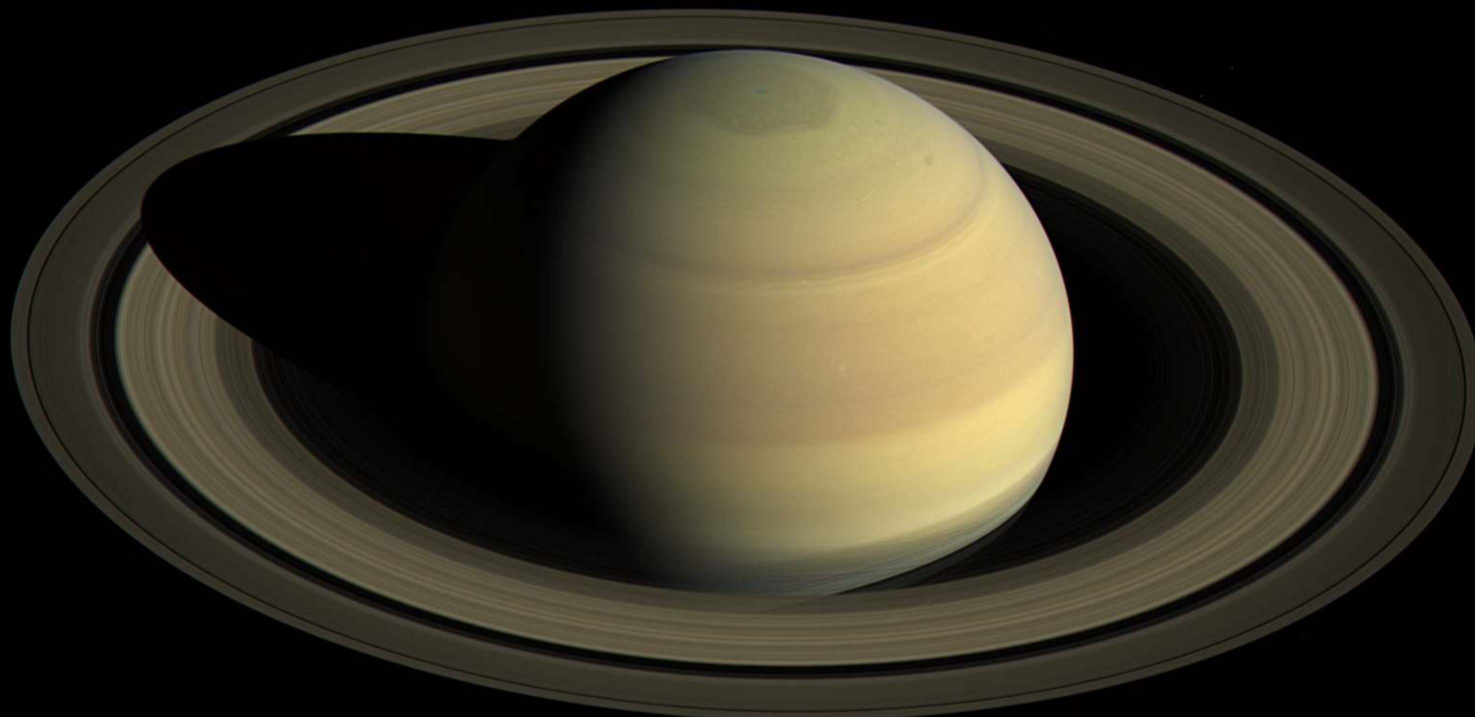
AST 2002
Introduction to Astronomy



A Few Quick Things…

E-mailing me: Must have AST2002 in the subject

Mary Hinkle, Graduate Teaching Assistant:

Office Hours: Mon 1:30-3:00pm. PSB 316

My office hours: Mon 3:00-4:00pm. PSB 308

Tue 3-4 pm. PSB 308

Last Midterm: Mon 9th April. (Best of 2 will count towards final grade)

Final: Friday 27th April. 7am-9:50 am. (on all chapters)

LAST Knights Under the Stars Event – Thursday 19th April

Opportunity to make up the 1% extra credit that was offered (if you haven't been yet, worth 2%) – Last chance for extra credit..

What Have We Covered, What's Next?

Chapter 13: Star Stuff

13.1. Star Birth

- How do stars form?
- How massive are newborn Stars?

13.2. Life as a Low-Mass Star

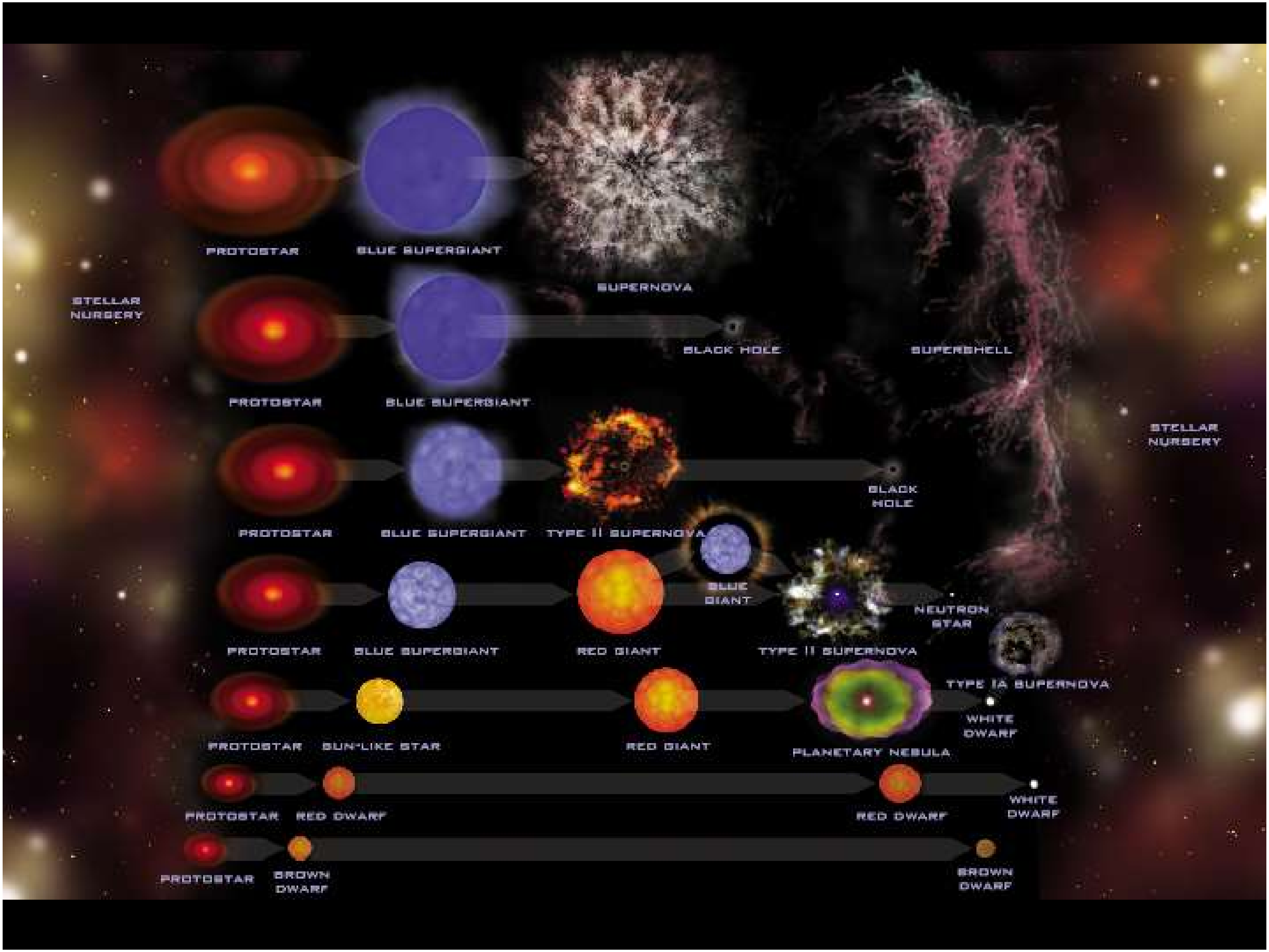
- What are the stages of a low-mass star?
- How does a low-mass star die?

13.3. Life as a High-Mass Star

- What are the life stages of a high-mass star?
- How do high-mass stars make the elements necessary for life?
- How does a high-mass star die?

13.4. Stars in Close Binaries

- How are the lives of stars with close companions different?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RED DWARF
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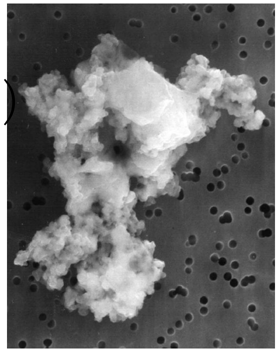
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

