted by ultraviolet radiation from nearby stars (not seen in this image) that heats and erodes the dark gas.

Infrared light passes through the dark gas, so the pillars become almost transparent . . .

. . . allowing us to see newborn stars that were hidden in the visible-light image.

Images of longer-wavelength infrared light show the glow of thermal radiation from the pillars.

How do stars form?

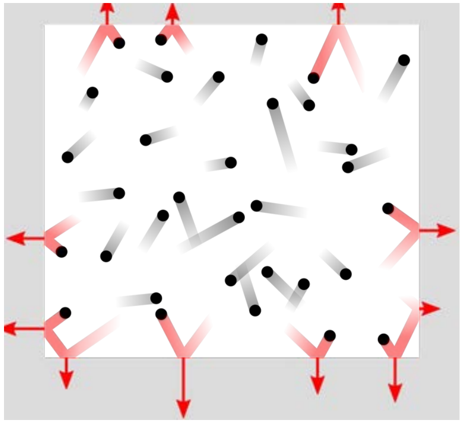


Stars form when gravity causes a molecular cloud to contract and fragment. The collapse continues until the central object gets hot enough to sustain nuclear fusion in its core.

A star remains stable because of a balance between the outward gas pressure and the inward pull of gravity.

Pressure of a Gas

- The **thermal pressure** of a gas is related to its temperature and density.



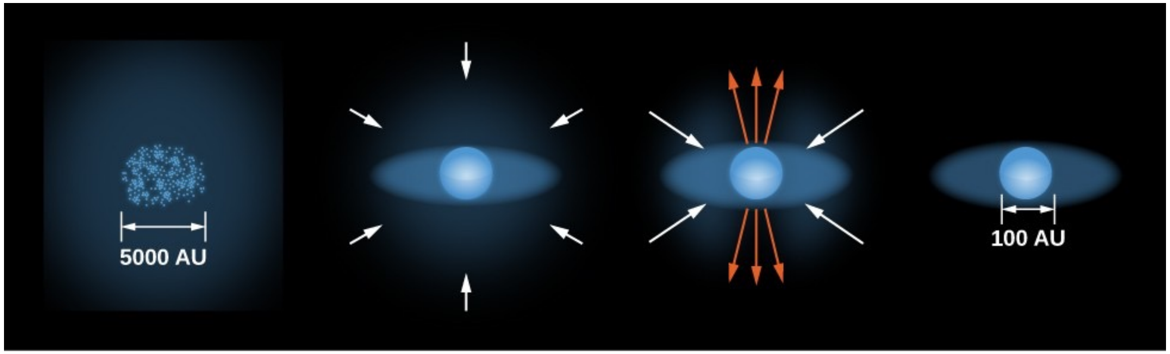
- $PV = NkT$ (ideal gas law)

Where P = pressure, V = volume,

N = number of molecules, T = temperature, $k_B = 1.3810^{-23}$ J/K

- There are other types of pressure: **degeneracy pressure** from electrons and neutrons, **radiation pressure, and magnetic pressure**.
- We refer to the pressure of a gas that depends on density and temperature as its **thermal pressure**.

Gravity versus Pressure in Molecular Clouds



- A typical molecular cloud (*T*~ 30 K, *n* ~ 300 particles/cm^3) must contain **at least ~100 M$_\odot$ for gravity to overcome pressure**.

- **In many molecular clouds gravity is stronger than thermal pressure** because of their low temperature. Their high density results in a significant increase in the gravitational force.

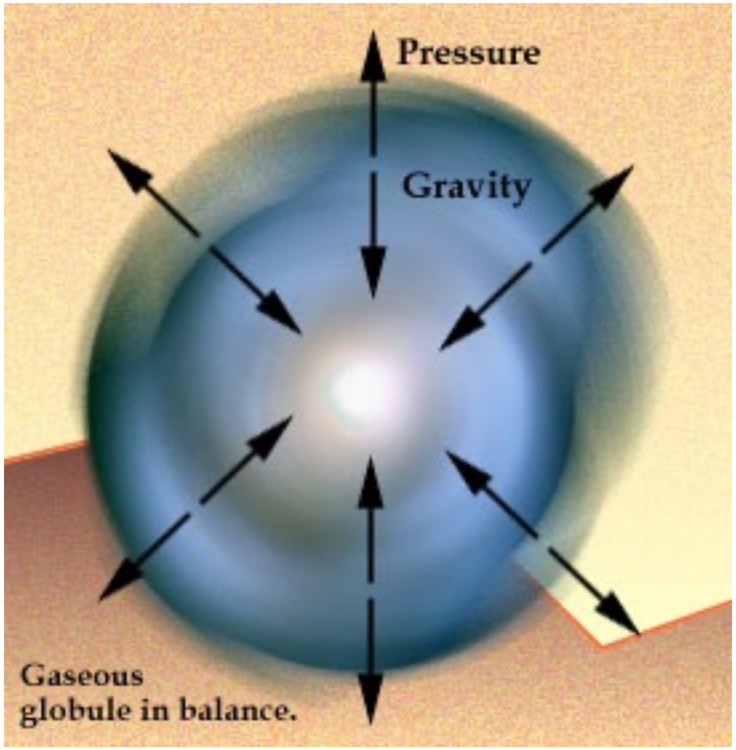
Preventing a Pressure Buildup During Collapse

- As gravity makes a molecular cloud collapse **gravitational energy is converted to kinetic energy** and the gas heats up leading to an increase in the outward pressure.

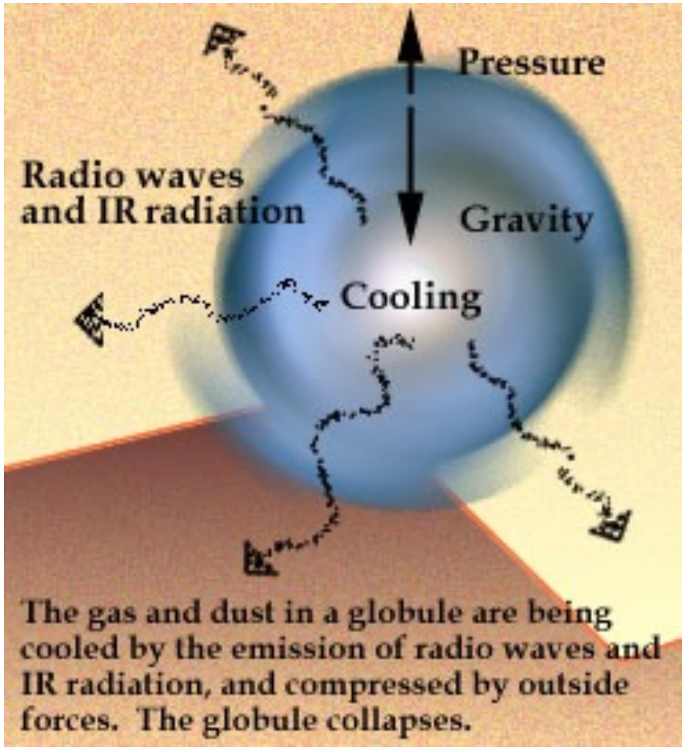
- **If the heat does not escape the cloud** the pressure would build up and prevent the cloud from collapsing.

- **Molecular clouds get rid of the pressure build up by radiating**. **Molecules such as CO** can radiate in the IR and radio thus lose kinetic energy and reduce the pressure of the gas.

Collapse of Molecular Gas Cloud

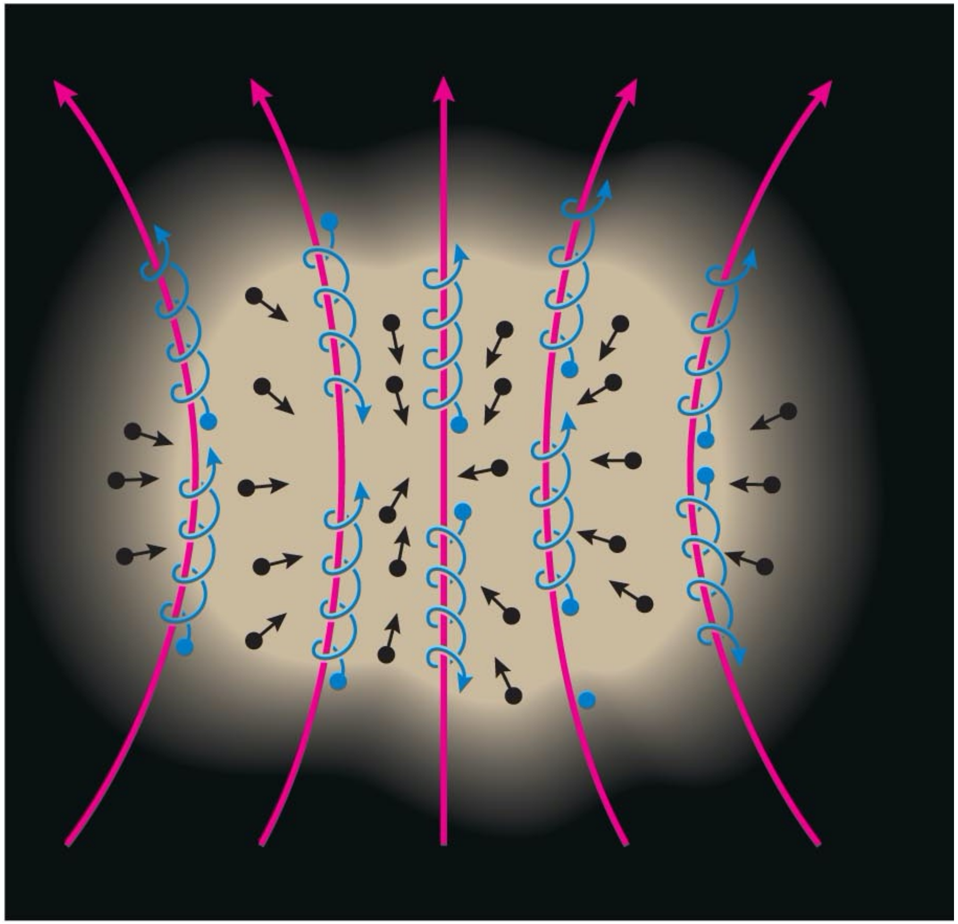


Gaseous globule in balance.



The gas and dust in a globule are being cooled by the emission of radio waves and IR radiation, and compressed by outside forces. The globule collapses.

Resistance to Gravity



- A cloud must have even more mass to begin contracting if there are additional forces opposing gravity.
- Both magnetic fields and turbulent gas motions increase resistance to gravity.

Thought Question

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 internal pressure would increase.

