Chapter 16
Star Birth

16.1 Stellar Nurseries

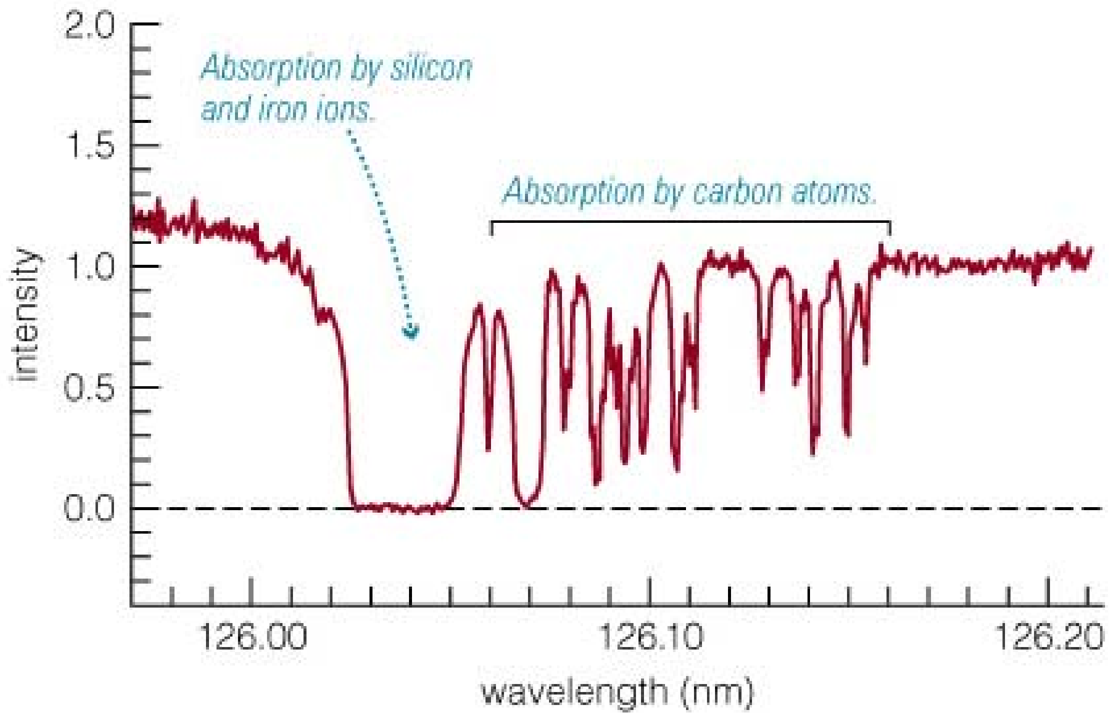
- Our goals for learning
- Where do stars form?
- Why do stars form?

Where do stars form?

Star-Forming Clouds

- Stars form in dark clouds of dusty gas in interstellar space
- The gas between the stars is called 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

- Most of the matter in star-forming clouds is in the form of molecules (H_2, CO,…)
- These *molecular clouds* have a temperature of 10-30 K and a density of about 300 molecules per cubic cm

Molecular Clouds

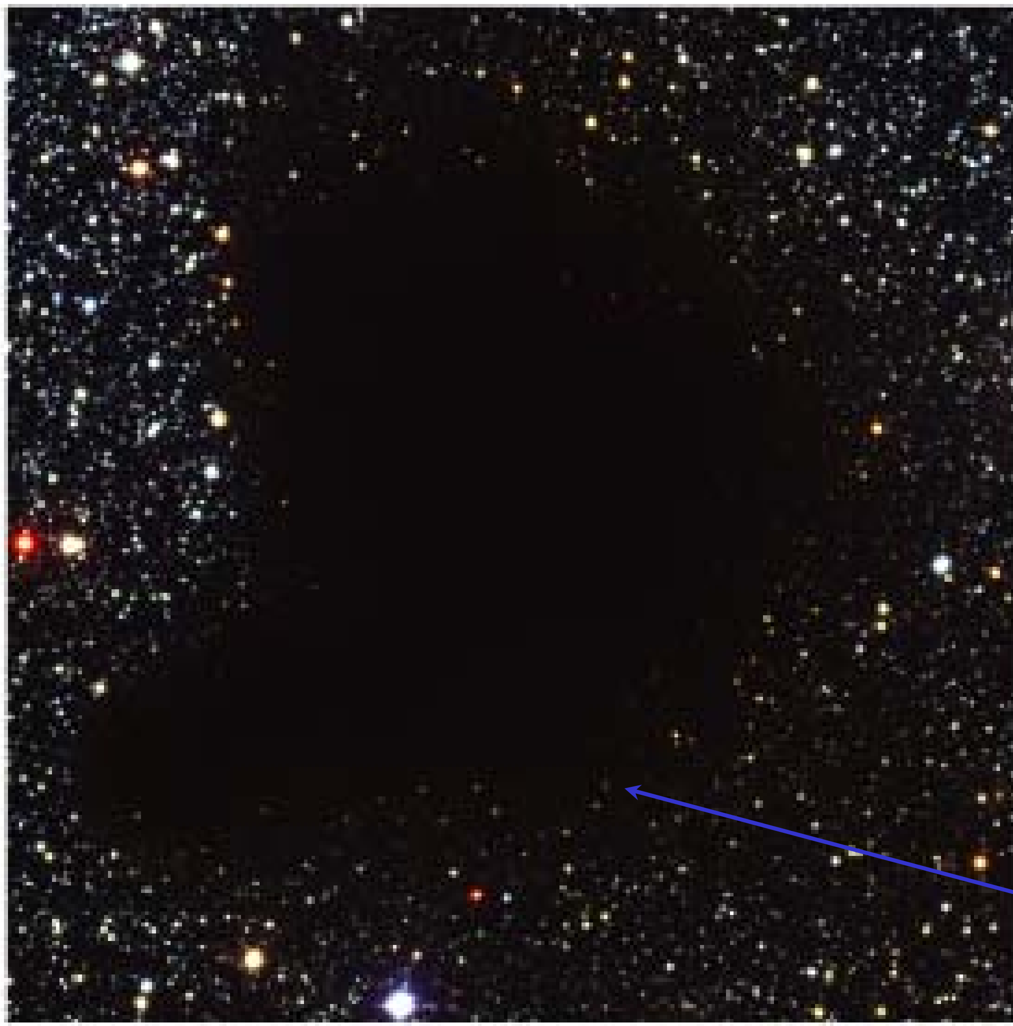
- Most of what we know about molecular clouds comes from observing the emission lines of carbon monoxide (CO)

Interstellar Dust

- Tiny solid particles of *interstellar dust* block our view of stars on the other side of a cloud

- Particles are < 1 micrometer in size and made of elements like C, O, Si, and Fe

Interstellar Reddening



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

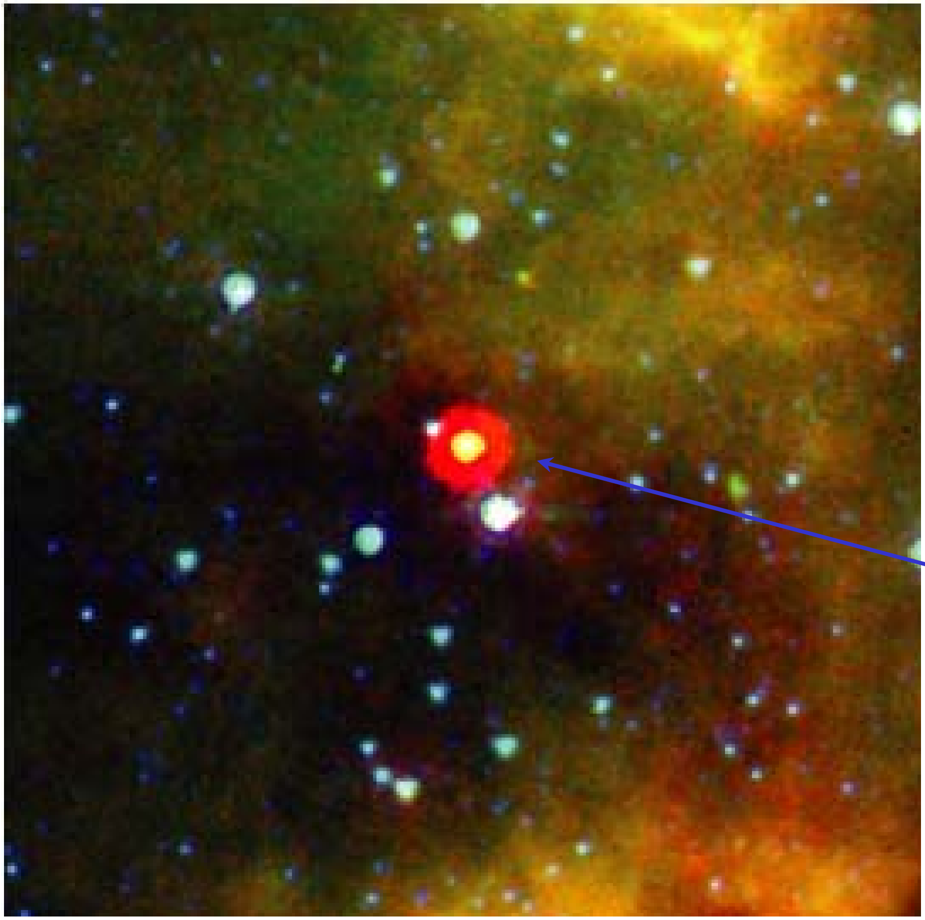
Interstellar Reddening

- Long-wavelength infrared light passes through a cloud more easily than visible light
- Observations of infrared light reveal stars on the other side of the cloud

Observing Newborn Stars

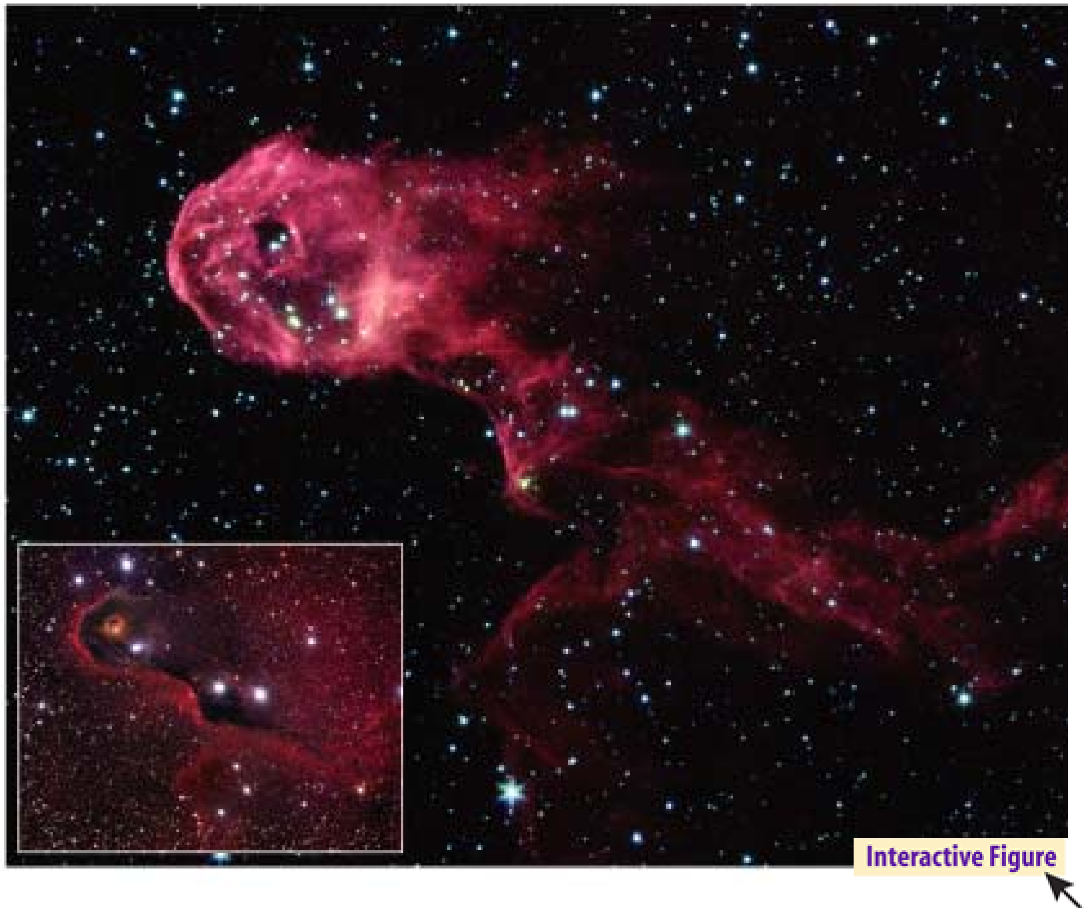
- Visible light from a newborn star is often trapped within the dark, dusty gas clouds where the star formed

Observing Newborn Stars



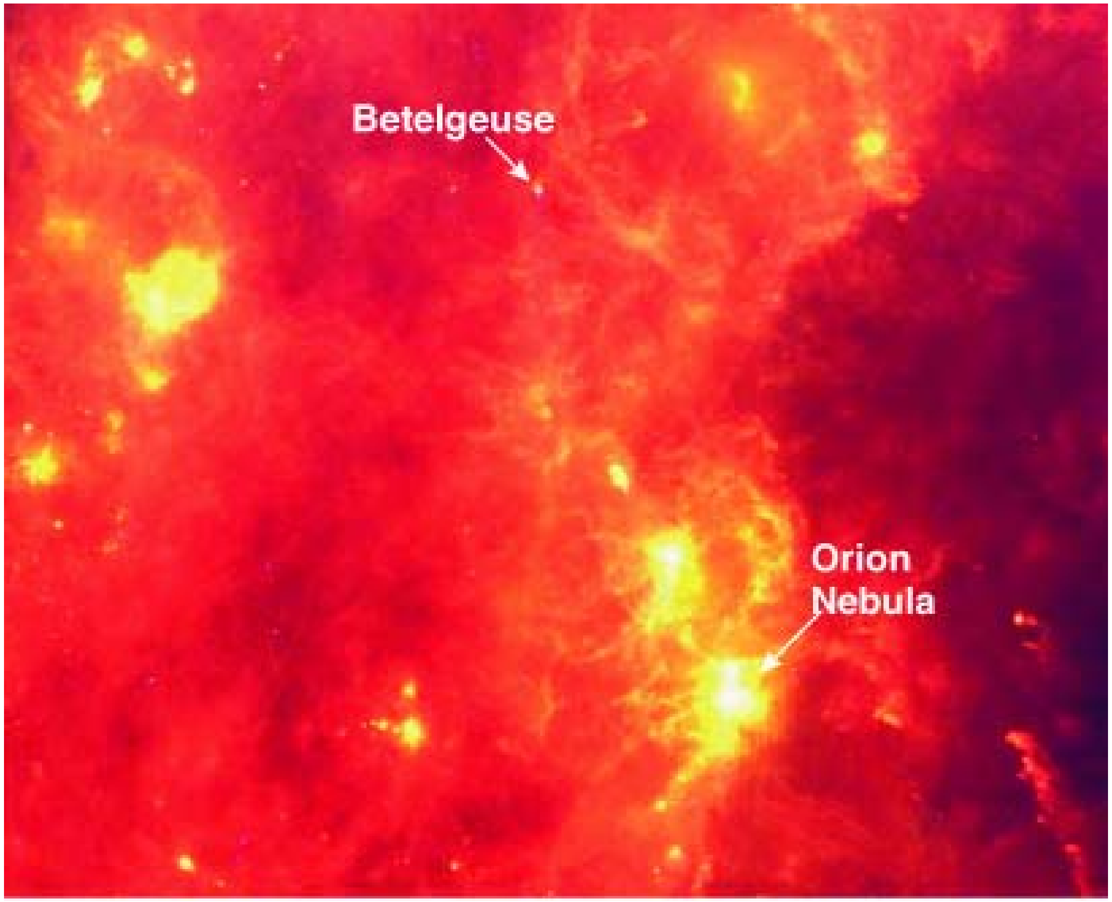
- Observing the infrared light from a cloud can reveal the newborn star embedded inside it

Glowing Dust Grains



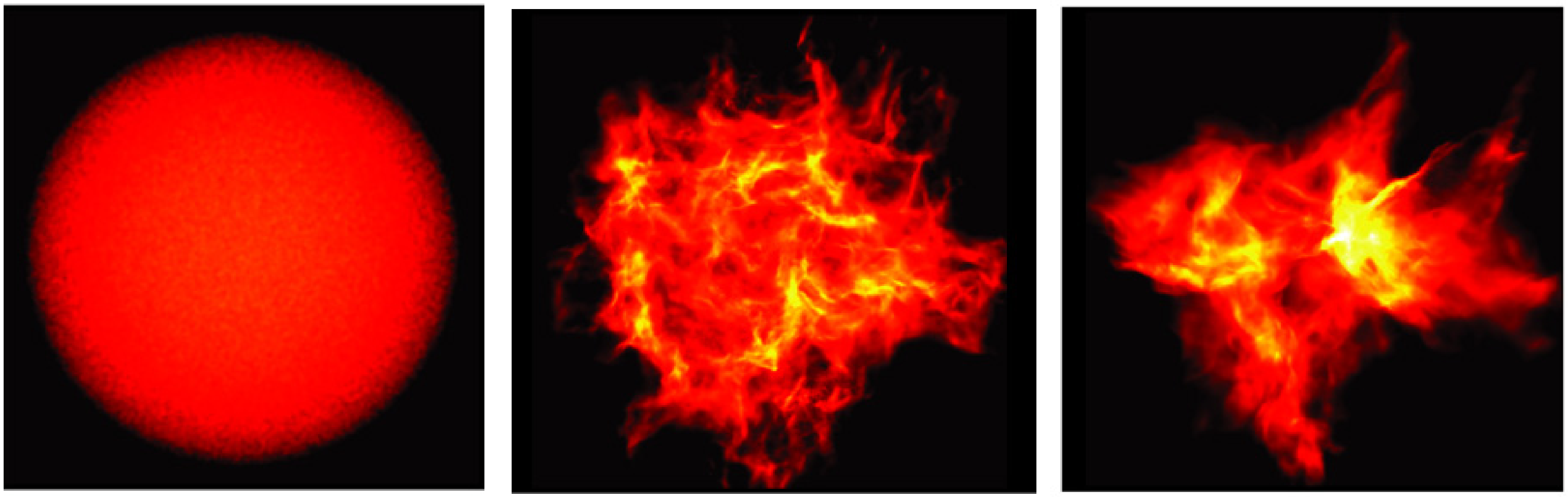
- Dust grains that absorb visible light heat up and emit infrared light of even longer wavelength

Glowing Dust Grains



- Long-wavelength infrared light is brightest from regions where many stars are currently forming

Why do stars form?