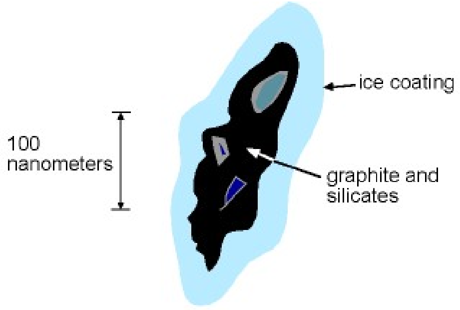

WHAT IS THE INTERSTELLAR MEDIUM?
All of the 'stuff' between the stars

Interstellar Dust Clouds

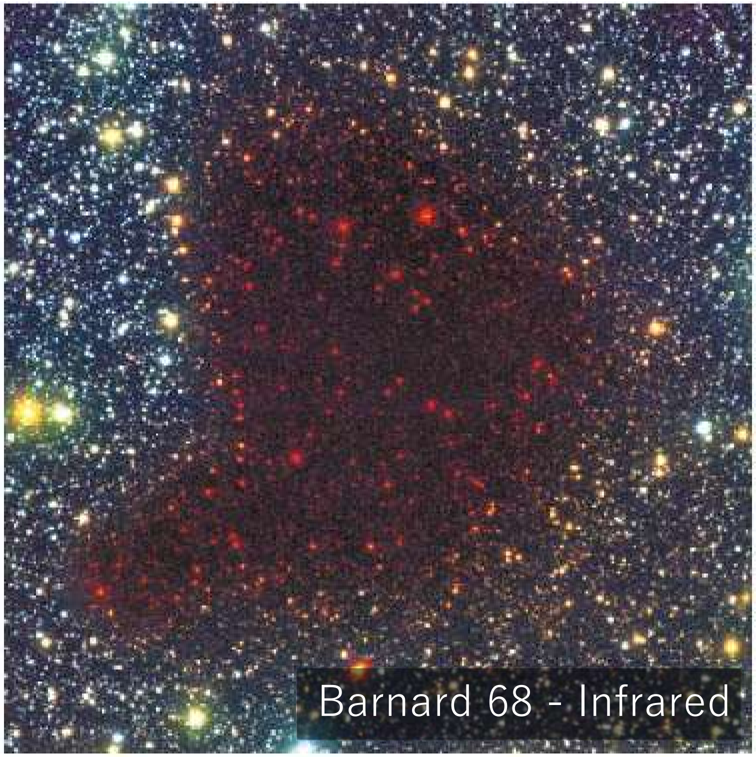
<u>Physical Conditions:</u>

- Dust is minor component ~ 1% (99% gas)
- VERY COLD, ~ 10 Kelvin inside clouds
- Pressure ~ 10^{-14} Torr…
- *Harsh Radiation Environment*

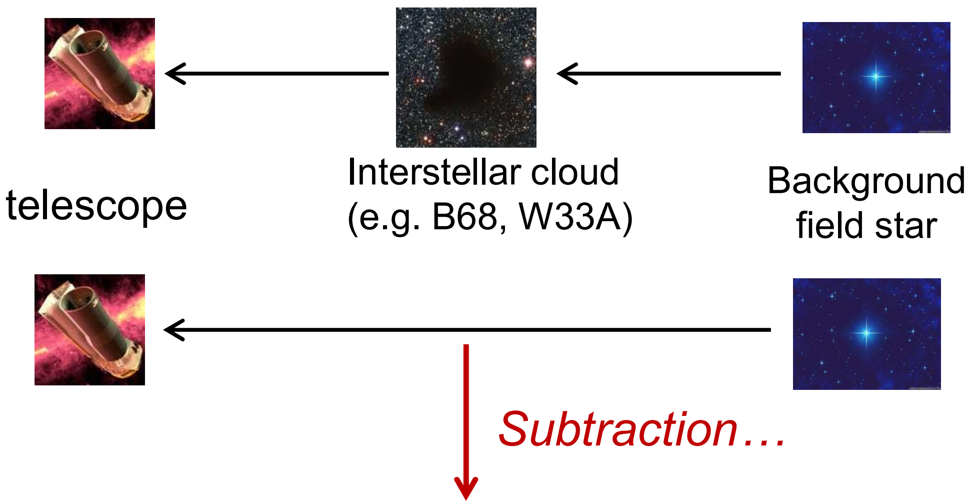




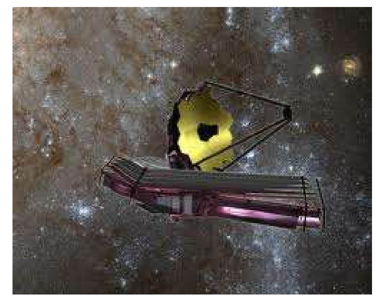
A typical dust grain (note the tiny scale!).



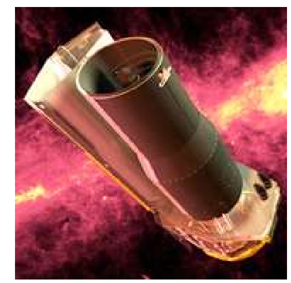
Inventory of Interstellar Ices

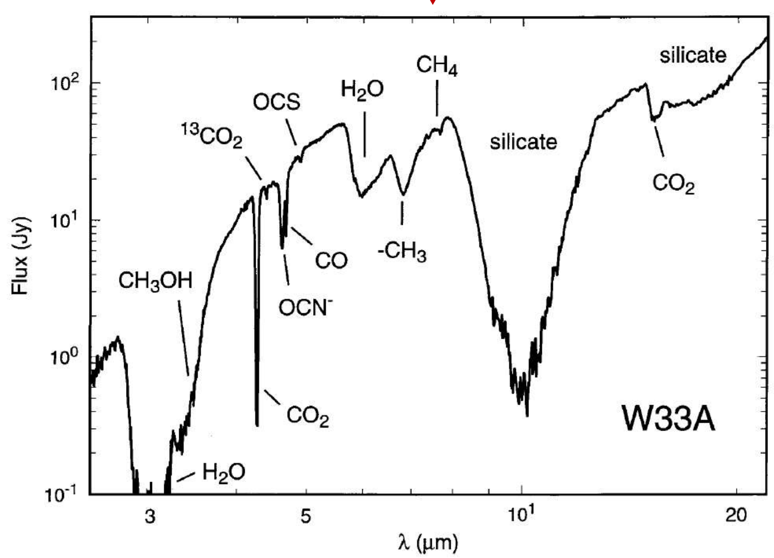


James-Webb



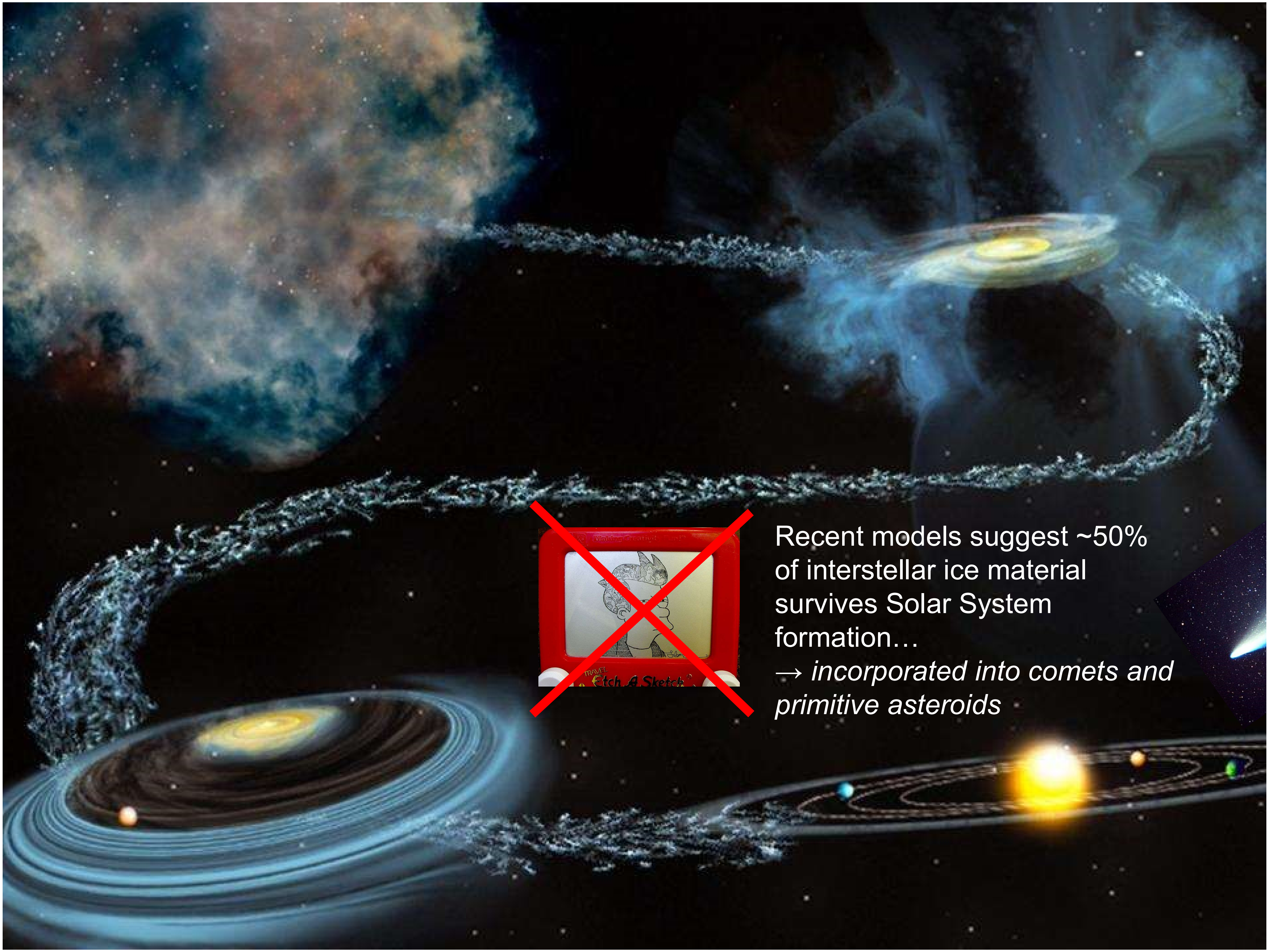
Spitzer





Molecule	Dark Clouds (Elias 16)	Embedded Young Stellar Object of Low Mass (Elias 29)	Embedded Young Stellar Object of High Mass (W33a)
H_2O	100	100	100
CO	25	5.6	9
CO_2	18	22	14
CH_4	1-2	<1.6	2
CH_3OH	<3	<4	22
H_2CO	2-6?	-	1.7-17
OCS	0.2	<0.08	0.3
NH_3	<10	<9.2	15
HCOOH	3?	-	0.4-2
OCN^-/XCN	<2	0.24	3-10
HCN	0.5-10	-	<3
O_3	<2	-	-