Thought Question

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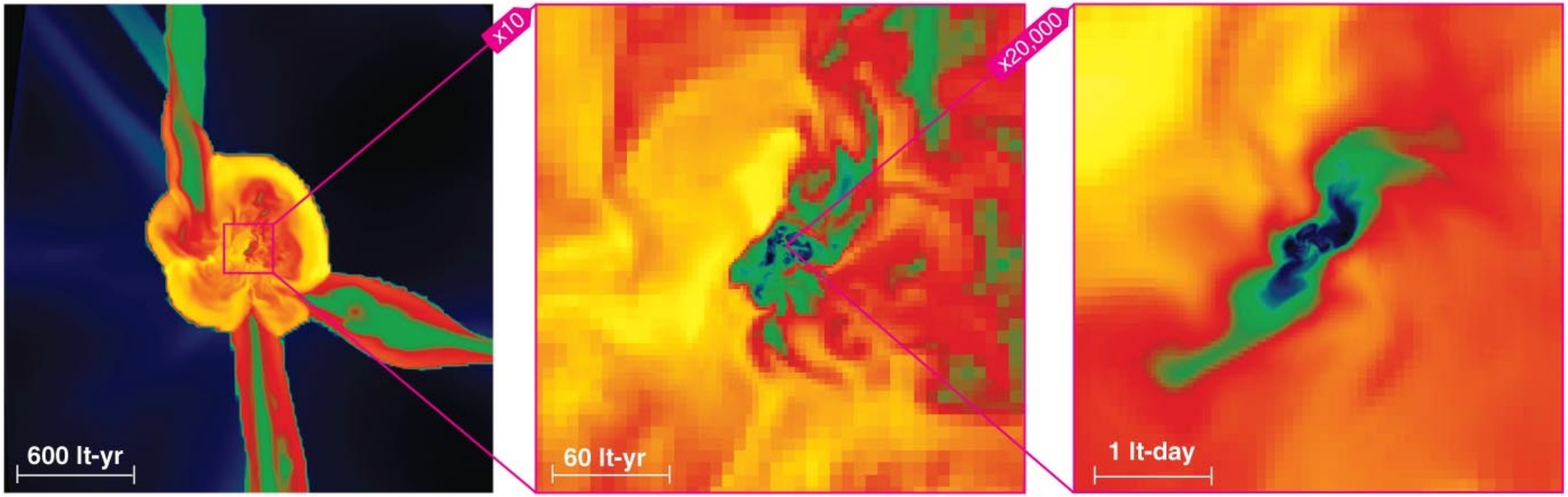
The First Stars

- Elements like carbon and oxygen had not yet been made when the first stars formed.

- Without CO molecules to provide cooling, the clouds that formed the first stars had to be considerably warmer than today's molecular clouds. (H_2 can radiate at temperatures > 100 K)

- **The first stars must therefore have been more massive** than most of today's stars, for gravity to overcome pressure.

Simulation of the First Star



a The orange blob is one of the first gas clouds that gravity forms in this simulation of the early universe.

b Hydrogen molecules near the center of the blob allow the gas there to cool to 100–300 K.

c At the center of the cloud, about $200M_{\text{Sun}}$ of gas collects into a newly forming star. The cloud cannot fragment further, because there are no complex molecules to cool it to lower temperatures.

- Simulations of early star formation suggest the first molecular clouds never cooled below 100 K, making stars of $\sim 100M_{\text{Sun}}$.

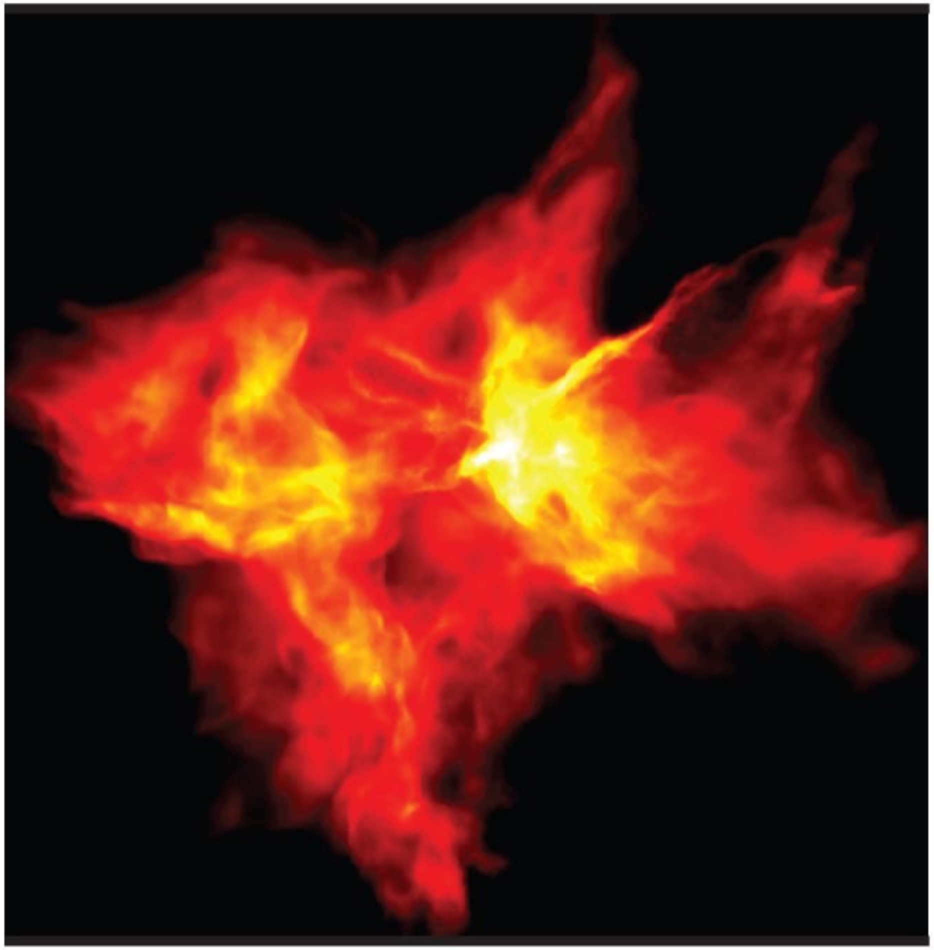
What have we learned?

- **Where do stars form?**
  - Stars form in dark, dusty clouds of molecular gas with temperatures of 10–30 K.
  - These clouds are made mostly of molecular hydrogen (H_2) but stay cool because of emission by carbon monoxide (CO).
- **How do stars form?**
  - Stars form in clouds that are massive enough for gravity to overcome thermal pressure (and any other forms of resistance).
  - Such a cloud contracts and breaks up into pieces that go on to form stars.

16.2 Stages of Star Birth

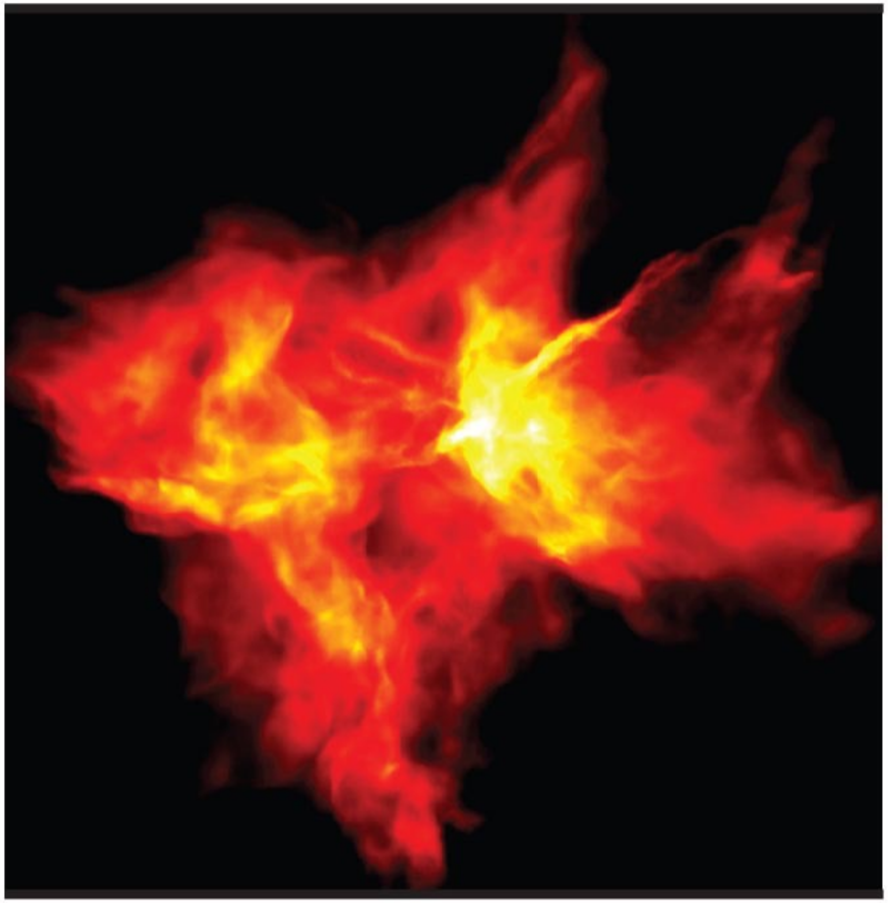
- Our goals for learning:
  - **What slows the contraction of a star-forming cloud?**
  - **What is the role of rotation in star birth?**
  - **How does nuclear fusion begin in a newborn star?**

What slows the contraction of a star-forming cloud?



As contraction packs the molecules and dust particles of a cloud closer together, **it becomes harder for infrared and radio photons to escape.**