Gravity versus Pressure

- Gravity can create stars only if it can overcome the force of thermal pressure in a cloud

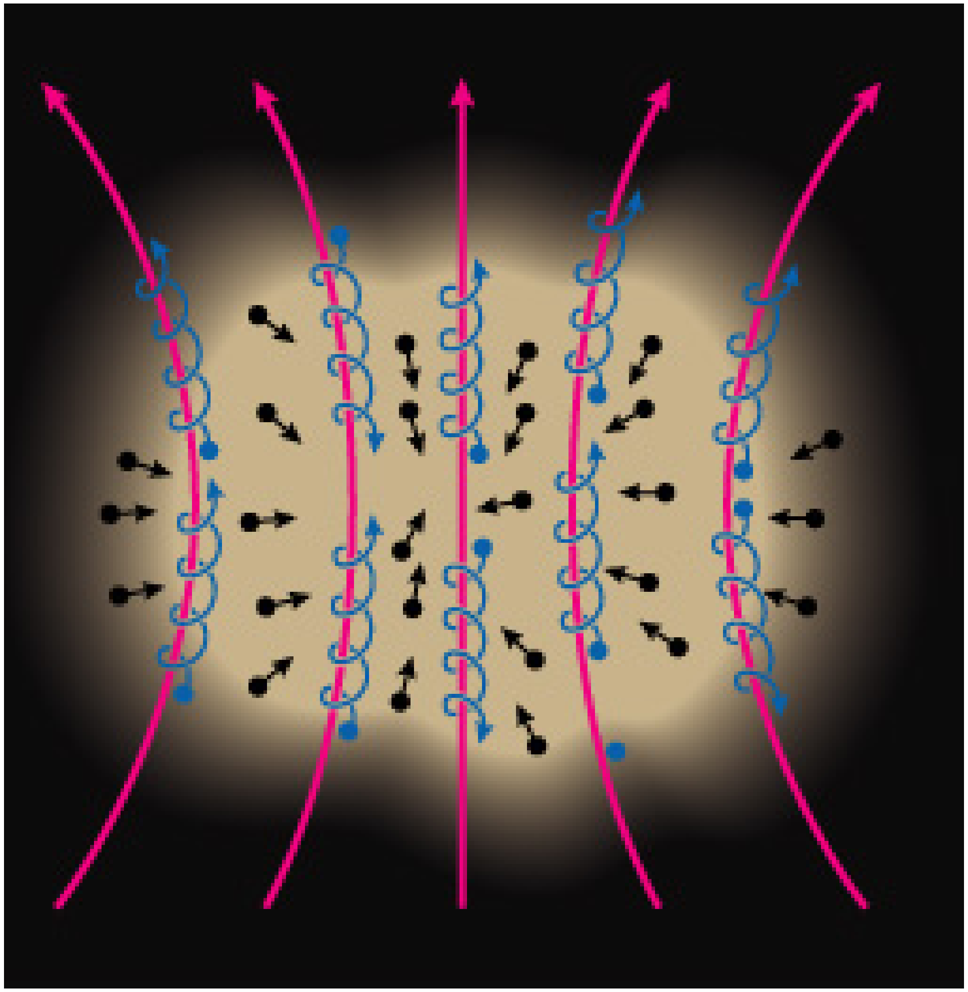
- Emission lines from molecules in a cloud can prevent a pressure buildup by converting thermal energy into infrared and radio photons

Mass of a Star-Forming Cloud

- A typical molecular cloud ($T \sim 30$ K, $n \sim 300$ particles/cm^3) must contain at least a few hundred solar masses for gravity to overcome pressure

- Emission lines from molecules in a cloud can prevent a pressure buildup by converting thermal energy into infrared and radio photons that escape the cloud

Resistance to Gravity



- A cloud must have even more mass to begin contracting if there are additional forces opposing gravity

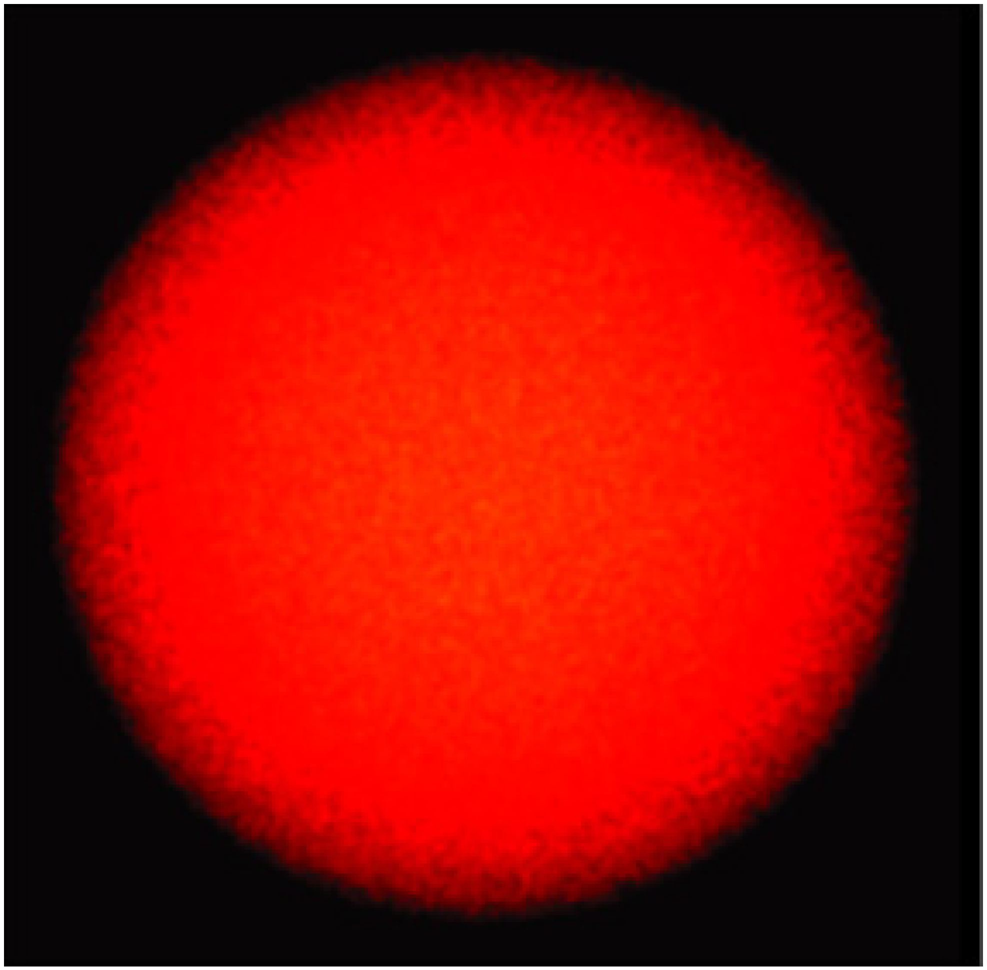
- Both magnetic fields and turbulent gas motions increase resistance to gravity

Fragmentation of a Cloud

- Gravity within a contracting gas cloud becomes stronger as the gas becomes denser

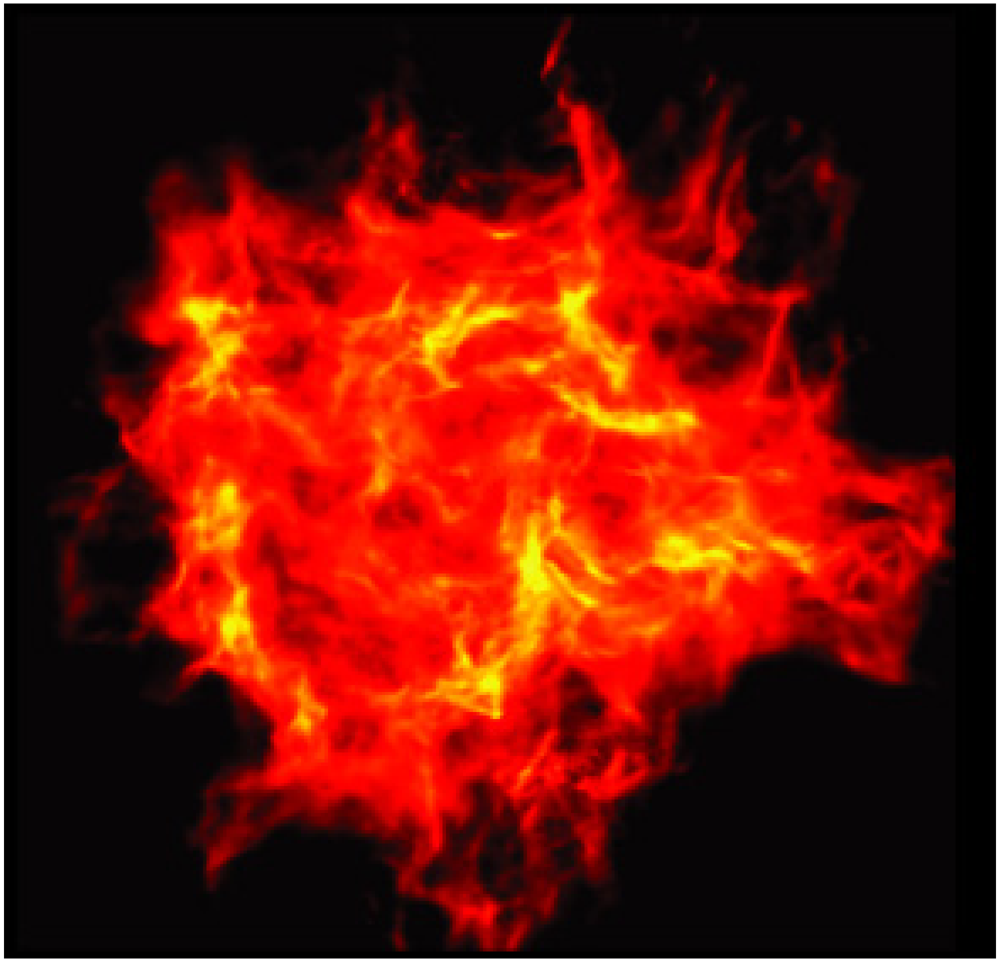
- Gravity can therefore overcome pressure in smaller pieces of the cloud, causing it to break apart into multiple fragments, each of which may go on to form a star

Fragmentation of a Cloud



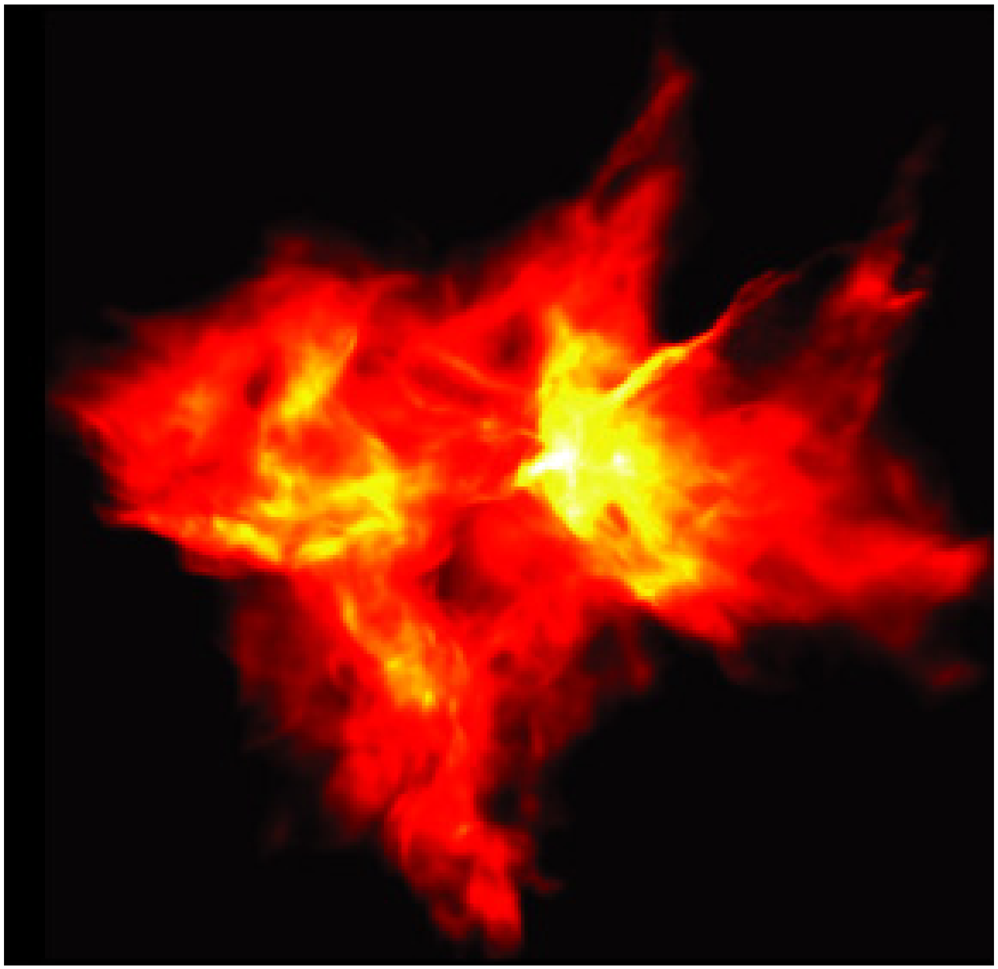
- This simulation begins with a turbulent cloud containing 50 solar masses of gas

Fragmentation of a Cloud



- The random motions of different sections of the cloud cause it to become lumpy

Fragmentation of a Cloud



- Each lump of the cloud in which gravity can overcome pressure can go on to become a star

