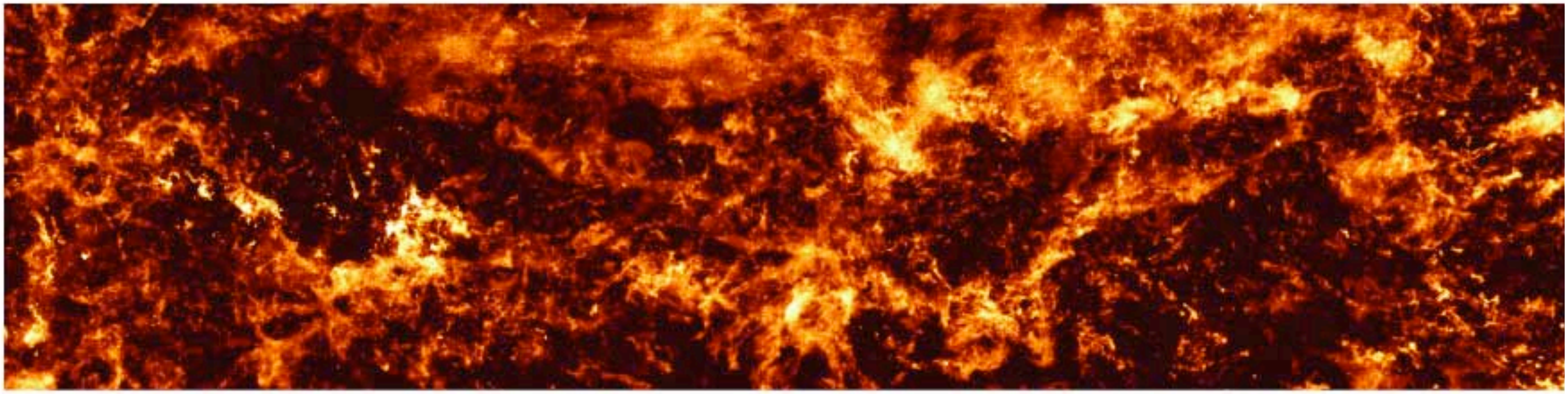
Star Birth

Star-Forming Clouds

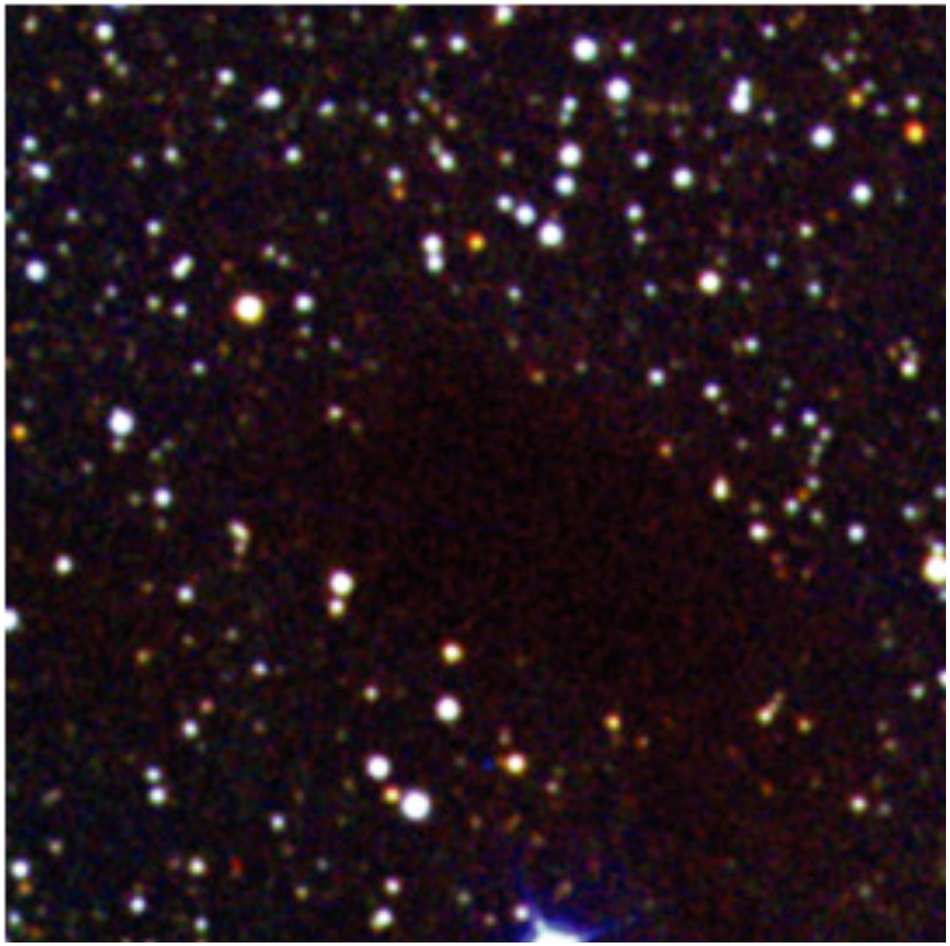
- Stars form in dark clouds of dusty gas in interstellar space
- The gas between the stars is called the **interstellar medium**

Molecular Clouds



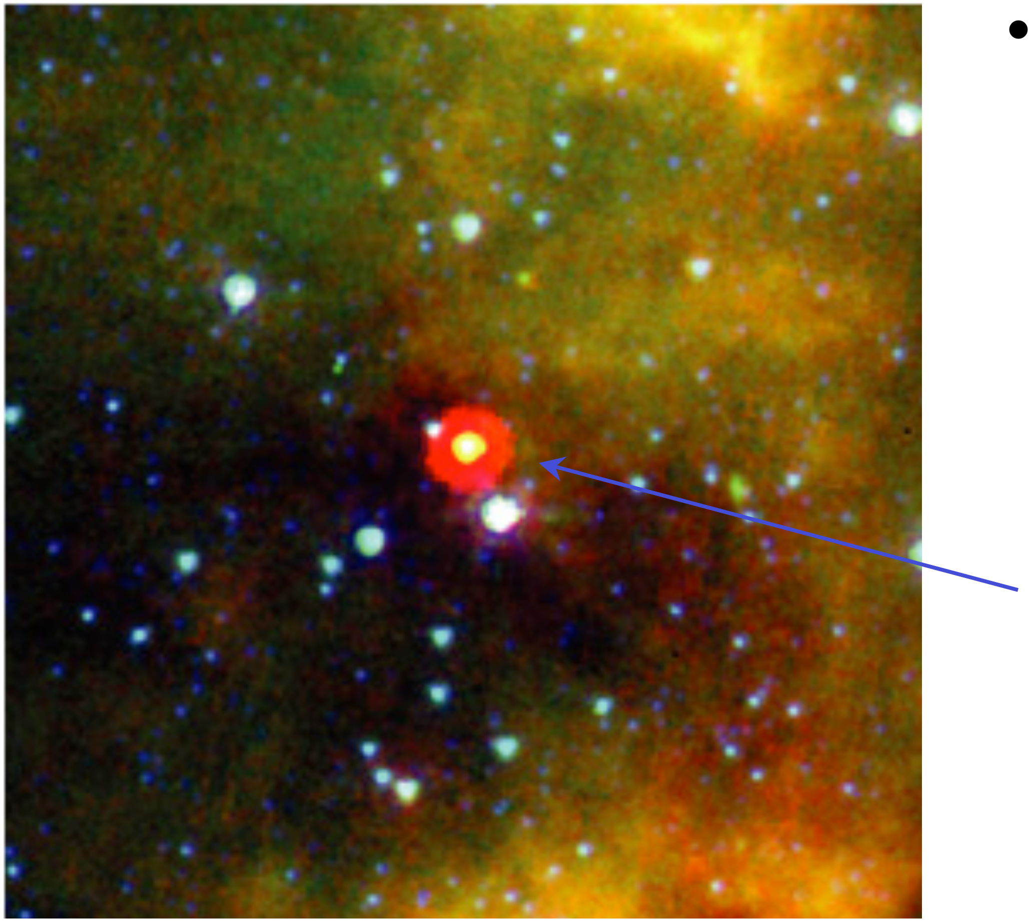
- Most of the matter in star-forming clouds is in the form of molecules (H_2, CO,…)
- These *molecular clouds* have a temperature of 10-30 K and a density of about 1000 molecules per cubic cm
- Most of what we know about molecular clouds comes from observing the emission lines of carbon monoxide: CO (More about this later)

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

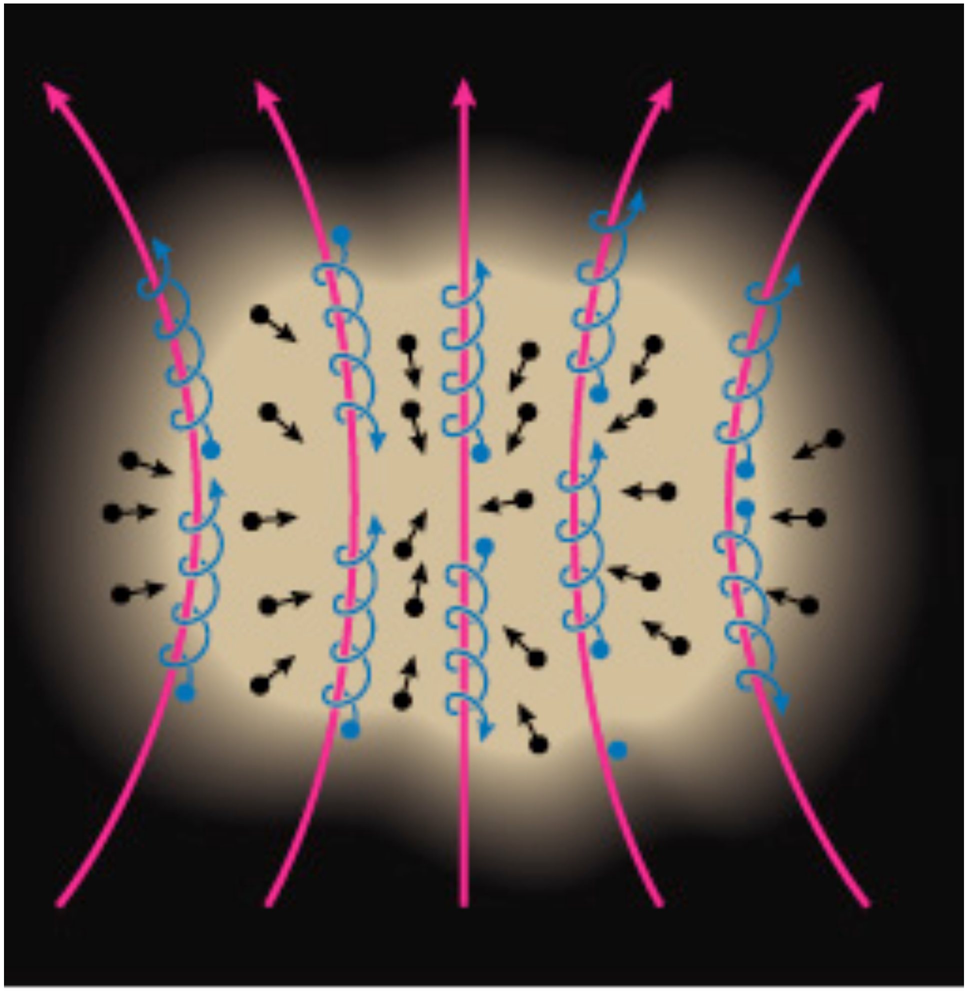


- Observing the infrared light from a cloud can reveal the newborn star embedded inside it

Gravity versus Pressure

- Gravity can create stars only if it can overcome the force of thermal pressure in a cloud
- A typical molecular cloud (T~ 30 K, n ~ 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

Resistance to Gravity



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

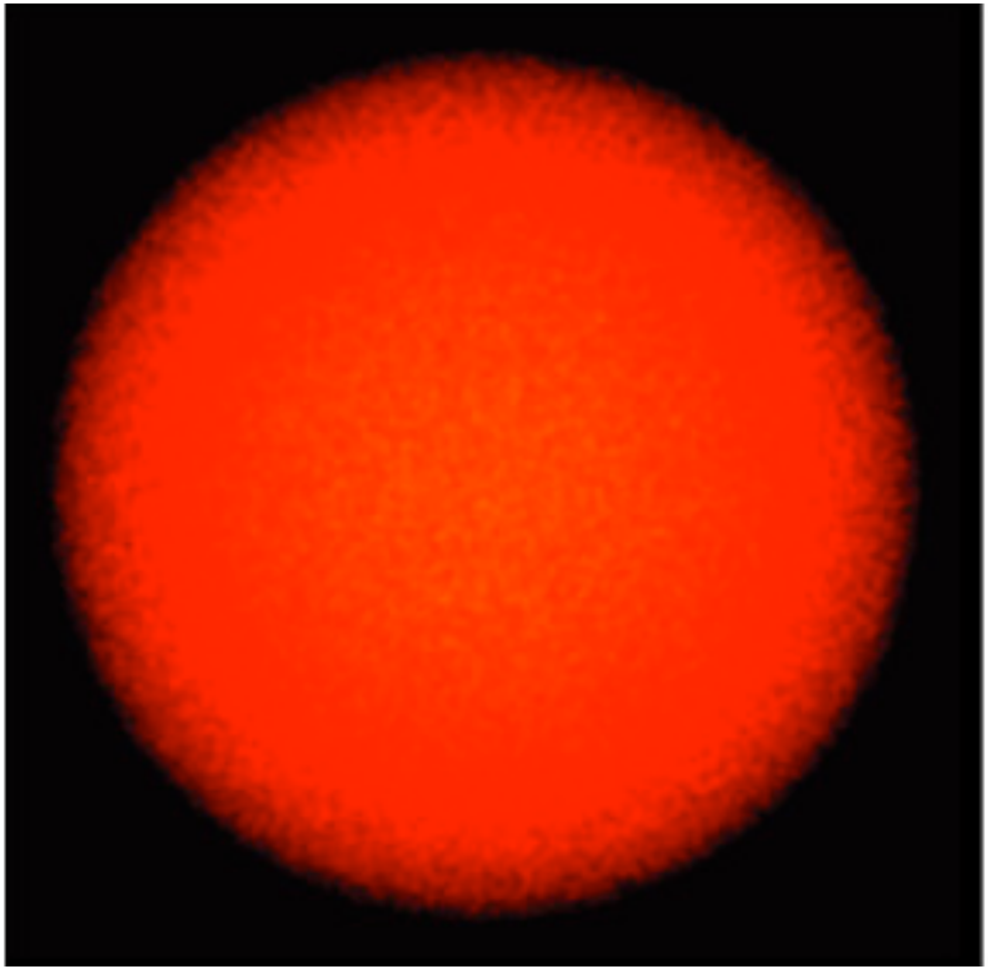
- Both magnetic fields and turbulent gas motions increase resistance to gravity

Fragmentation of a Cloud

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

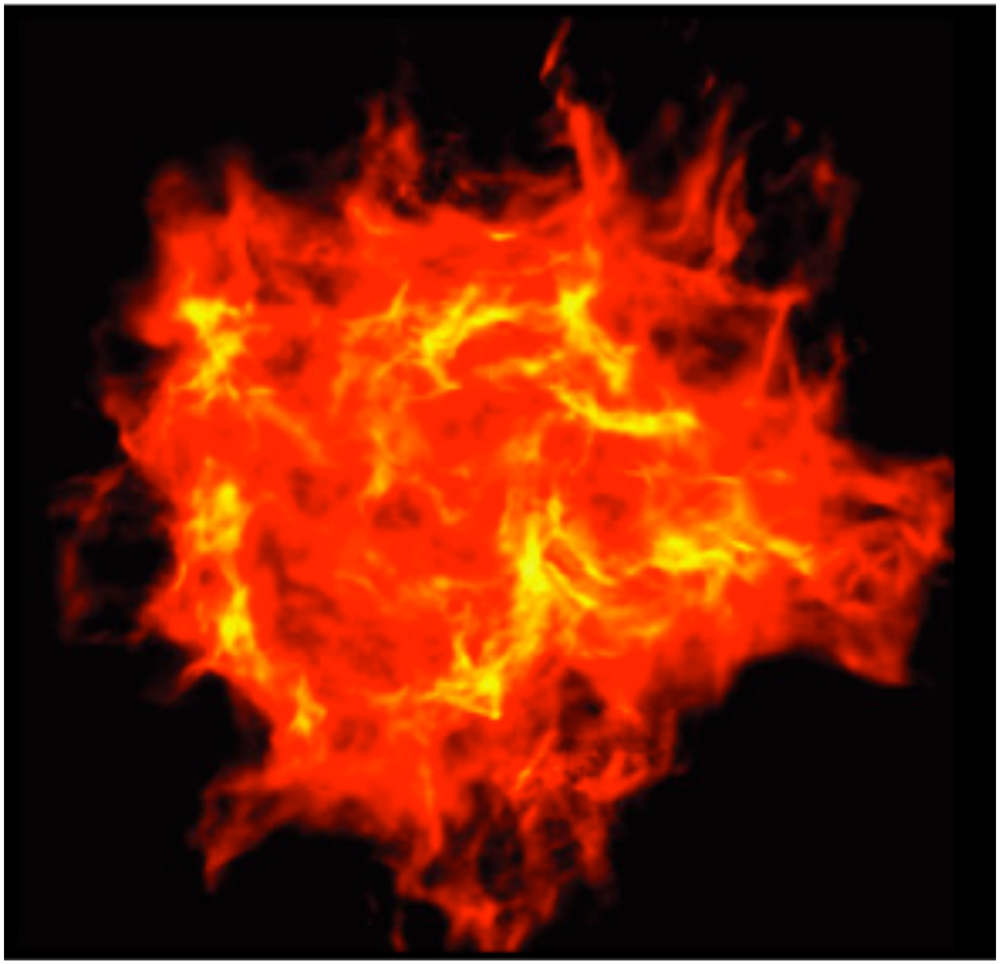
- Gravity can therefore overcome pressure in smaller pieces of the cloud, causing it to break apart into multiple fragments, each of which may go on to form a star