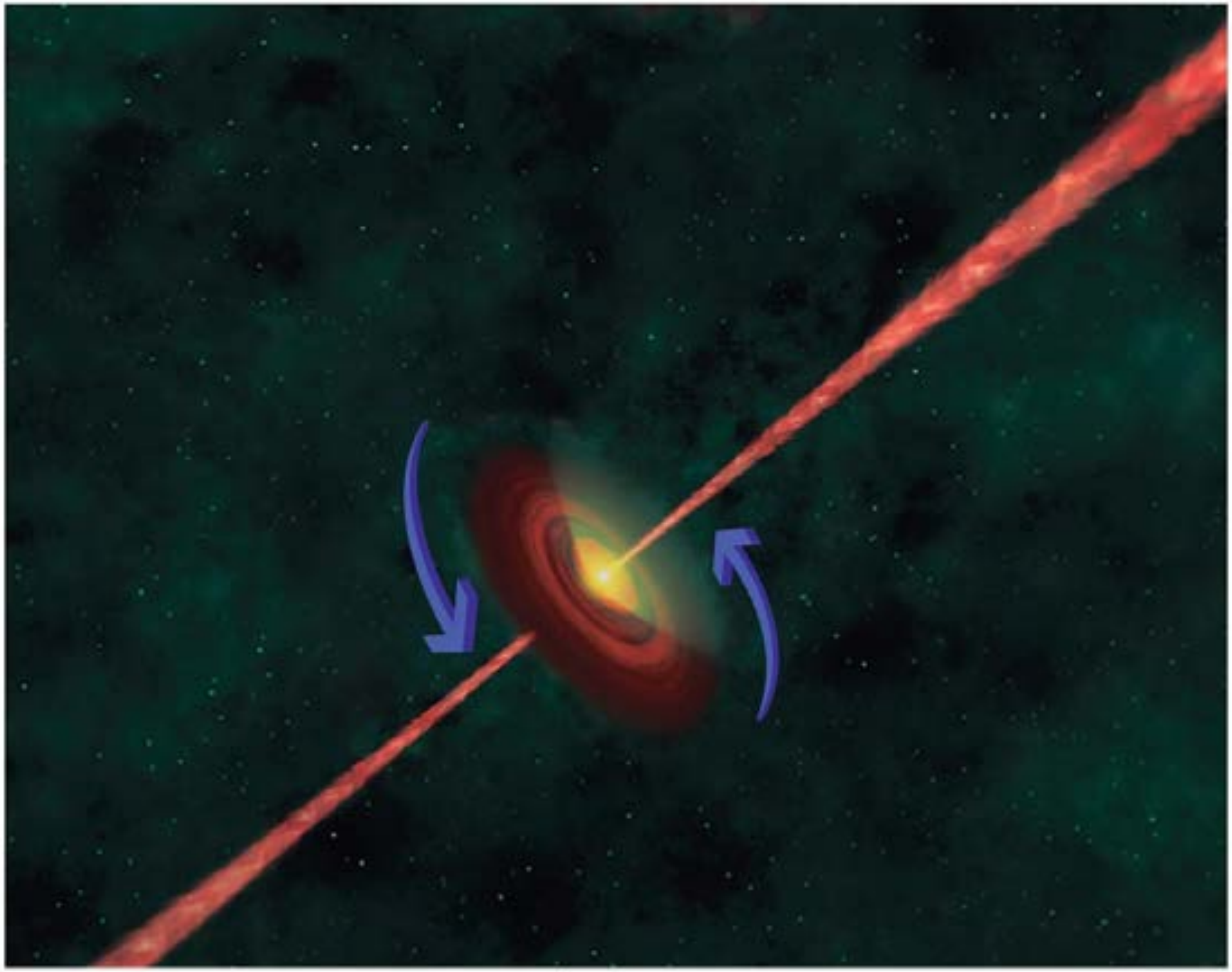
Trapping of Thermal Energy and Formation of a Protostar



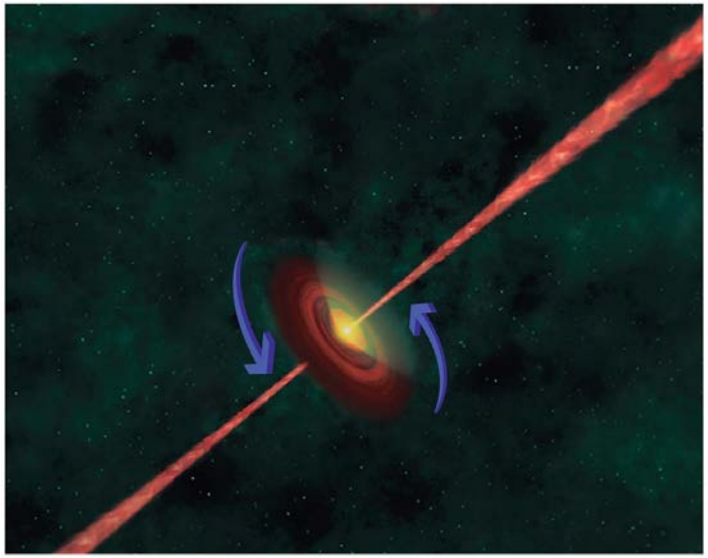
Thermal energy then begins to build up inside, increasing the internal pressure.

Contraction slows down, and the center of the cloud fragment becomes a **protostar.**

What is the role of rotation in star birth?



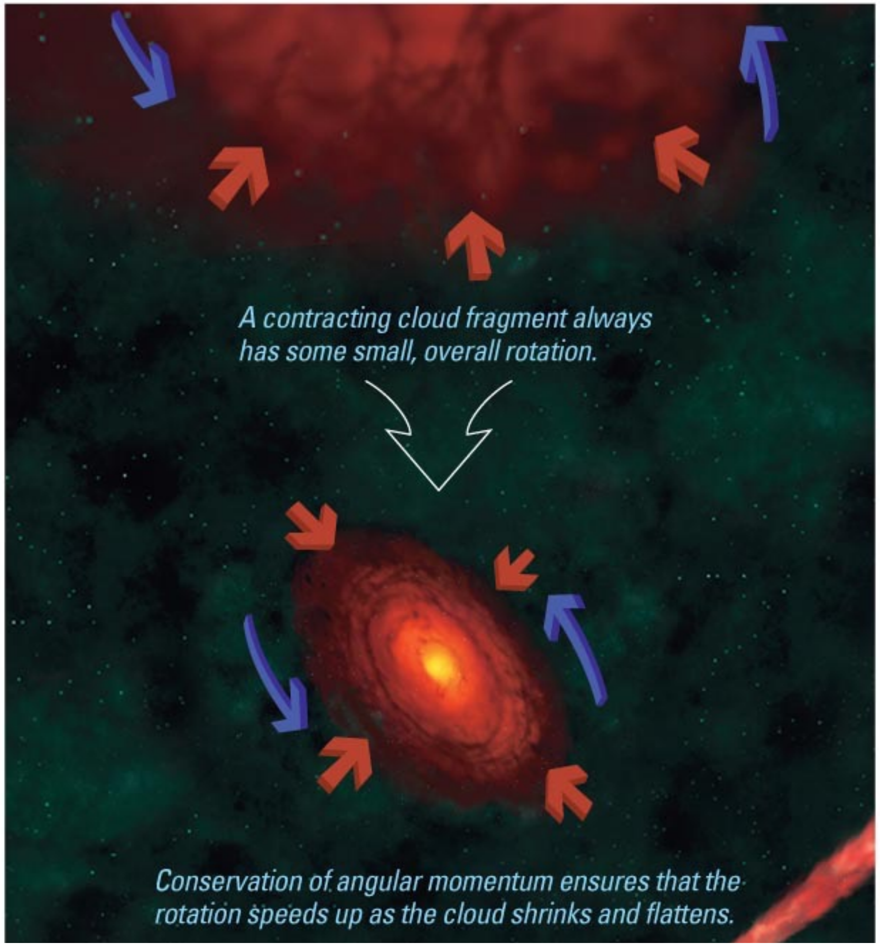
What is the role of rotation in star birth?



Rotation leads to the:

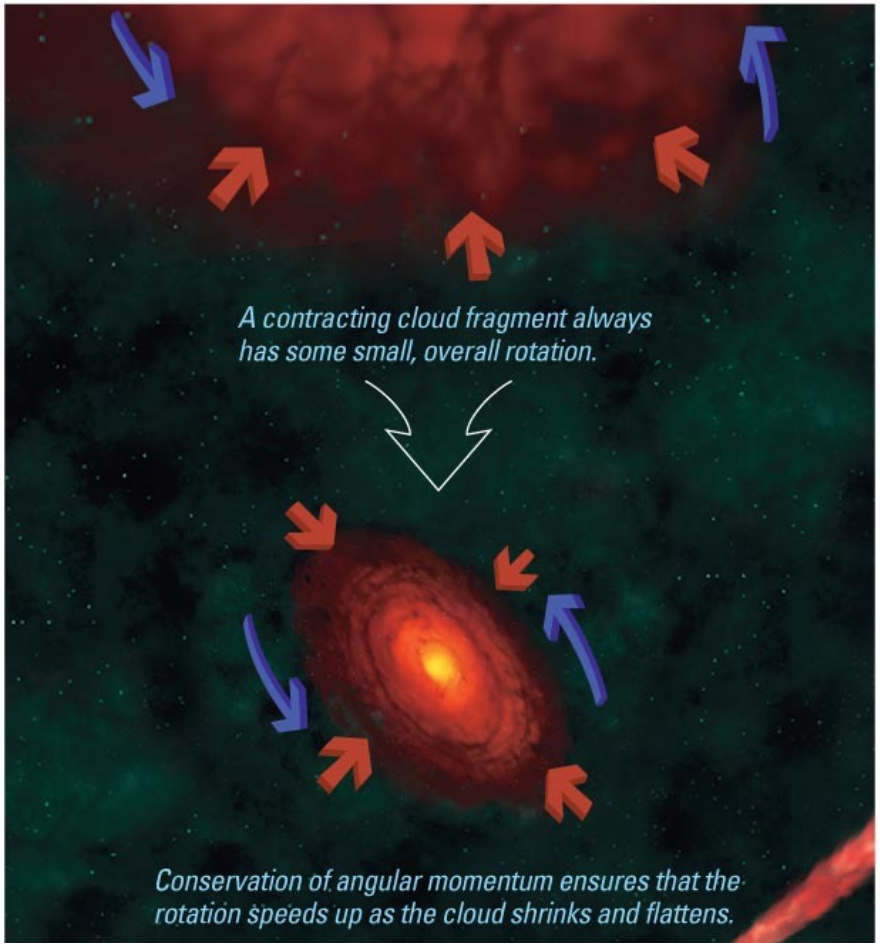
- Formation of a protostellar disk and eventually planets
- Formation of jets
- Formation of binary protostars

Formation of a Protostellar Disk



- As the molecular cloud collapses any small amounts of rotation will increase because of **conservation of angular momentum**.
- Conservation of angular momentum prevents the material from falling directly onto the protostar.
- Material can move along the axis of rotation and collisions lead to the formation of a flattened **protostellar disk** around the protostar.