- A large cloud can make a whole cluster of stars

Isolated Star Formation

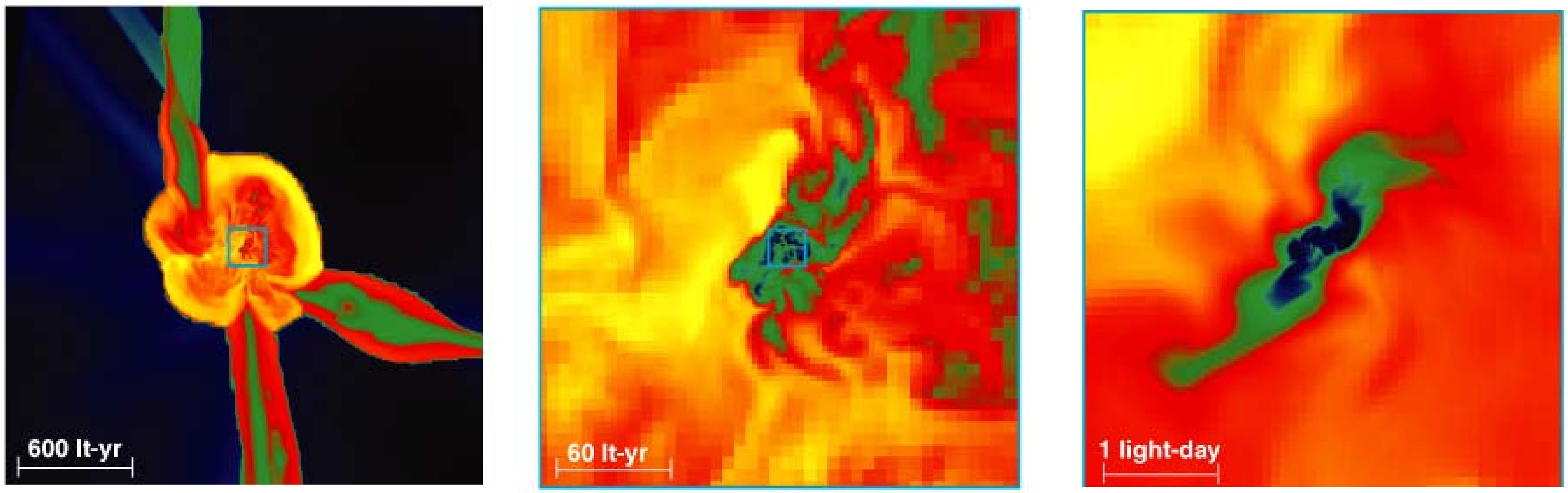
- Gravity can overcome pressure in a relatively small cloud if the cloud is unusually dense

- Such a cloud may make only a single star

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
- 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



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

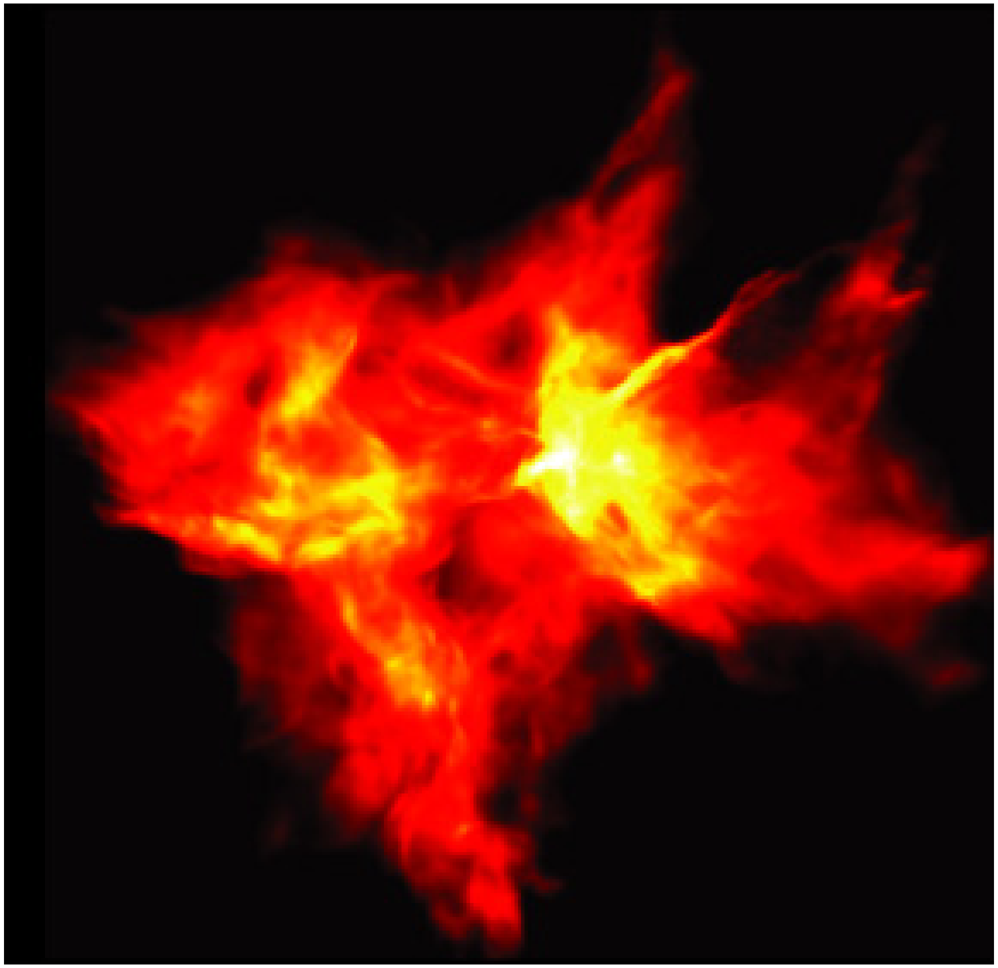
What have we learned?

- 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)
- Why 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?
- How does a cloud's rotation affect star birth?
- How does nuclear fusion begin in a newborn star?

What slows the contraction of a star-forming cloud?



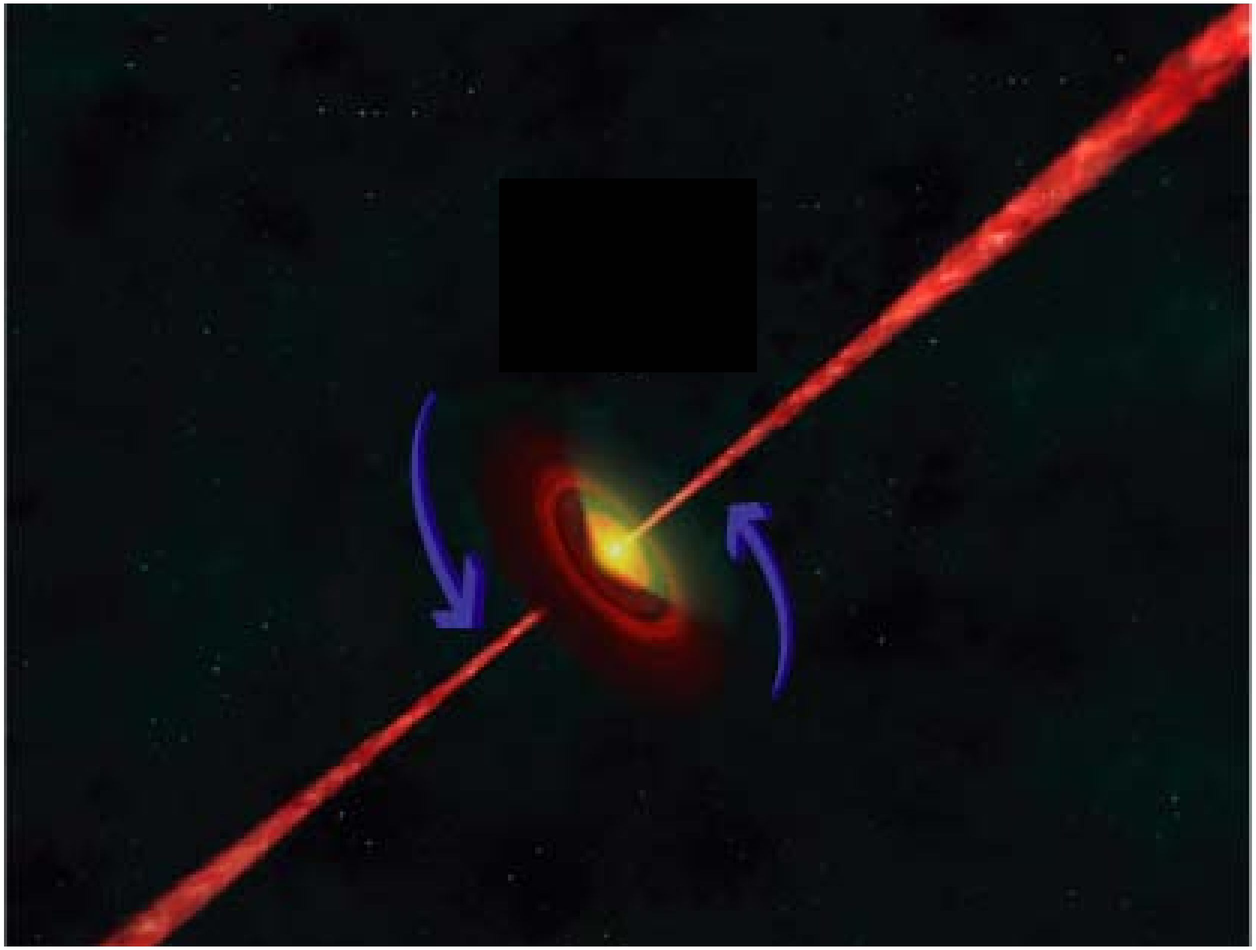
Trapping of Thermal Energy

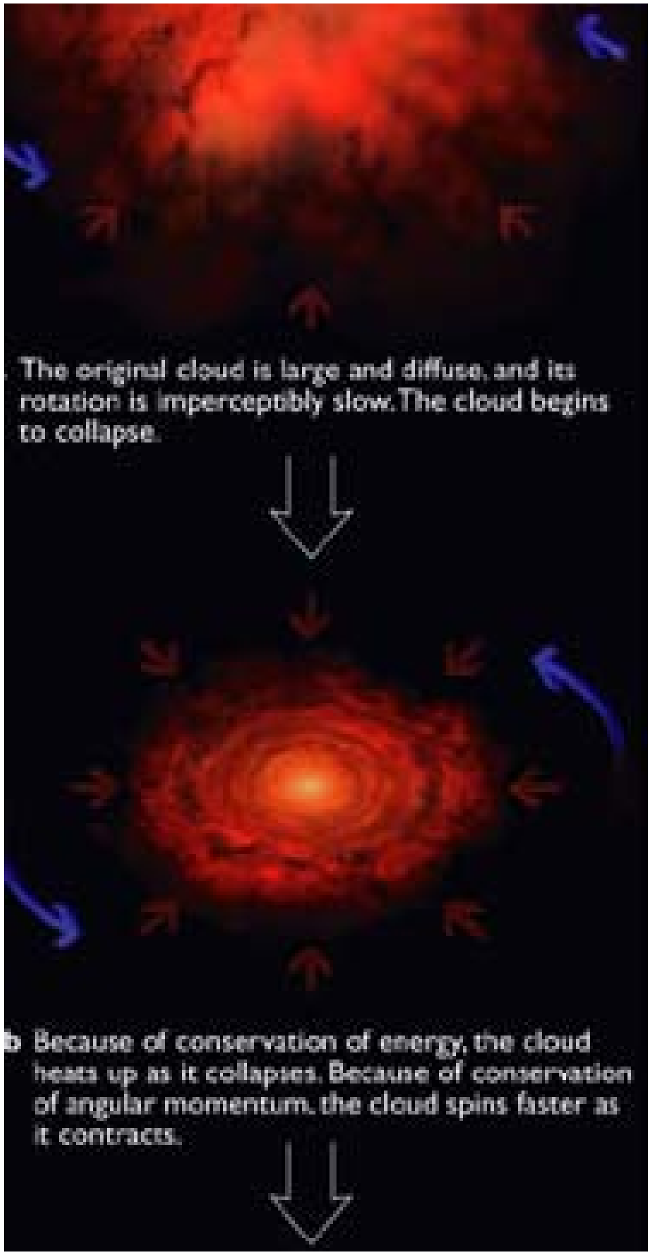
- As contraction packs the molecules and dust particles of a cloud fragment closer together, it becomes harder for infrared and radio photons to escape
- Thermal energy then begins to build up inside, increasing the internal pressure
- Contraction slows down, and the center of the cloud fragment becomes a **protostar**

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

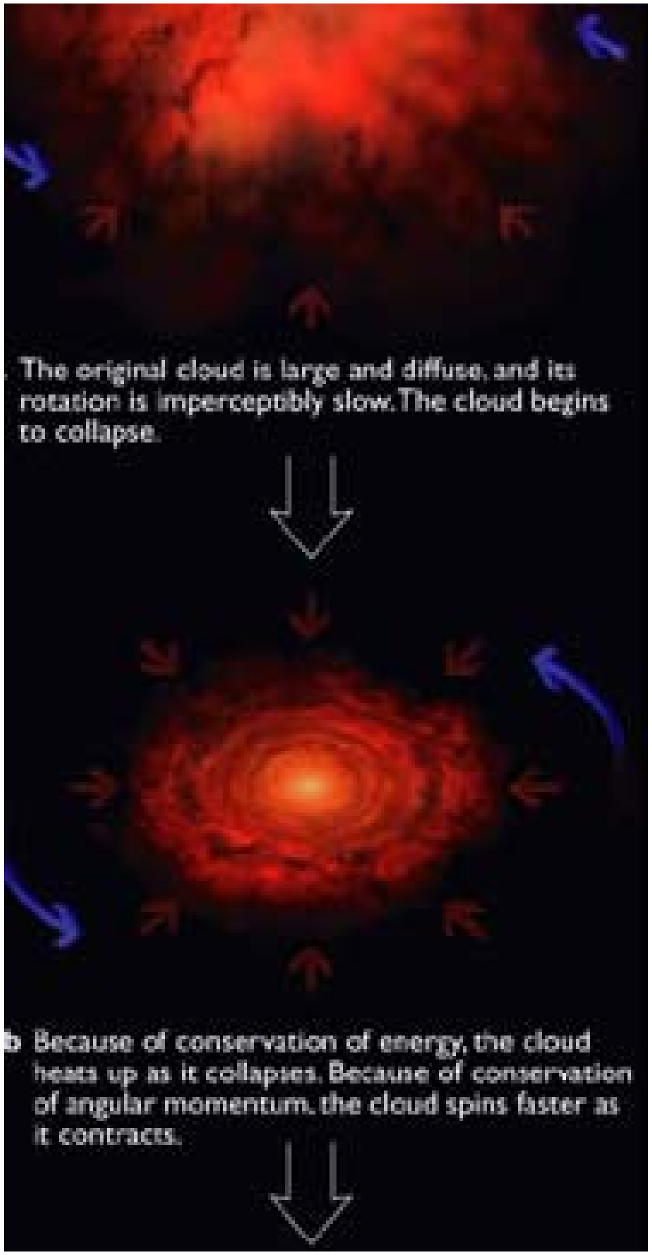
How does a cloud's rotation affect star birth?