Fragmentation of a Cloud



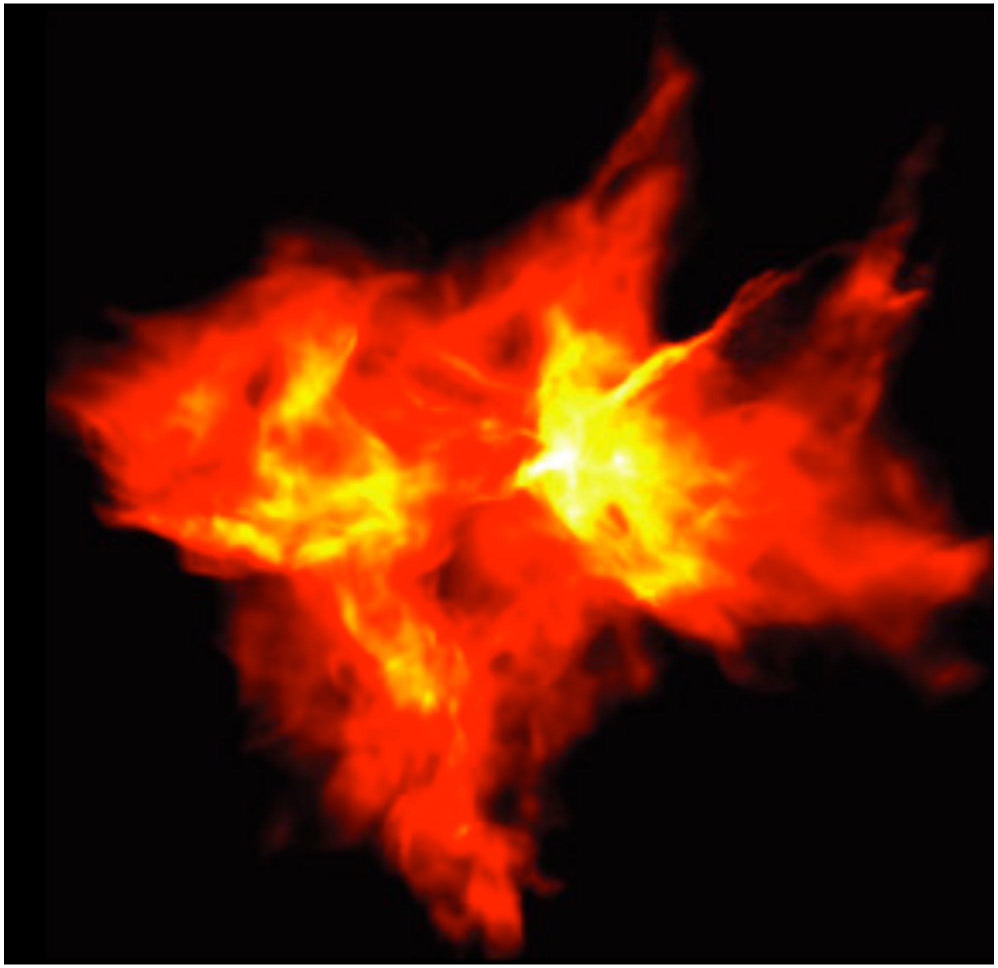
- This simulation begins with a turbulent cloud containing 50 solar masses of gas

Fragmentation of a Cloud



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

Fragmentation of a Cloud

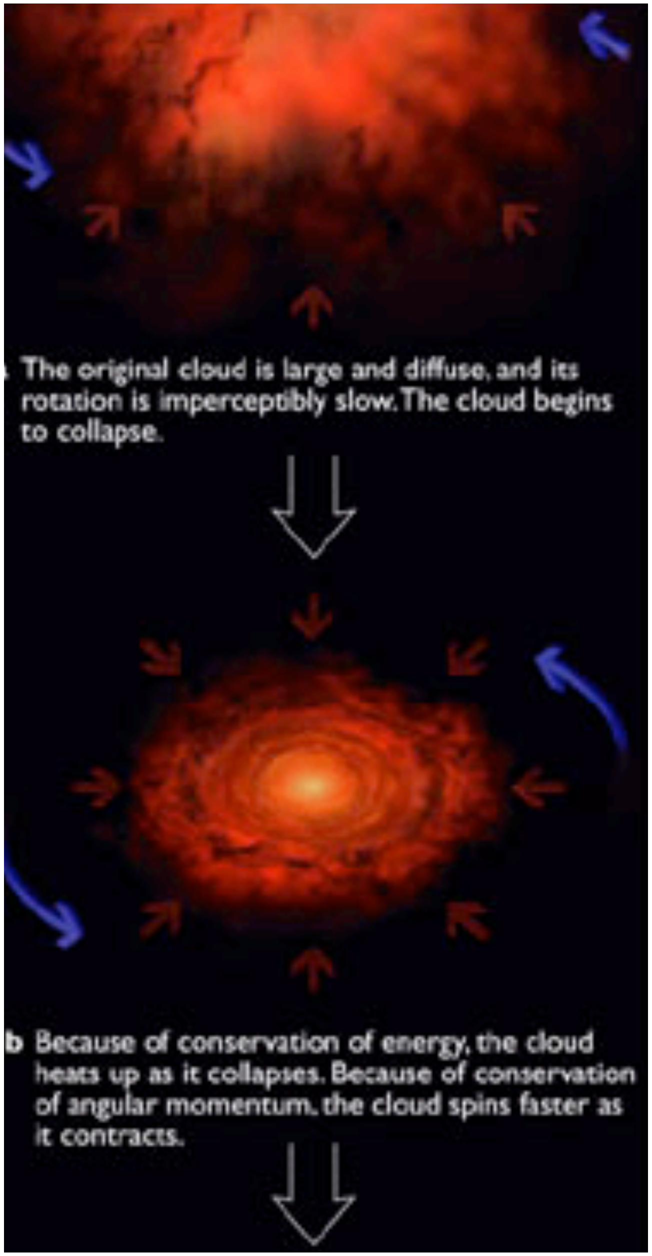


- Each lump of the cloud in which gravity can overcome pressure can go on to become a star

- A large cloud can make a whole cluster of stars

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



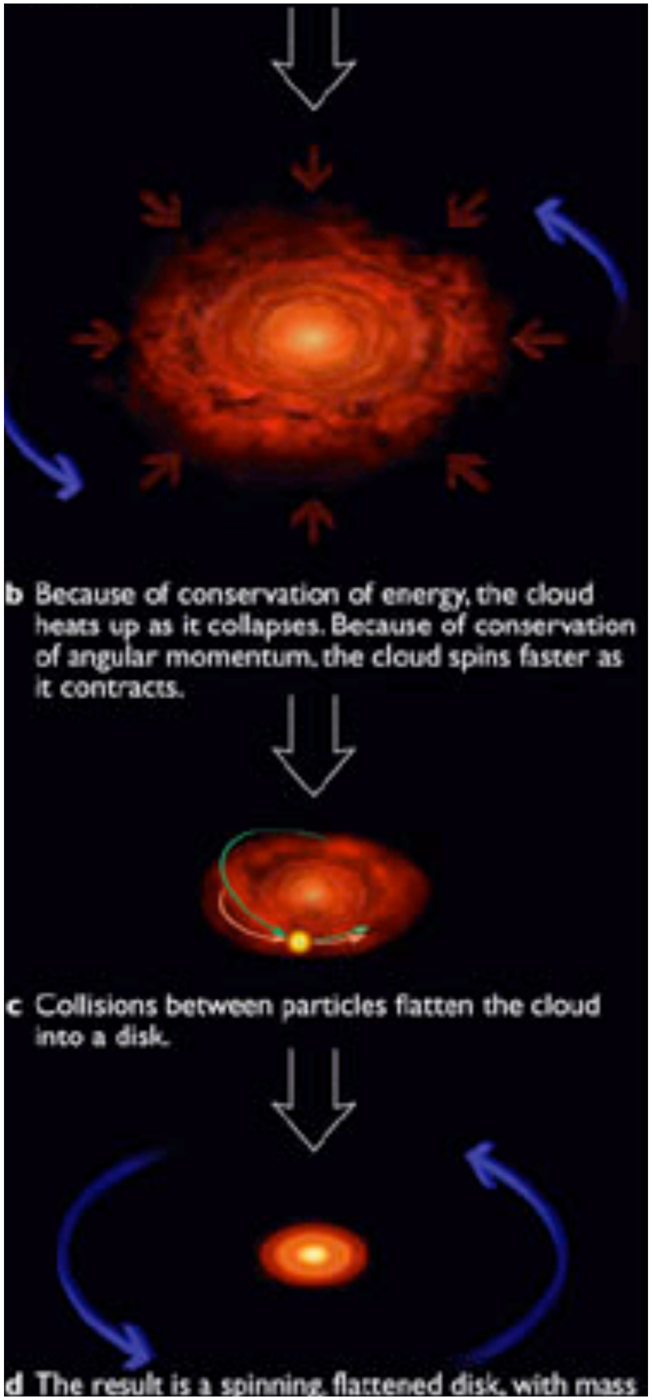
The original cloud is large and diffuse, and its rotation is imperceptibly slow. The cloud begins to collapse.

b Because of conservation of energy, the cloud heats up as it collapses. Because of conservation of angular momentum, the cloud spins faster as it contracts.

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



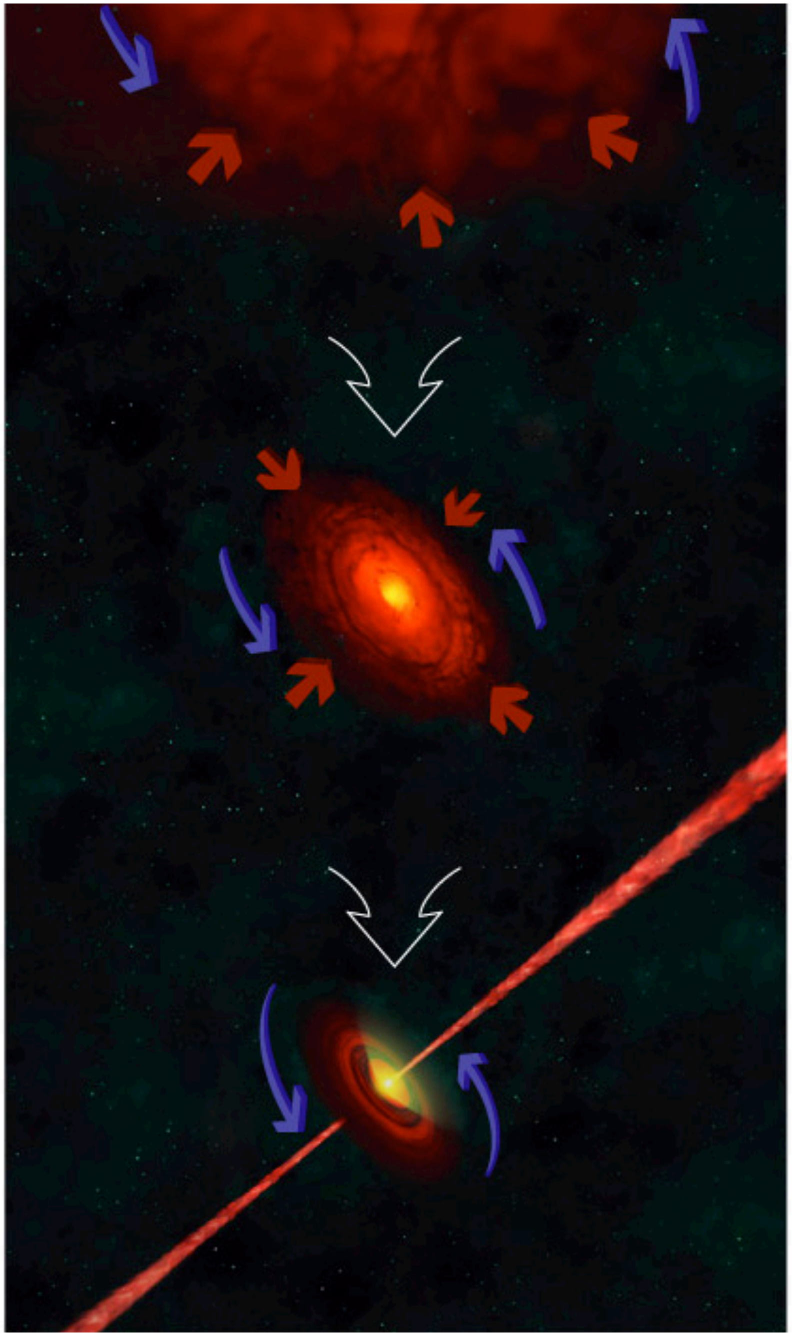
b Because of conservation of energy, the cloud heats up as it collapses. Because of conservation of angular momentum, the cloud spins faster as it contracts.

c Collisions between particles flatten the cloud into a disk.