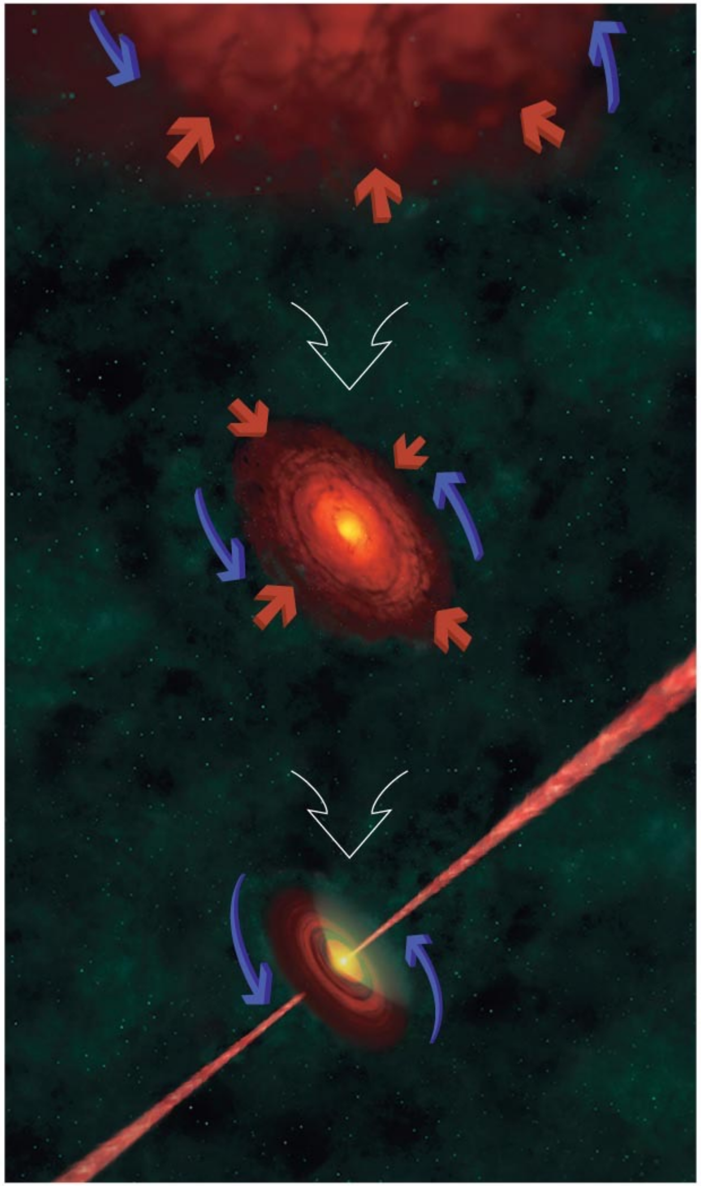
Accretion onto Protostar



- Material at different radii rotates at different velocities. Friction between neighboring particles leads to loss of energy and particles fall towards to protostar.

- The **protostar** gradually **accretes material** to become more massive.

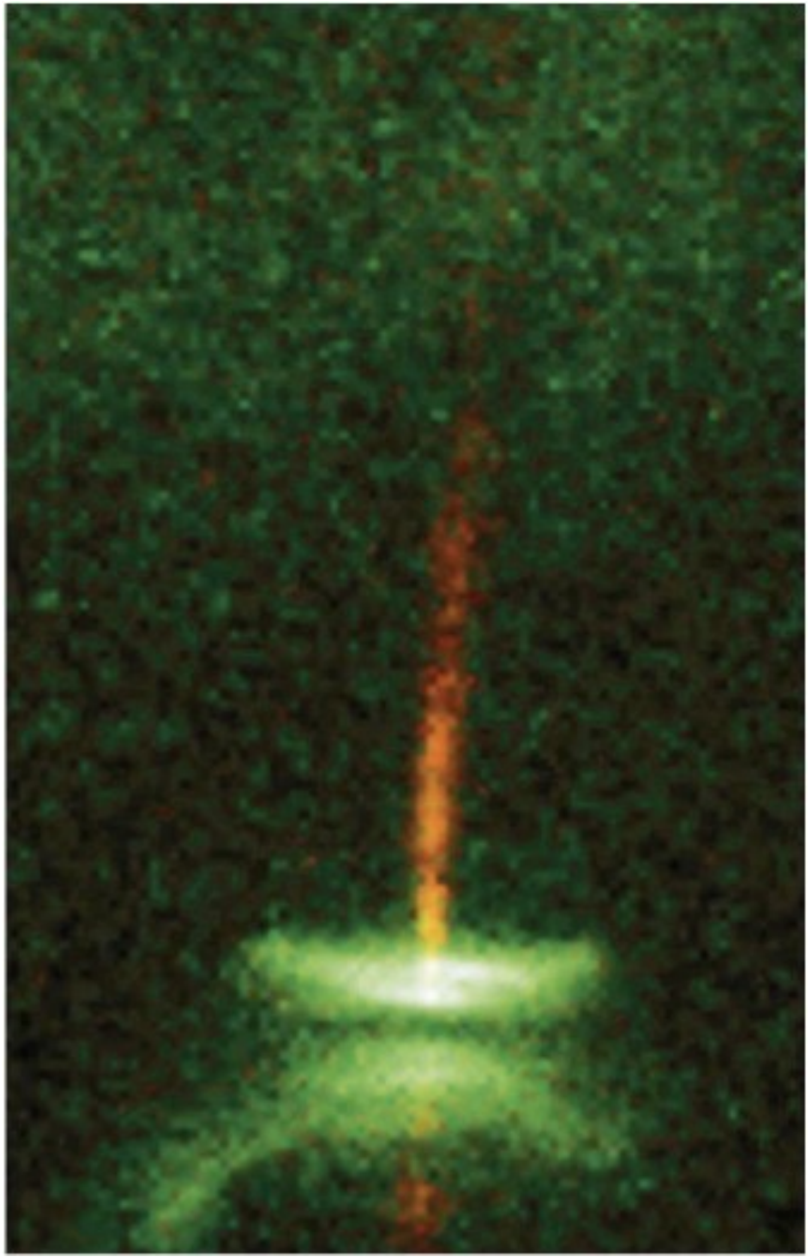
Formation of Jets and Herbig - Haro Objects



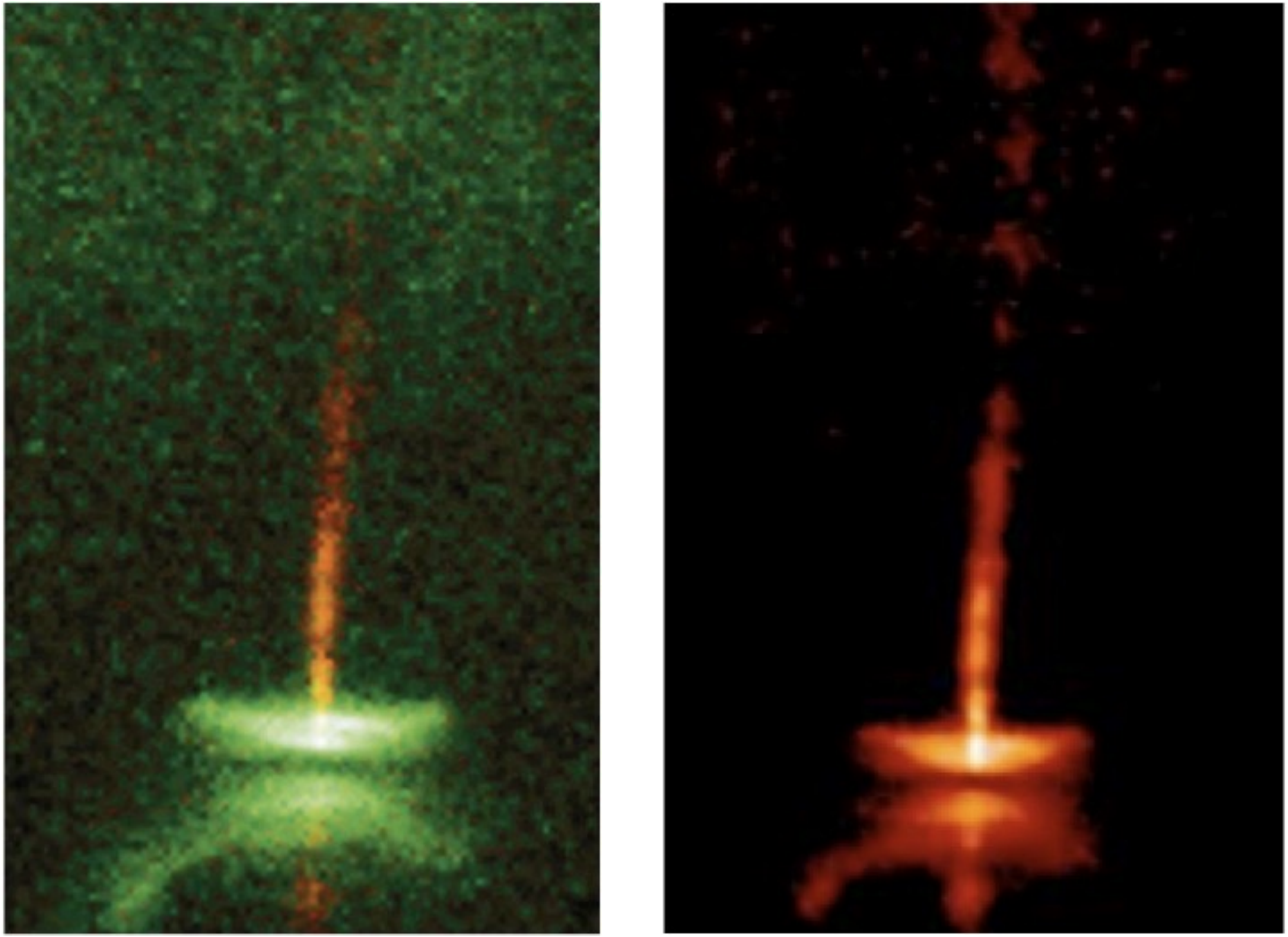
- Many protostars are observed to launch **jets** of material that is highly **collimated along the rotation axis**.

- These jets occasionally collide with clumps of interstellar gas to form hot spots on either end of these jets (**Herbig - Haro Objects**).

- Jets are thought to be formed by the **twisting of magnetic filed lines** that thread the protostellar disk. The spinning protostellar disk twists the magnetic field lines to channel jets of charged particles along the rotation axis.



- Jets are observed coming from the centers of disks around protostars.



Thought Question

What would happen to a protostar that formed without any rotation at all?

A. Its jets would go in multiple directions.
B. It would not have planets.
C. It would be very bright in infrared light.
D. It would not be round.

Thought Question

What would happen to a protostar that formed without any rotation at all?