Evidence from the Solar System

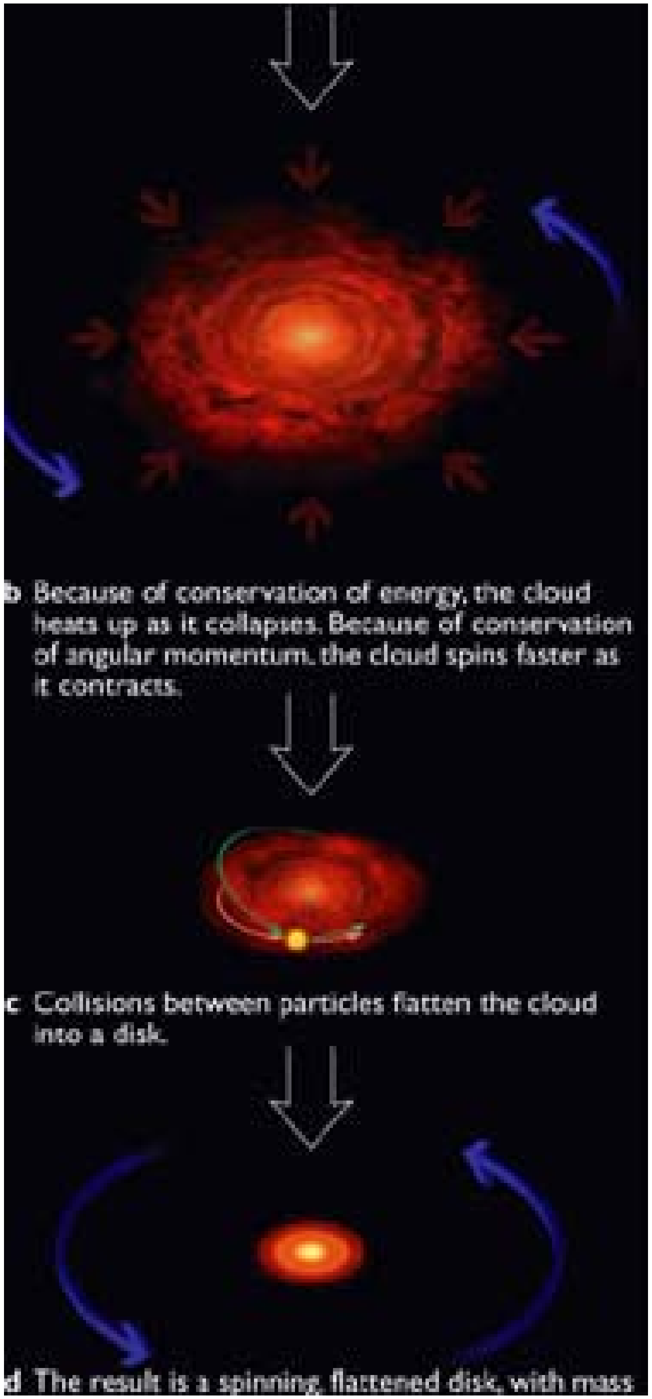
- The nebular theory of solar system formation illustrates the importance of rotation



Conservation of Angular Momentum

- The rotation speed of the cloud from which a star forms increases as the cloud contracts

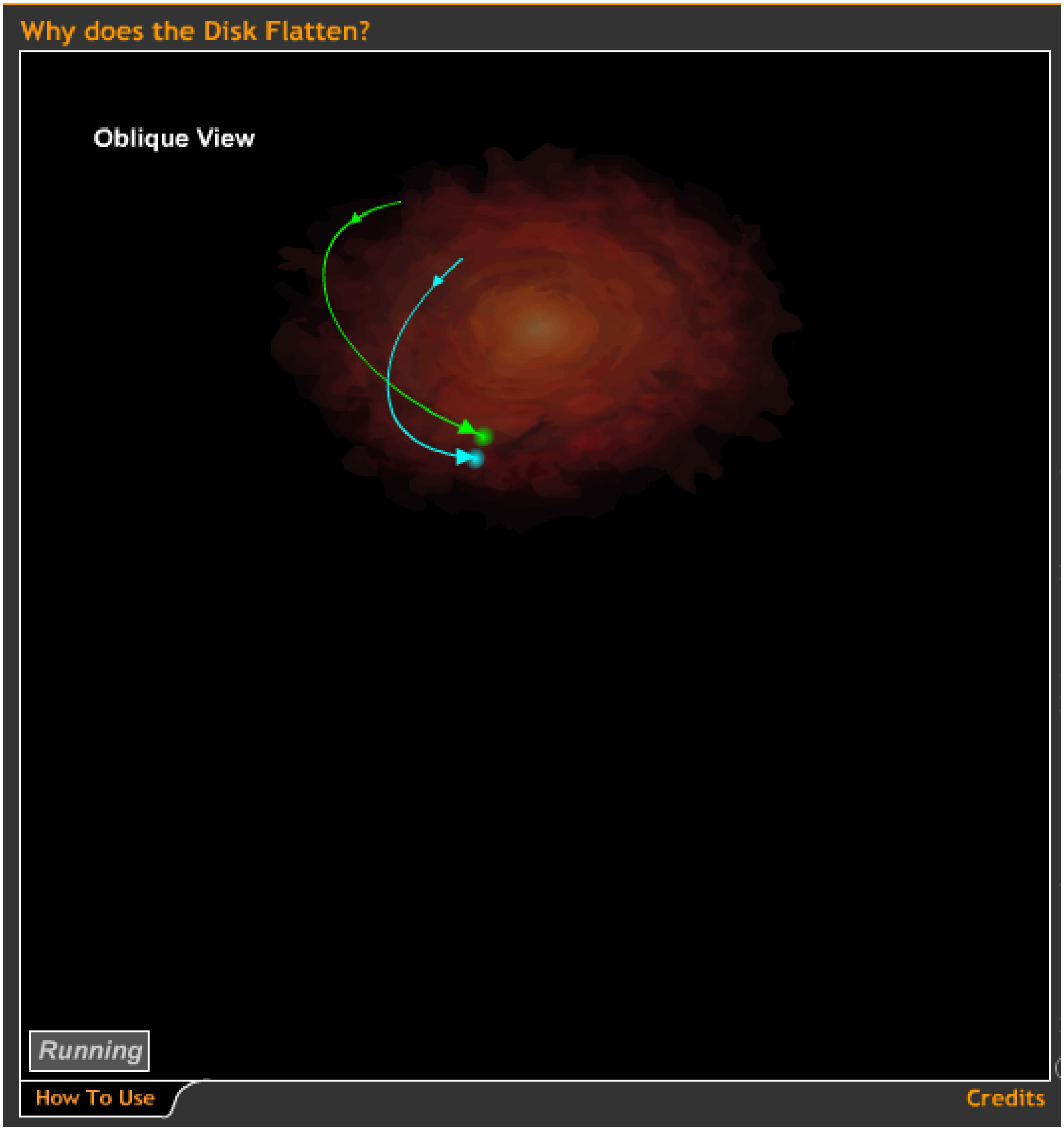
Rotation of a contracting cloud speeds up for the same reason a skater speeds up as she pulls in her arms



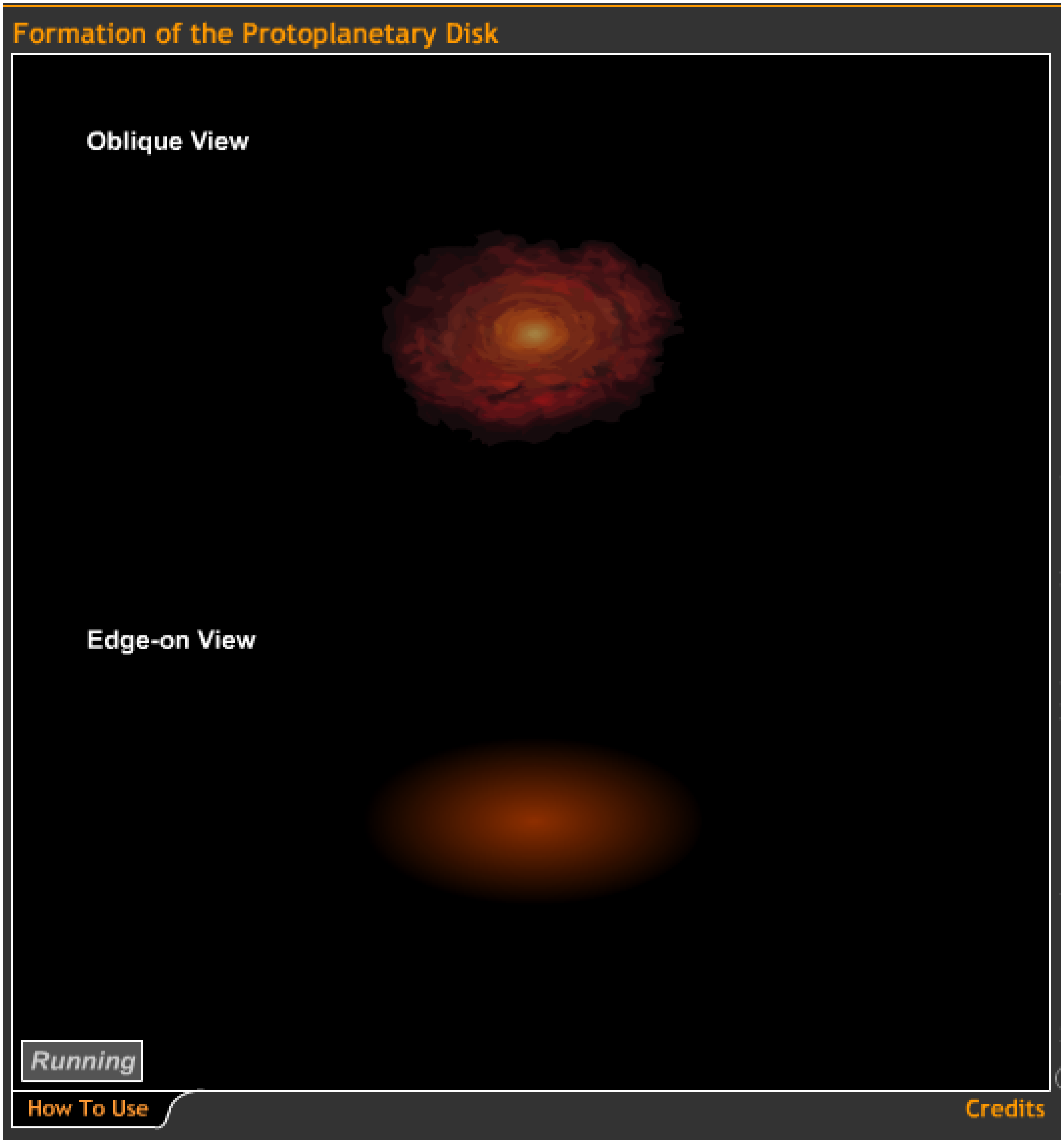
Flattening

- Collisions between particles in the cloud cause it to flatten into a disk

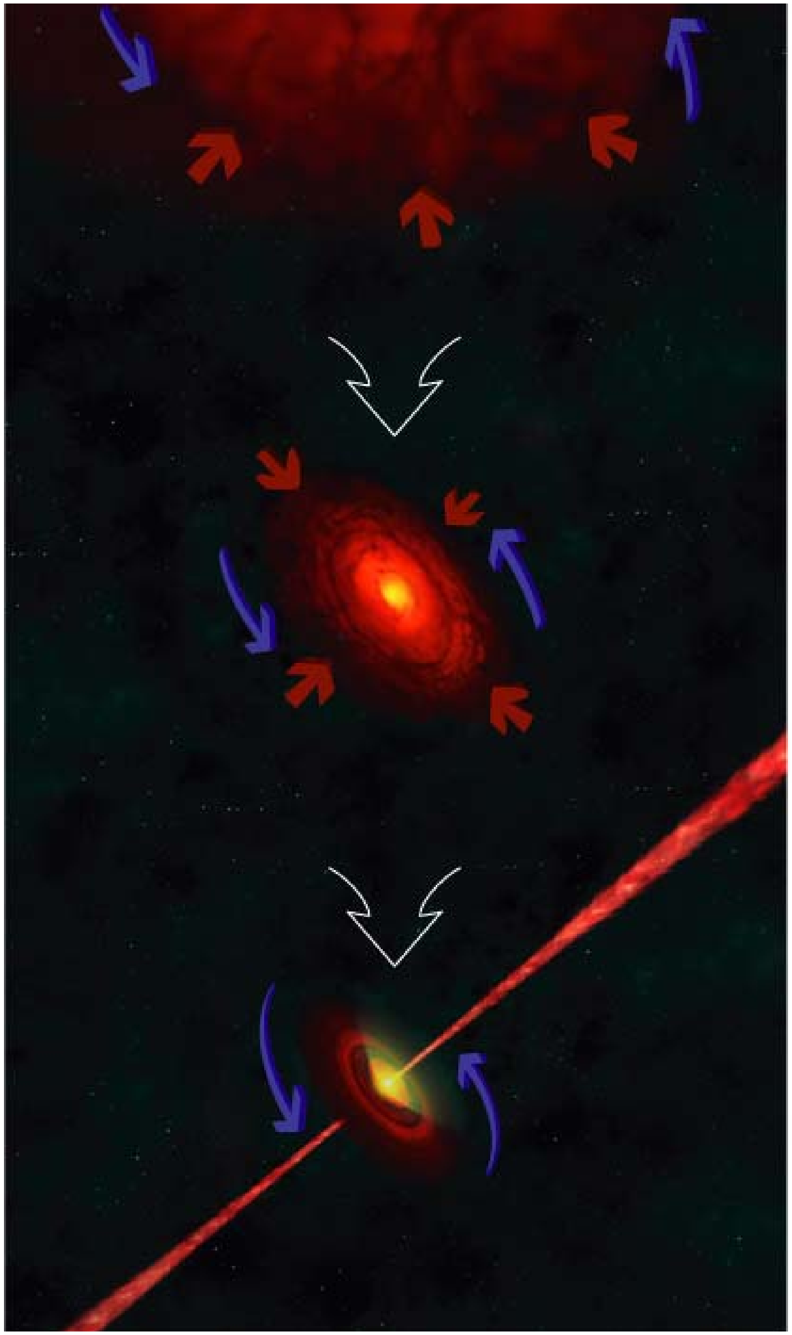
Collisions between gas particles in cloud gradually reduce random motions