d The result is a spinning, flattened disk, with mass

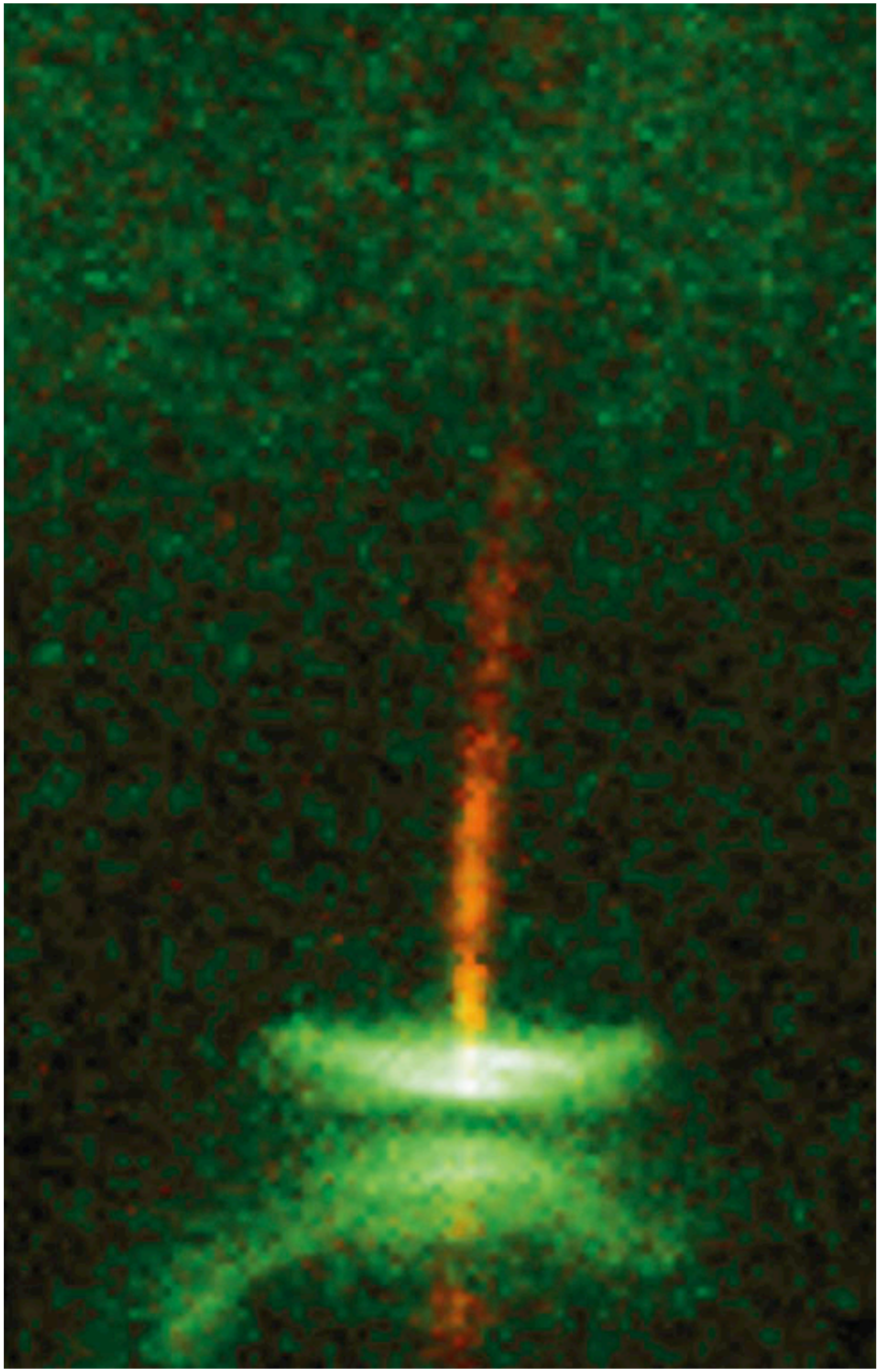
Flattening

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



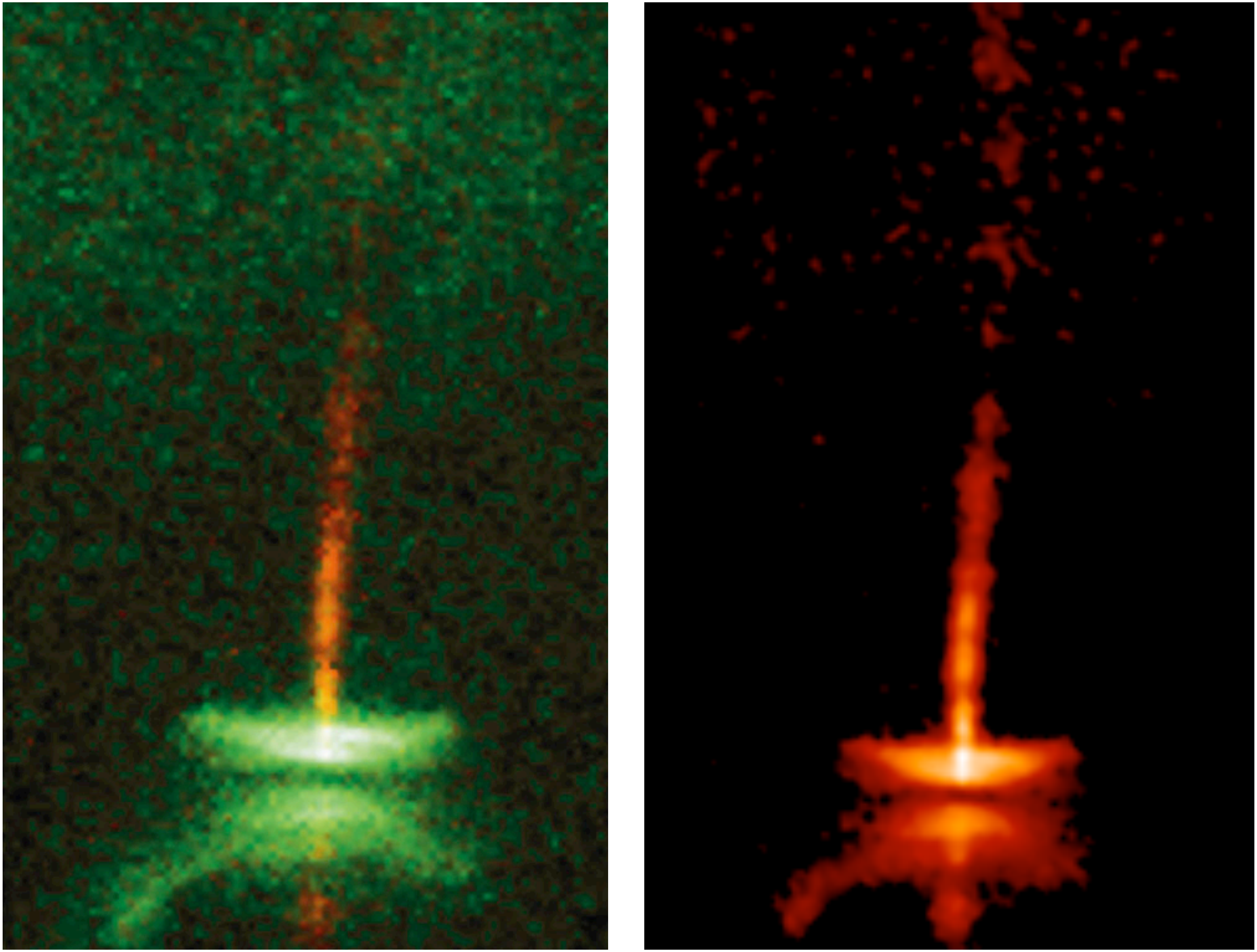
Formation of Jets

- Rotation provides a preferential direction for expulsion of high energy gas causing jets of matter to shoot out along the rotation axis



Jets & Disks

Jets are observed coming from the centers of disks around protostars



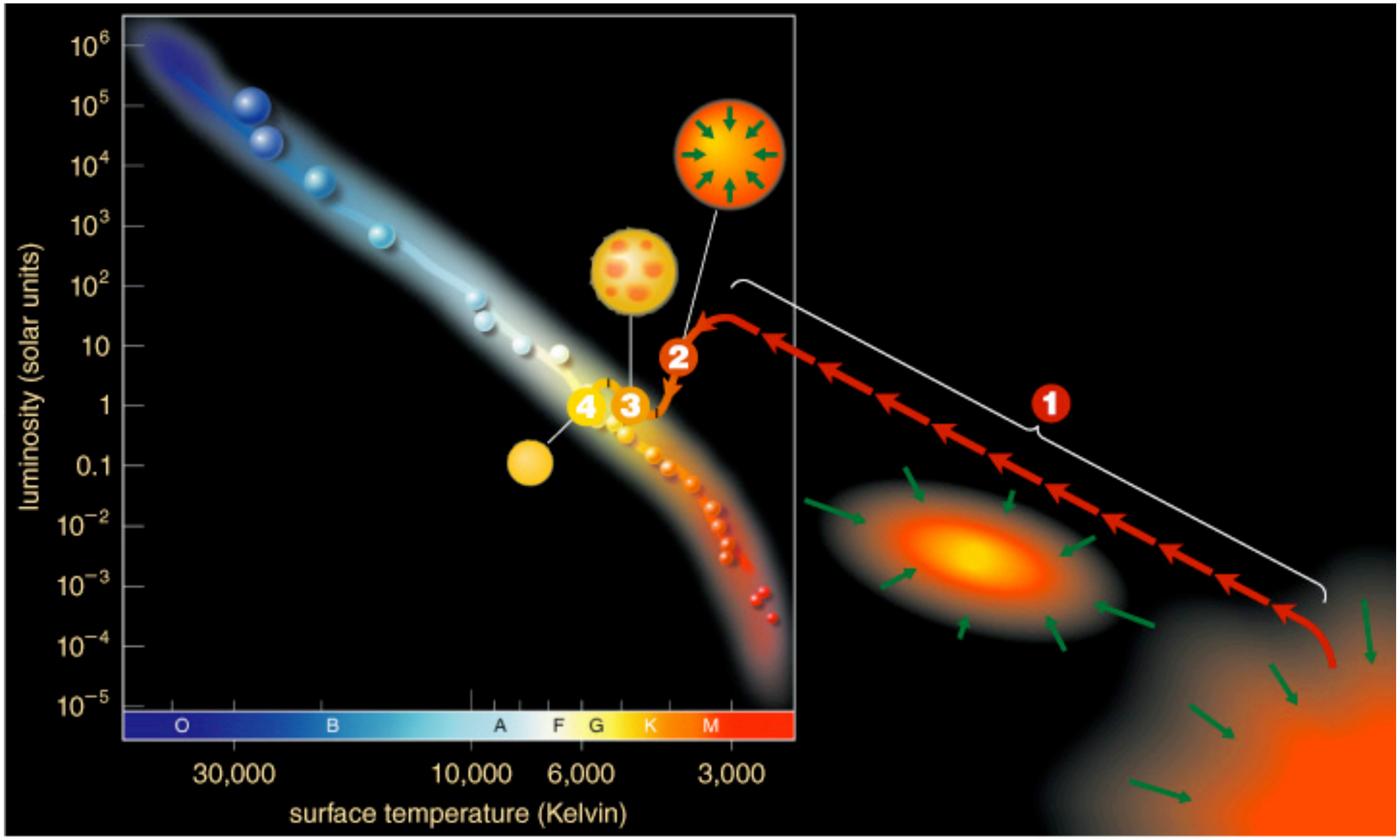
From Protostar to Main Sequence

- 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

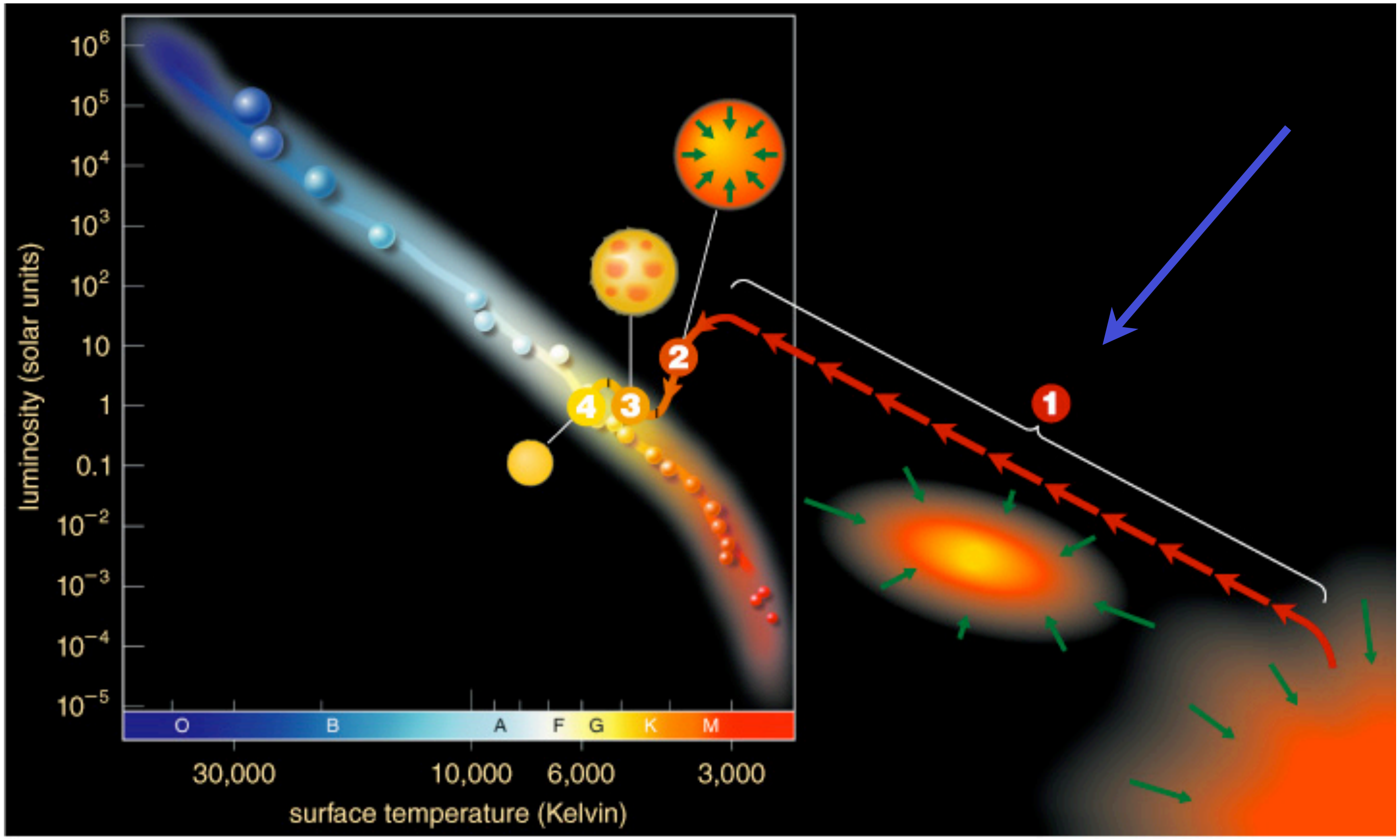
- Contraction stops when the energy released by core fusion balances energy radiated from the surface—the star is now a *main-sequence star*

Birth Stages on a Life Track



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

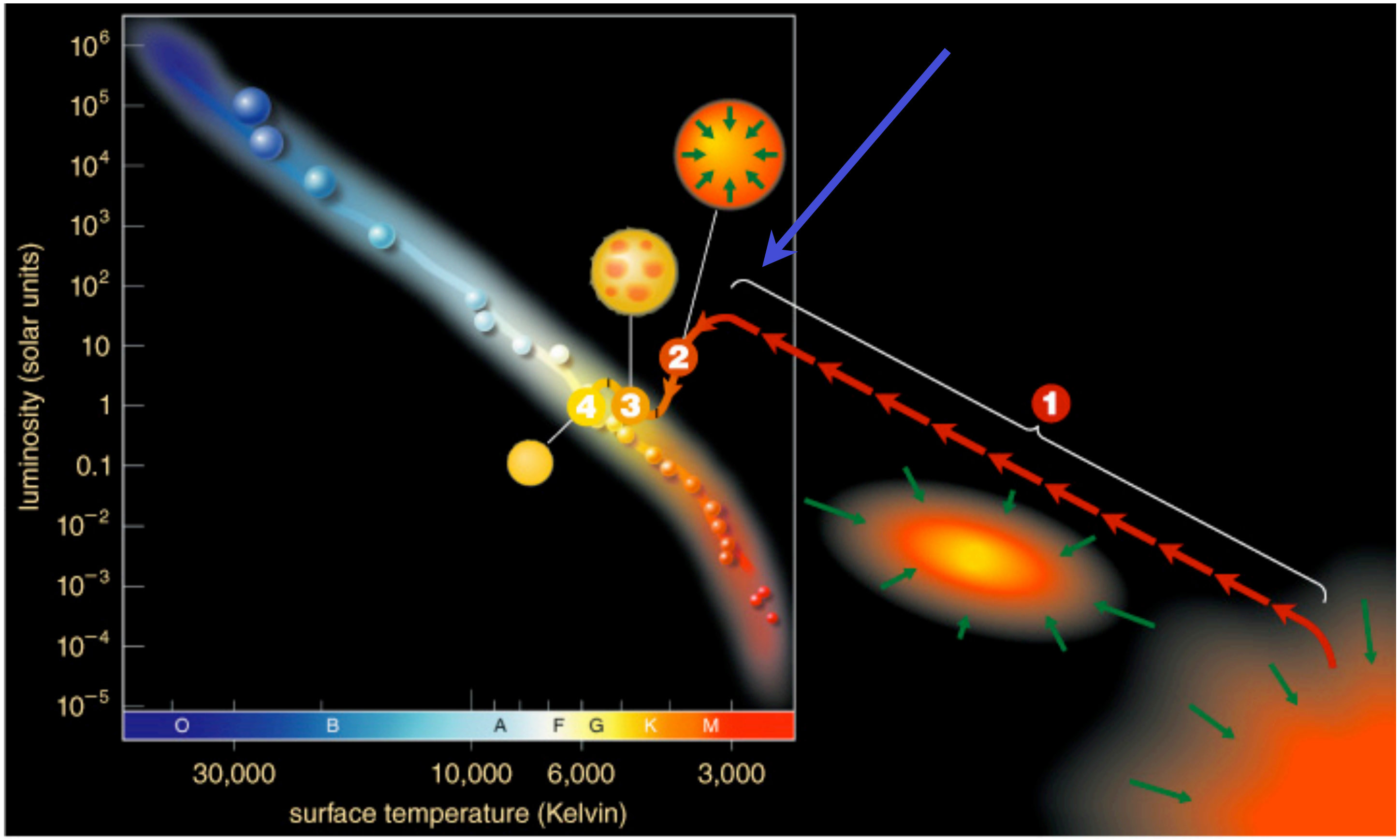
Assembly of a Protostar



- Luminosity and temperature grow as matter collects into a protostar

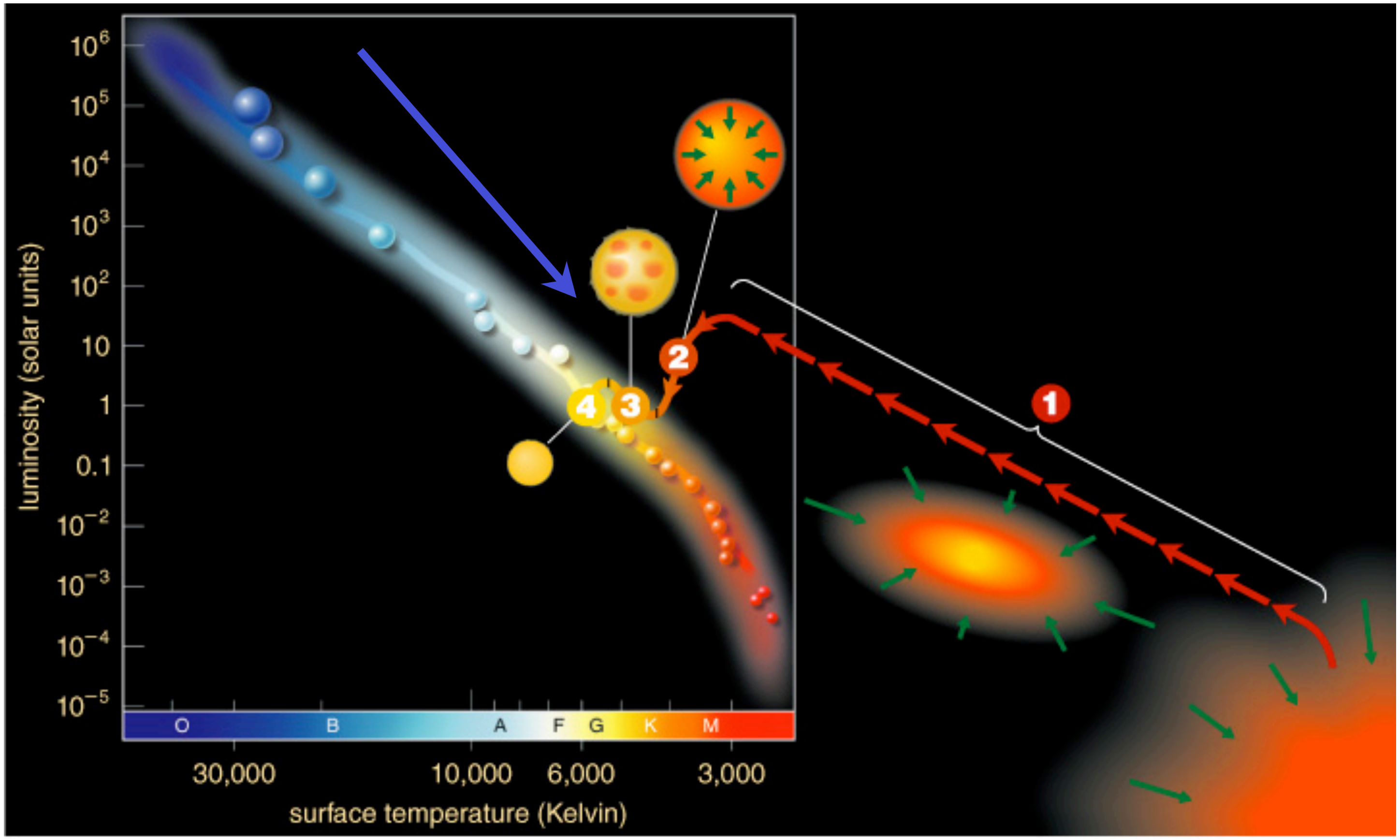
1. Protostar: star is cool, embedded in molecular cloud; energy source is ***Gravity.***