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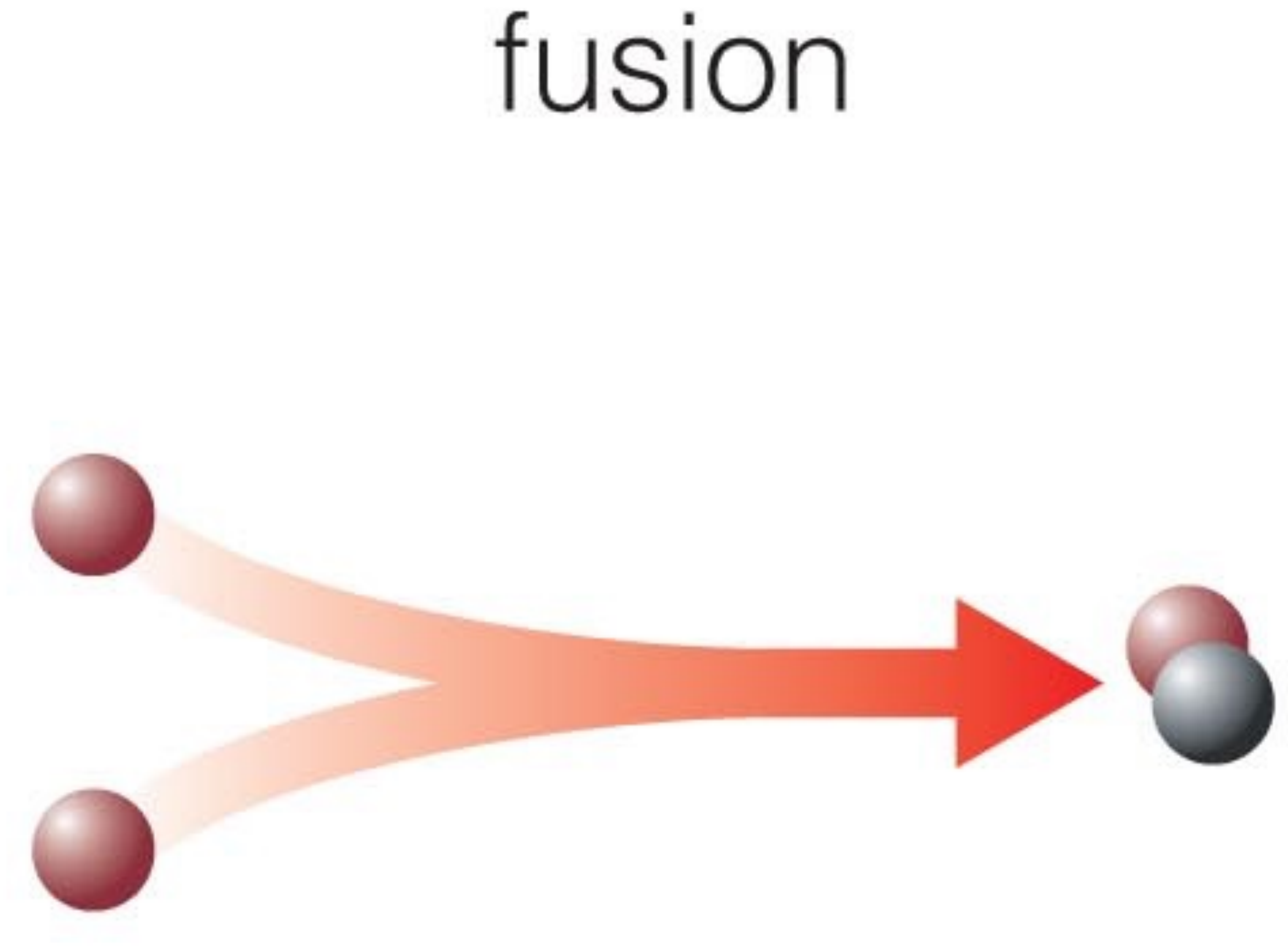
How does nuclear fusion begin in a newborn star?



From Protostar to Main Sequence

The **central temperature of a newly formed protostar is about 1 million degrees**. The protostar needs to contract to increase its temperature to about 10 million degrees before fusion may begin. How does it do this?

Answer: Thermal energy in the interior decreases by radiation emitted at the protostars surface. This decrease in thermal energy results in the further collapse and increase in the core temperature.

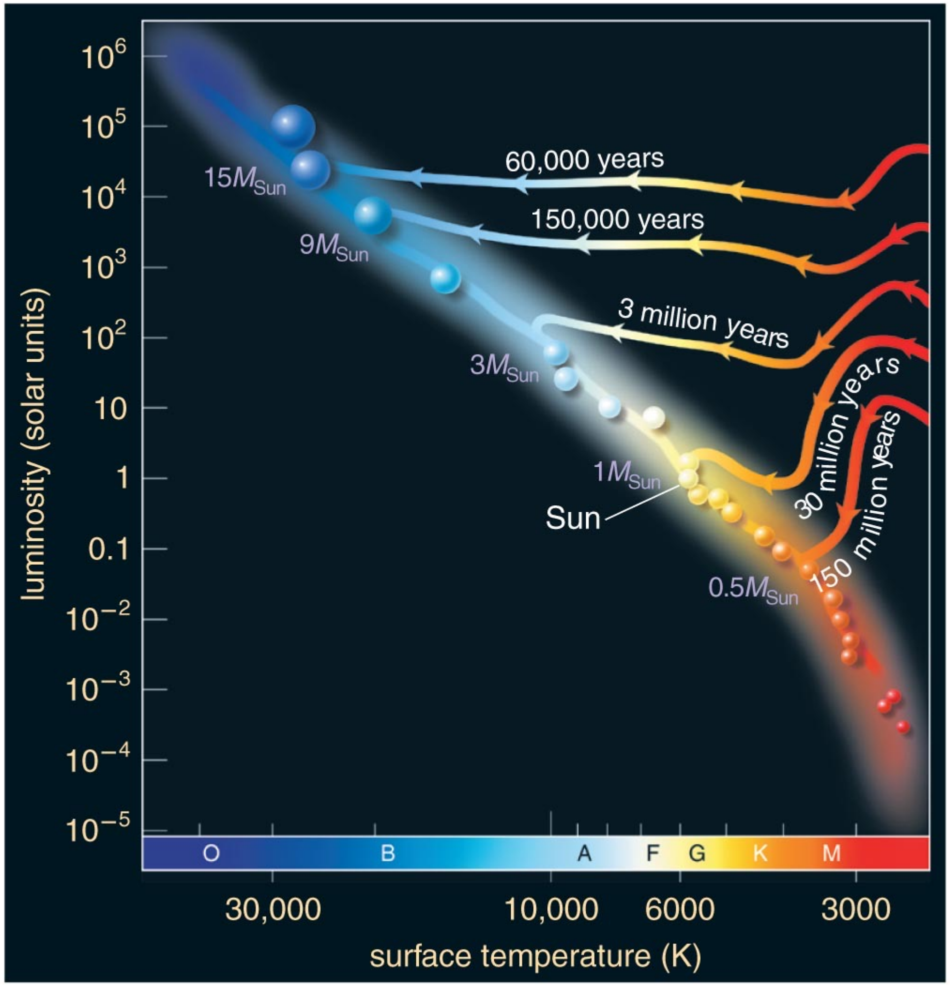
When the core temperature reaches ~10 million degrees fusion of H to He begins. This is when the protostar becomes a star and moves onto the main sequence.

From Protostar to Main Sequence

- Contraction stops when the energy released by core fusion balances energy radiated from the surface—**the star is now a *main-sequence star***.

- The length of time needed to go from the formation of a protostar to the onset of fusion depends on the mass of the protostar. **Massive protostars evolve faster**.

Life Tracks for Different Masses



- Models show that Sun required about 30 million years to go from protostar to main sequence.
- Higher-mass stars form faster.
- Lower-mass stars form more slowly.

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 infrared and radio photons can no longer escape due to increased density.
- **What is the role of rotation in star birth?**
  - Conservation of angular momentum leads to the formation of disks around protostars.

What have we learned?

- **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.

16.3 Masses of Newborn Stars

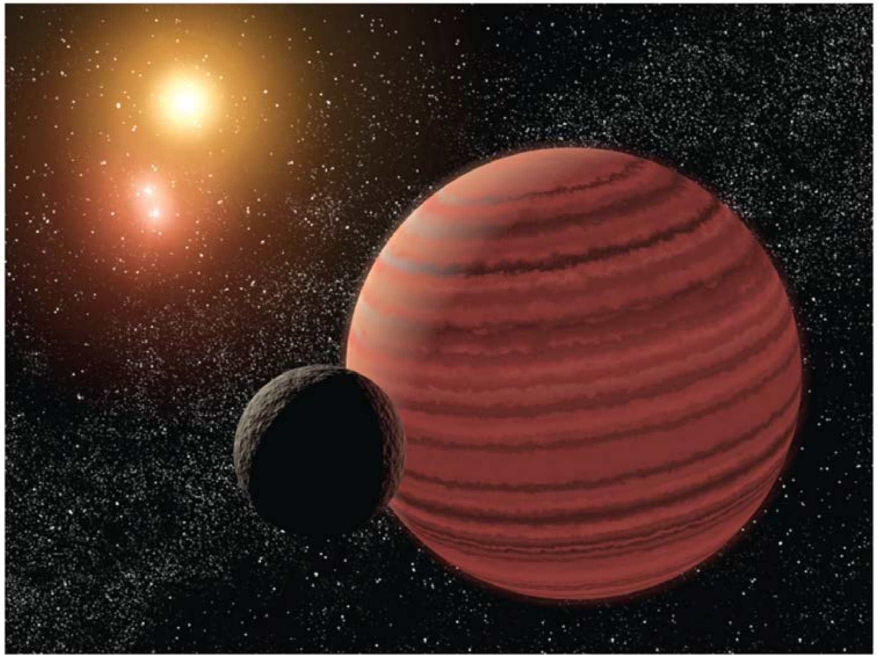
- Our goals for learning:
  - **What is the smallest mass a newborn star can have?**
  - **What is the greatest mass a newborn star can have?**
  - **What are the typical masses of newborn stars?**

16.3 Masses of Newborn Stars

Astronomers observe that the masses of stars range between 0.08 $M_\odot$ to 150 $M_\odot$

Why this mass range limit?

What is the smallest mass a newborn star can have?



Stars cannot have masses less than ~ 0.08 $M_\odot$.The reason for this limit is that **degeneracy pressure** of electrons prevents protostars with a mass of less than 0.08 $M_\odot$ to collapse.

Thermal pressure depends on density and temperature.

Degeneracy pressure depends on density but not on Temperature

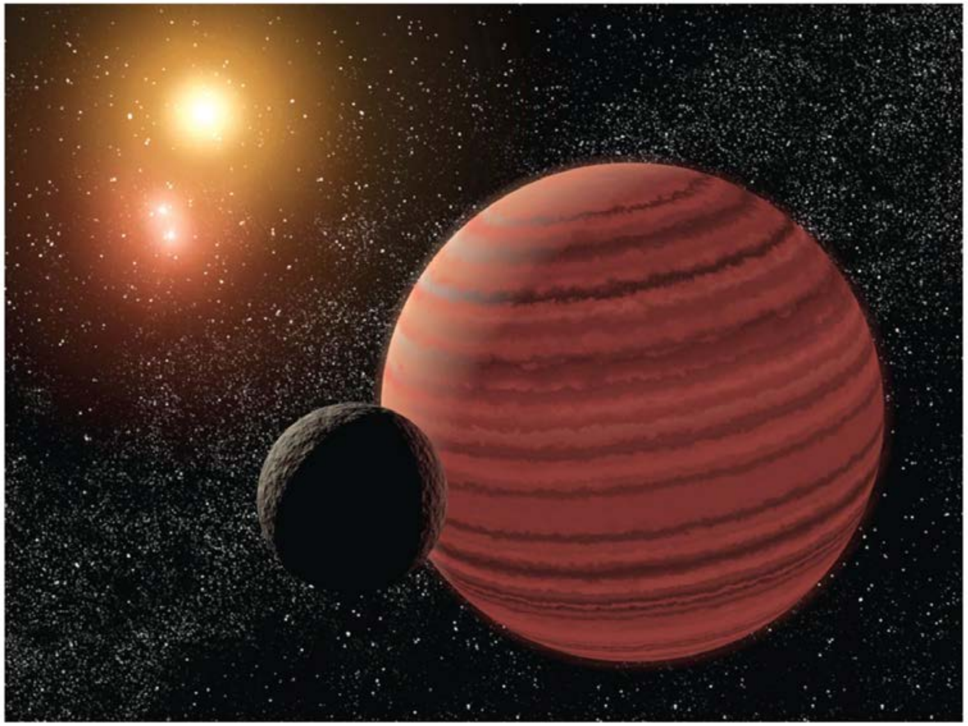
DEGENERACY PRESSURE

Closely packed electrons resist compression. The reason for this is that no two electrons too close to each other can have the same four quantum numbers n, l, m_l, m_s (**The Pauli exclusion principle**).