Collisions between gas particles also reduce up and down motions

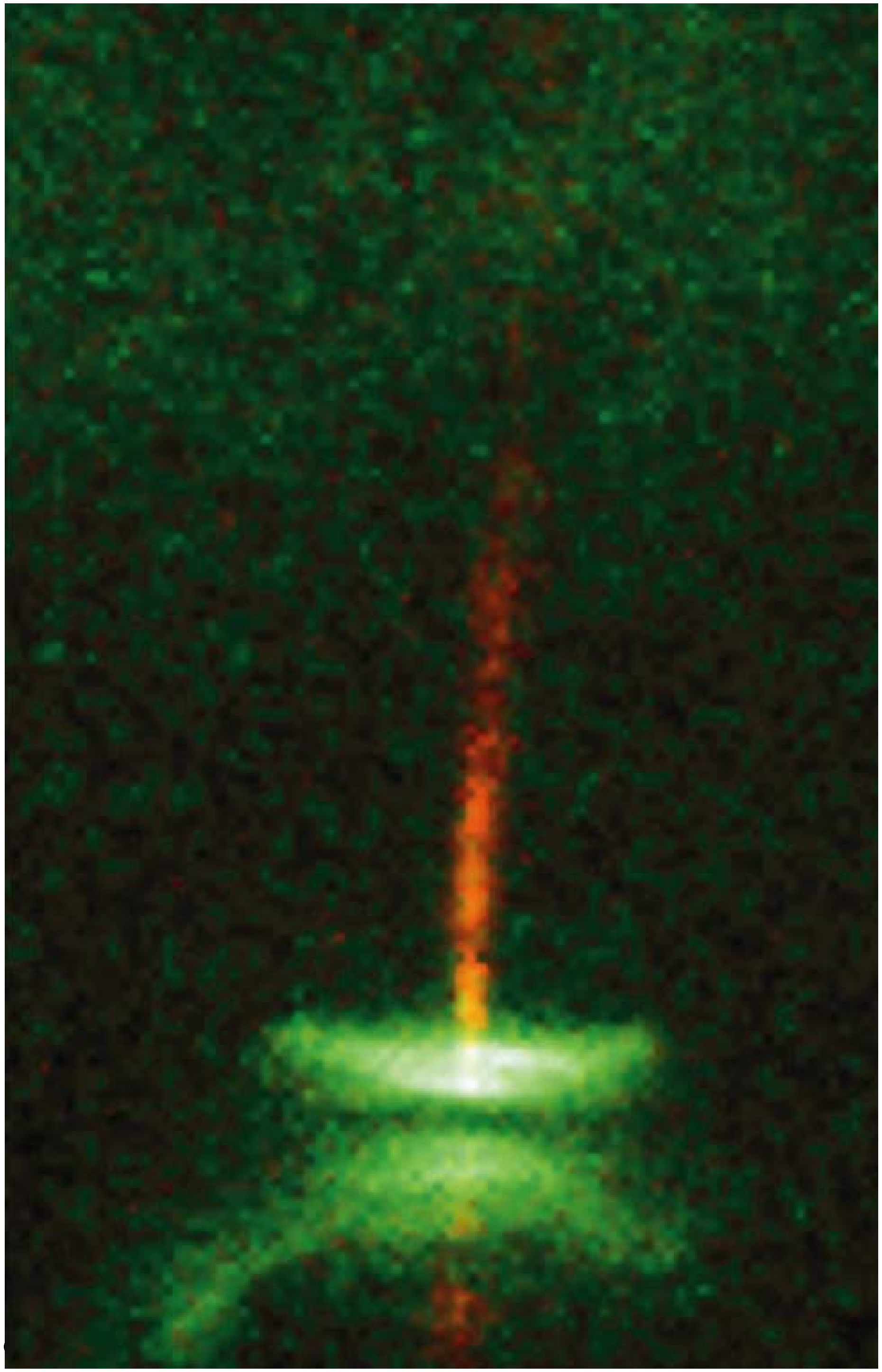


Spinning cloud flattens as it shrinks

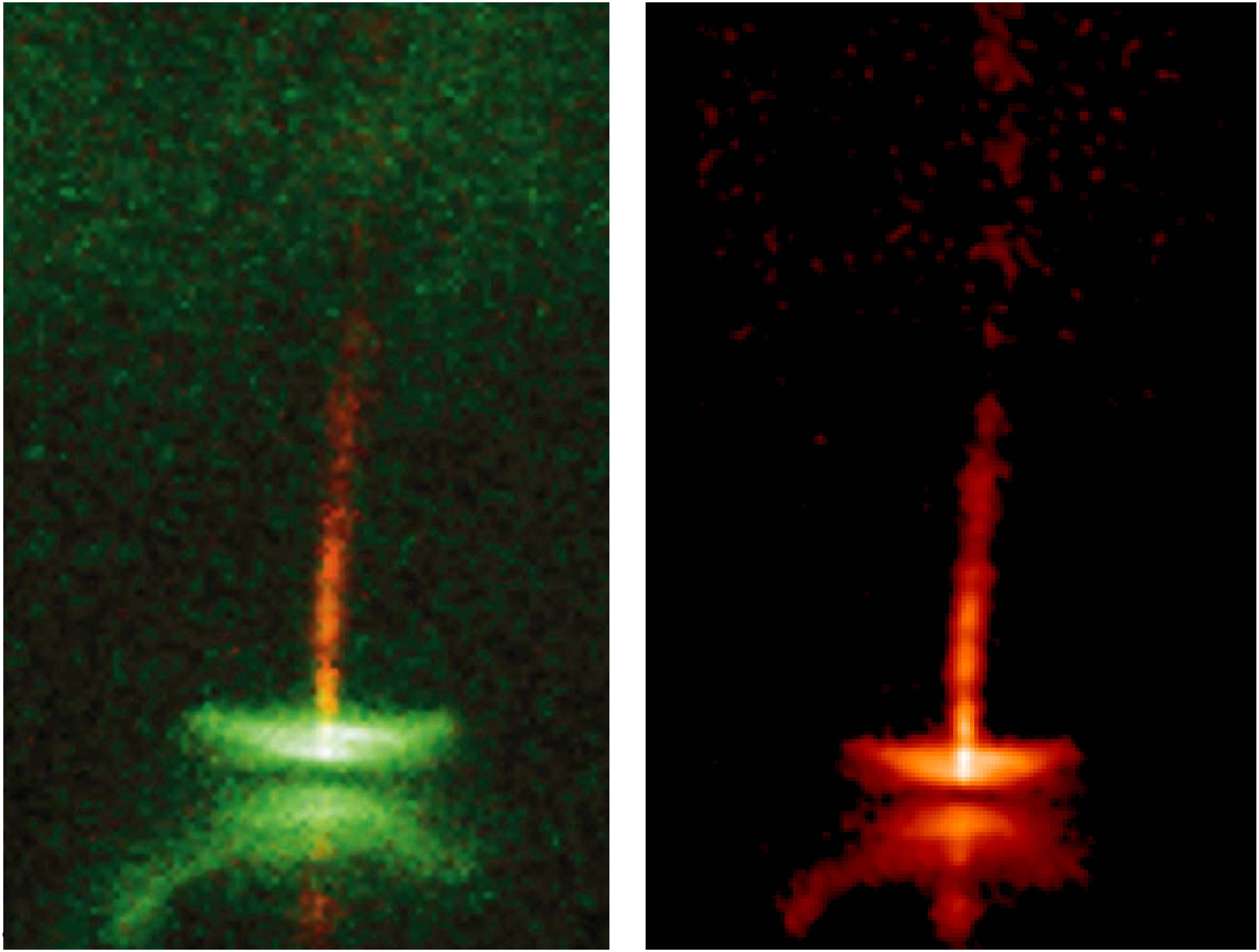


Formation of Jets

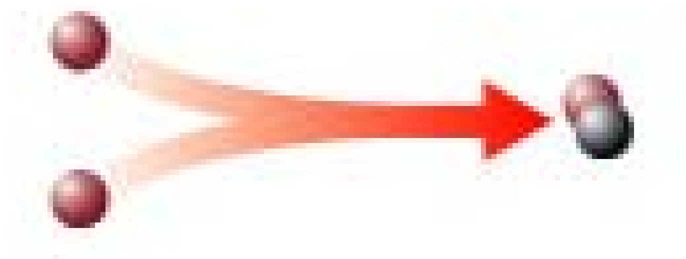
- Rotation also causes jets of matter to shoot out along the rotation axis



Jets are observed coming from the centers of disks around protostars



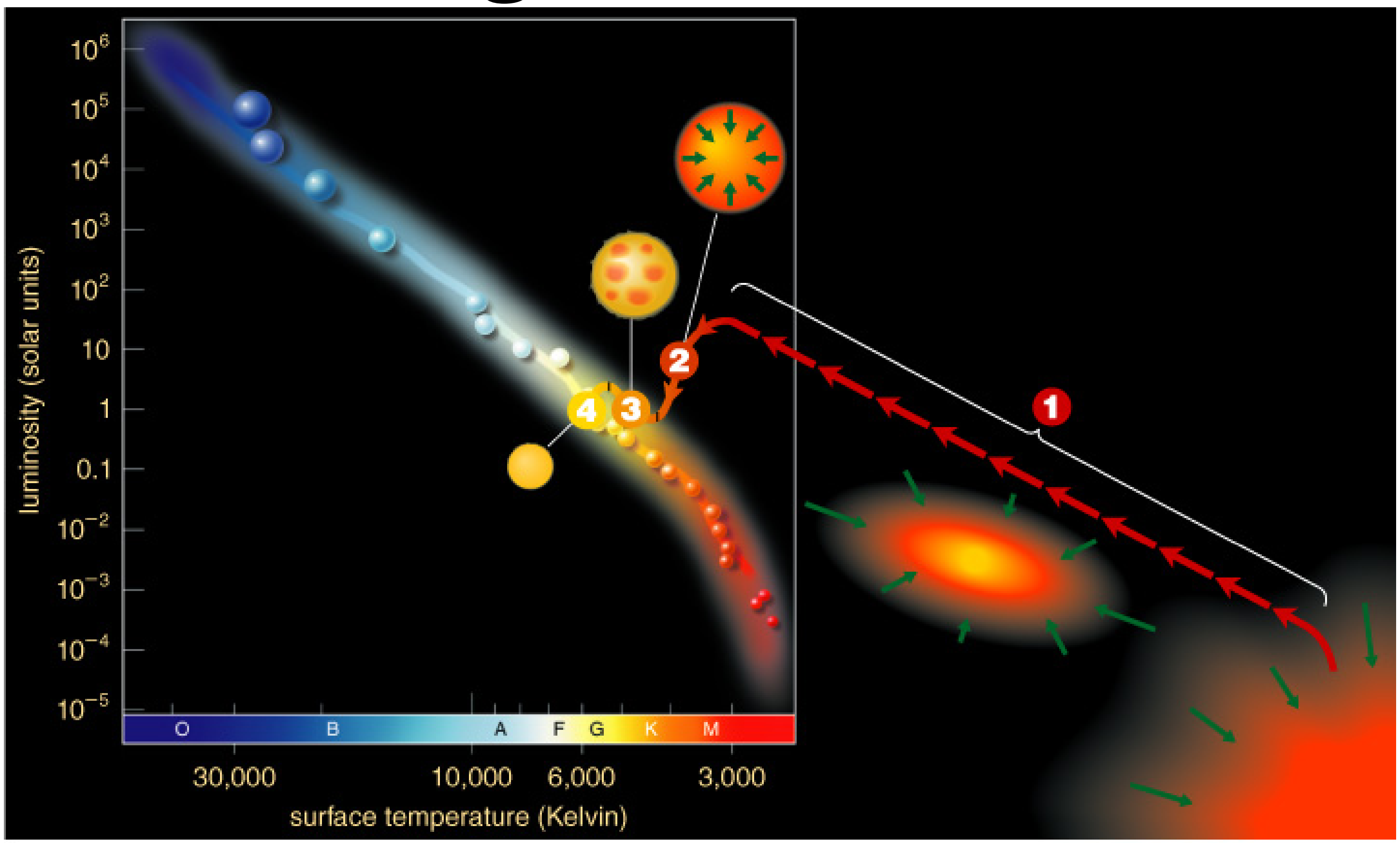
How does nuclear fusion begin in a newborn star?



From Protostar to Main Sequence

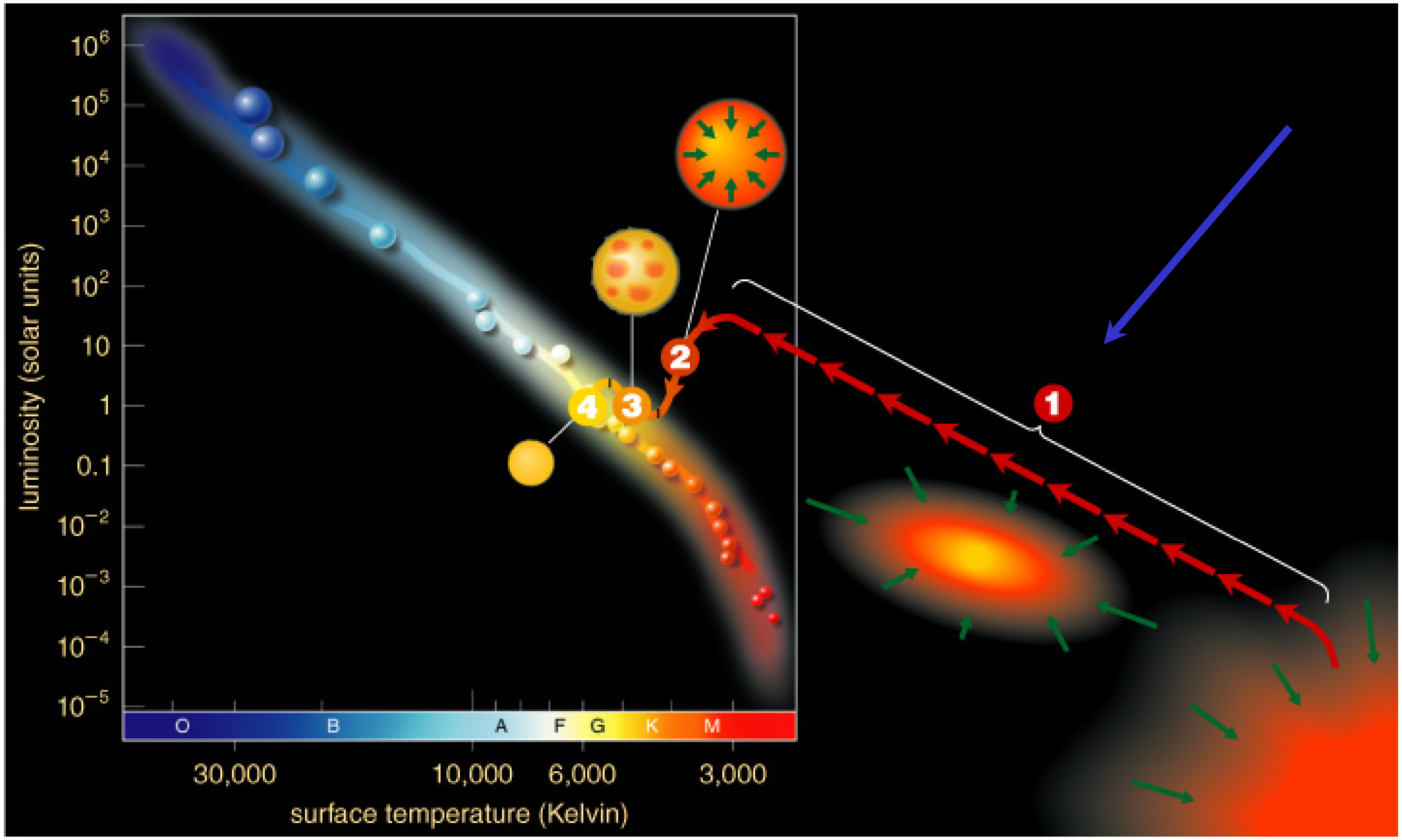
- Protostar looks starlike after the surrounding gas is blown away, but its thermal energy comes from gravitational contraction, not fusion
- Contraction must continue until the core becomes hot enough for nuclear fusion
- Contraction stops when the energy released by core fusion balances energy radiated from the surface—the star is now a *main-sequence star*

Birth Stages on a Life Track



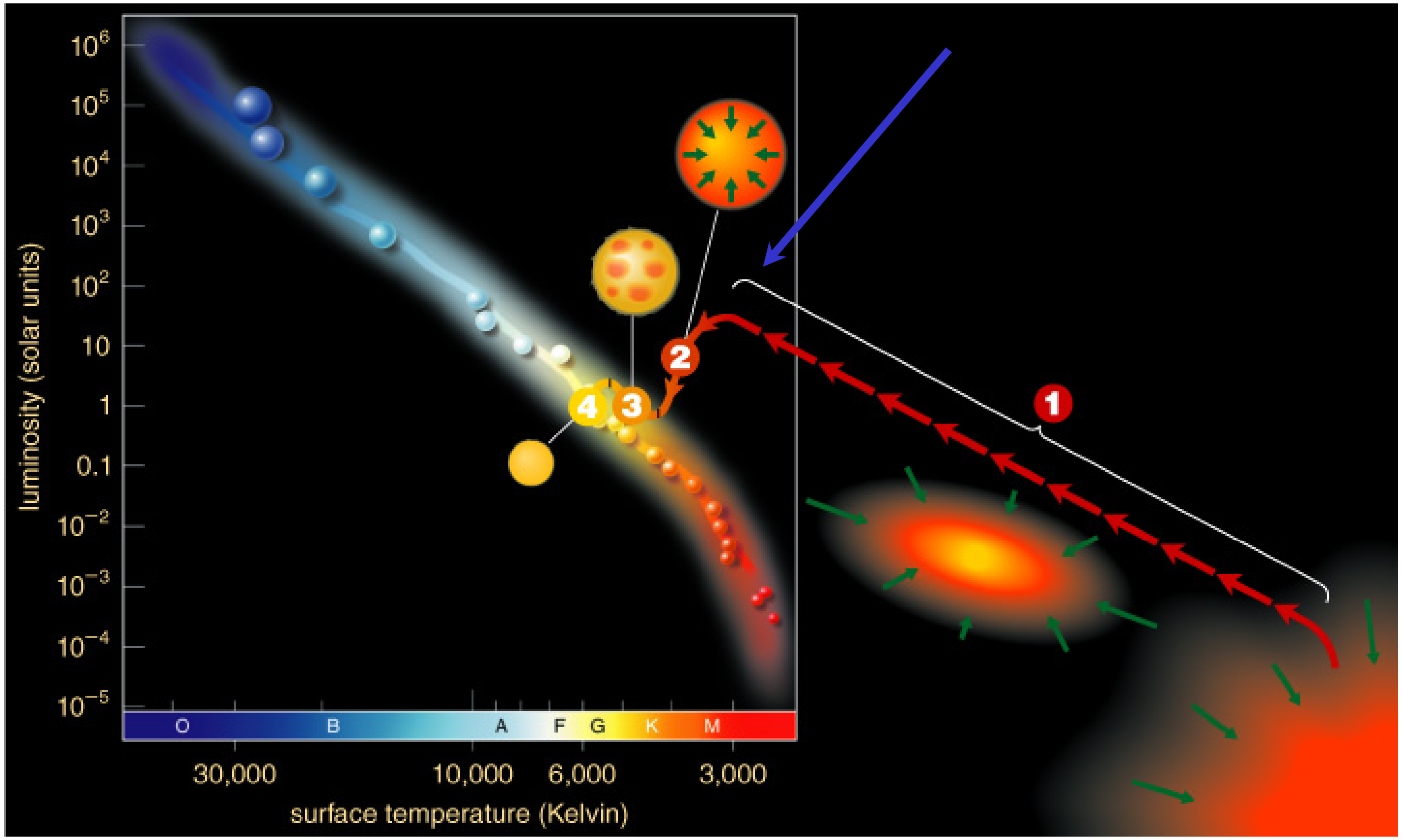
- Life track illustrates star's surface temperature and luminosity at different moments in time