Convective Contraction



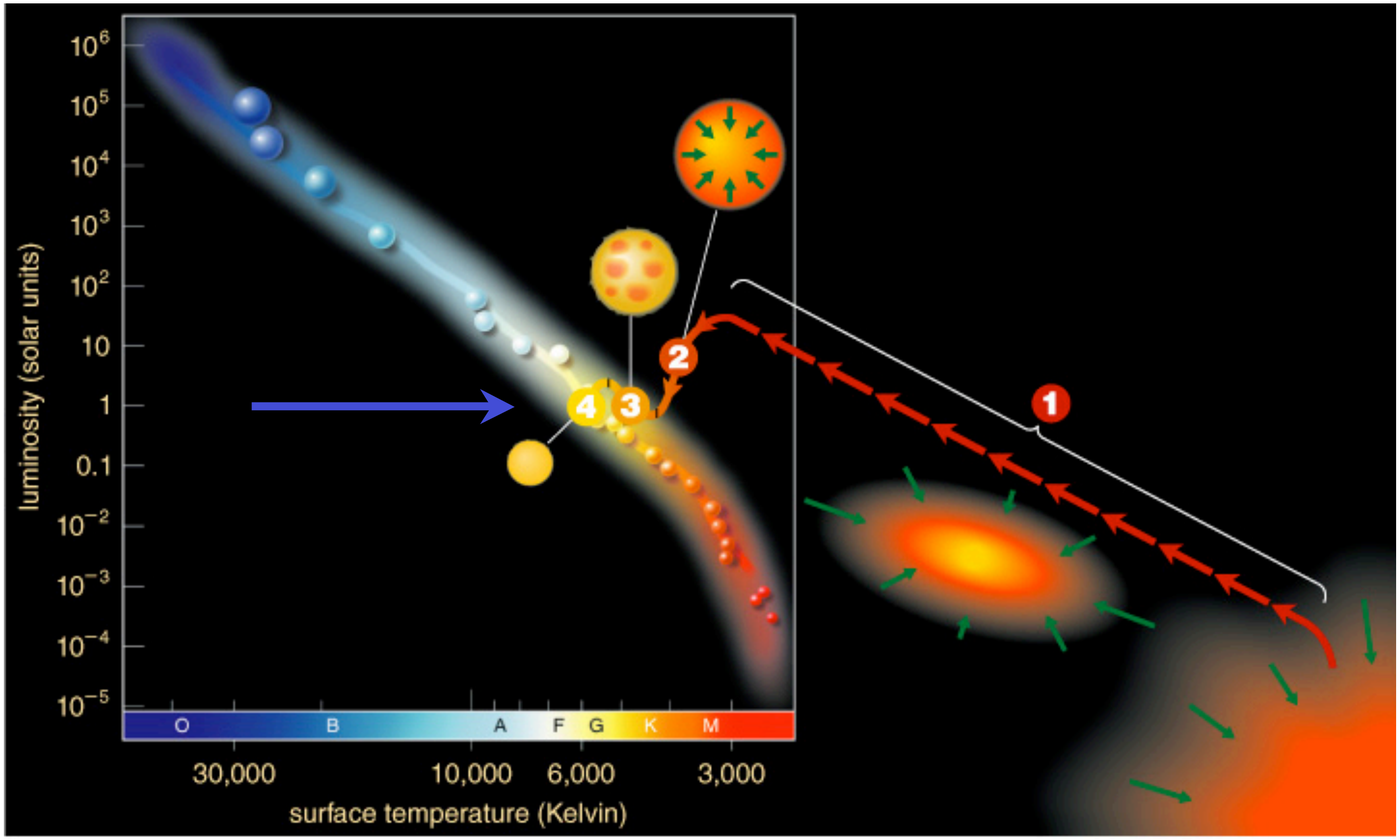
- Surface temperature remains near 3,000 K ***Gravity*** as energy source produces energy throughout protostar: ***convection*** is main energy transport mechanism

Radiative Contraction



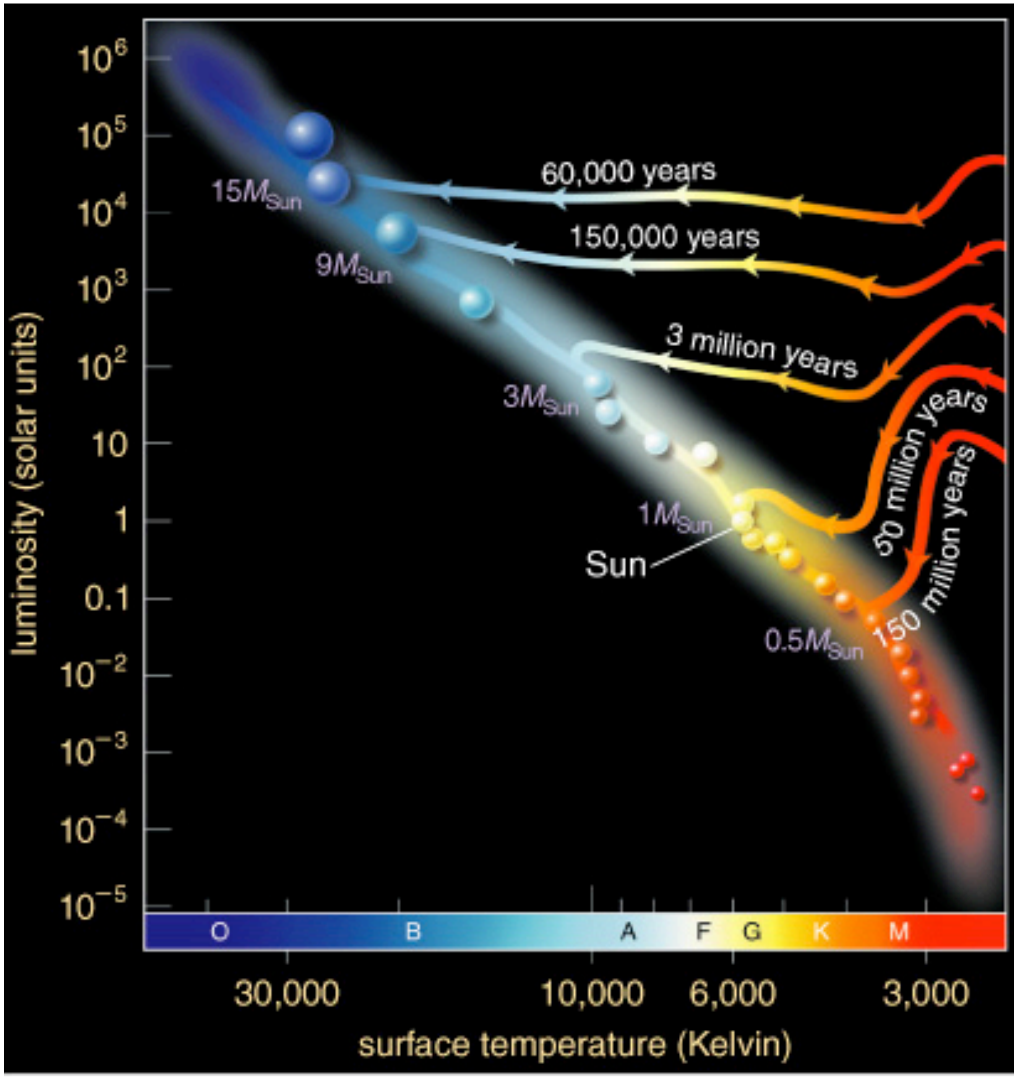
- Nuclear reactions “turn on”. Luminosity remains nearly constant as contraction of core continues. Energy is from ***gravity*** and ***nuclear reactions***, while ***radiation*** is transporting energy

Self-Sustaining Fusion



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

Life Tracks for Different Masses

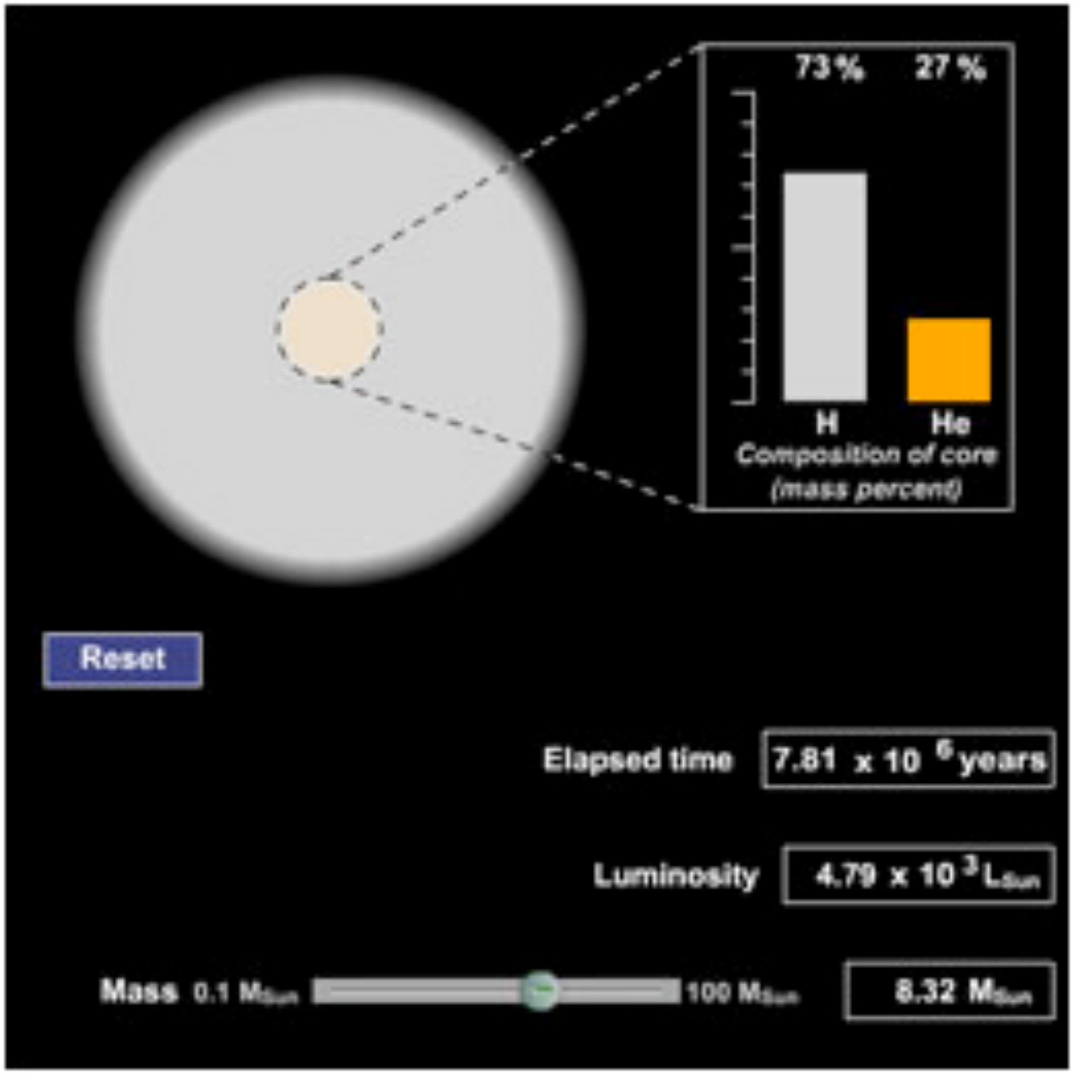


- Models show that Sun required about 30 million years to go from protostar to main sequence

- Higher-mass stars form faster

- Lower-mass stars form more slowly

Main Sequence H-burning



Elapsed time 7.81×10^{6} years

Luminosity 4.79×10^{3} L_{Sun}

Mass 8.32 M_{Sun}

A star remains on the main sequence as long as it can fuse hydrogen into helium in its core

Thought Question

What happens when a star can no longer fuse hydrogen to helium in its core?

A. Core cools off
B. Core shrinks and heats up
C. Core expands and heats up
D. Helium fusion immediately begins

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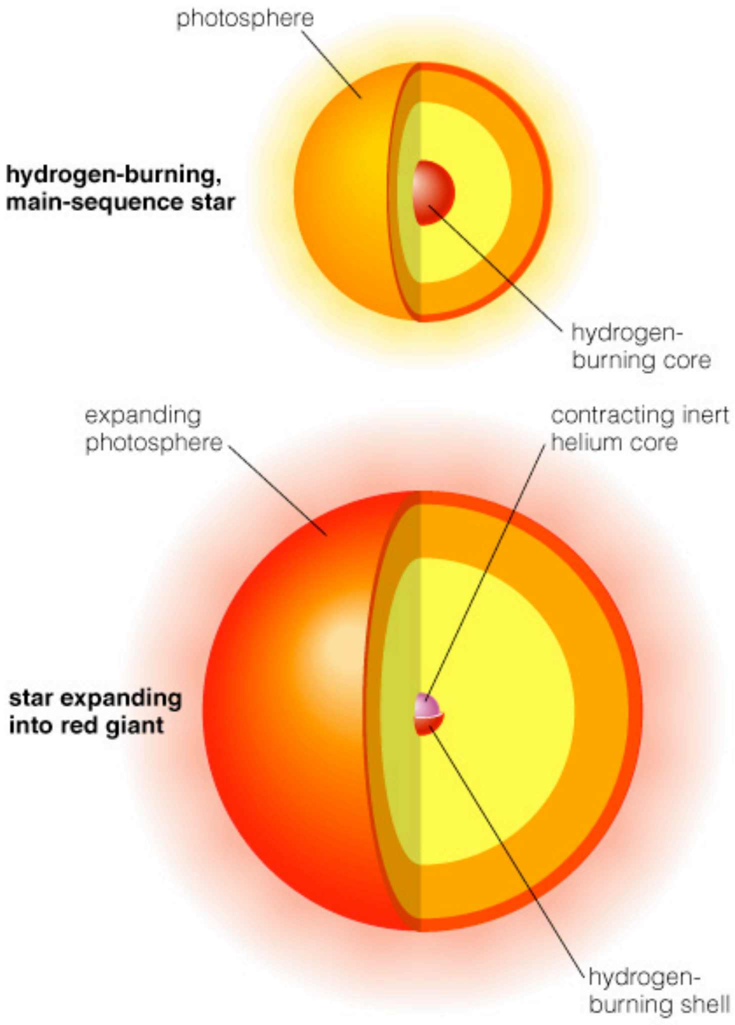
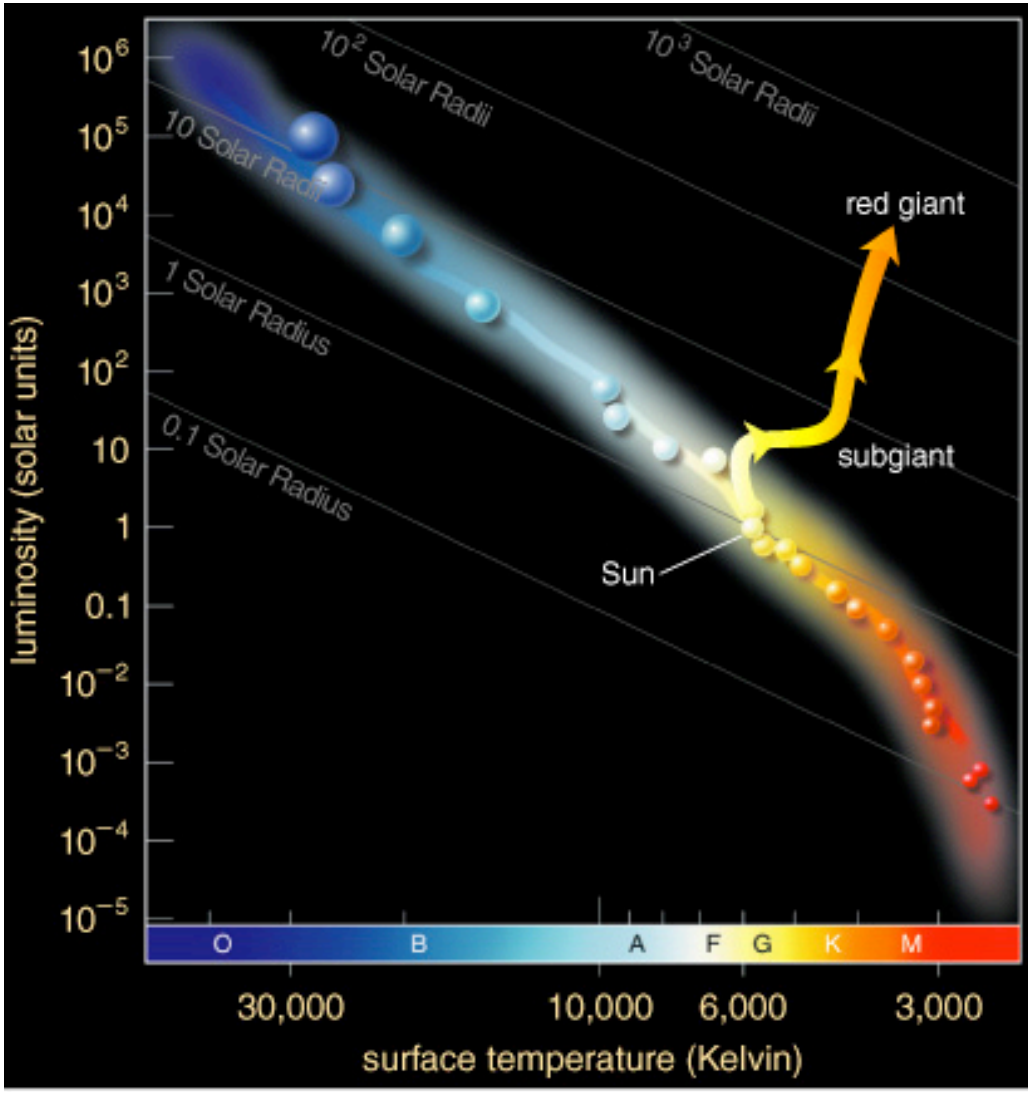
Broken Thermostat