Characteristic Infrared Vibrations of Molecules


Etch A Sketch
Recent models suggest ~50% of interstellar ice material survives Solar System formation…
→ *incorporated into comets and primitive asteroids*

Conditions for Star Birth

- Star formation is actually a difficult process that does not *typically* happen spontaneously… why?
- Temperature acts as a pressure, even at the low temperatures of a cloud (say 30 K) this can be enough to resist gravity – up to a point…
- As a cloud becomes denser it can help overcome the outward pressure of temperature more effectively
- The relationship between pressure, density and gravity is described by the Jean's instability relationship

Approximation to Jean's Instability Criteria – Minimum Mass

$$M_{minimum} = 18 M_{Sun} \sqrt{\frac{T^3}{n}}$$

Incredibly sensitive to the temperature and quite sensitive to the number density…

- If T = 30 K, n = 300 cm^{-3}, $M_{minimum}$ = 171 M_{Sun}

Effect of temperature (typical for dense clouds):

- If T = 10 K, n = 300 cm^{-3}, $M_{minimum}$ = 33 M_{sun}

Effect of number density (typical for dense clouds):

- If T = 10 K, n = 104 cm^{-3}, $M_{minimum}$ = 6 M_{sun}

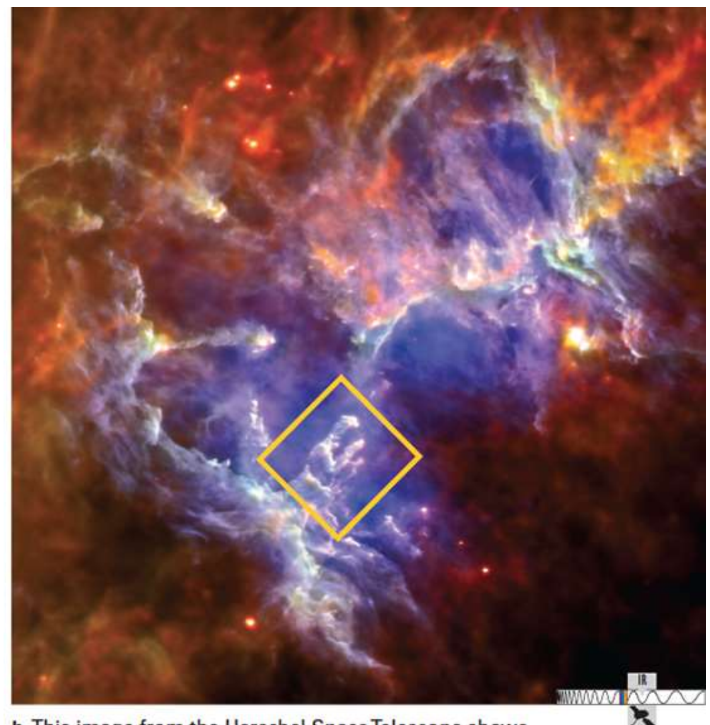
Not the full story: Cloud collapse may be triggered by an initial instability (e.g., a shock from a nearby supernova)

Hidden Star Formation: Glowing Dust Grains

- As stars begin to form, dust grains that absorb visible light heat up and emit infrared light.

a This visible-light image from the Hubble Space Telescope shows part of the Eagle Nebula, a gas cloud in which stars are currently forming.

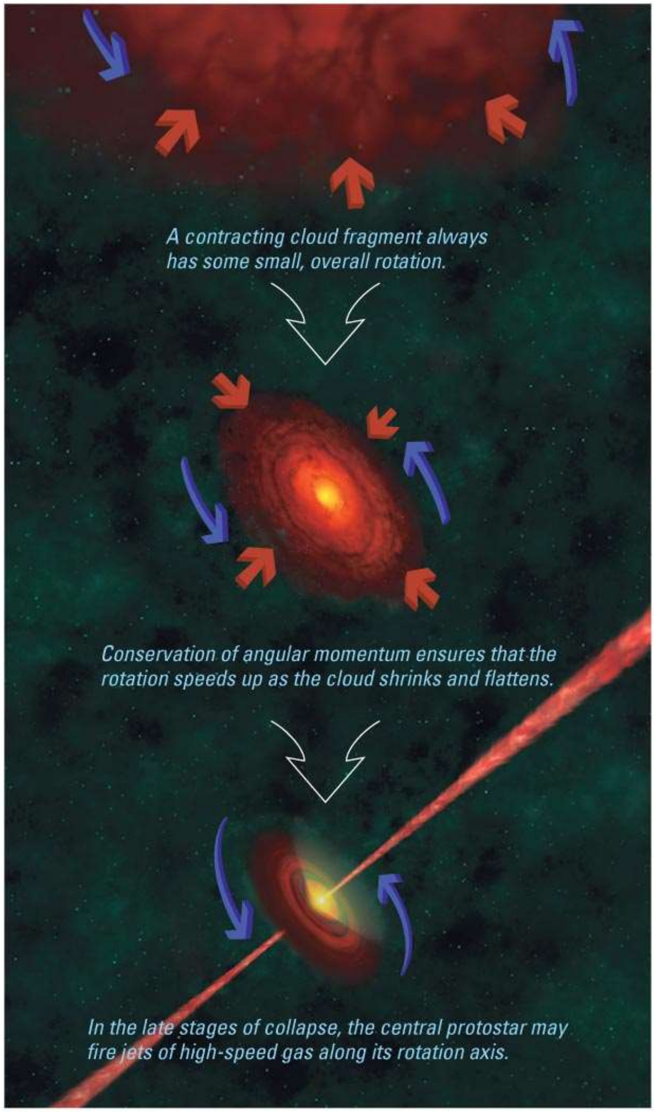
In visible light, as in this image, the star forming regions still appear dark.



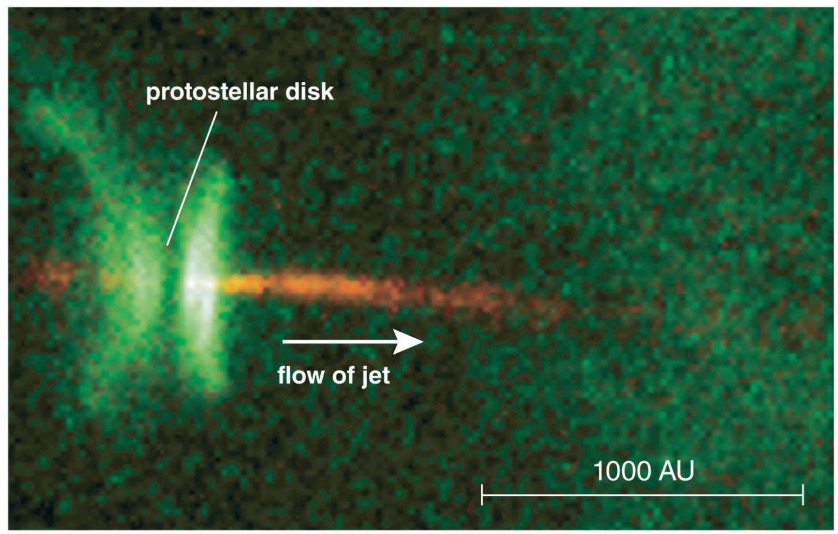
b This image from the Herschel Space Telescope shows infrared light from the Eagle Nebula, with the portion shown in part a outlined by the yellow square. Notice that the dark clouds in the visible-light image are glowing in the infrared image.

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

Formation of Jets



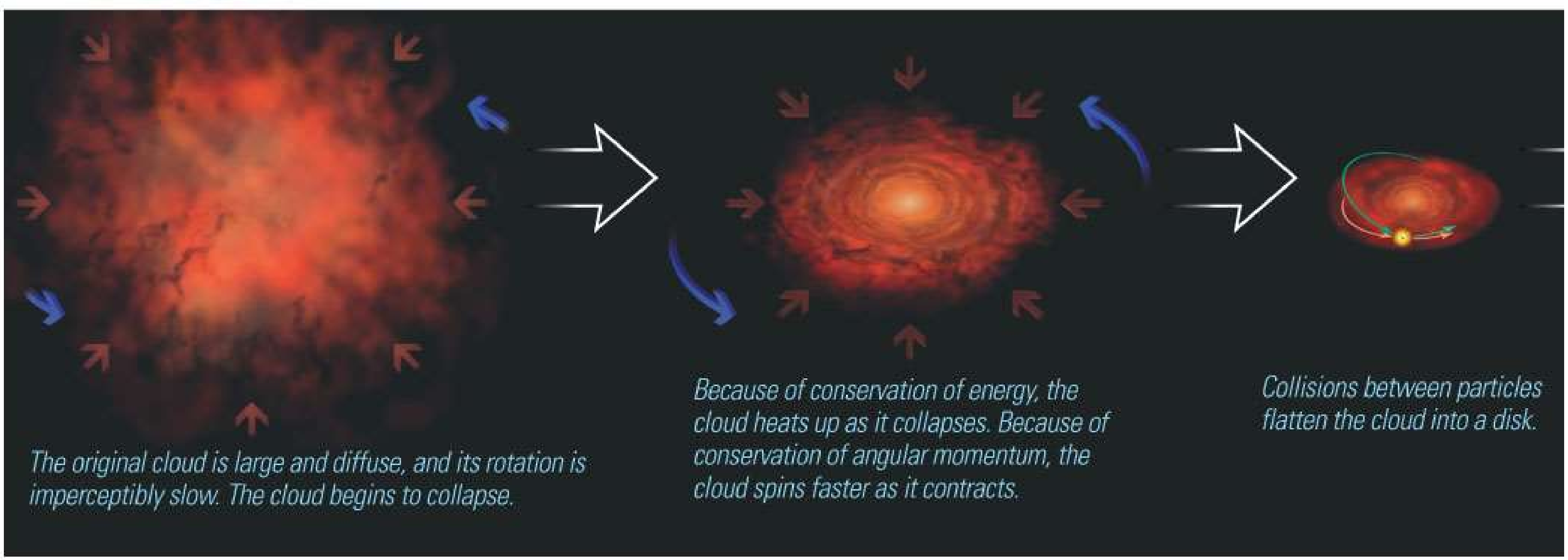
- Rotation also causes jets of matter to shoot out along the rotation axis.
- Jets are observed coming from the centers of disks around protostars.