The pressure of the electrons resisting compression is called degeneracy pressure.

Wolfgang Pauli

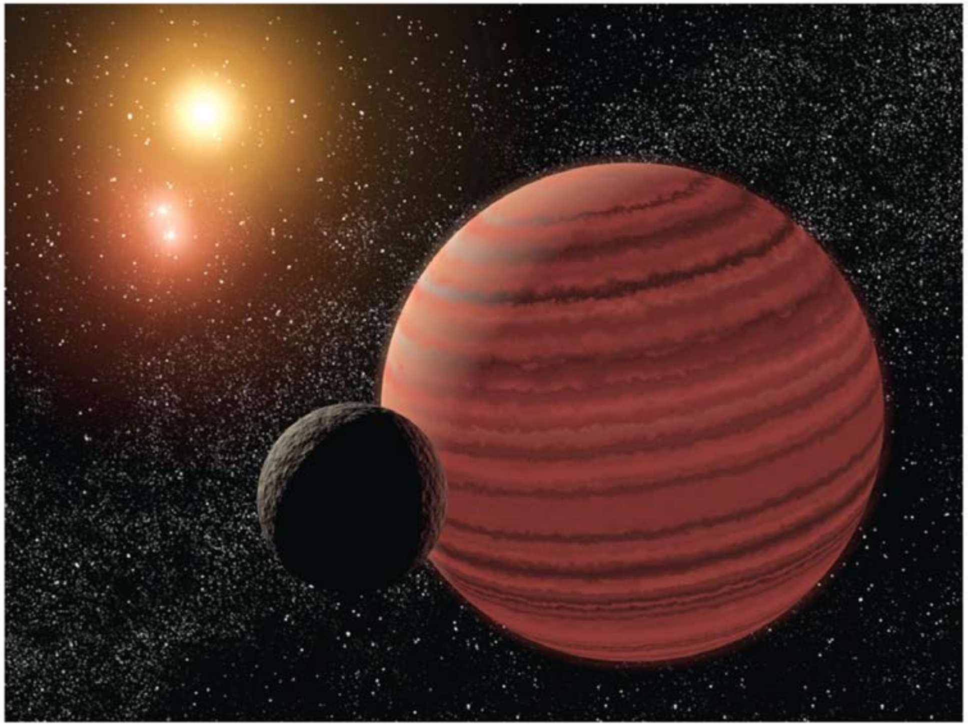
Brown Dwarfs



- Degeneracy pressure halts the contraction of objects with $< 0.08M_\odot$ before core temperature becomes hot enough for fusion.

- Starlike objects not massive enough to start fusion ($M < 0.08M_\odot$) are called **brown dwarfs**.

Brown Dwarfs

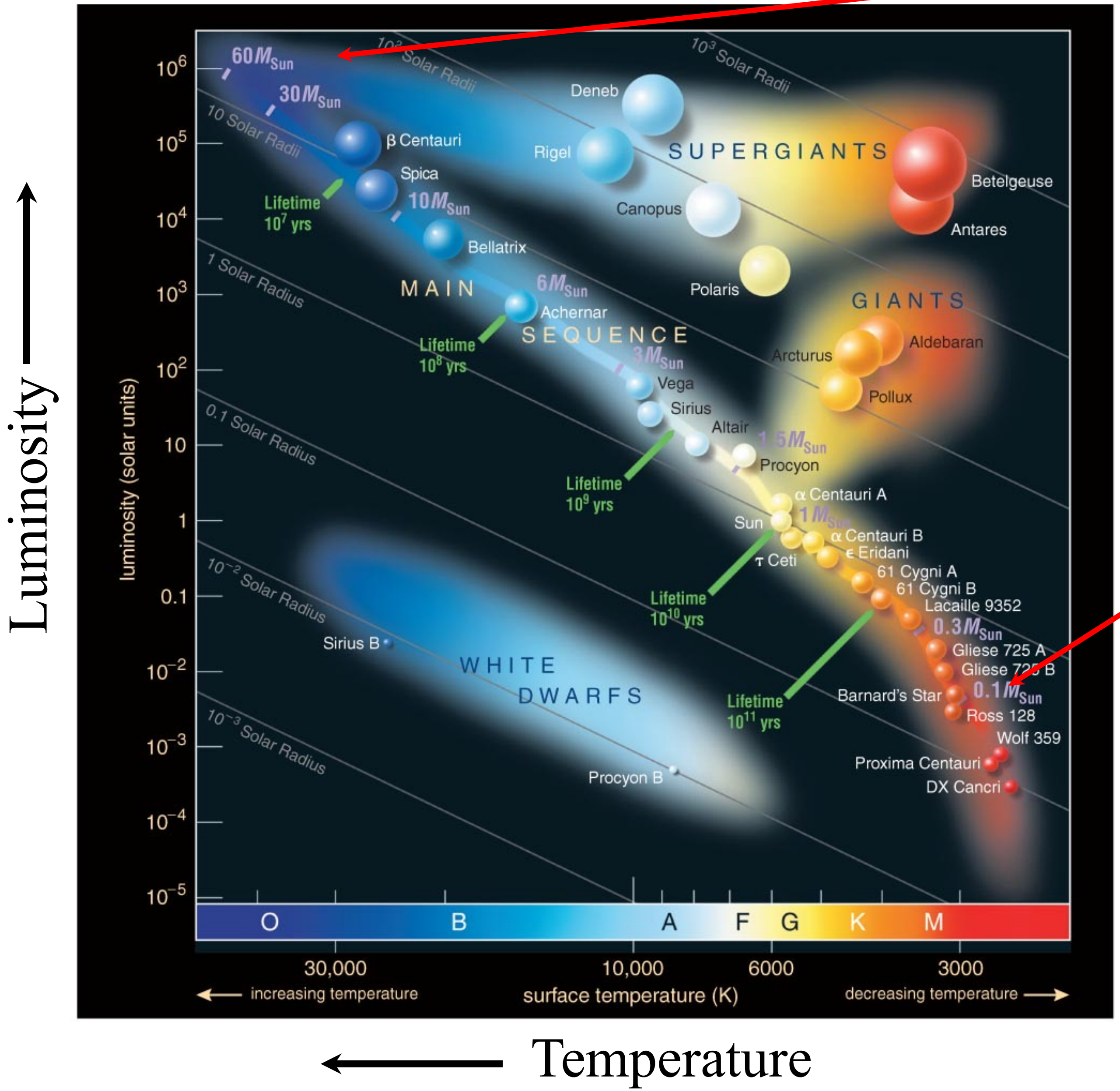


- A brown dwarf emits infrared light because of heat left over from contraction.
- Its luminosity gradually declines with time as it loses thermal energy.

What is the greatest mass a newborn star can have?

Radiation Pressure

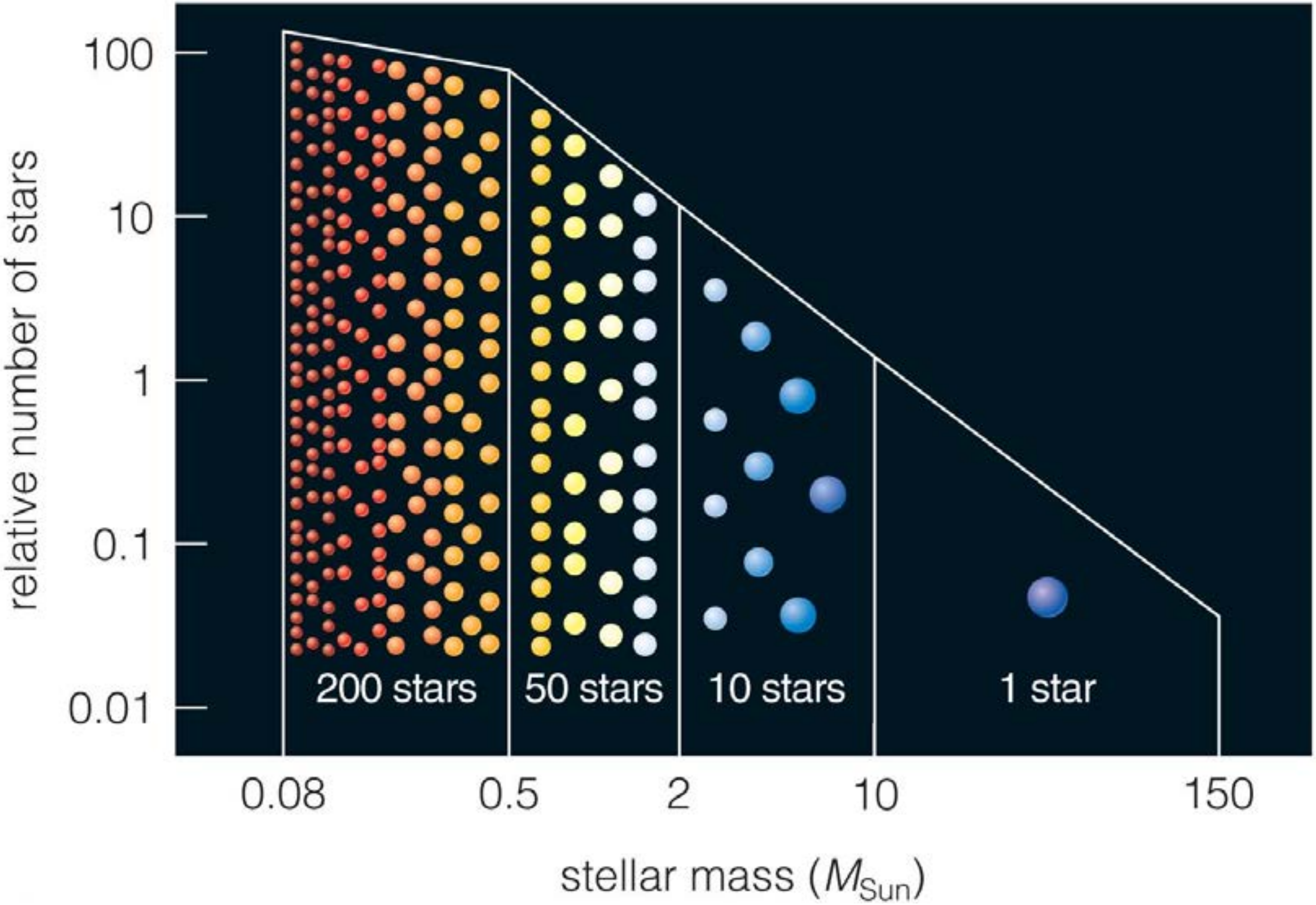
- Photons exert pressure when they strike matter (**radiation pressure**).
- Very massive stars ($M>150M_{\odot}$) are so luminous that their radiation pressure can blow apart the star.