Assembly of a Protostar



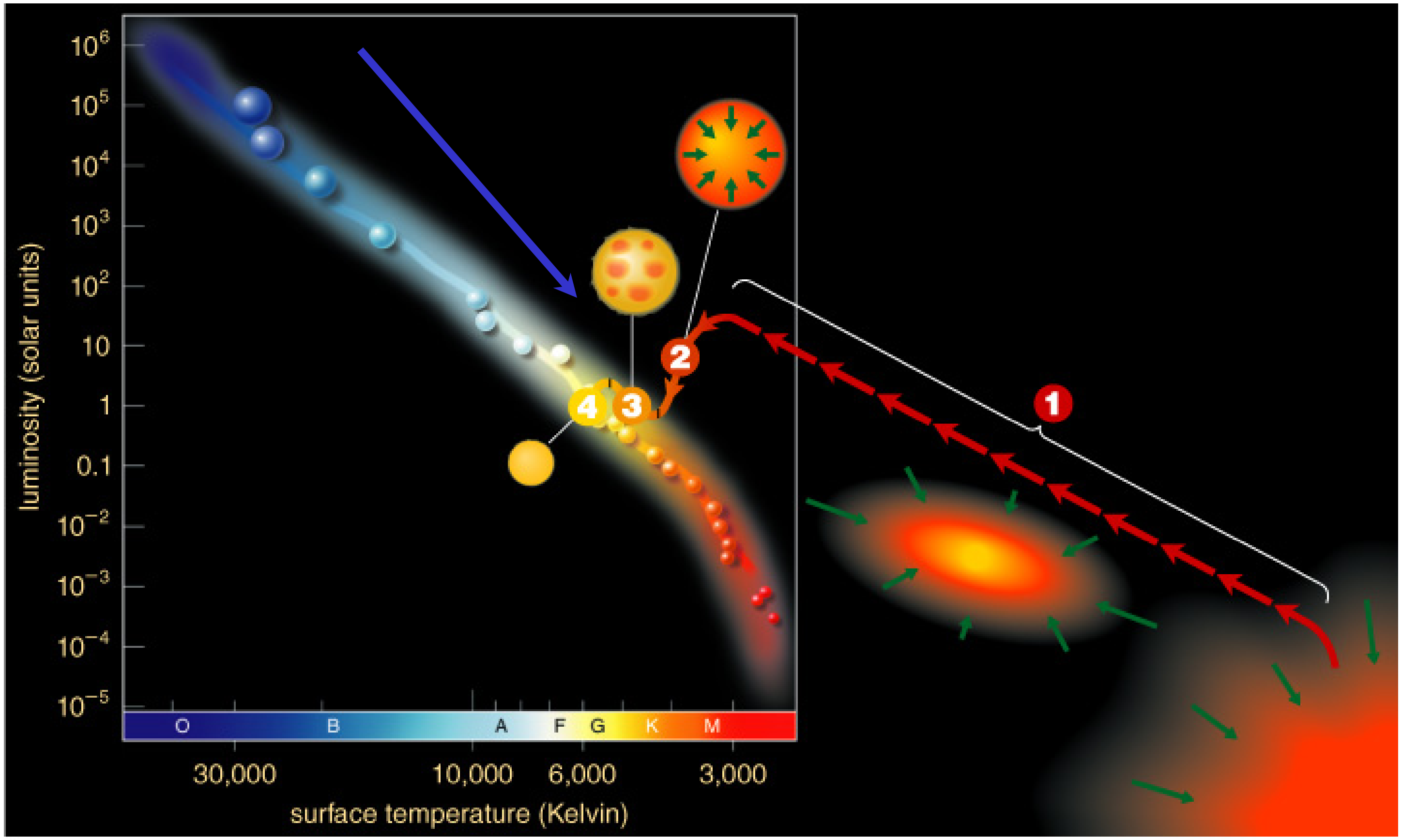
- Luminosity and temperature grow as matter collects into a protostar

Convective Contraction



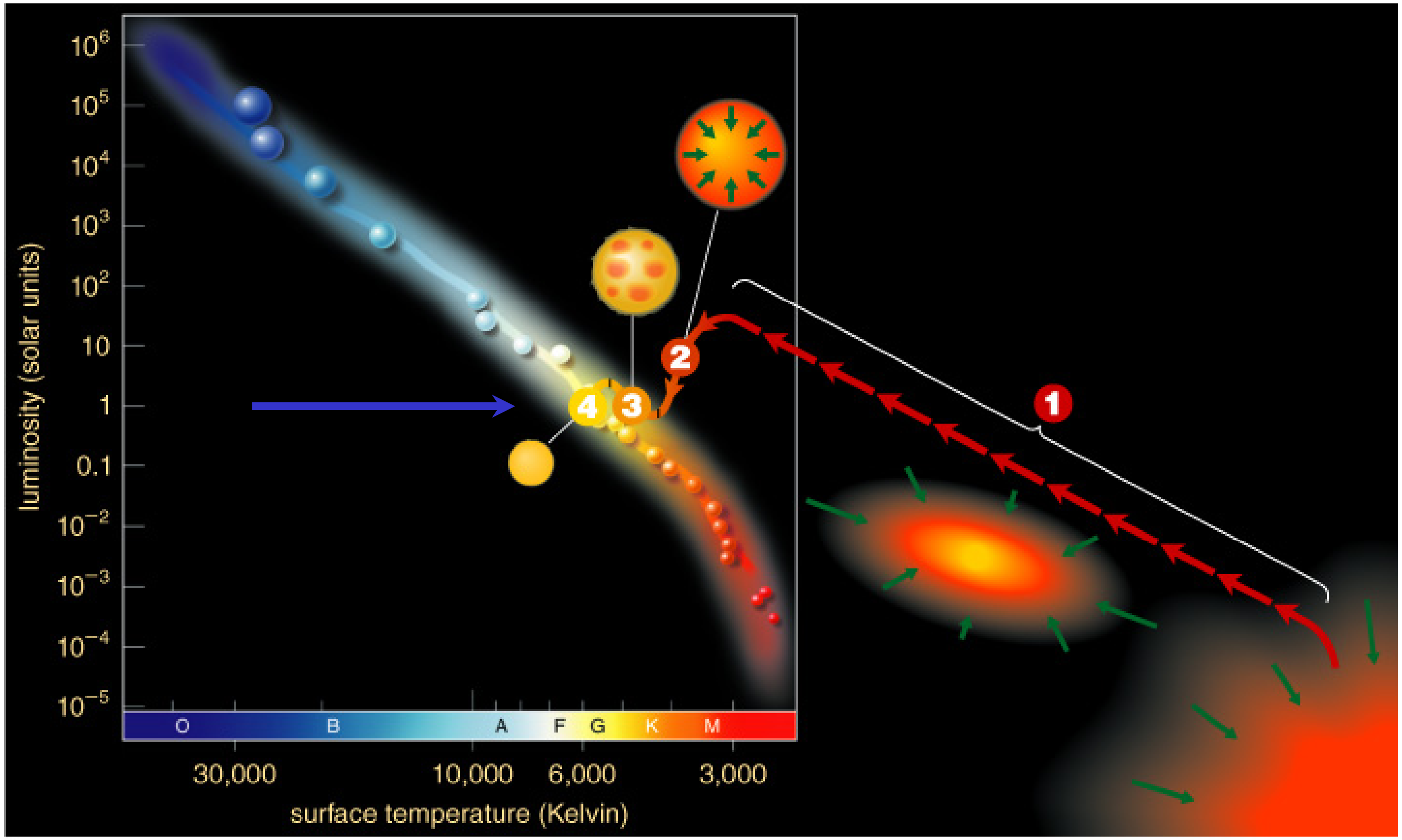
- Surface temperature remains near 3,000 K while convection is main energy transport mechanism

Radiative Contraction



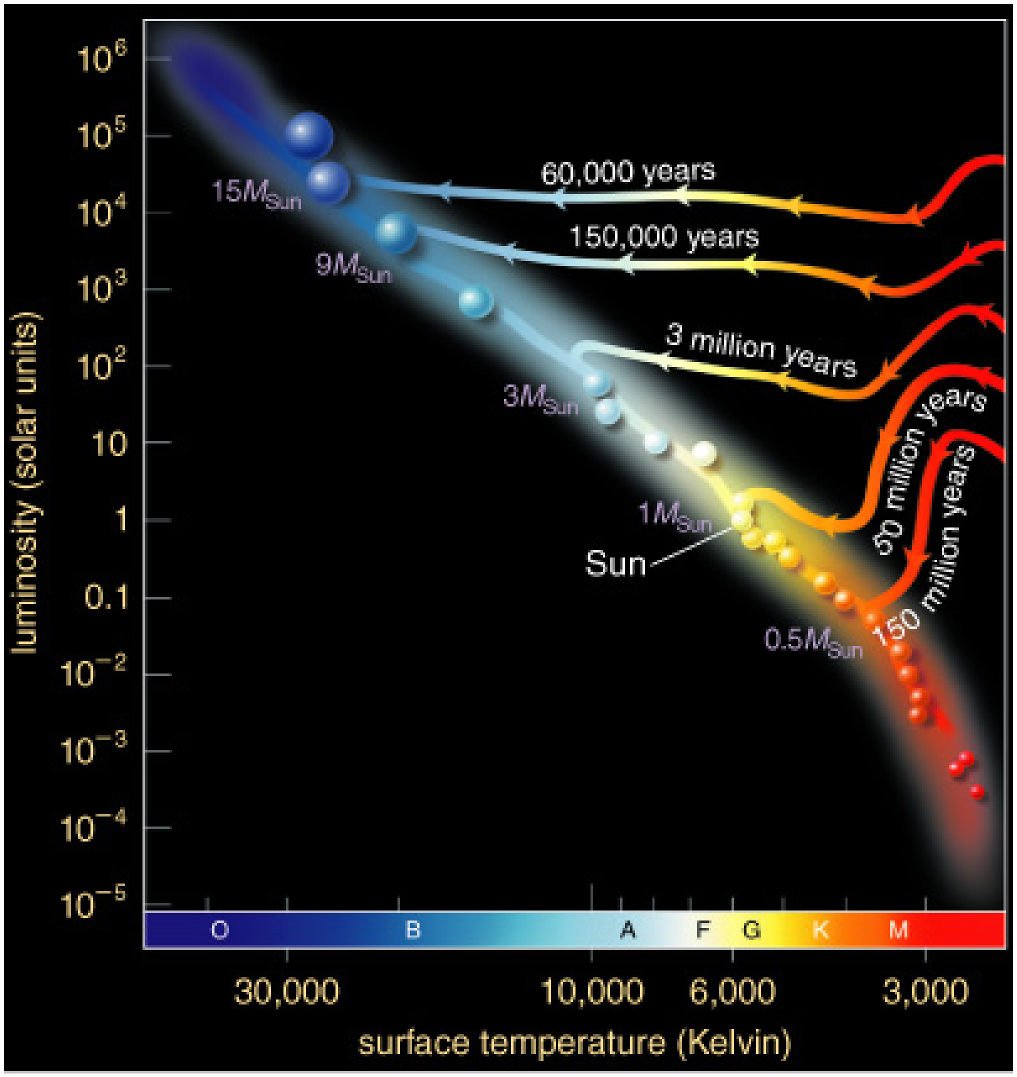
- Luminosity remains nearly constant during late stages of contraction, while radiation is transporting energy through star

Self-Sustaining Fusion



- Core temperature continues to rise until star arrives on the main sequence

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
- How does a cloud's rotation affect star birth?
  - Conservation of angular momentum leads to the formation of disks around protostars

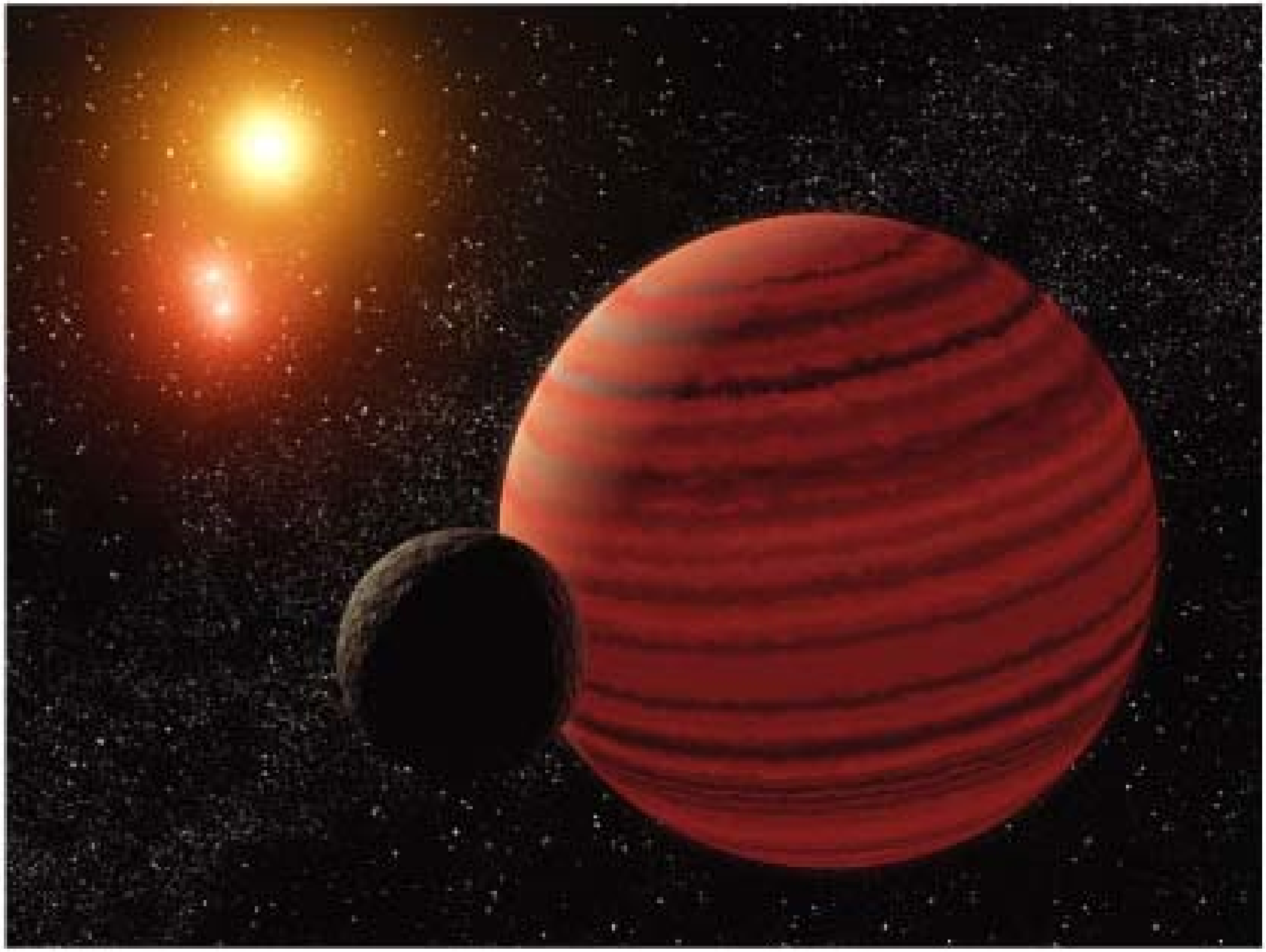
What have we learned?

- 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

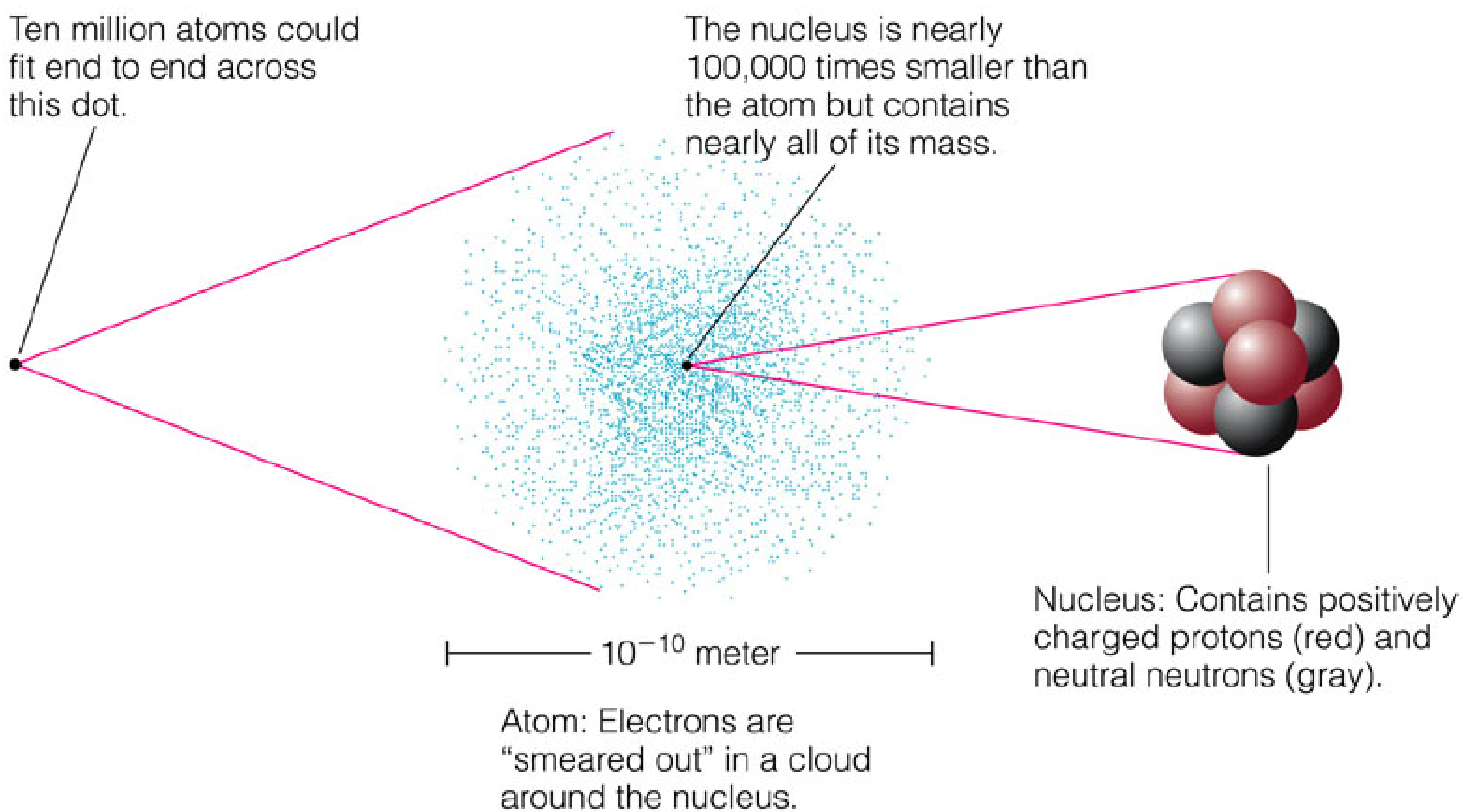
- Our goals for learning
- What is the smallest mass a newborn star can have?
- What is the greatest mass a newborn star can have?
- What are the typical masses of newborn stars?