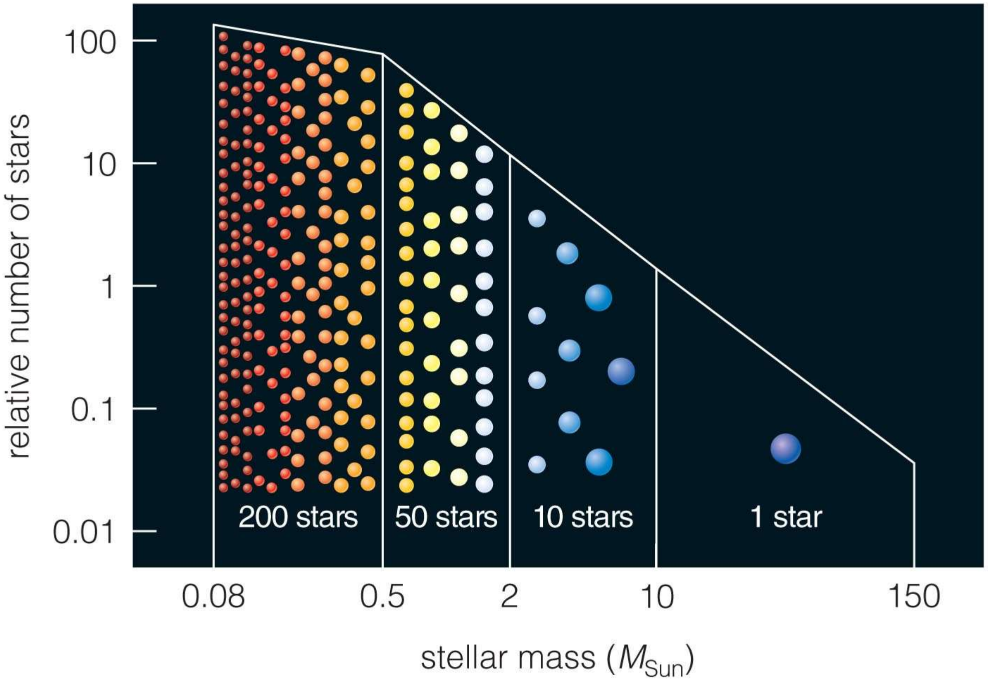
b This photograph shows a close-up view of a jet (red) and a disk of gas (green) around a protostar. We are seeing the disk nearly edge-on. The top and bottom surfaces of the disk are glowing, but we cannot see the darker middle layers of the disk.

Summary of Star Birth

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



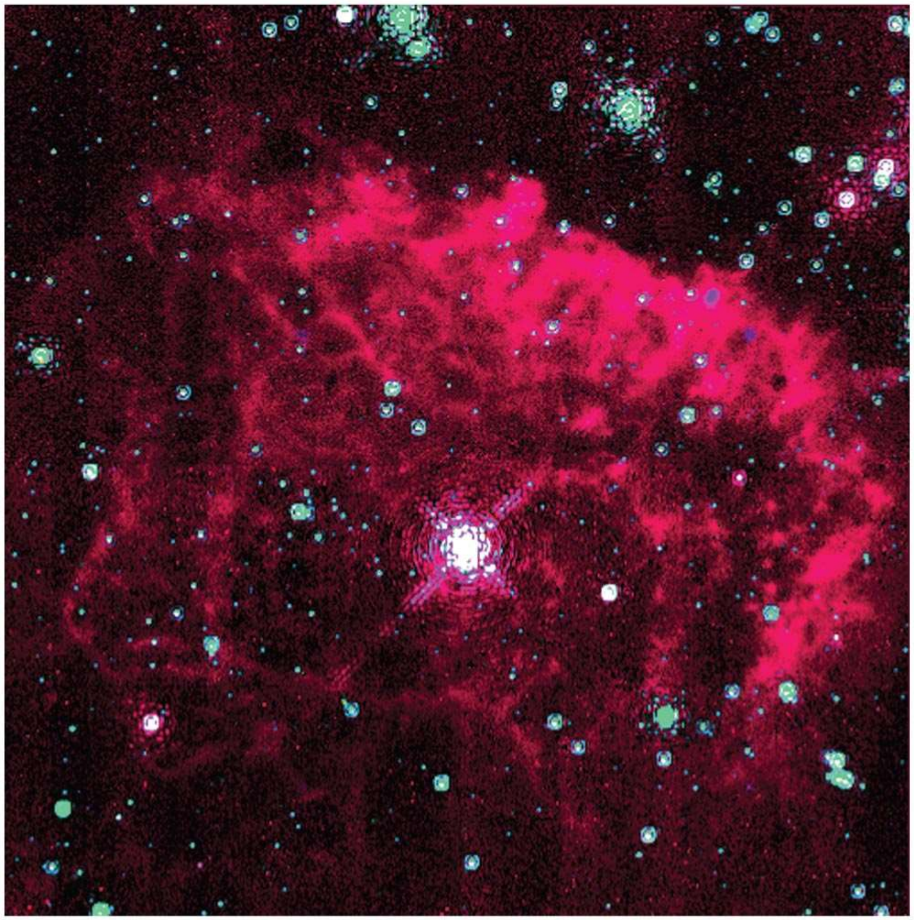
How Common are Massive Stars?



- Very massive stars are rare.
- In contrast, low-mass stars are very common.

→ What are the upper and lower limits to Star formation?

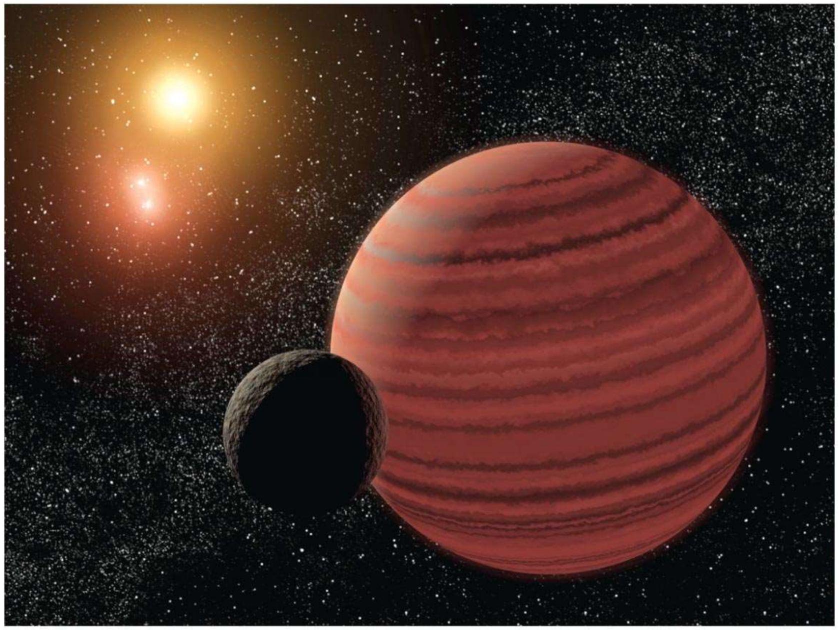
Upper Limit on a Star's Mass



- 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.
- 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 **$300M_{Sun}$. (RMC 136a1 $315M_{Sun}$)**

Lower Limit on a Star's Mass: Brown Dwarfs

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

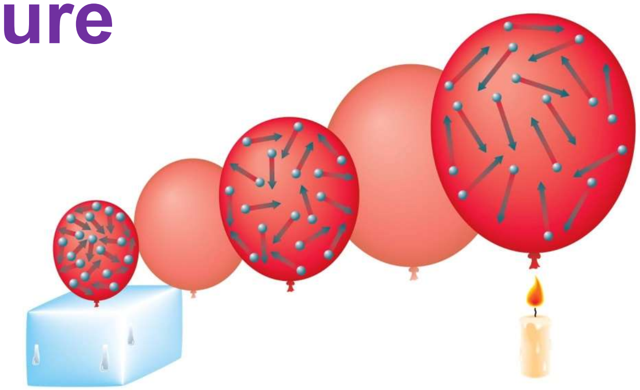


a Artist's conception of a brown dwarf, orbited by a planet (to its left) in a system with multiple stars. The reddish color approximates how a brown dwarf would appear to human eyes. The bands are shown because we expect brown dwarfs to look more like giant jovian planets than stars.

The Difference Between Thermal Pressure and Degeneracy Pressure

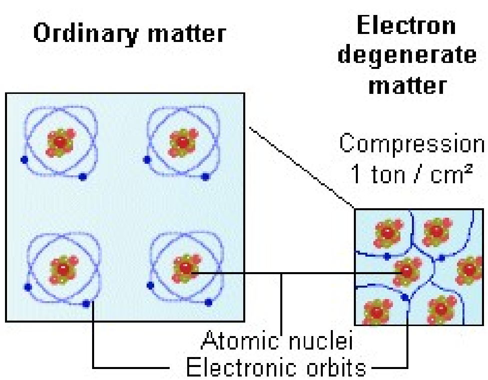
Thermal Pressure:

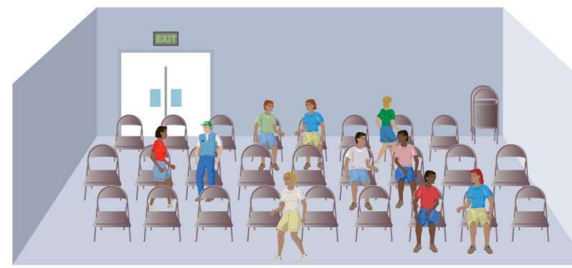
- Depends on heat content
- The main form of pressure in most stars



Degeneracy Pressure:

- Particles can't be in same state in same place
- Does not depend on heat content
- **For electrons:** Laws of quantum mechanics prohibit two electrons from occupying the same state in the same place.





a When there are many more available places (chairs) than particles (people), a particle is unlikely to try to occupy the same place as another particle. The only pressure comes from the temperature-related motion of the particles.

b When the number of particles (people) approaches the number of available places (chairs), finding an available place requires that the particles move faster than they would otherwise. The extra motion creates degeneracy pressure.

iClicker Question

When does a star leave the main sequence?