- As the core contracts, H begins fusing to He in a shell around the core

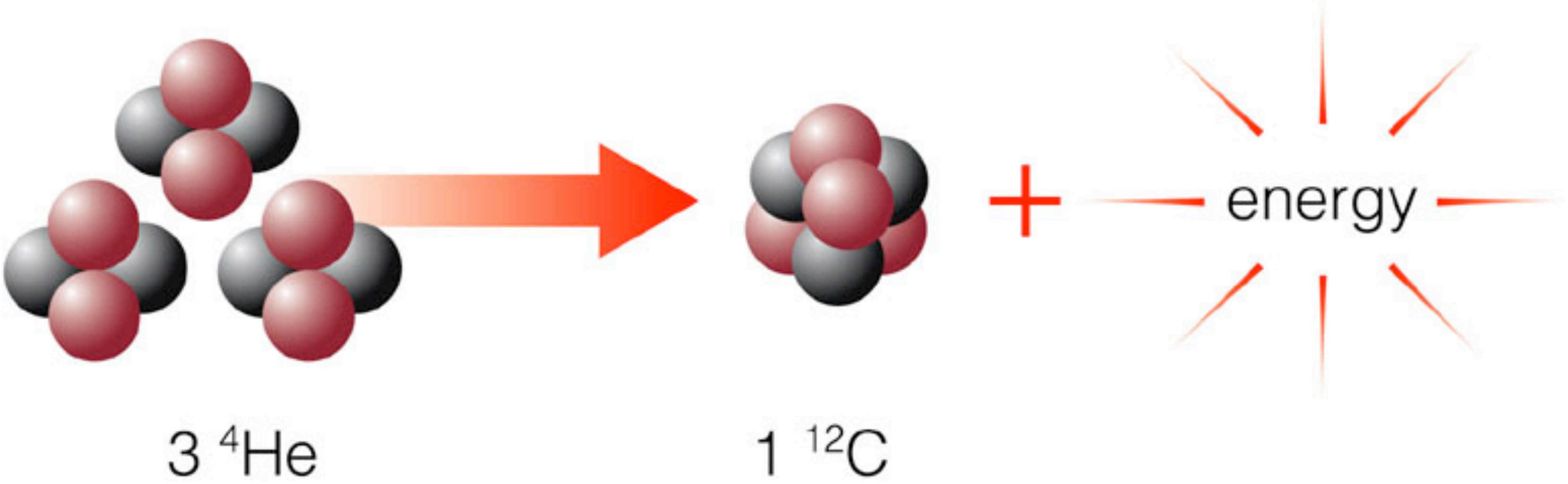
- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting

Life Track after Main Sequence



- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over

Helium Fusion - Triple Alpha Process



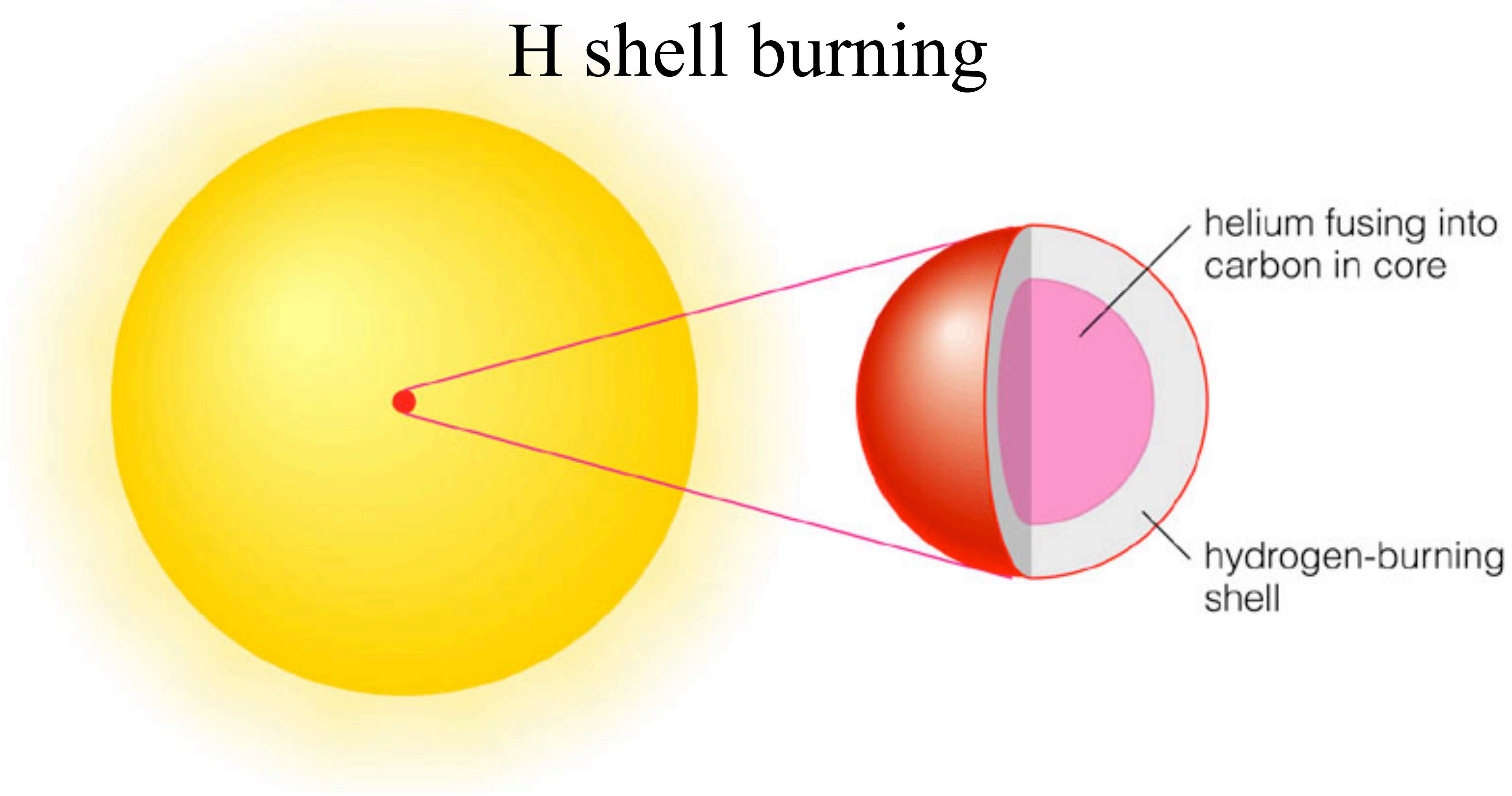
Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion

Fusion of two helium nuclei doesn’t work, so helium fusion must combine three He nuclei to make carbon

Helium Flash

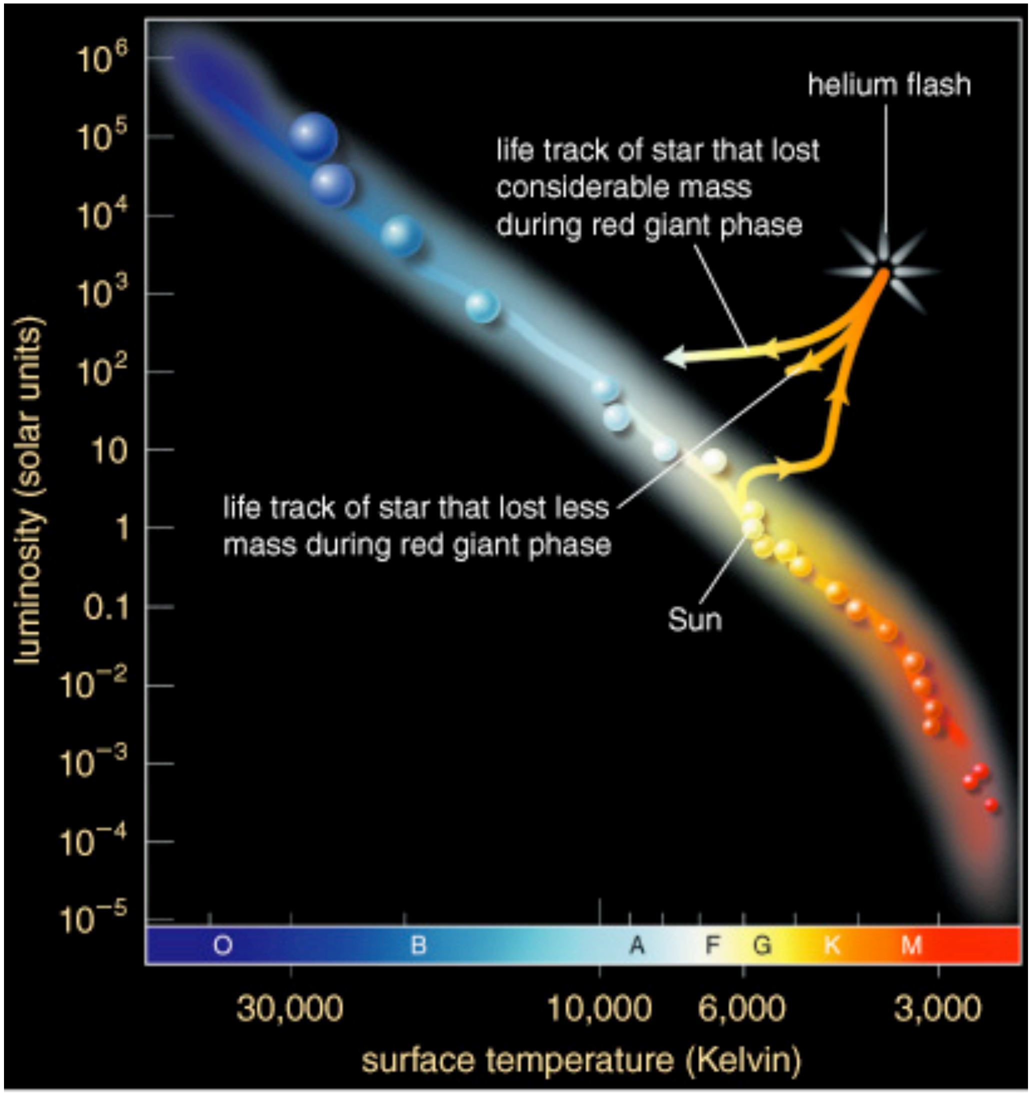
- Thermostat is broken in low-mass red giant because degeneracy pressure supports core
- Core temperature rises rapidly when helium fusion begins
- Helium fusion rate skyrockets until thermal pressure takes over and expands core again

Helium burning in core; H shell burning



Helium burning stars neither shrink nor grow because core thermostat is temporarily fixed.

Life Track after Helium Flash



- Models show that a red giant should shrink and become less luminous after helium fusion begins in the core

Double Shell Burning

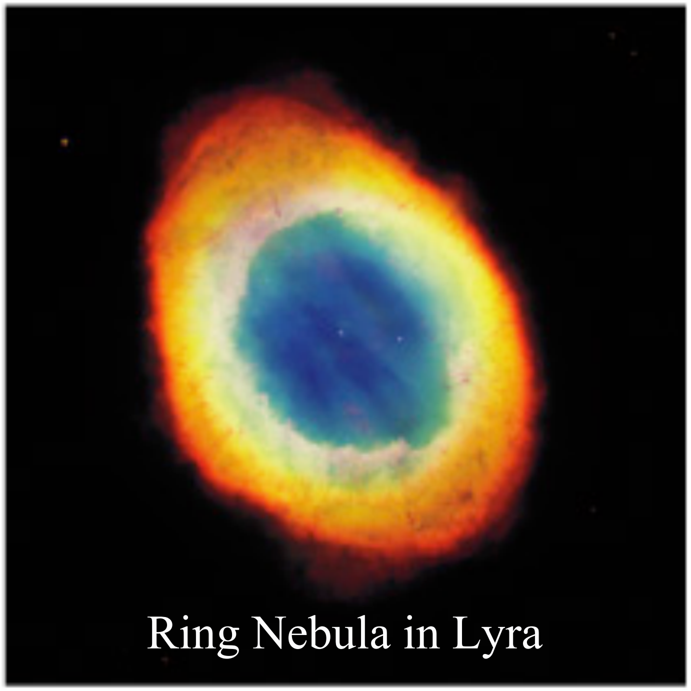
- After core helium fusion stops, He fuses into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer

- This double-shell burning stage never reaches equilibrium—fusion rate periodically spikes upward in a series of *thermal pulses*

- With each spike, convection dredges carbon up from core and transports it to surface

End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen)
- Degeneracy pressure supports the white dwarf against gravity