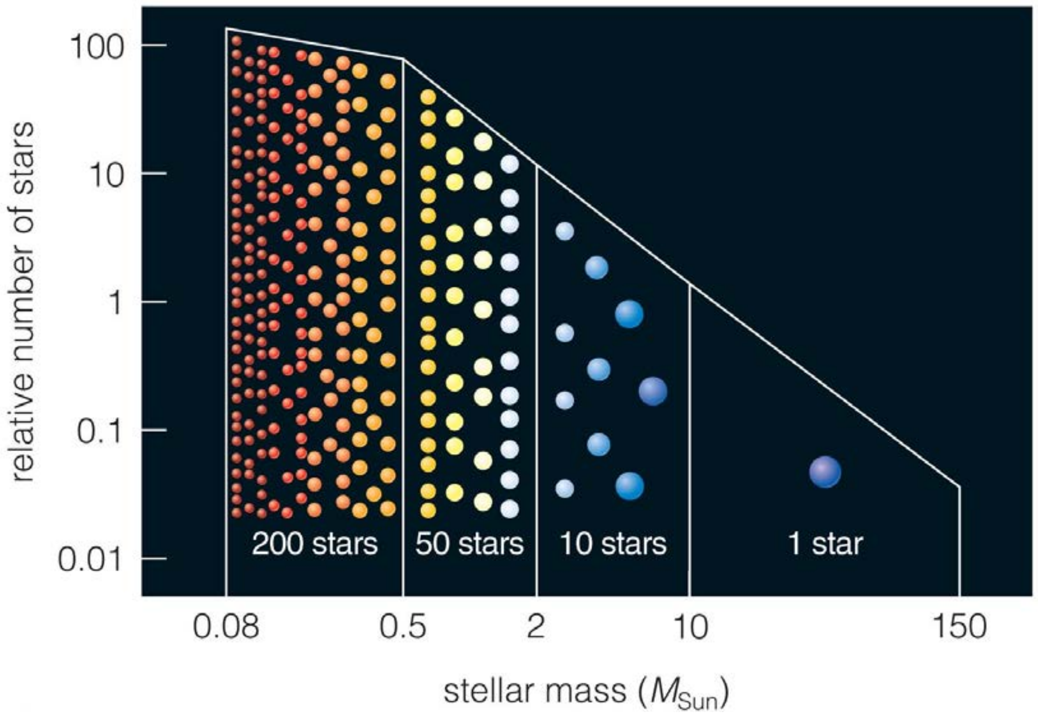
Stars more massive than $150M_{\text{Sun}}$ would blow apart.

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

What are the typical masses of newborn stars?



Demographics of Stars



By studying stars in clusters astronomers have inferred the distribution of the masses of stars. Most stars have masses smaller than that of the sun and it is rare to find stars with masses larger than our sun.

The distribution of stellar masses found in a star cluster depends on the age of the star cluster. In older star clusters the more massive stars will have evolved off the main sequence and there will be much less of them.

What have we learned?

- **What is the smallest mass a newborn star can have?**
  - Degeneracy pressure stops the contraction of objects $<0.08 M_{\text{Sun}}$ before fusion starts.
- **What is the greatest mass a newborn star can have?**
  - Stars greater than about $150 M_{\text{Sun}}$ would be so luminous that radiation pressure would blow them apart.
  - New observations may require raising this limit.

What have we learned?

- **What are the typical masses of newborn stars?**
  - Star formation makes many more low-mass stars than high-mass stars.

EXTRA SLIDES

Growth of a Protostar

- Matter from the cloud continues to fall onto the protostar until either the protostar or a neighboring star blows the surrounding gas away.

Resistance to Gravity

Question: Many molecular clouds exist with masses ~1000's M_{solar}. How do they resist gravity long enough to grow to such large masses?

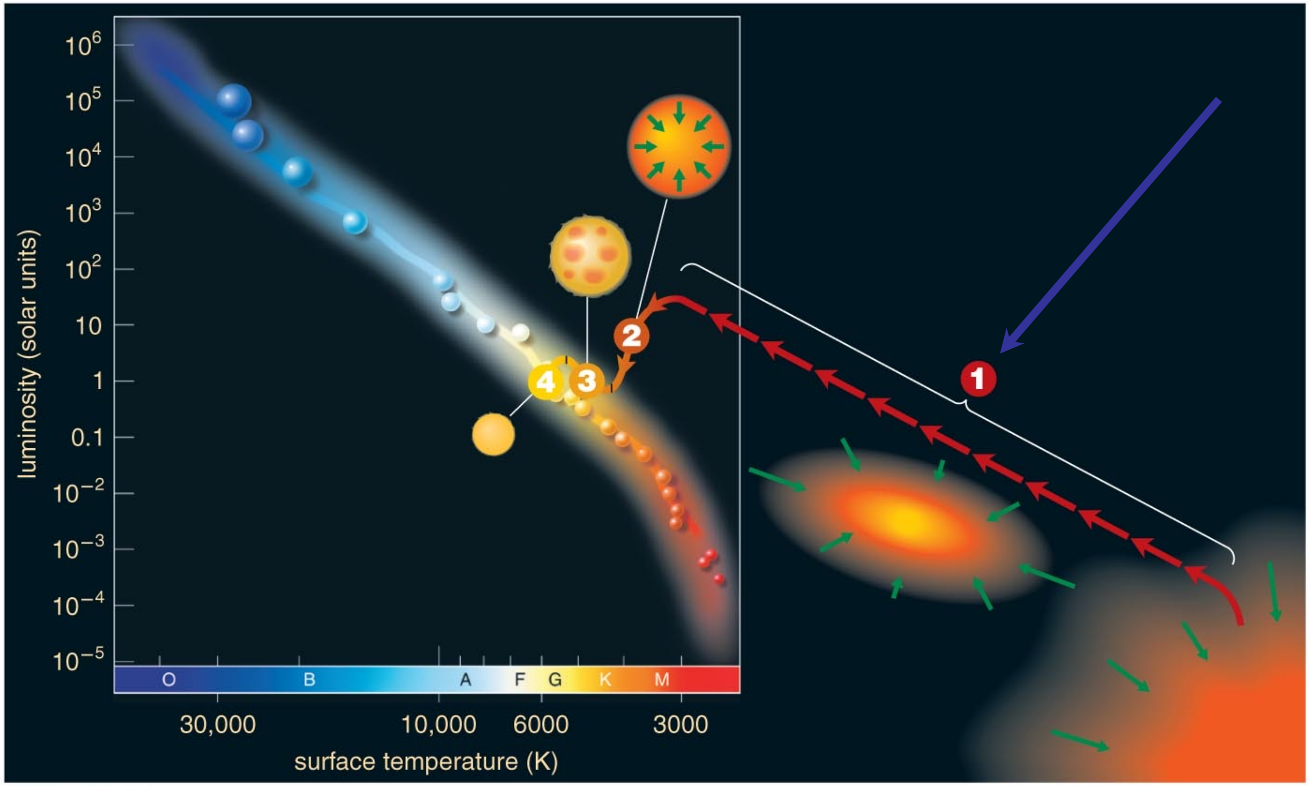
Answer: Turbulence and magnetic fields can hinder the collapse of a molecular cloud.

Fragmentation of a Cloud

Question: Why does a large molecular cloud not collapse to a single massive star but collapses and fragments to form many smaller stars?

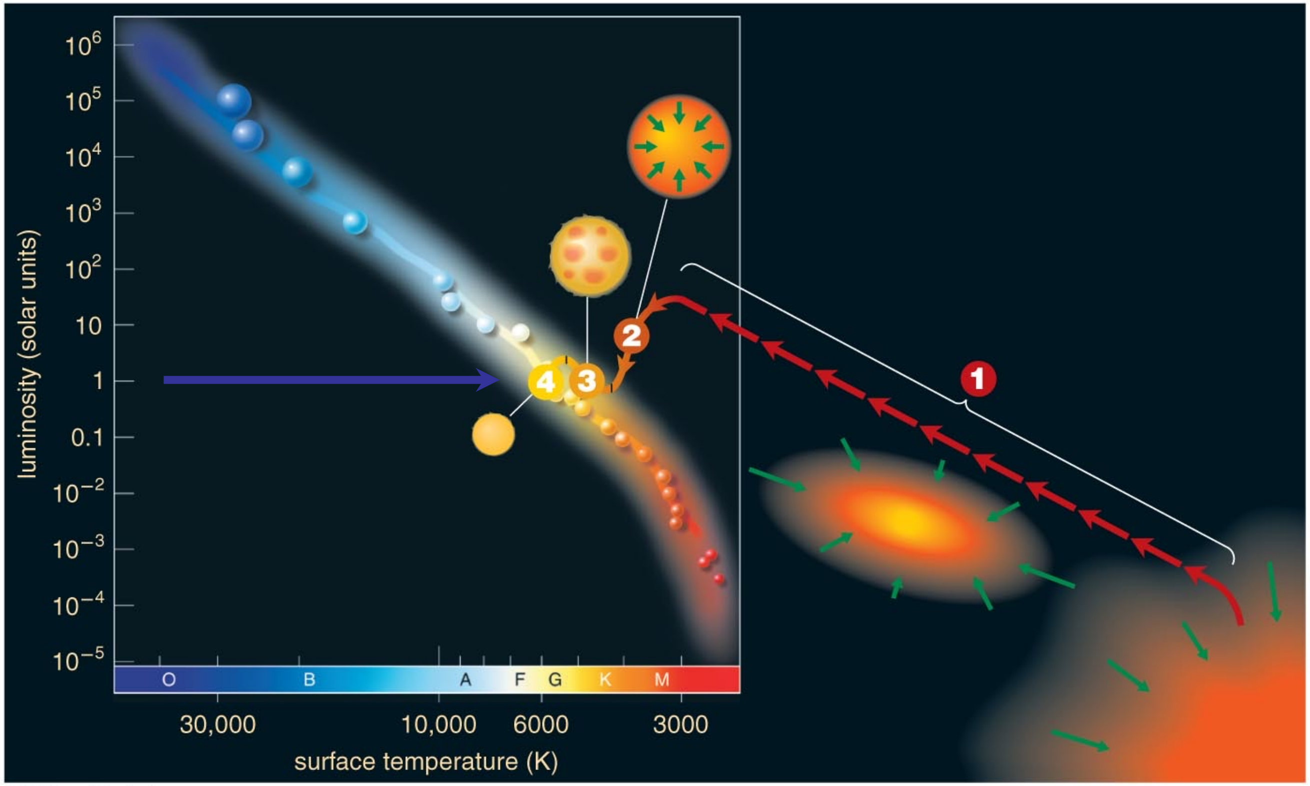
Answer: Molecular clouds are lumpy and turbulent. Within each clump the force of gravity can overcome the pressure of the clump even if the condition is not satisfied over the entire molecular cloud. Thus, the gas within relatively small clumps will be compressed first.