A. After a few million years
B. After a few billion years
C. It depends on its mass
D. When the hydrogen fuel in its core is used up
E. C and D

iClicker Question

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iClicker Question

Why can’t a cloud with less than 0.08 times the mass of the Sun become a star?

A. It will become a star, but a small and faint one

B. Gravity will be too weak, and it will come apart

C. It will never get hot enough for fusion to start

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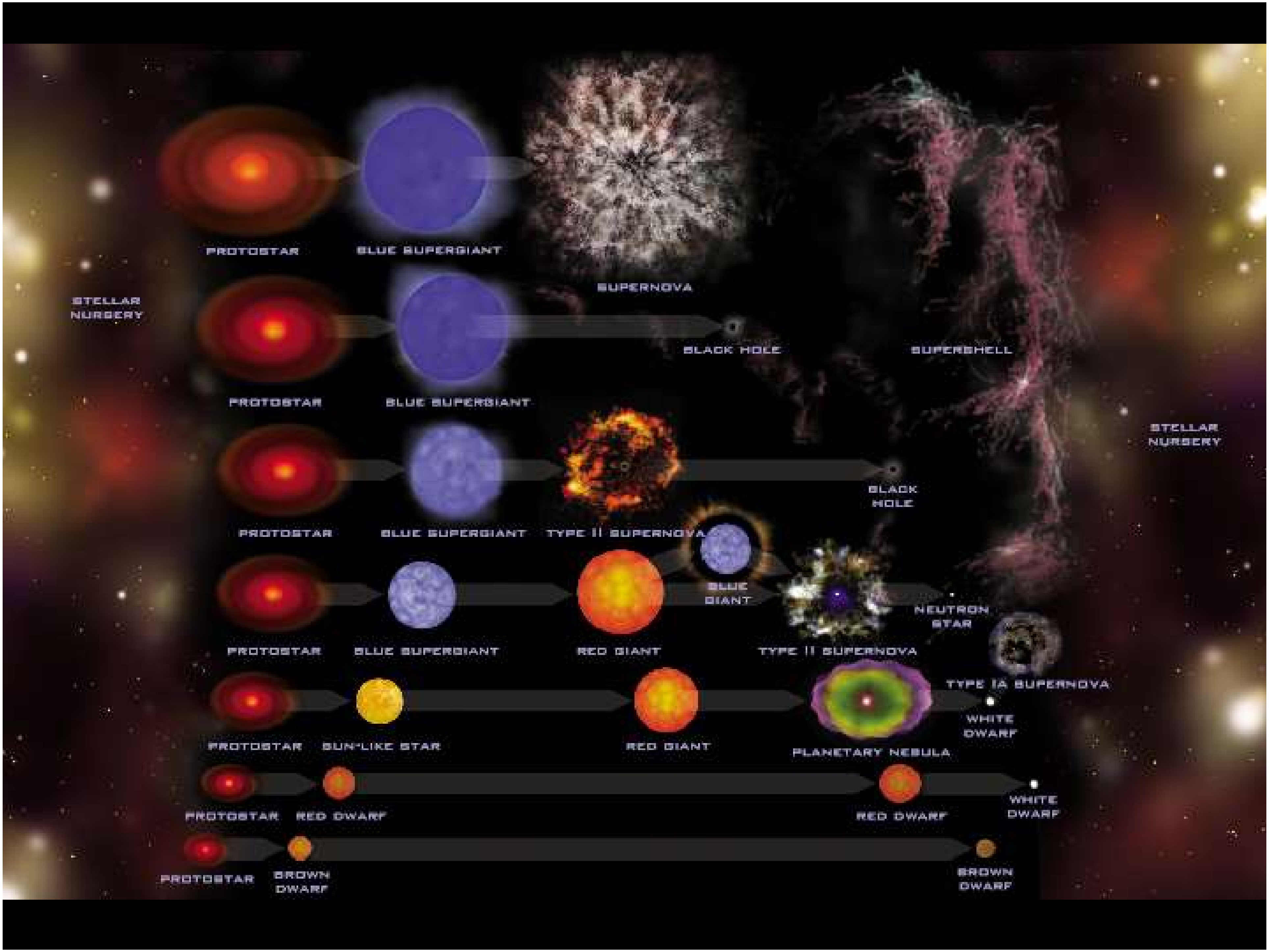

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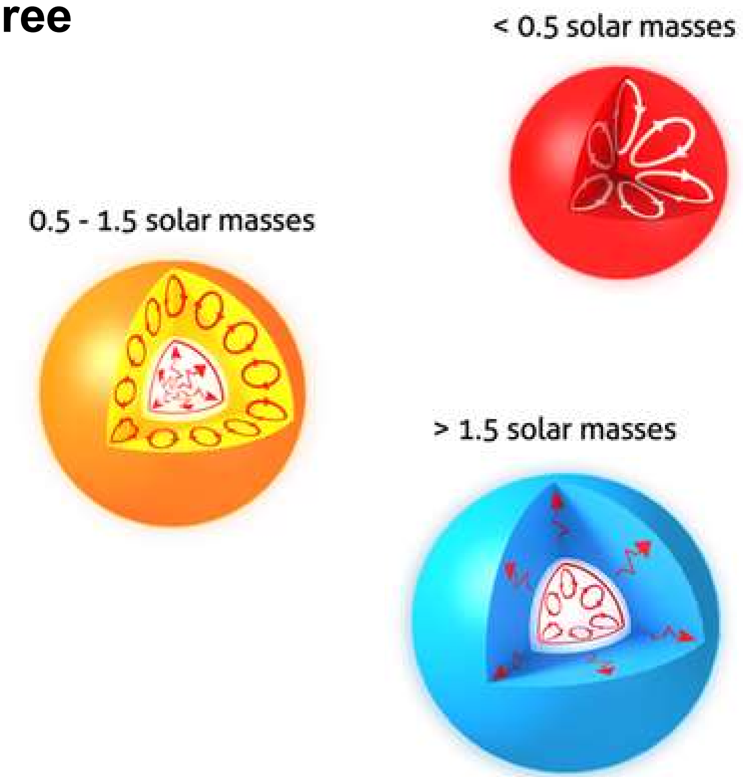
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

Categories of Stellar Mass

The life of stars falls into approximately three categories, based on stellar mass…



Low Mass Stars:

- Have birth masses below 2 M_{Sun}
- Lower limit ~0.08 M_{Sun}

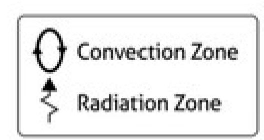
Intermediate Mass Stars:

- Have birth masses from 2-8 M_{Sun}

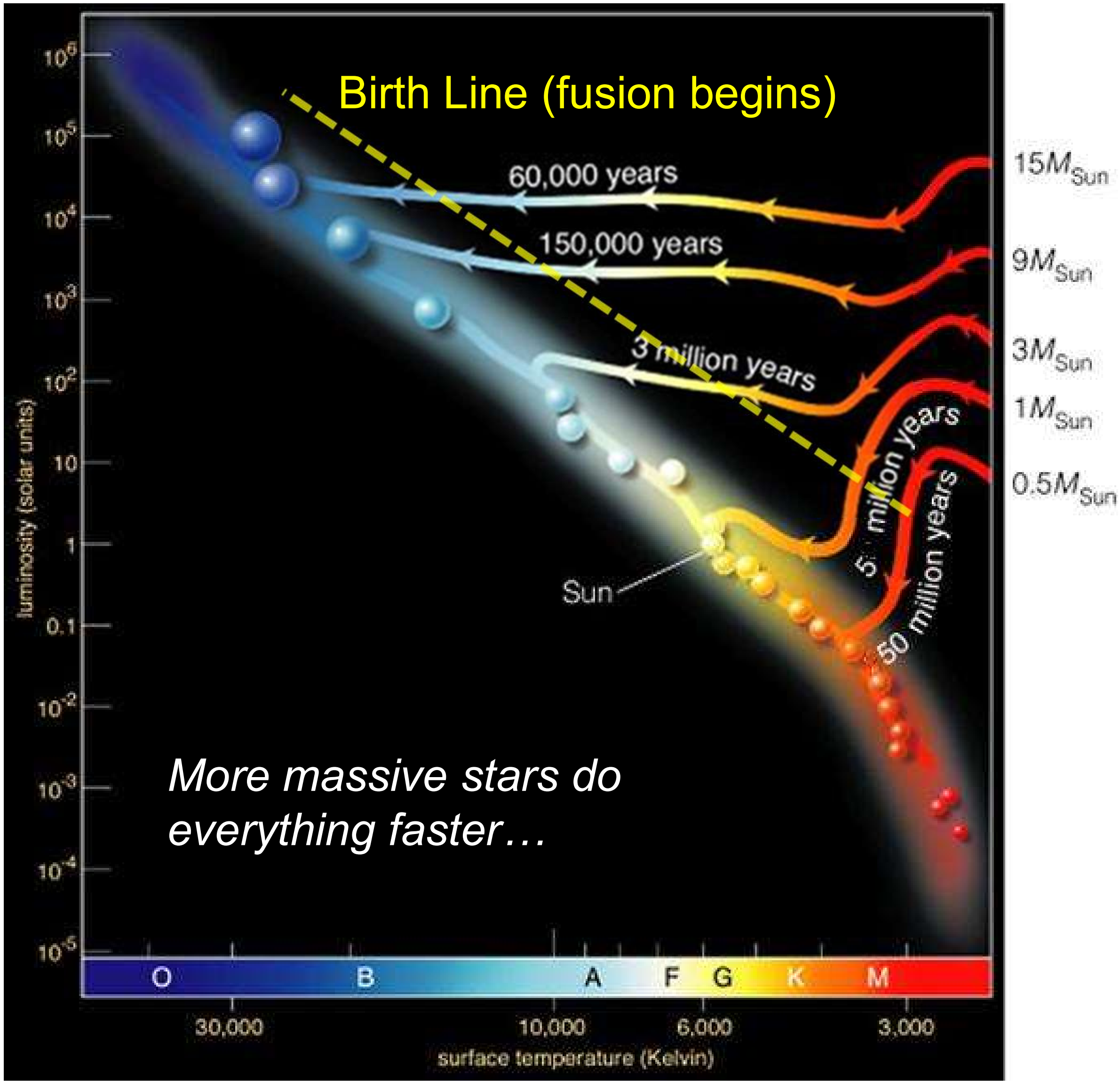
High Mass Stars:

- Have birth masses over ~8 M_{Sun}
- Upper limit ~300 M_{Sun}

Note: *Convection and radiation zones vary considerably and are switched for high mass stars (we won't talk about this in depth here).*



Entering the Main Sequence
Hayashi tracks of protostars



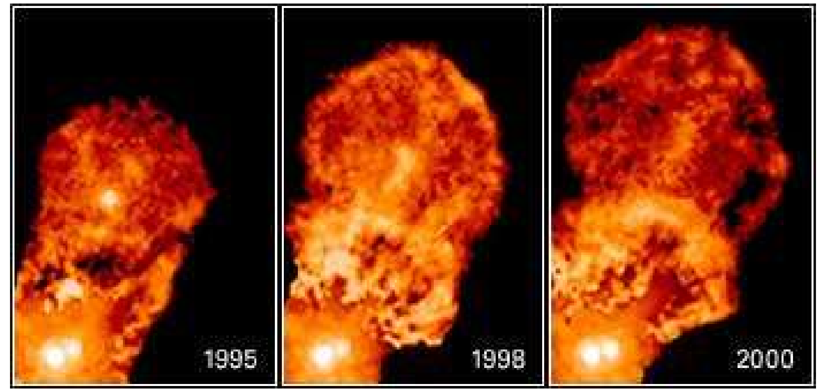
As stars begin to collapse under gravity:

- They warm up, and have high luminosities and surface areas…
- After 10 million K is reached, fusion begins slowing down gravitational collapse…

Hydrostatic Equilibrium:

- They are not considered main sequence stars until the radiation pressure from fusion and gravity is balanced

T-Tauri stars



T-Tauri stars are young stars (100,000 to 10 million years old):

- Spectral analysis shows they still contain lithium, an element consumed early on…

They are irregular and highly variable F, G, K, M spectral type stars (<2-3 $M_\odot$)

Their central temperatures are too low for hydrogen fusion

Surface temperatures are similar to those of main-sequence stars of the same mass, but they are significantly more luminous because their radii are larger

They are still collapsing and undergoing significant mass loss

- 10^{-8} – 10^{-7} $M_\odot$ per year, ejected at 500,000 km hr^{-1}
- This stage will last ~ 10 million years, ejecting ~ $M_\odot$

They are located just to the right of the main sequence on the HR diagram.

Thought Question

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

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

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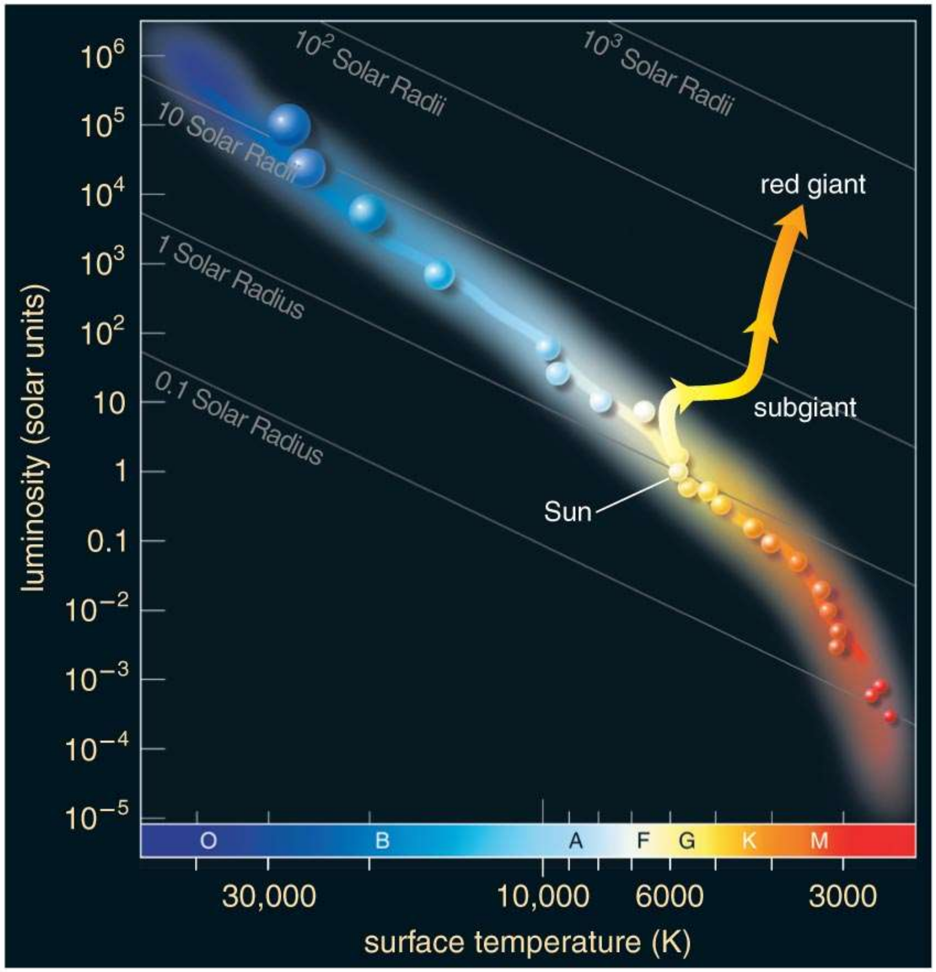
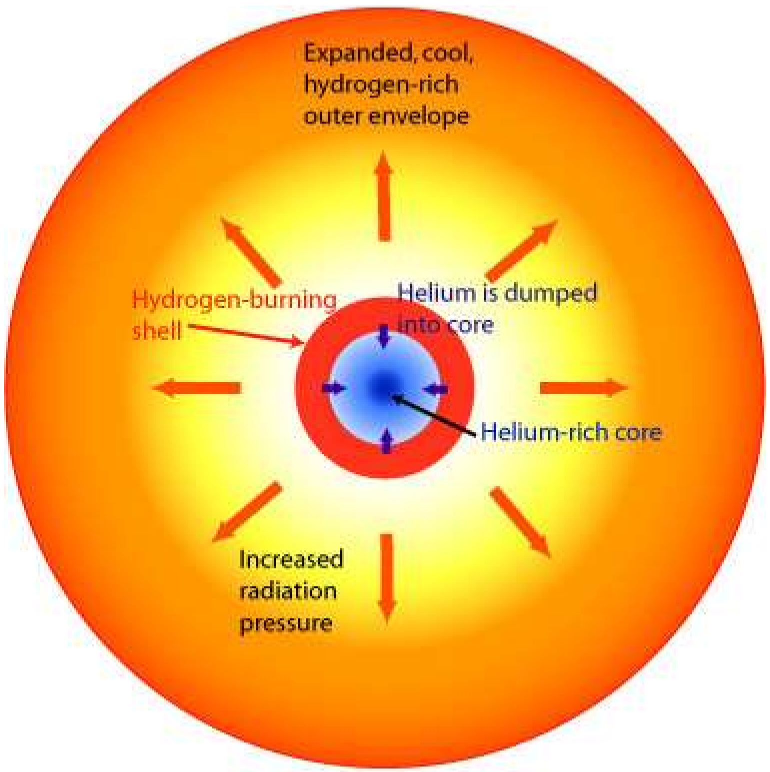
Life Track After Main Sequence



- Stars spend approximately 90% of their lives on the main sequence, regardless of mass

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

The Red Giant Brach:
A Broken Solar Thermostat



Hydrogen Shell Burning on the Red Giant Branch

Helium generated from the proton-proton chain accumulates in the core, but it is not hot enough for He fusion (100 million K).