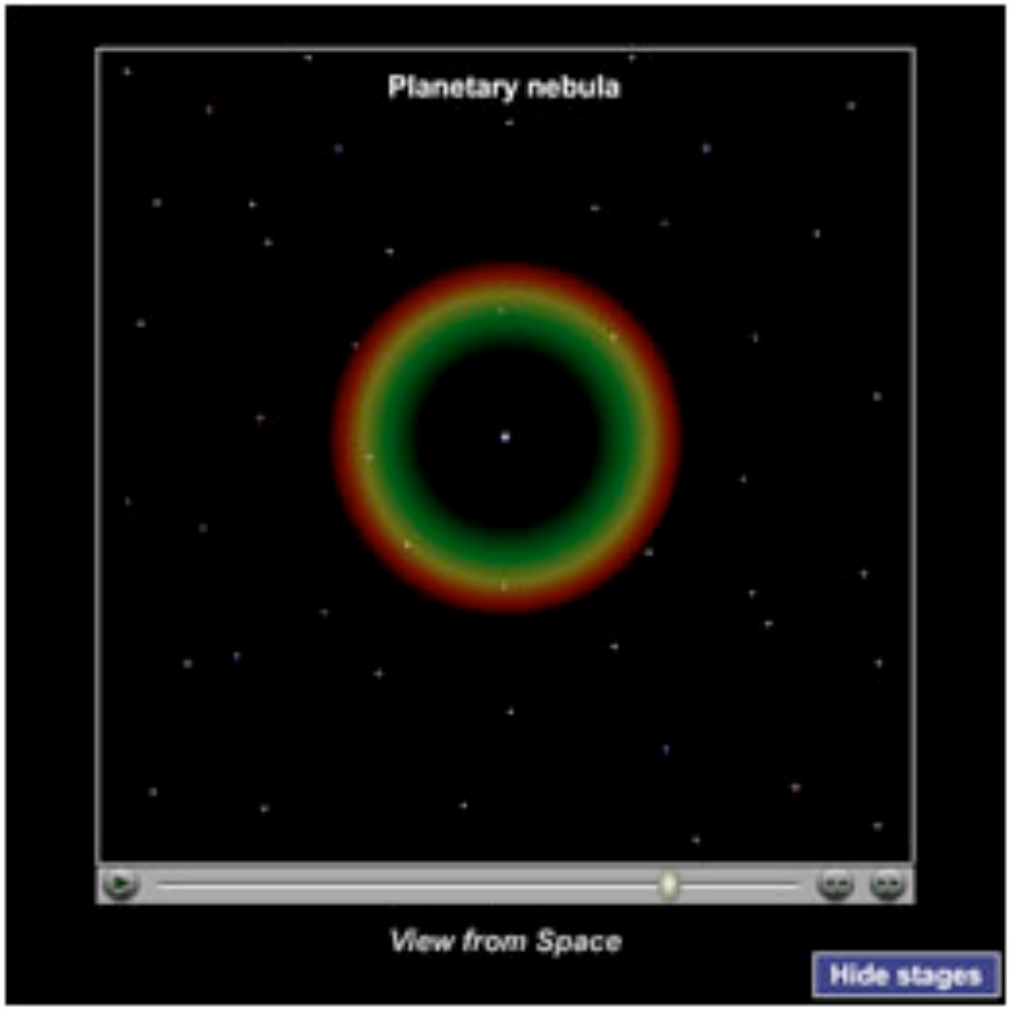

Ring Nebula in Lyra

Planetary Nebulae

- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*

- The core left behind becomes a white dwarf

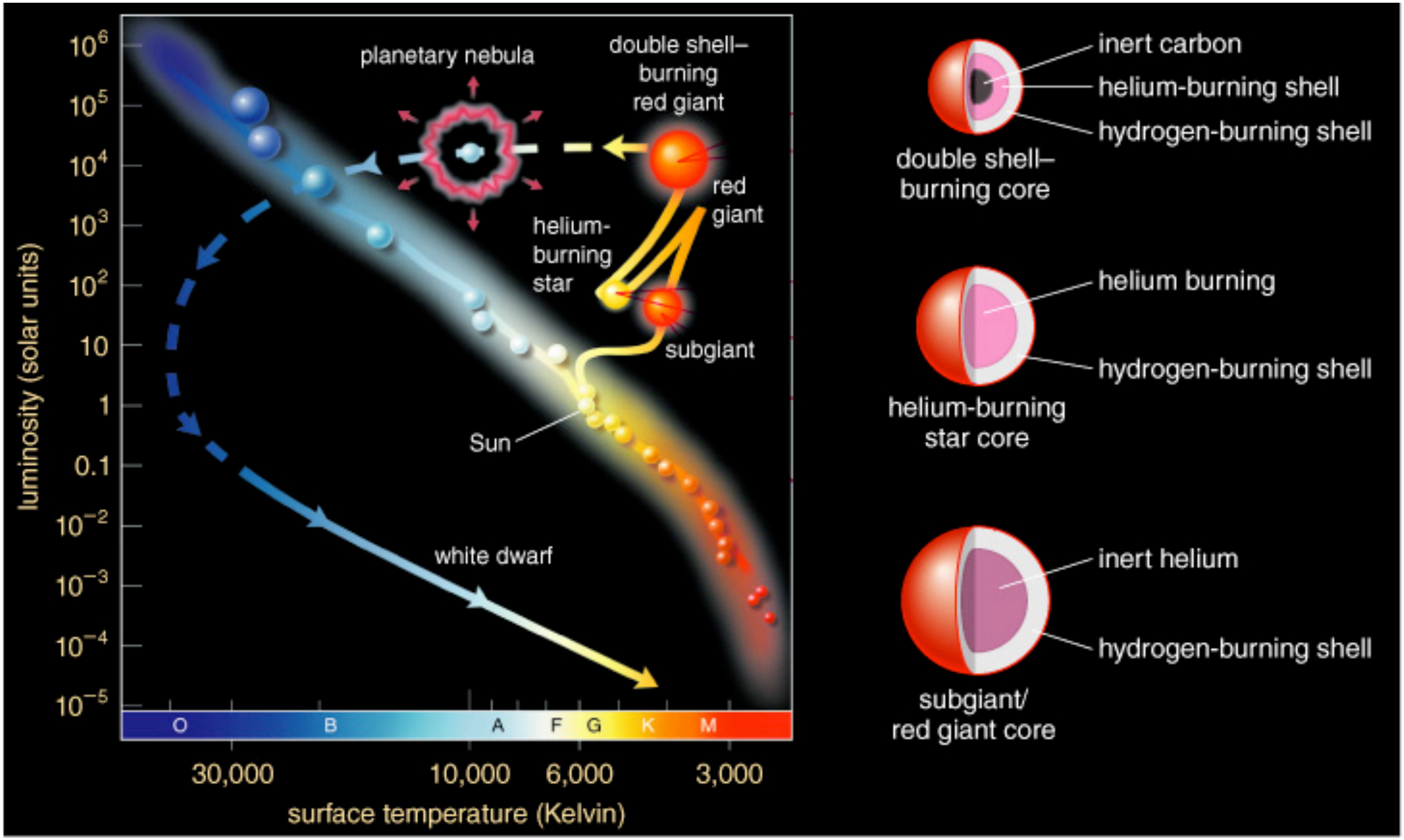
Life Stages: $1M_{sun}$ Star



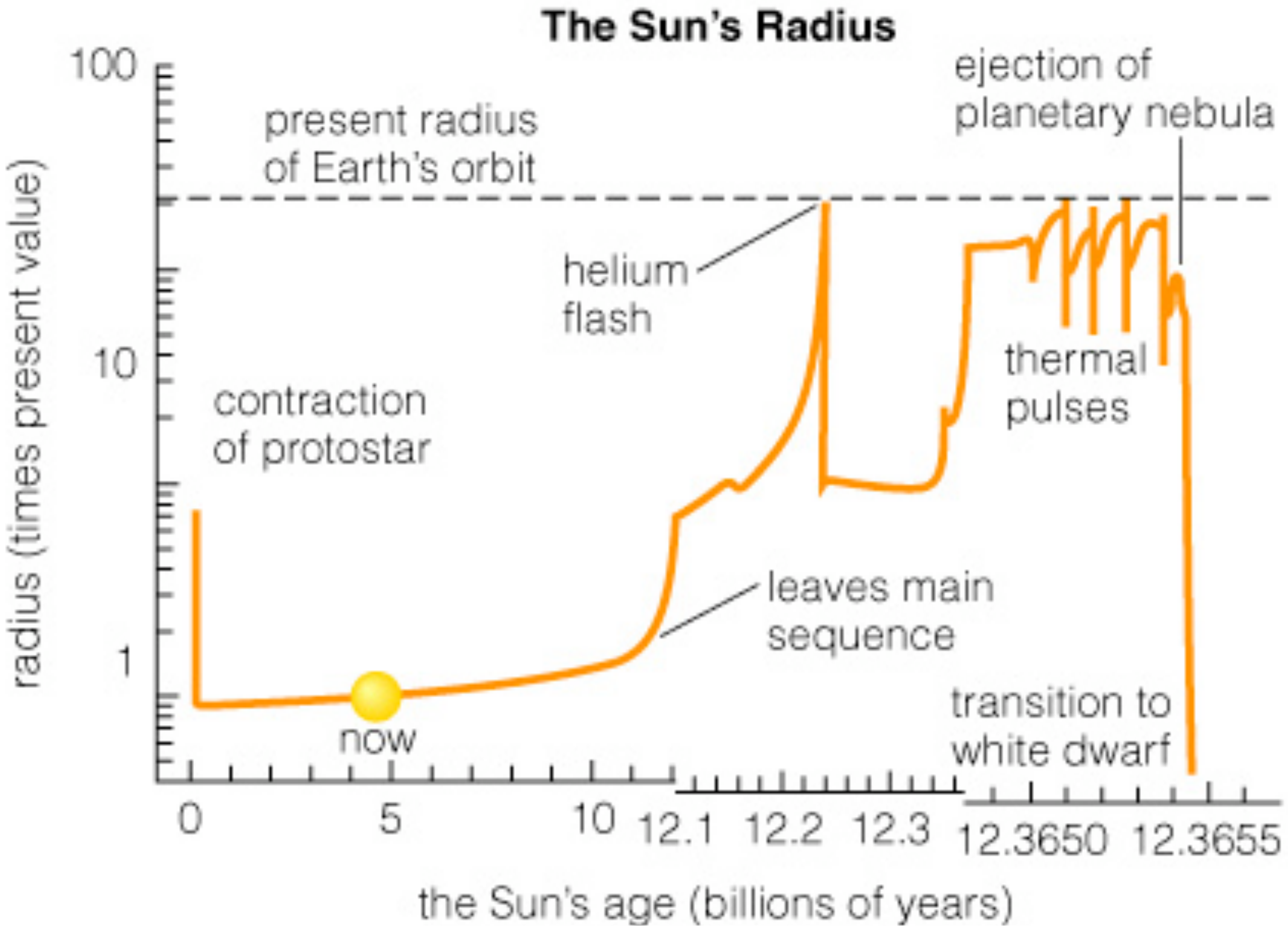
The evolution of the Sun is typical of *Low Mass Stars*

$0.08 < M < 8M_{sun}$

Life Track of a Sun-Like Star

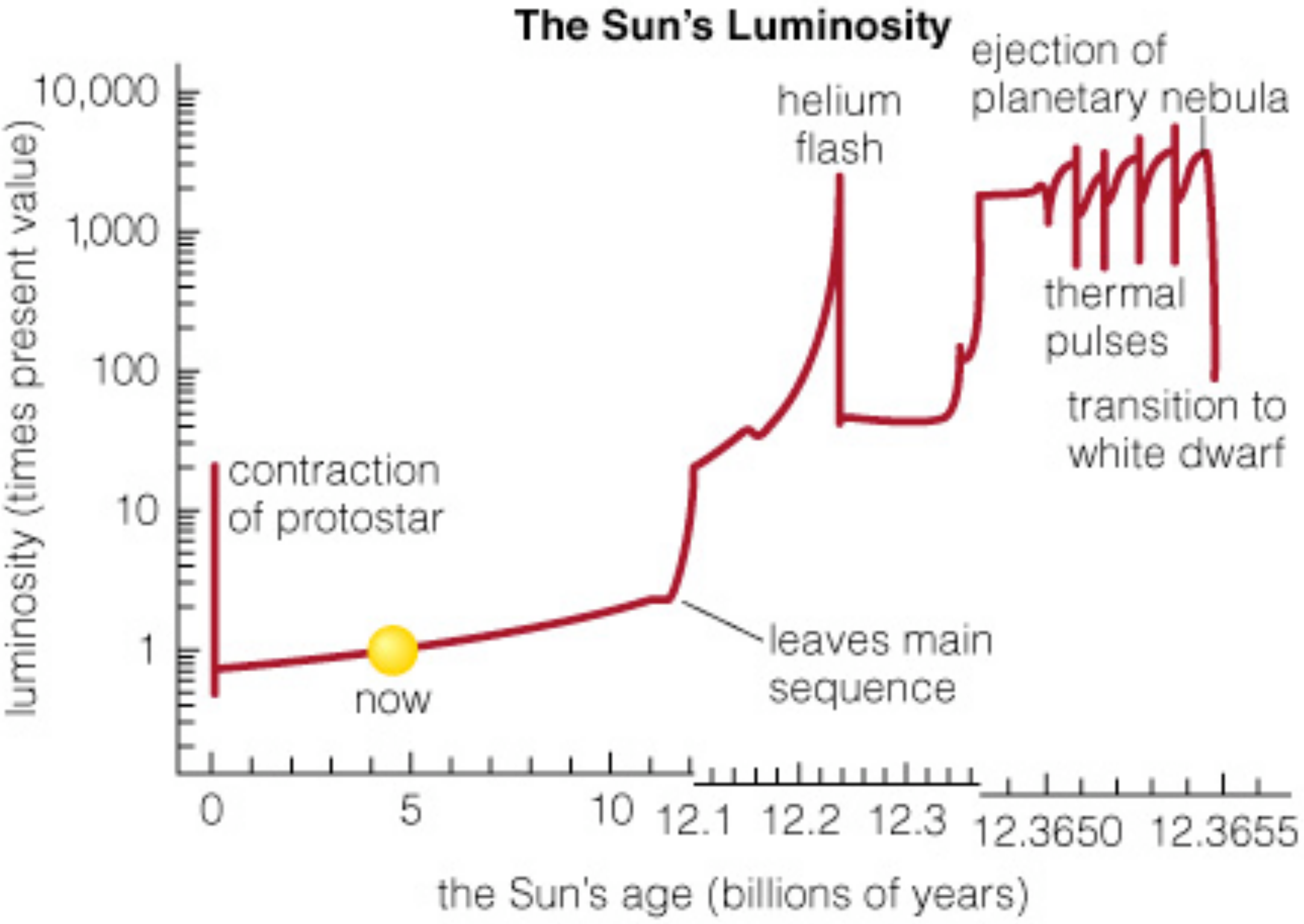


Earth’s Fate



- Sun’s radius will grow to near current radius of Earth’s orbit

Earth’s Fate

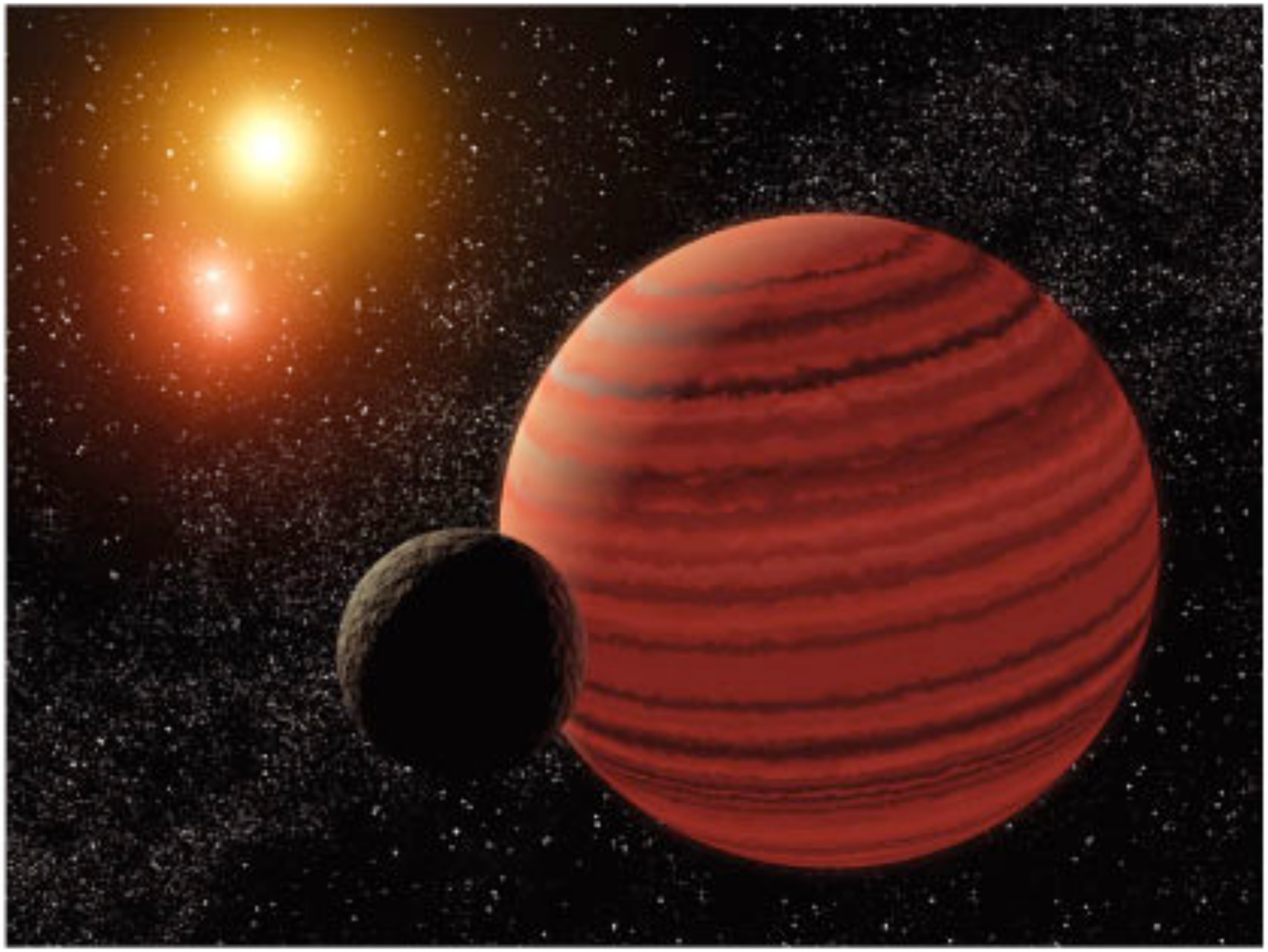


- Sun’s luminosity will rise to 1,000 times its current level—too hot for life on Earth