What is the smallest mass a newborn star can have?



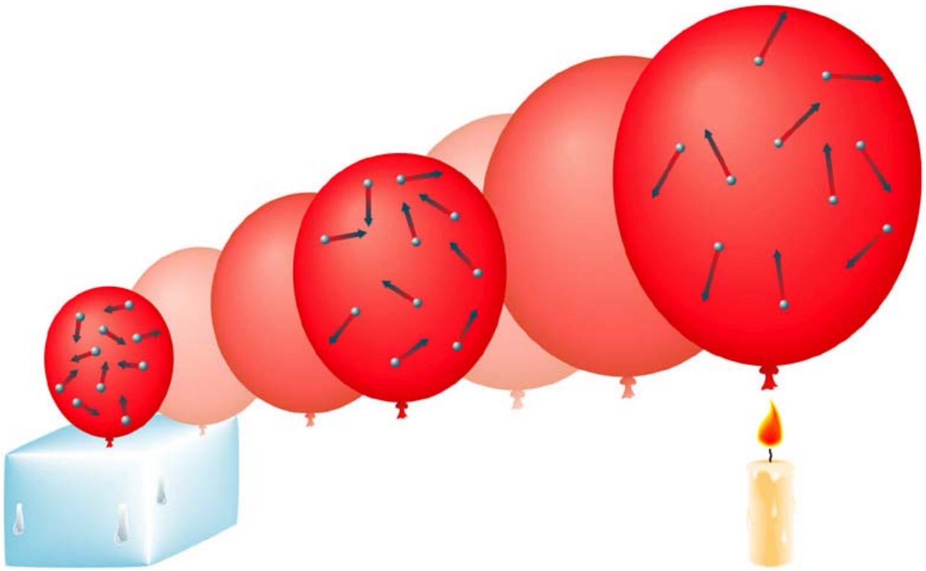
Fusion and Contraction

- Fusion will not begin in a contracting cloud if some sort of force stops contraction before the core temperature rises above 10^7 K.
- Thermal pressure cannot stop contraction because the star is constantly losing thermal energy from its surface through radiation
- Is there another form of pressure that can stop contraction?



Degeneracy Pressure:

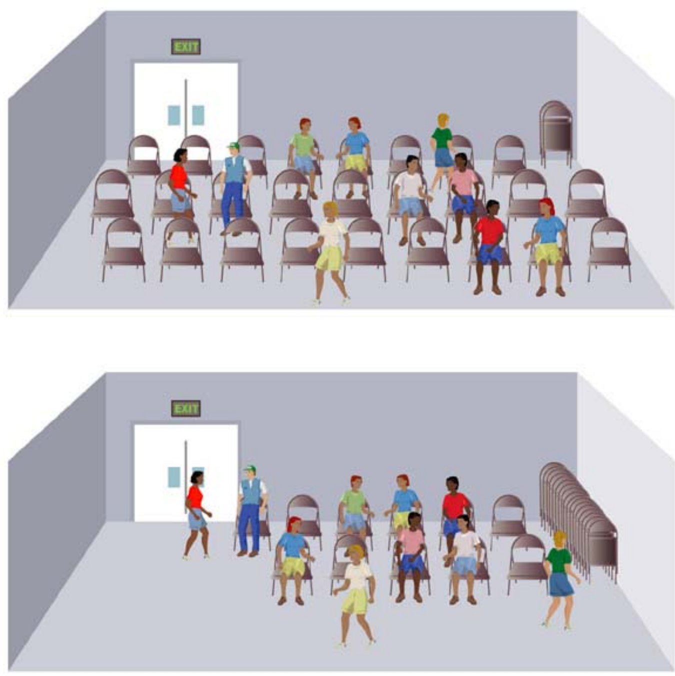
Laws of quantum mechanics prohibit two electrons from occupying same state in same place



Thermal Pressure:

Depends on heat content

The main form of pressure in most stars

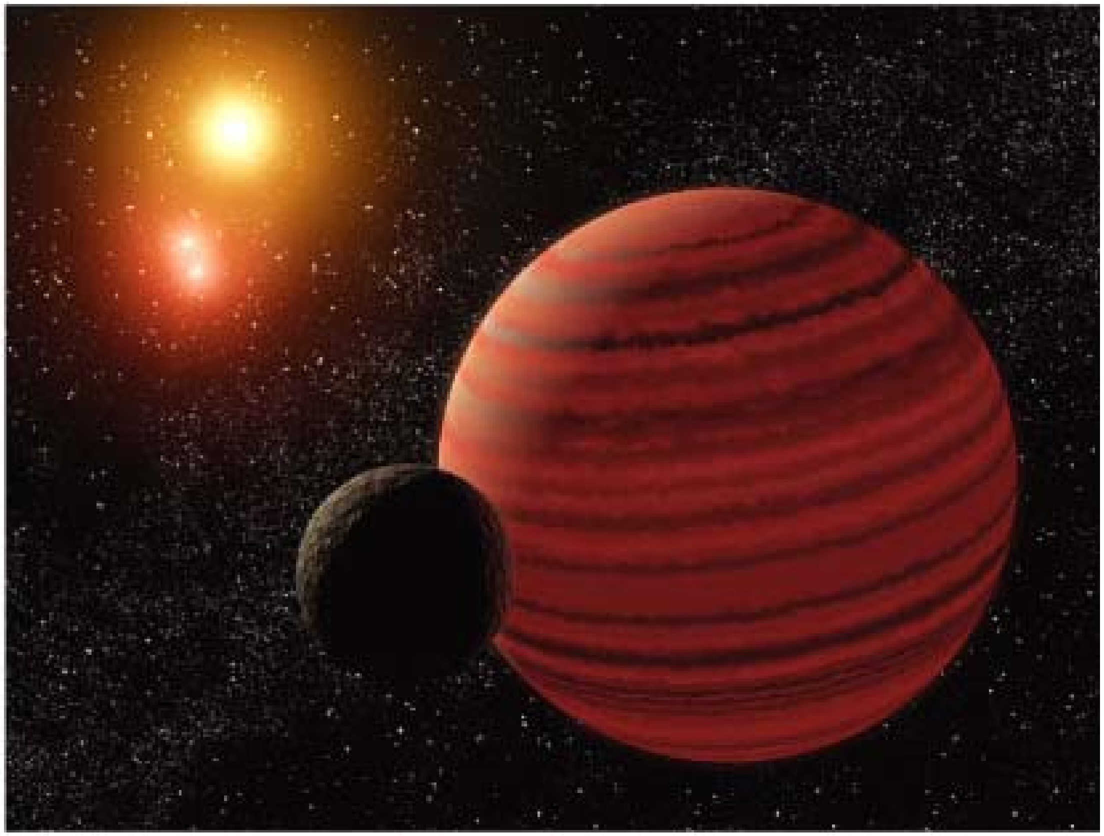


Degeneracy Pressure:

Particles can’t be in same state in same place

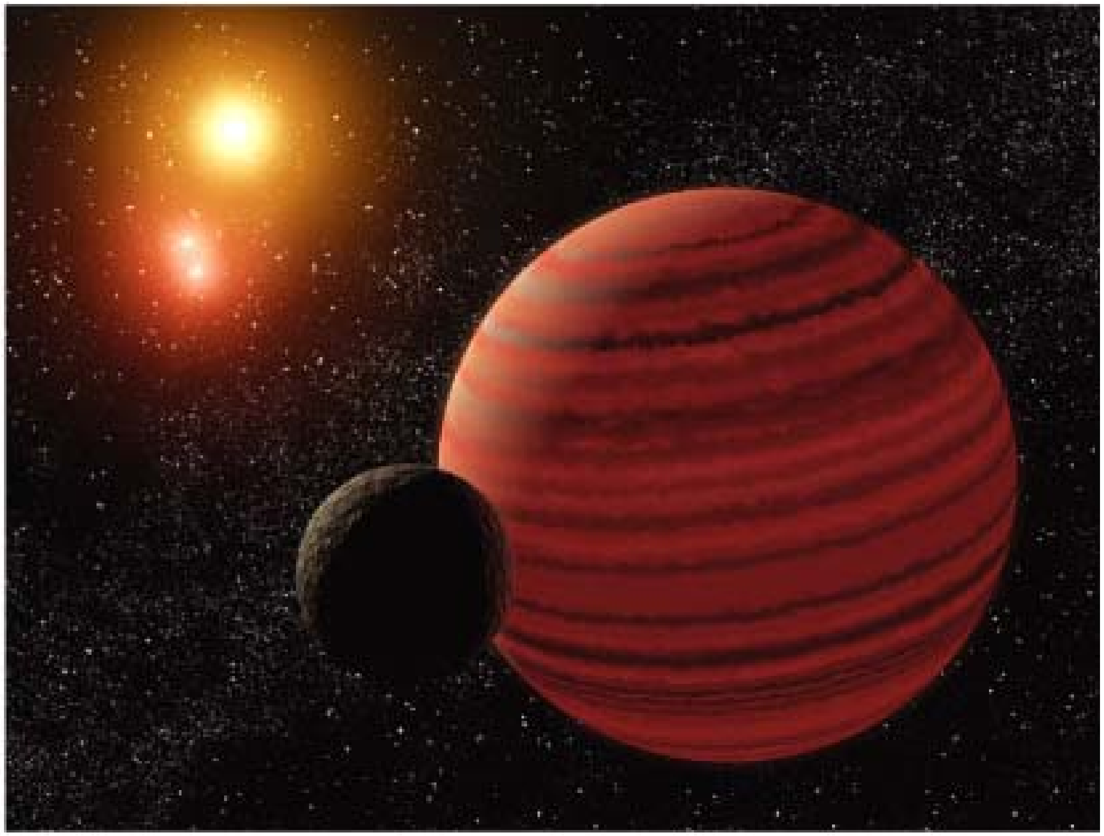
Doesn’t depend on heat content

Brown Dwarfs



- Degeneracy pressure halts the contraction of objects with $<0.08M_{Sun}$ before core temperature become hot enough for fusion
- Starlike objects not massive enough to start fusion are **brown dwarfs**

Brown Dwarfs

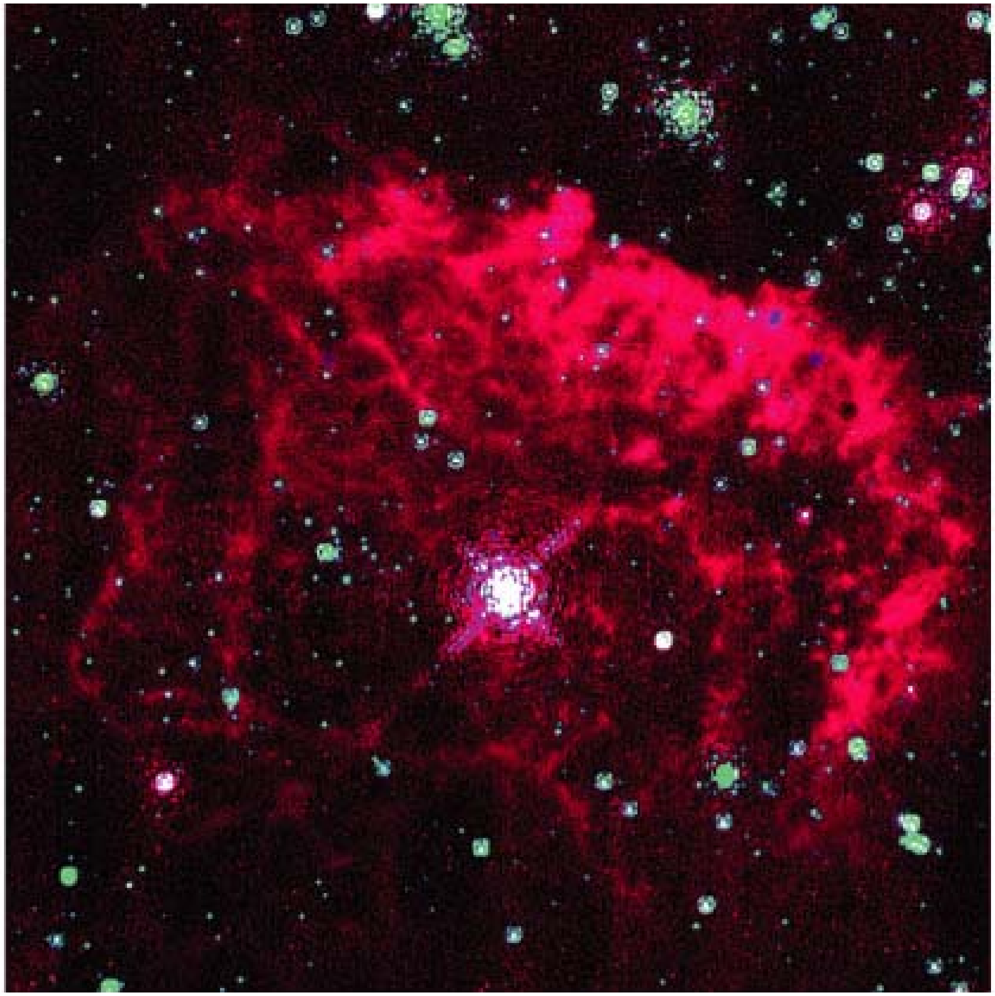


- A brown dwarf emits infrared light because of heat left over from contraction
- Its luminosity gradually declines with time as it loses thermal energy

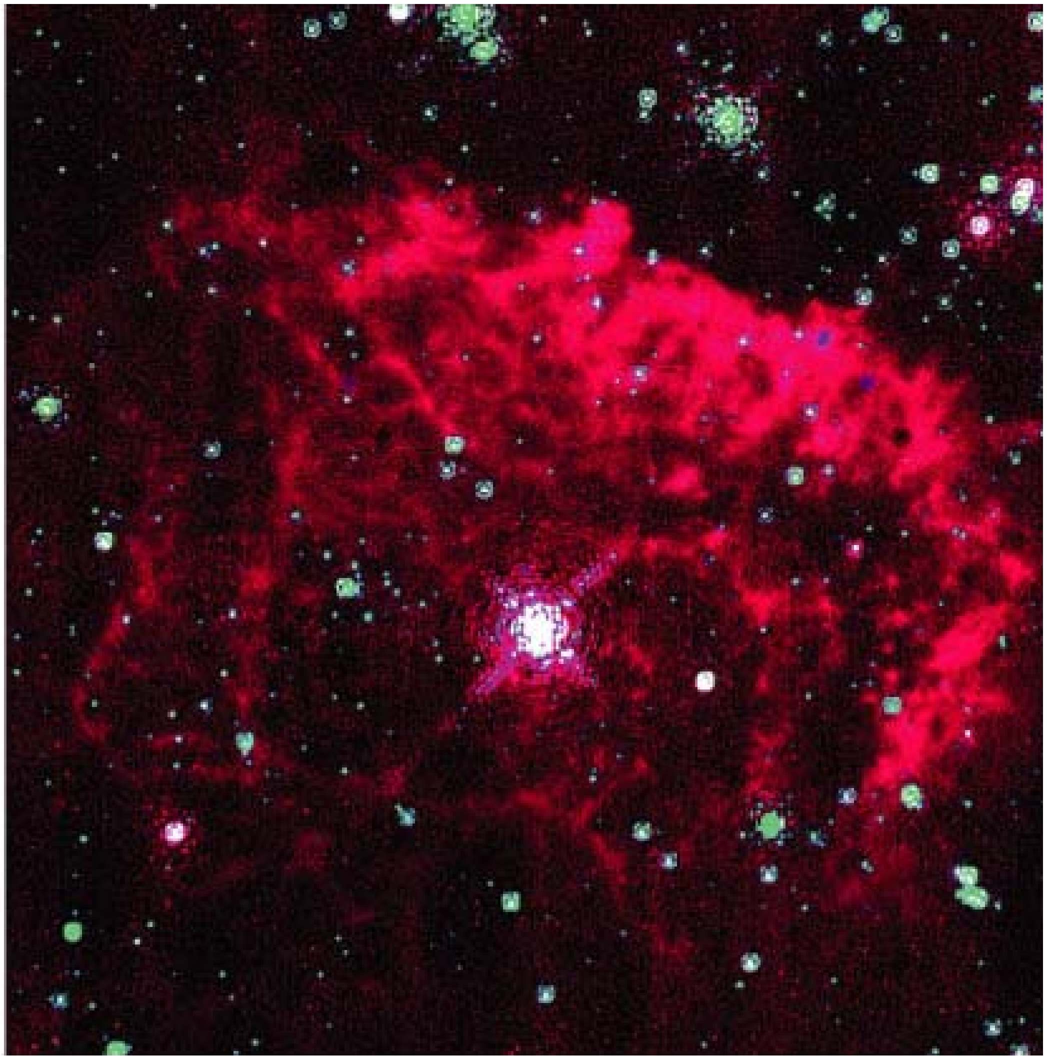
Brown Dwarfs in Orion

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

What is the greatest mass a newborn star can have?