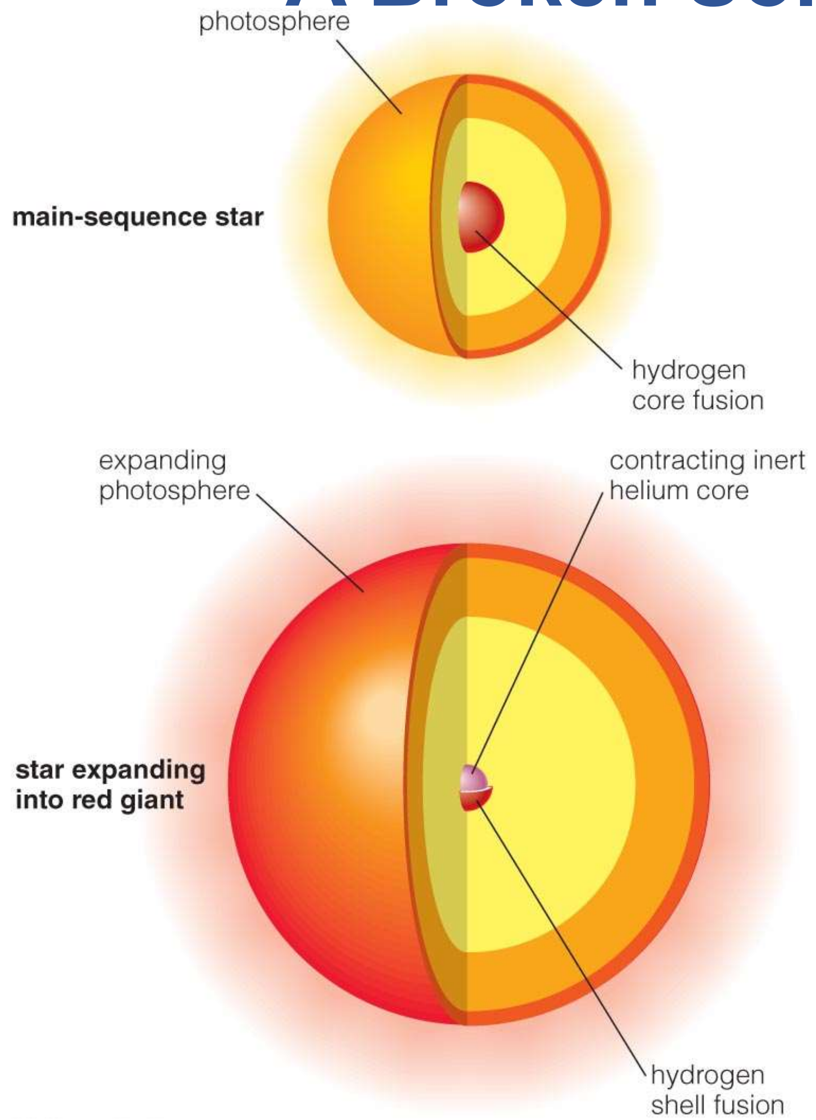
Helium collapses as far as degeneracy will allow, the temperature surrounding the He core becomes sufficient for hydrogen fusion in a shell around the core (proton-proton chain)

This proceeds at an ever-increasing rate…

- More helium is dumped on degenerate core (cannot expand)
- Higher temperatures make proton-proton chain more efficient..

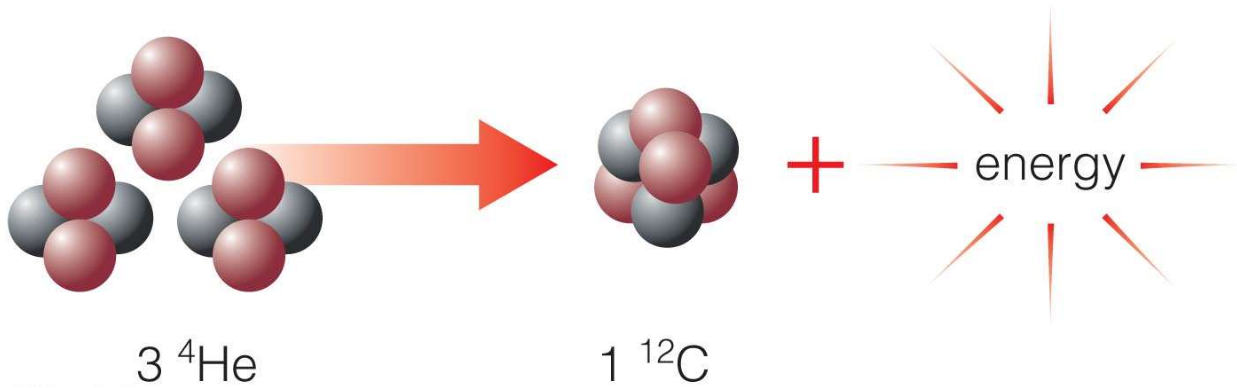
Luminosity increases by ~ 1000 times
Radius increases by ~ 100 times
Increased mass loss from 10^{-17} to 10^{-7} $M_{\odot}$ year

The Red Giant Brach:
A Broken Solar Thermostat



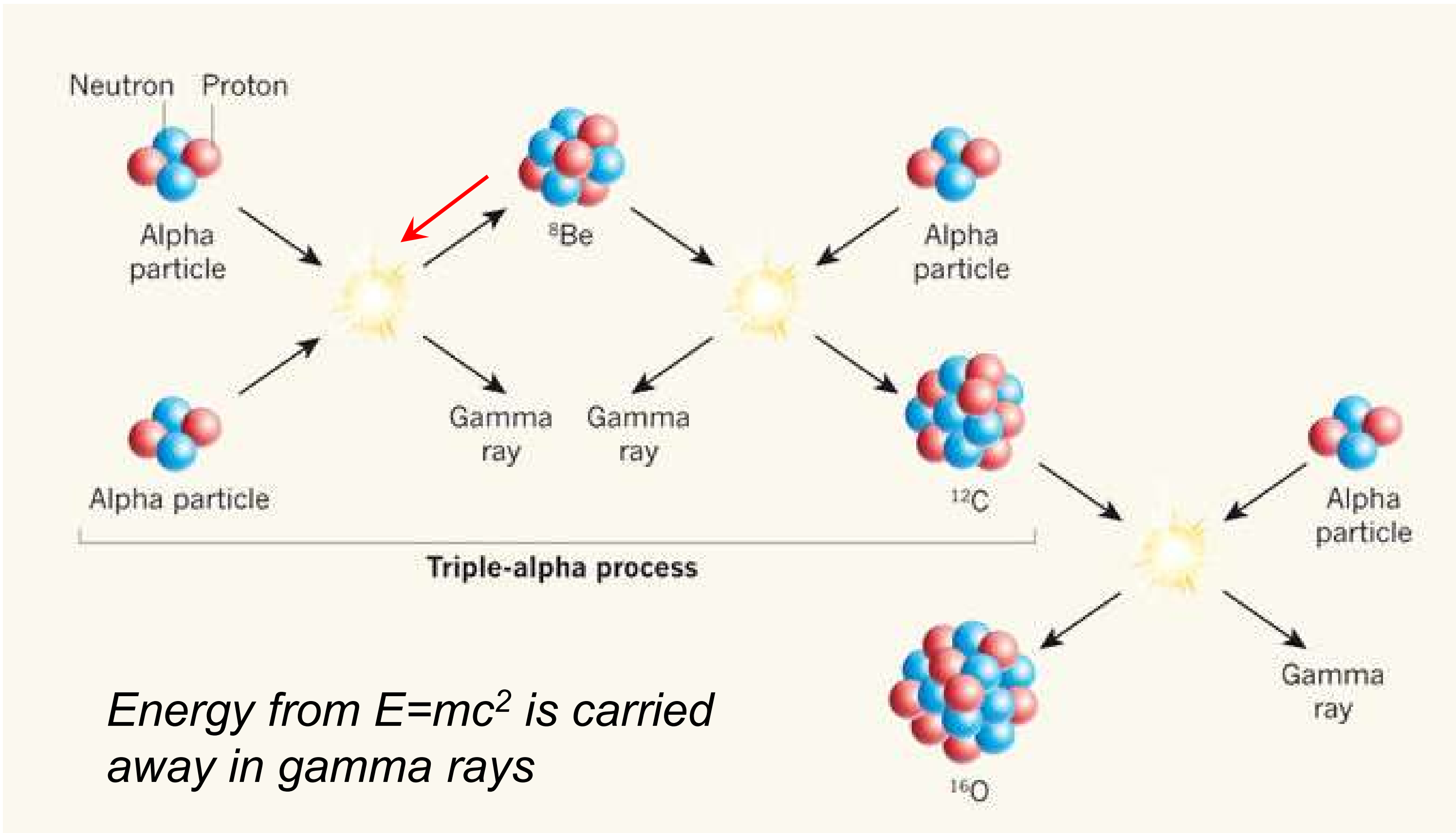
- As the core contracts, H begins fusing to He in a shell around the core.
- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting.
- The He core collapses a lot and is supported by degeneracy pressure

Helium Fusion
the Triple Alpha Process



- Occurs once the collapsing Helium core reaches 100 million K
- Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion; the larger charges from two protons in each nucleus leads to greater repulsion so higher velocities are needed to overcome this.
- The fusion of two helium nuclei forms an unstable form of Beryllium, which returns to helium unless another helium nucleus also reacts before this decay occurs to make carbon (and oxygen)

Helium Fusion
the Triple Alpha Process



Energy from $E=mc^2$ is carried away in gamma rays

Beryllium barrier: Be formed through this process is not stable, so undergoes fission immediately… requires high He density!

Thought Question

What happens in a low-mass star when core temperature rises enough for helium fusion to begin?

A. Helium fusion slowly starts up.

B. Hydrogen fusion stops.

C. Helium fusion rises very sharply.

(*Hint:* Degeneracy pressure is the main form of pressure in the inert helium core.)