Life Stages

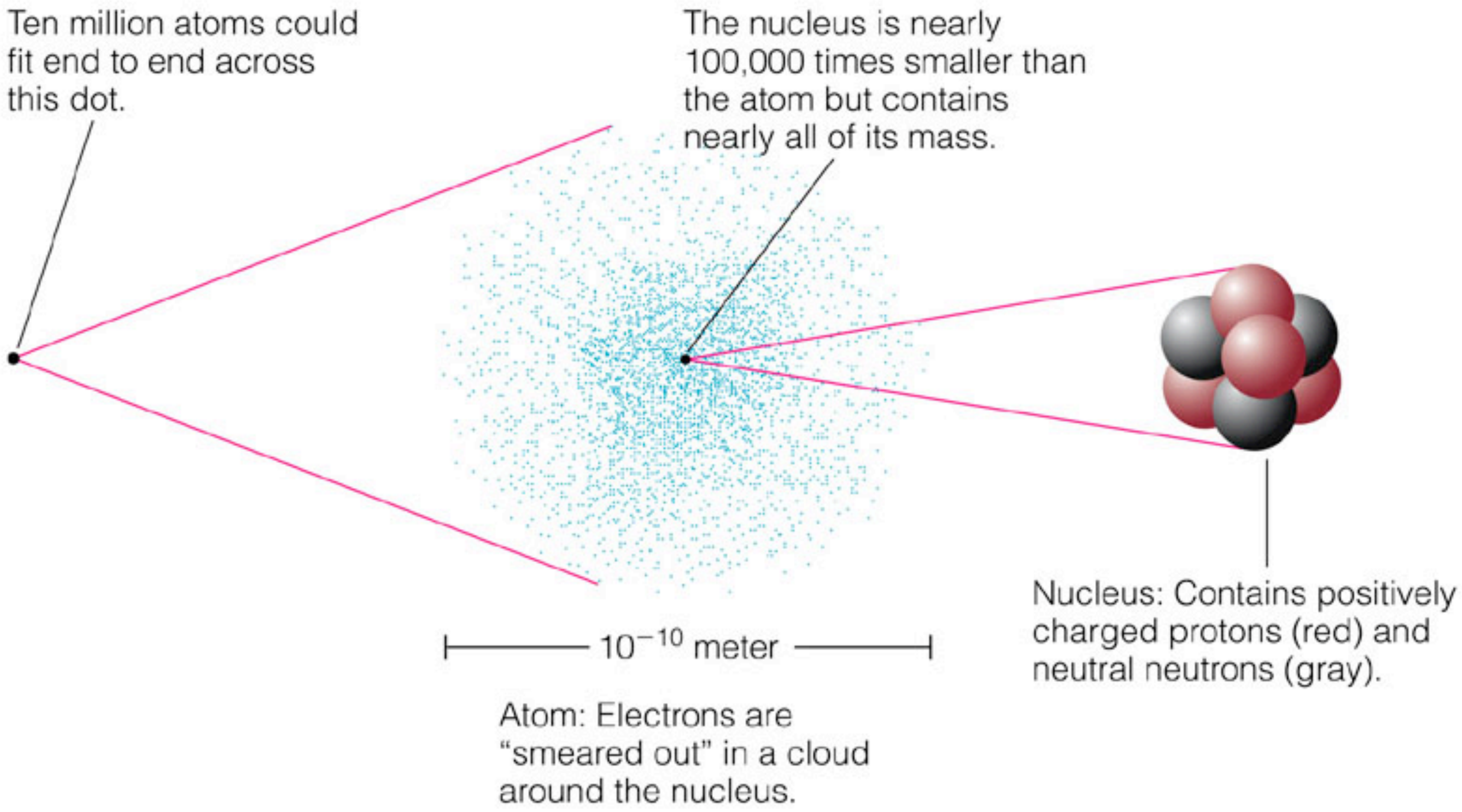
1. *Protostar*: gravitational contraction
2. Onset of Nuclear Reactions: gravity plus nukes
3. *Main Sequence*: ^{1}H --> ^{4}He fusion (p-p chain) in core
4. End of M/S - 10 billion yrs
5. *Red Giant*: ^{1}H -->^{4} He fusion in shell around contracting core (leading to He Flash)
6. *He Main Sequence*: He fusion in core (horizontal branch)
7. Double-shell (^{4}He --> ^{12}C; ^{1}H --> ^{4}He) burning (red giant)
8. Ejection of H and He in a *Planetary Nebula* reveals hot (100,000K) stellar core
9. Leaving behind an inert *White Dwarf* (radiates store of thermal energy)

What is the smallest mass a newborn star can have?



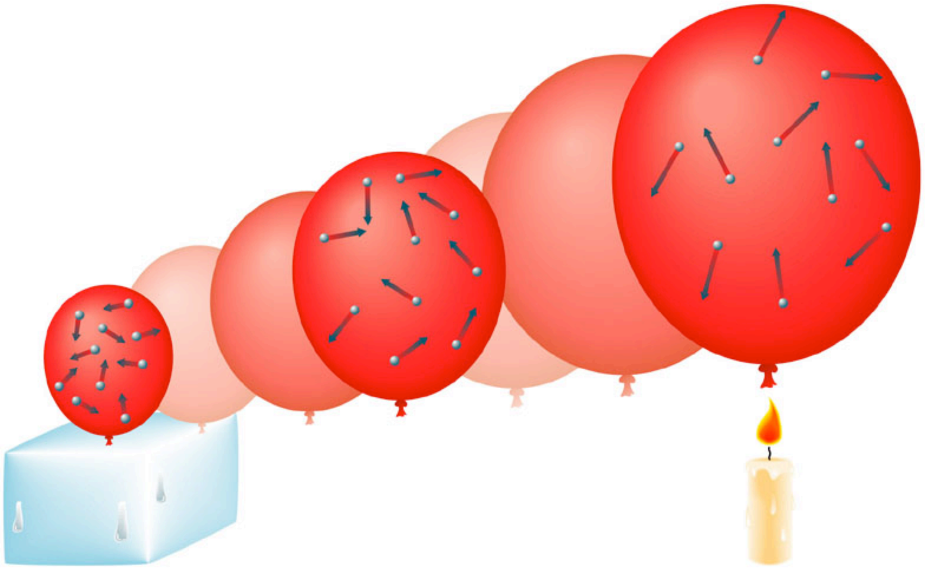
Fusion and Contraction

- 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:

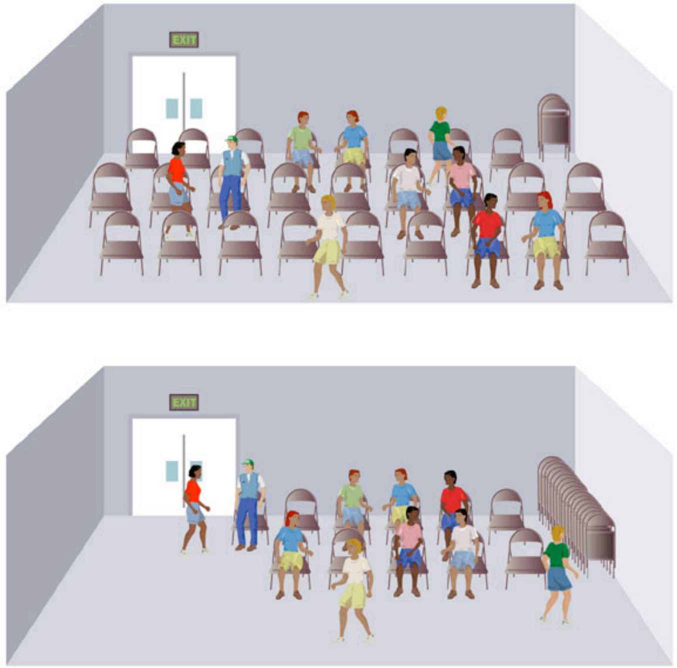
Laws of quantum mechanics prohibit two electrons from occupying same state in same place



Thermal Pressure:

Depends on heat content

The main form of pressure in most stars



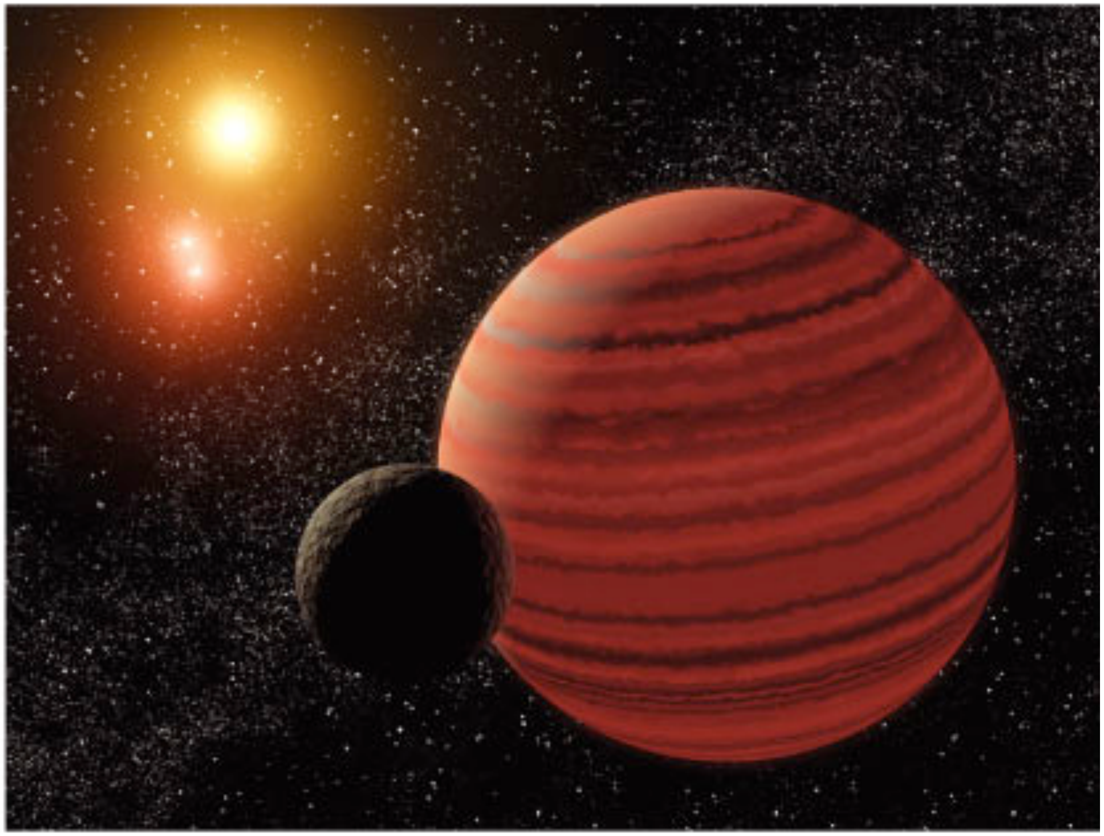
n Education, publishing as Addison Wesley

Degeneracy Pressure:

Particles can't be in same state in same place

Doesn't depend on heat content

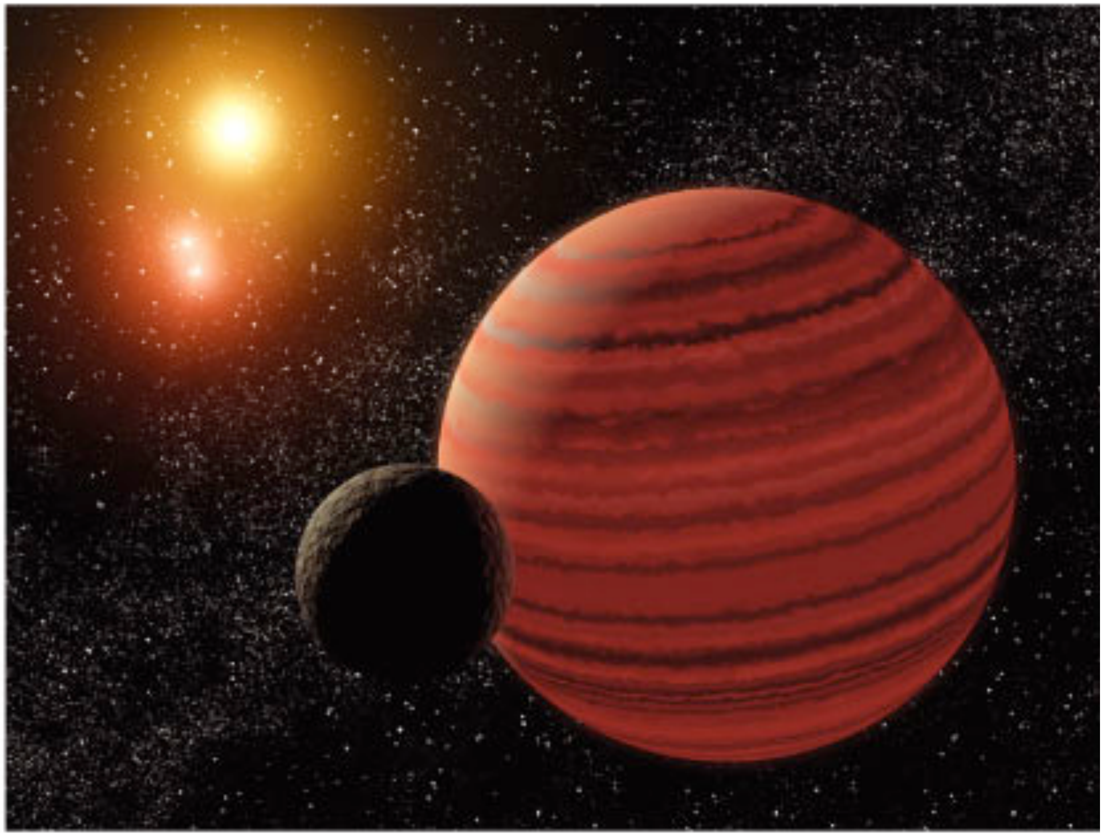
Brown Dwarfs



- Degeneracy pressure halts the contraction of objects with $<0.08M_{\text{Sun}}$ before core temperature become hot enough for fusion

- Starlike objects not massive enough to start fusion are **brown dwarfs**

Brown Dwarfs



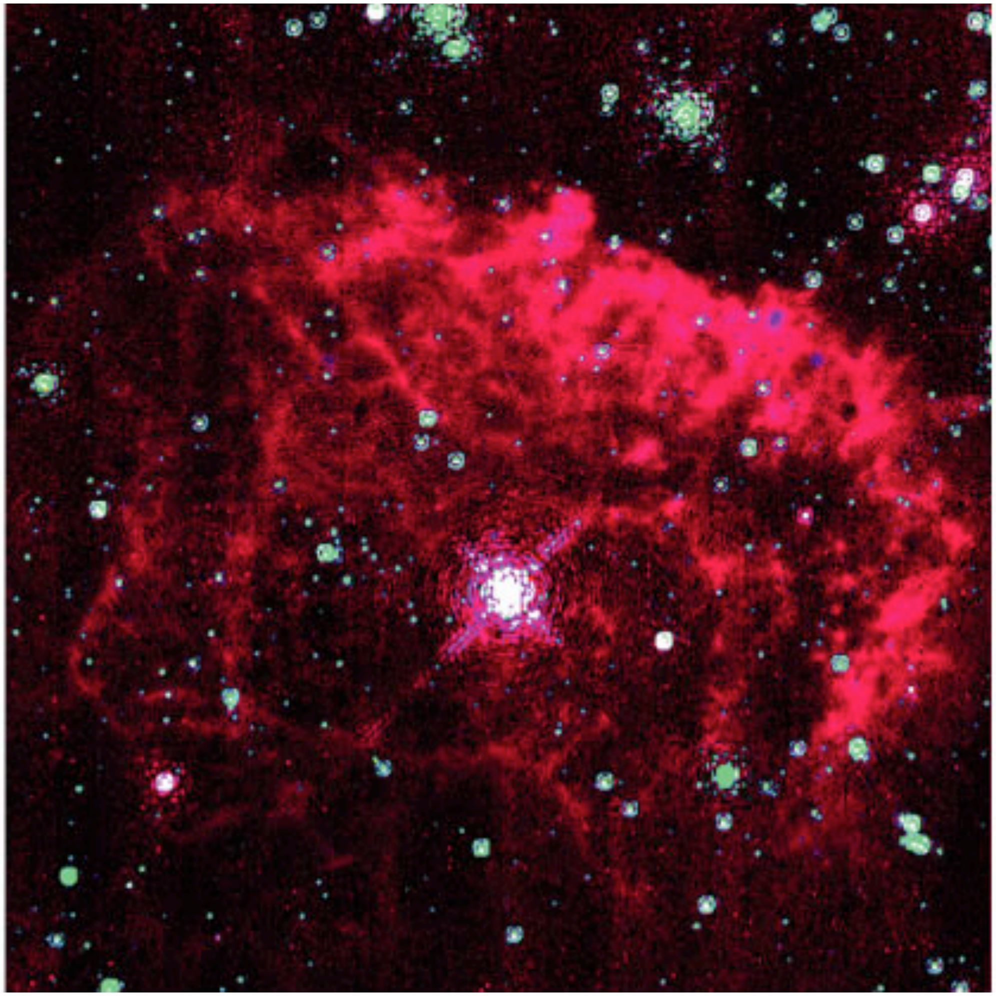
- A brown dwarf emits infrared light because of heat left over from contraction

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

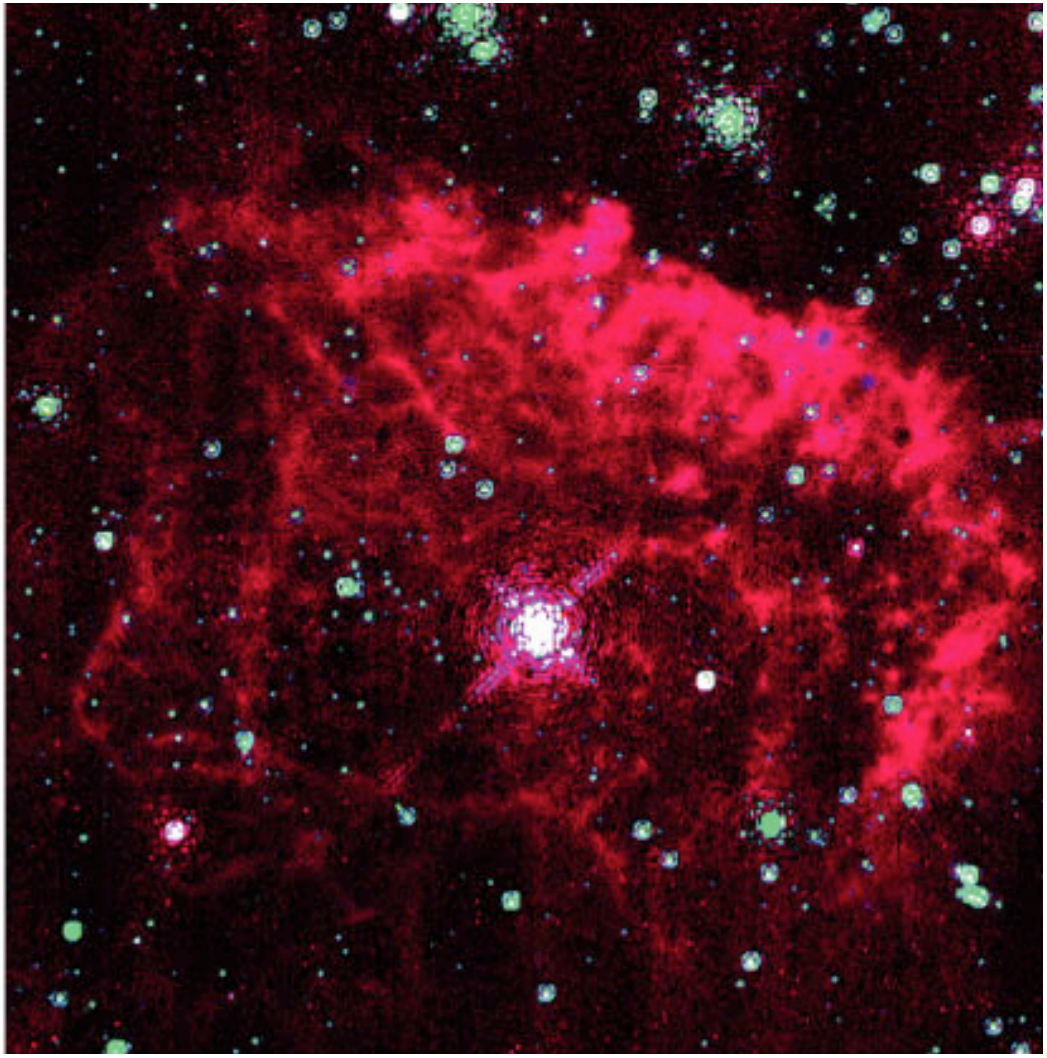
Brown Dwarfs in Orion

- 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?