Assembly of a Protostar



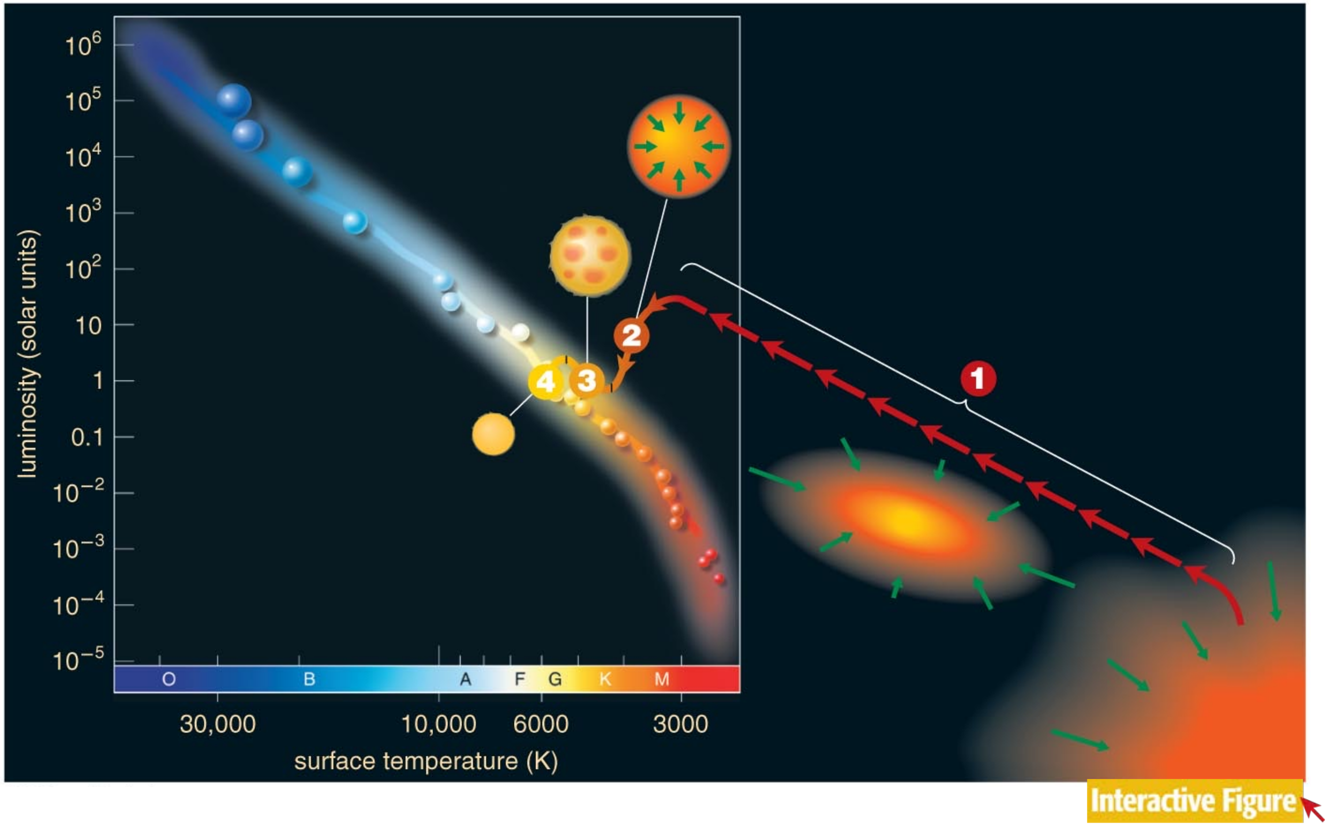
- Luminosity and temperature grow as matter collects into a protostar.

Self-Sustaining Fusion



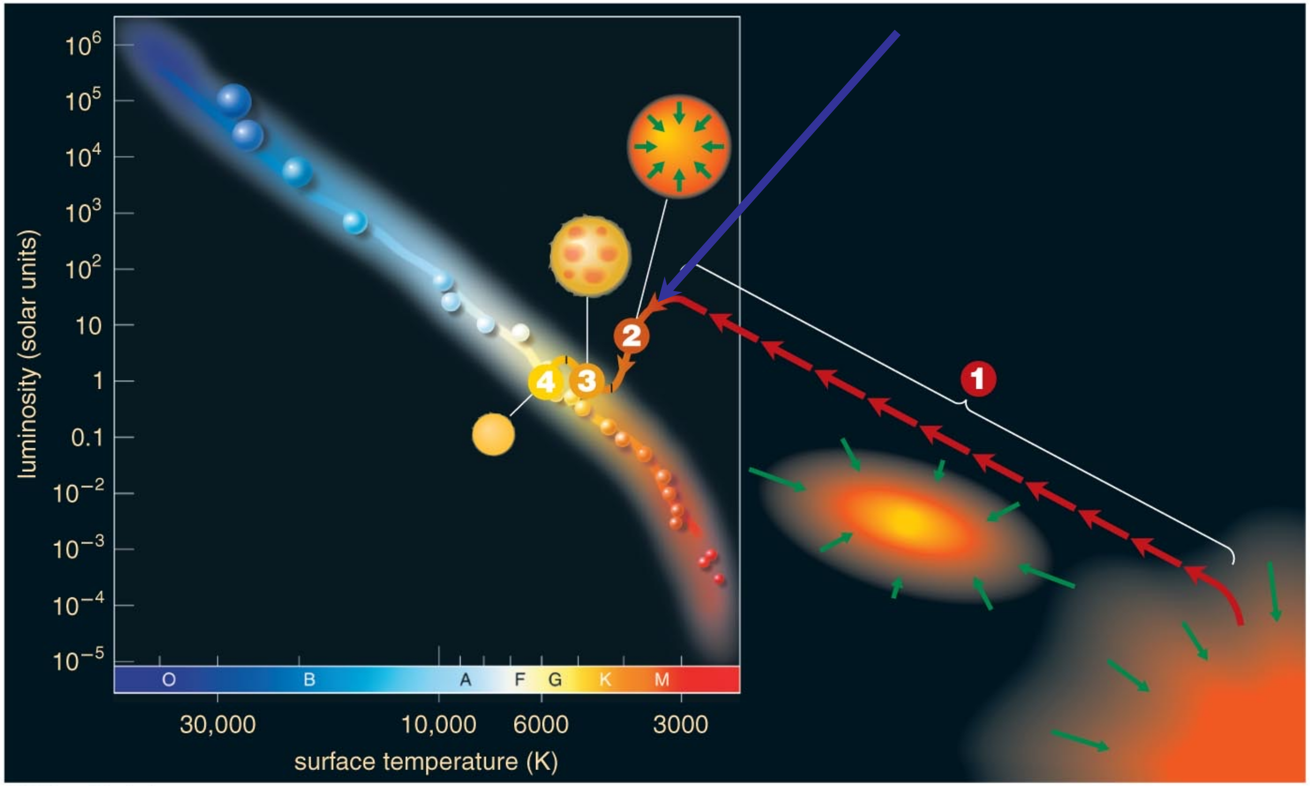
- Core temperature continues to rise until star begins fusion and arrives on the main sequence.

Birth Stages on a Life Track



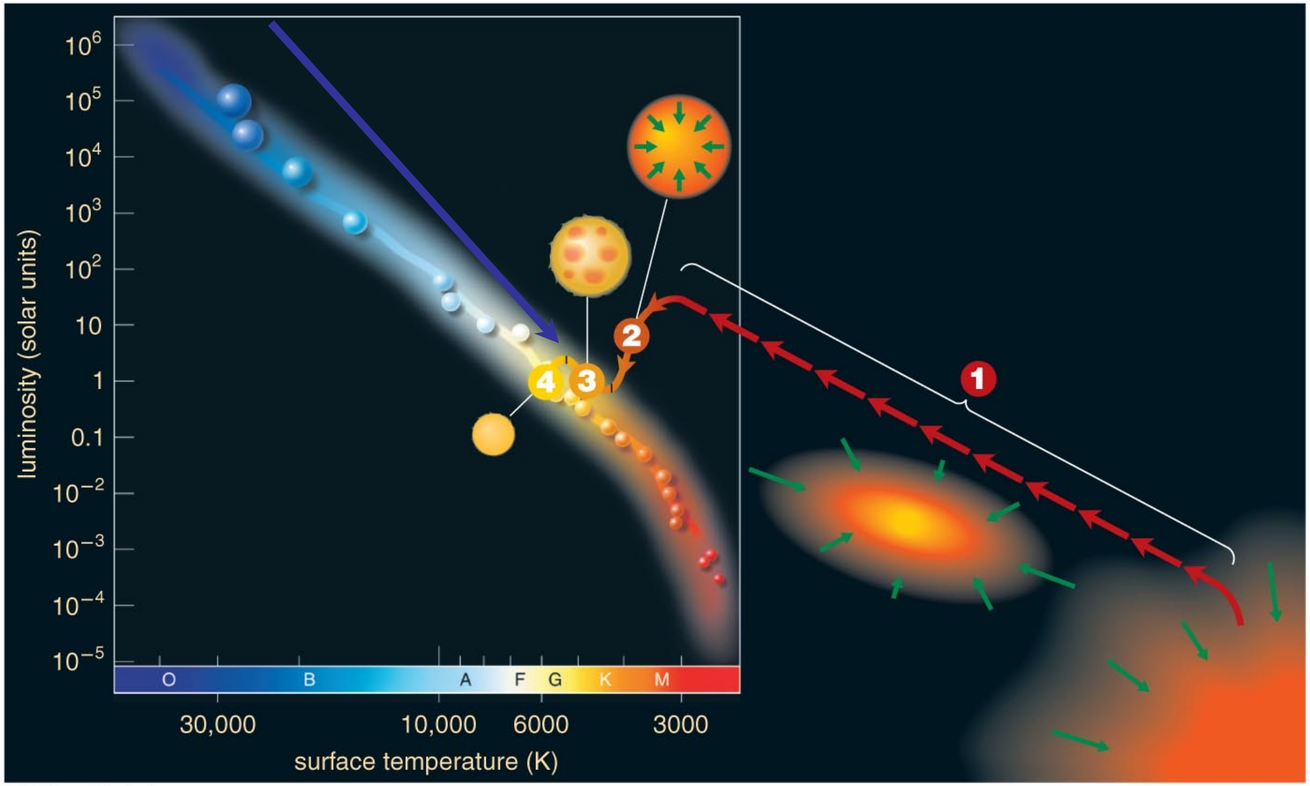
- A life track illustrates a star's surface temperature and luminosity at different moments in time.

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 transports energy through star.