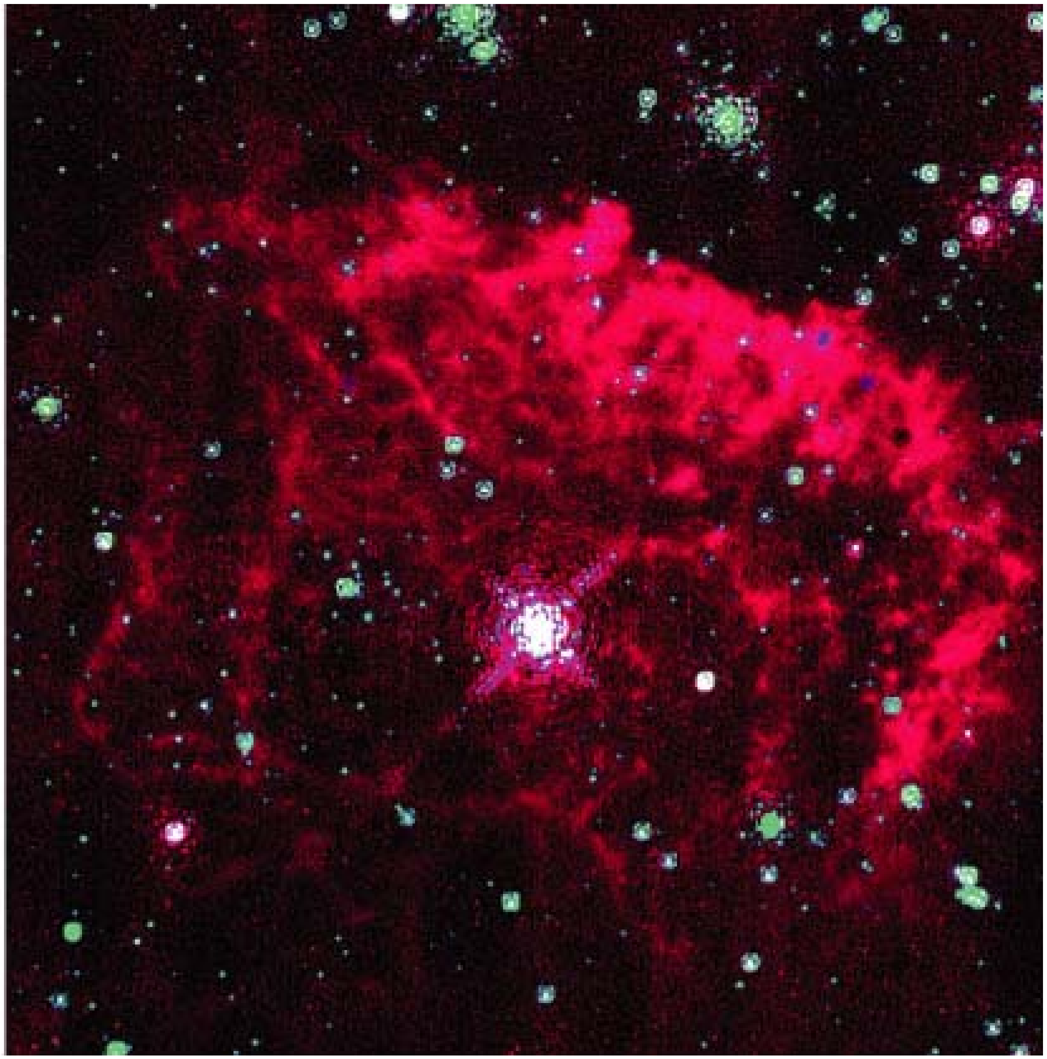


Radiation Pressure



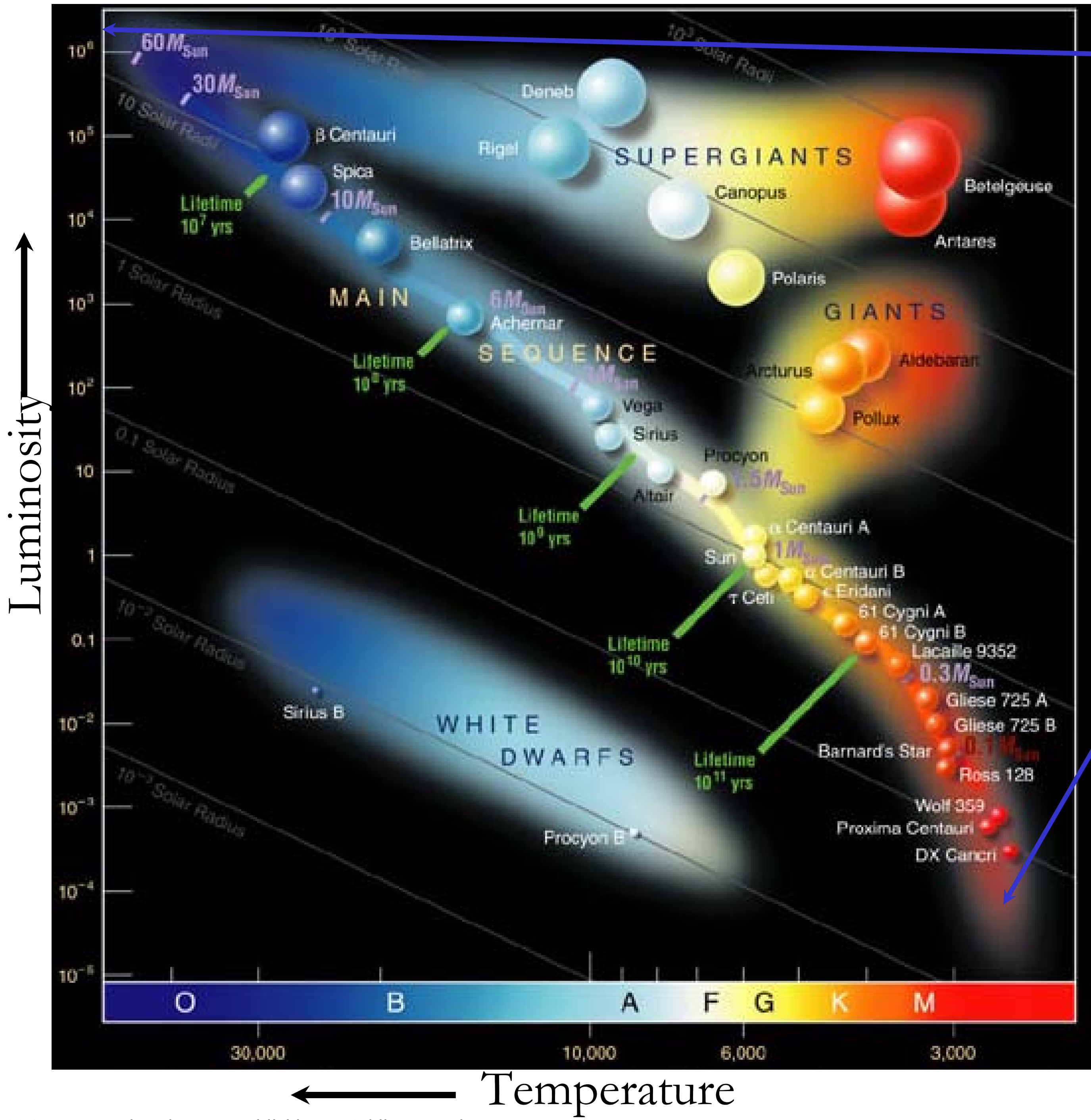
- Photons exert a slight amount of pressure when they strike matter
- Very massive stars are so luminous that the collective pressure of photons drives their matter into space

Upper Limit on a Star’s Mass



- Models of stars suggest that radiation pressure limits how massive a star can be without blowing itself apart

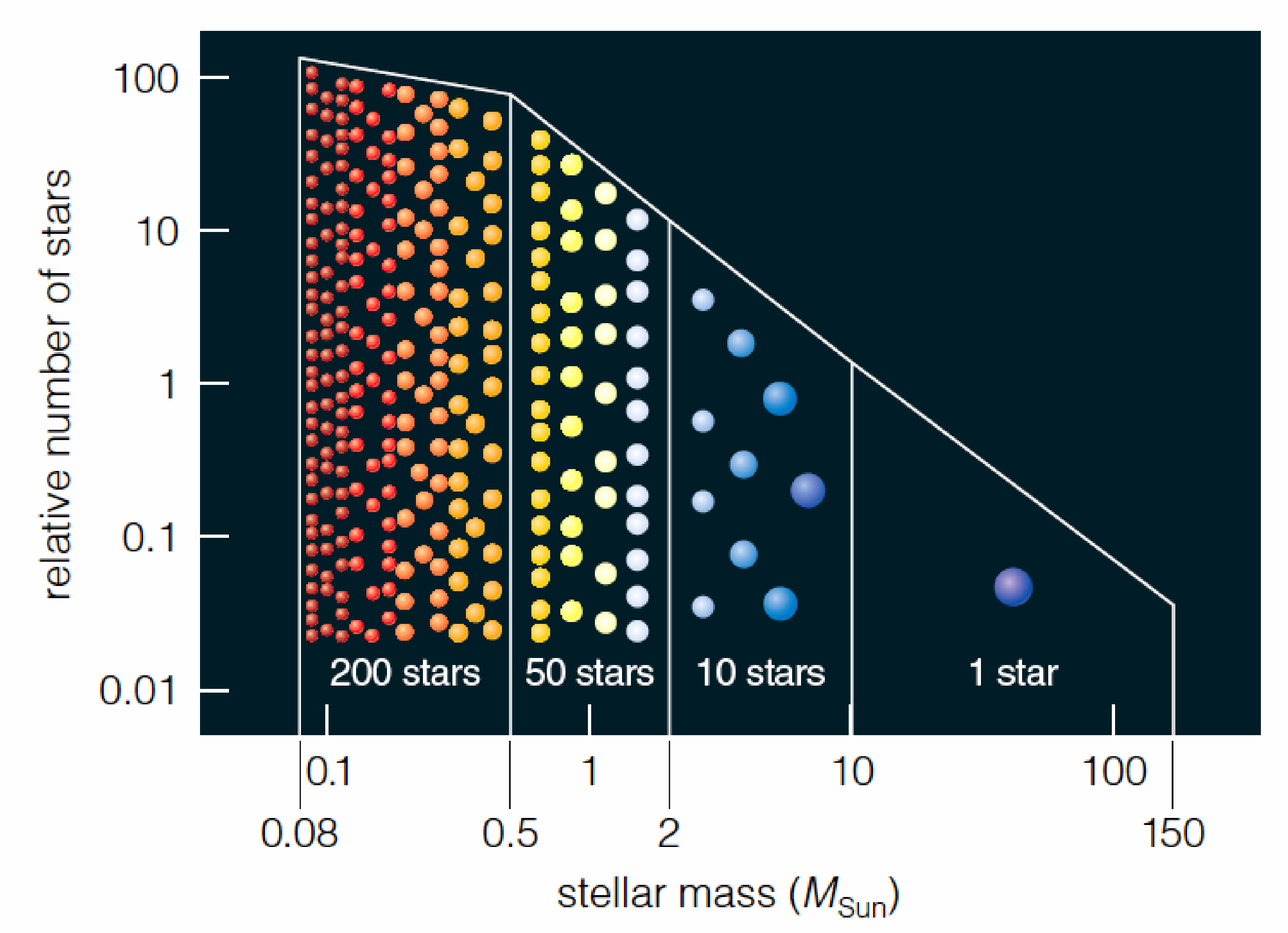
- Observations have not found stars more massive than about $150M_{\text{Sun}}$



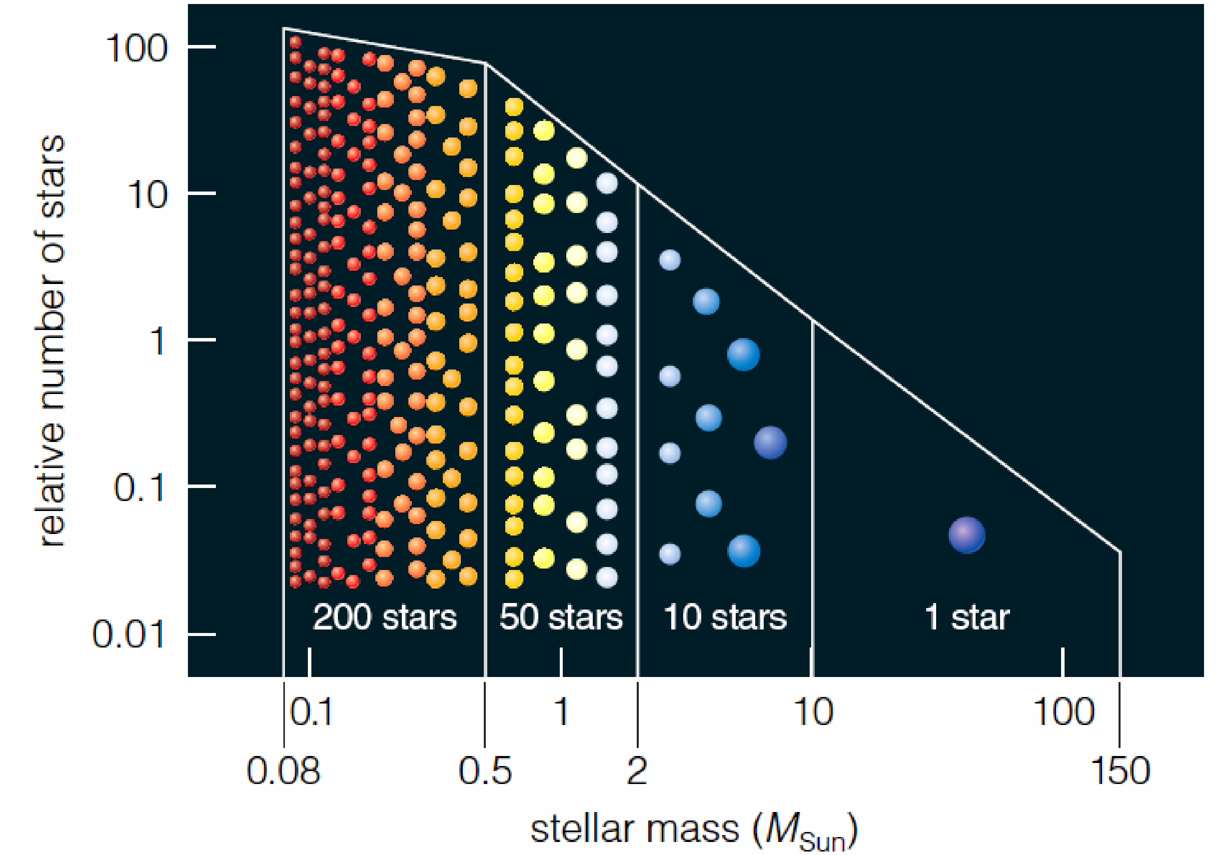
Stars more massive than $150 M_{\text{Sun}}$ would blow apart

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

What are the typical masses of newborn stars?



Demographics of Stars



- Observations of star clusters show that star formation makes many more low-mass stars than high-mass stars

What have we learned?

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

What have we learned?

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