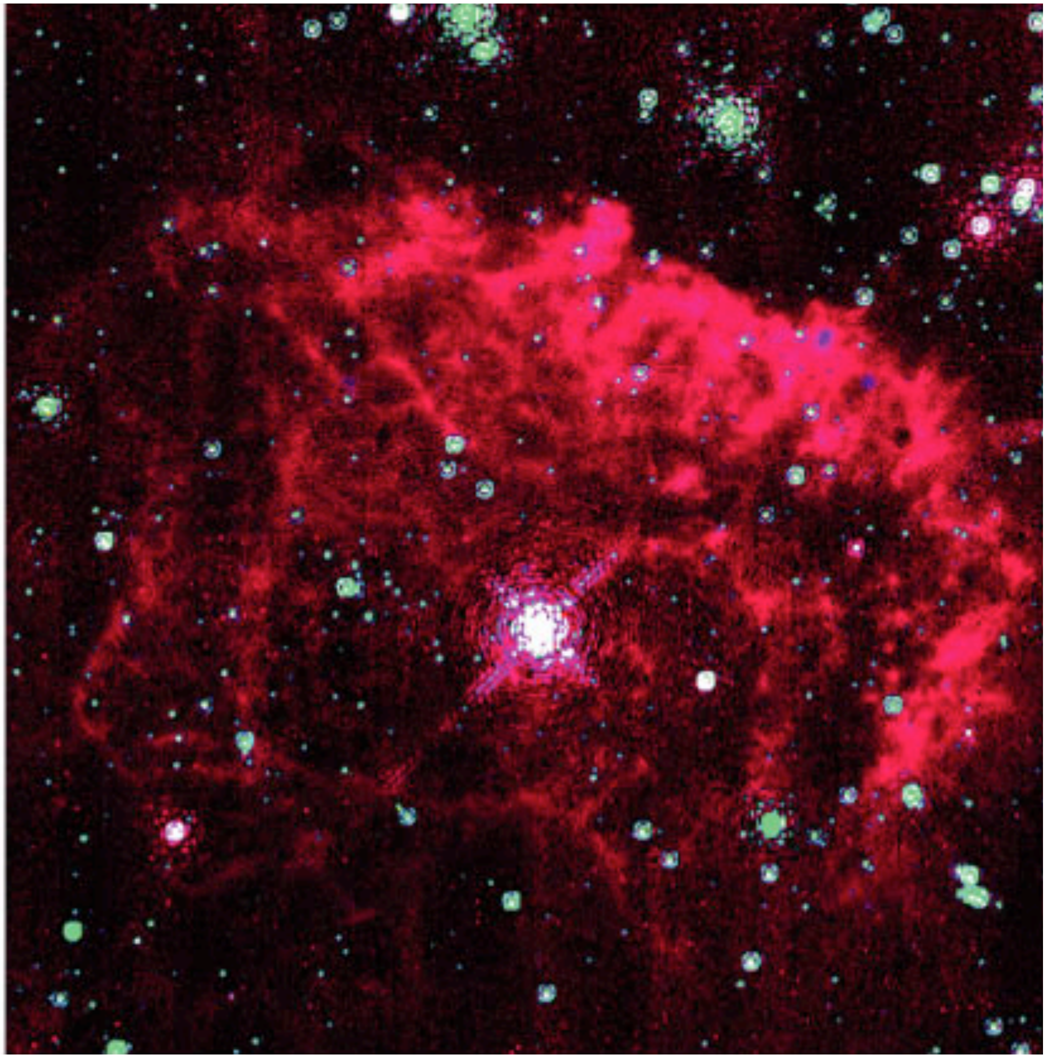


Radiation Pressure

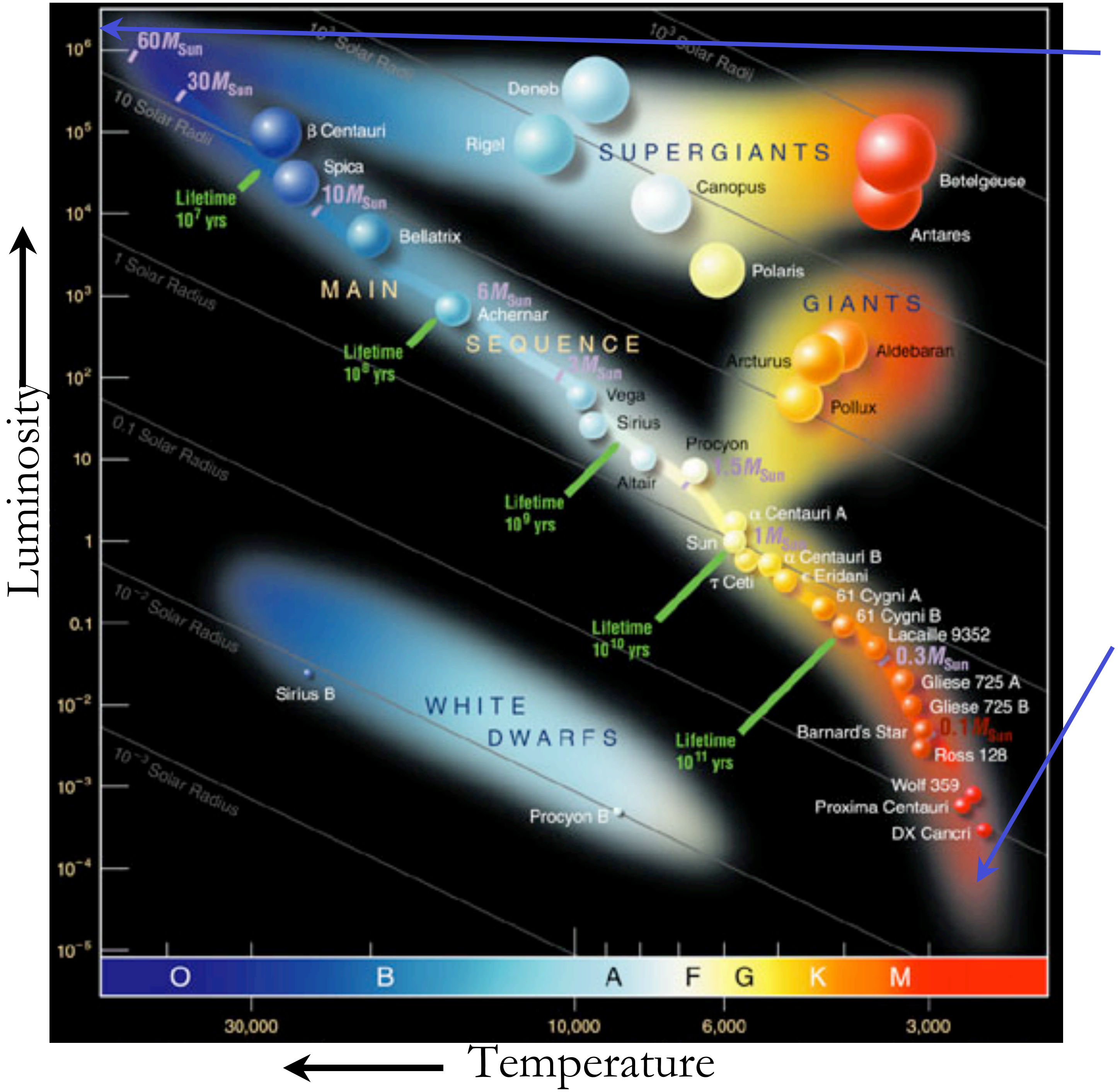


- Photons exert a slight amount of pressure when they strike matter
- Very massive stars are so luminous that the collective pressure of photons drives their matter into space

Upper Limit on a Star’s Mass



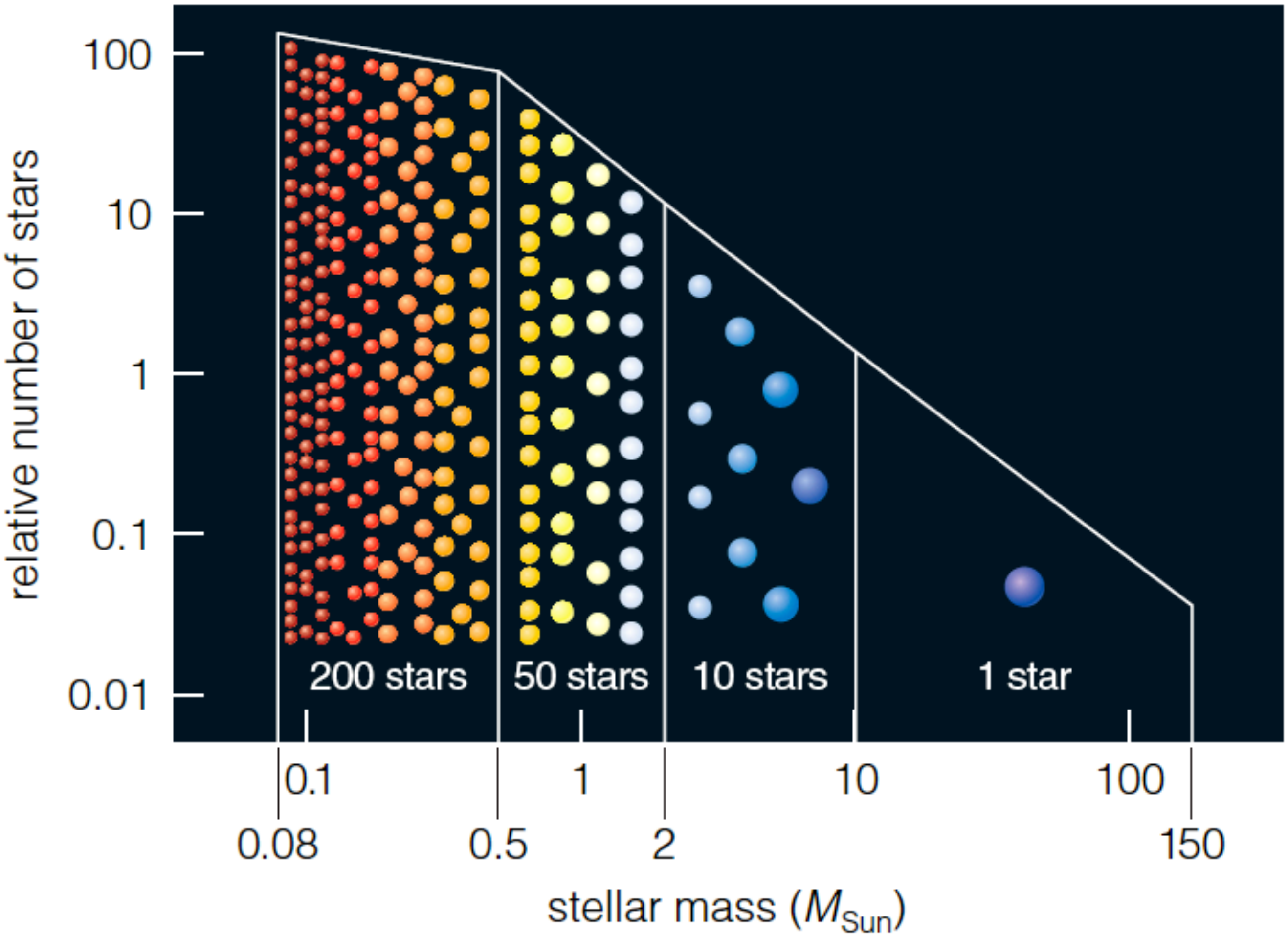
- Models of stars suggest that radiation pressure limits how massive a star can be without blowing itself apart
- Observations have not found stars more massive than about $150M_{\text{Sun}}$



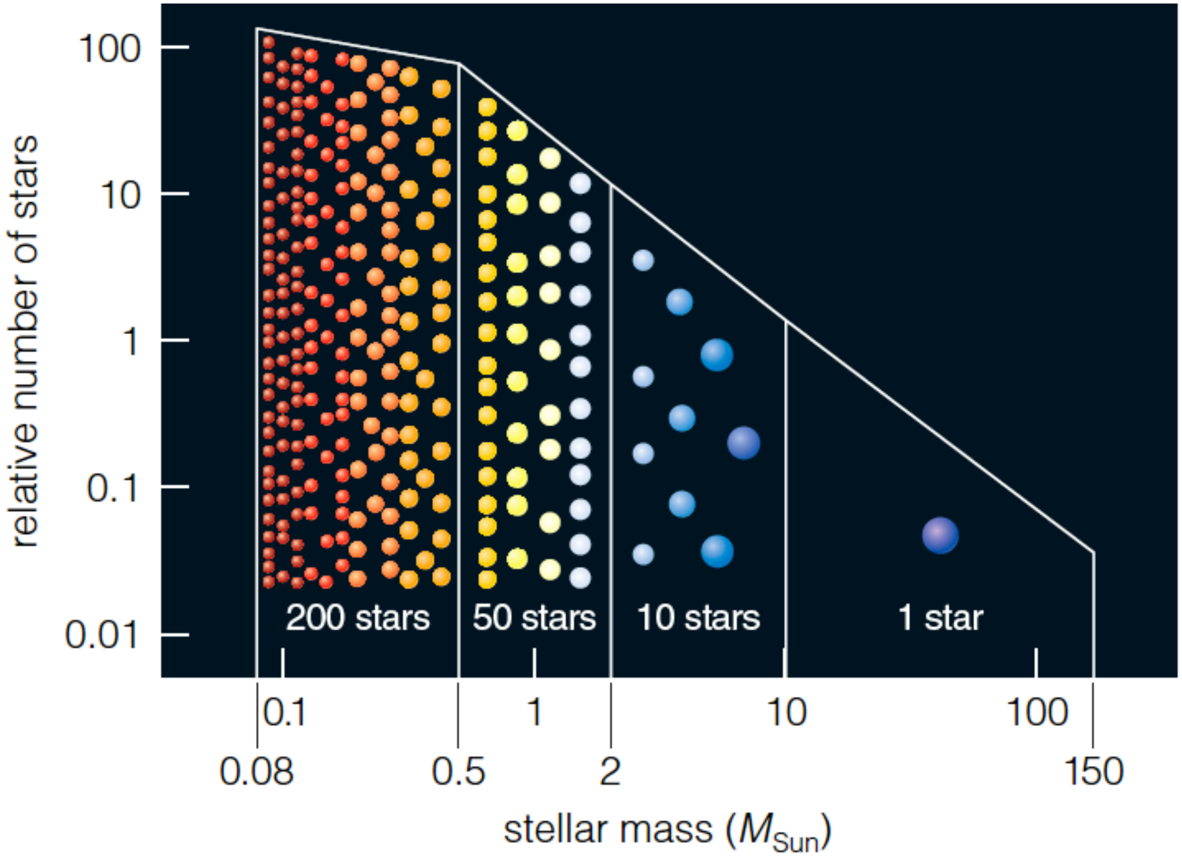
Stars more massive than $150 M_{\text{Sun}}$ would blow apart

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