Thought Question

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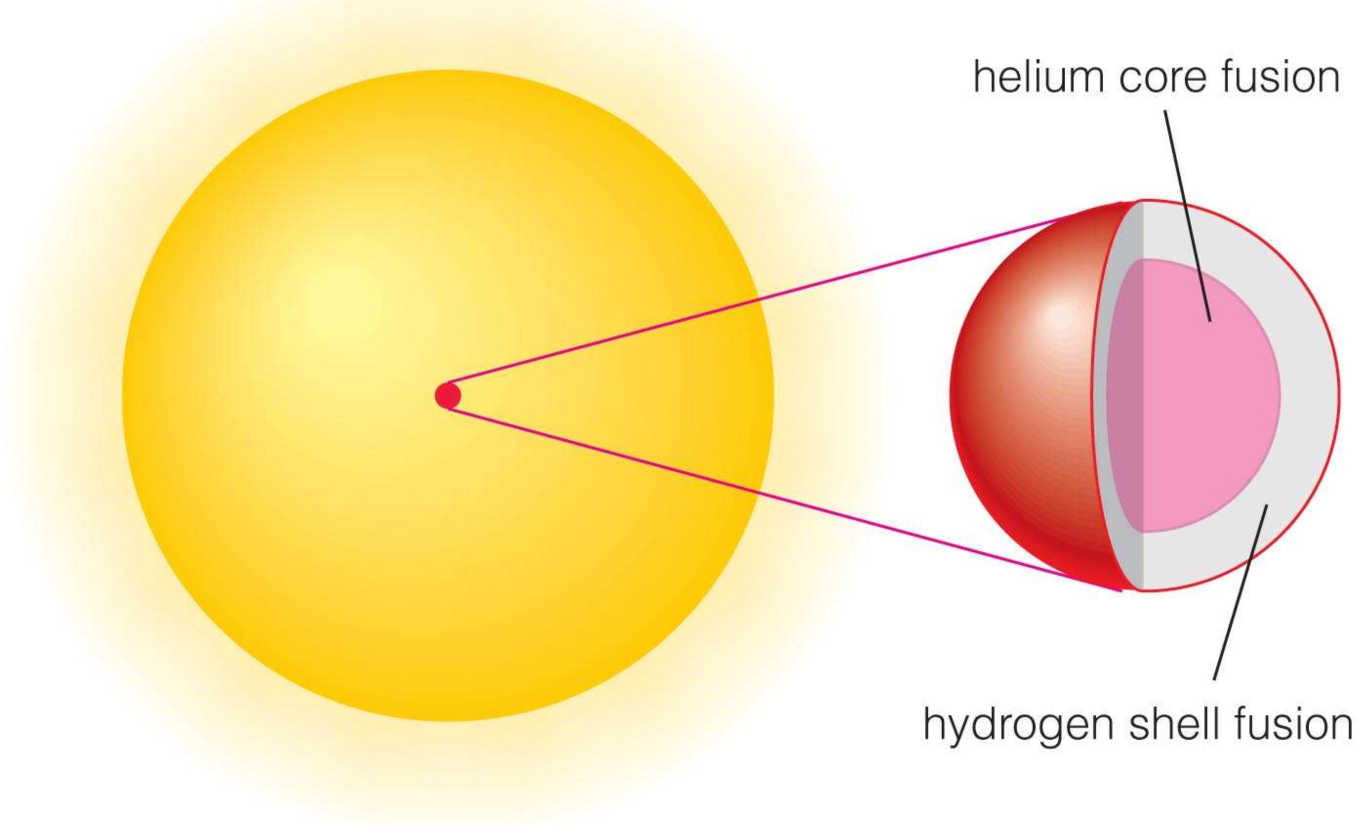
The Helium Flash

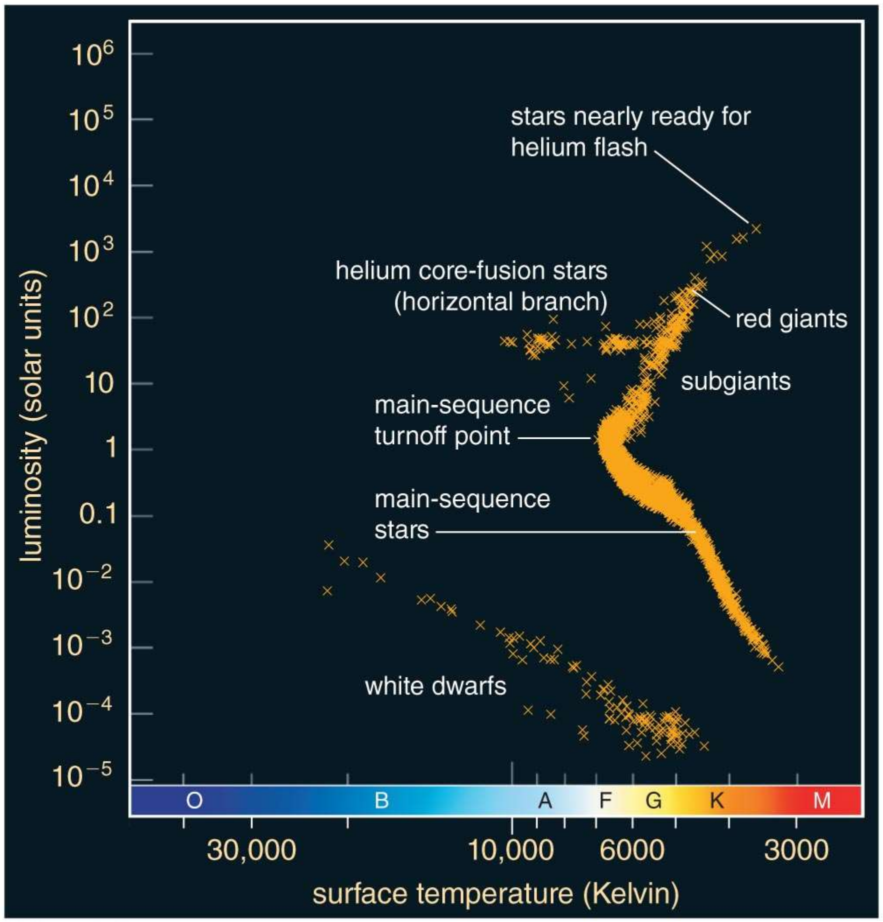
- The thermostat is broken in a low-mass red giant because degeneracy pressure supports the core, which is independent of temperature and cannot contract further (while degeneracy pressure is sufficient).
- **That means that He-burning won't immediately cause the core to expand back outward.**
- The core temperature rises rapidly when helium fusion begins.
- The helium fusion rate skyrockets until thermal pressure takes over and expands the core again.
  - ***This process takes a few minutes to propagate through the entire core***

The Horizontal Branch
A brief (100 Myr) return to normalcy



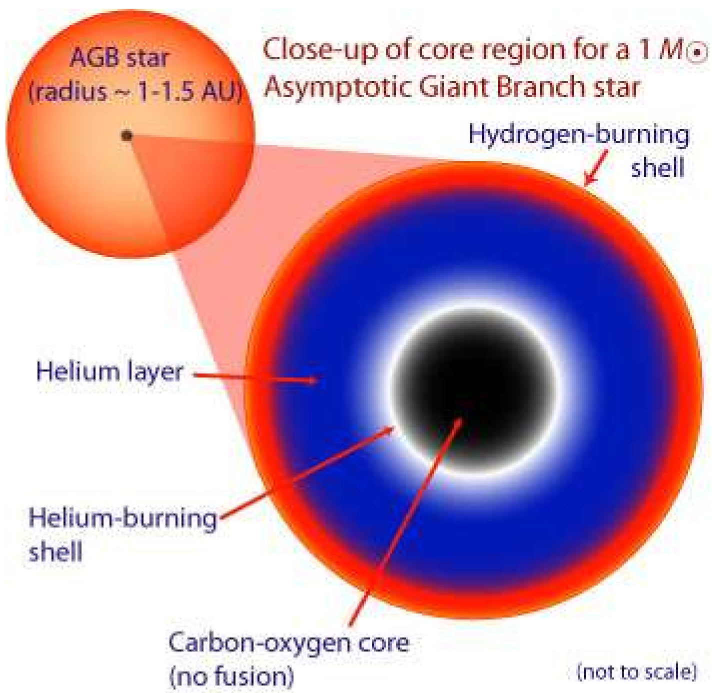
- Helium fusion in the core, with hydrogen shell fusion on the outside
- Helium core-fusion stars neither shrink nor grow considerably because the core thermostat is temporarily fixed, moves back to main sequence.

Evidence for Horizontal Branch



- Observations of star clusters agree with these models.
- Helium core-fusion stars are found in a *horizontal branch* on the H-R diagram.

The Asymptotic Giant Branch
The thermostat is broken again…



Luminosity increases by ~ 10,000 times
Radius increases by ~ 300-1000 times
Increased mass loss to 10^{-6} – 10^{-4} $M_\odot$ year

The Helium in the core has been turned to carbon and oxygen

Fusion of carbon requires temperatures of 600 million K (only occurs in Stars of ~ 8 solar masses)

As carbon/oxygen core contracts, the layers surrounding it become hot enough for He fusion

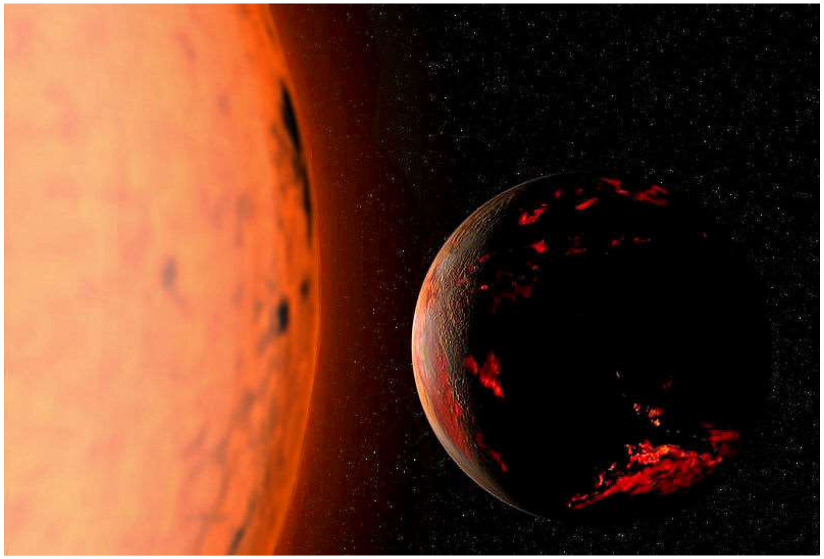
→ **Onion like structure**

- Carbon/Oxygen core
- Helium burning shell
- Outer Hydrogen burning shell

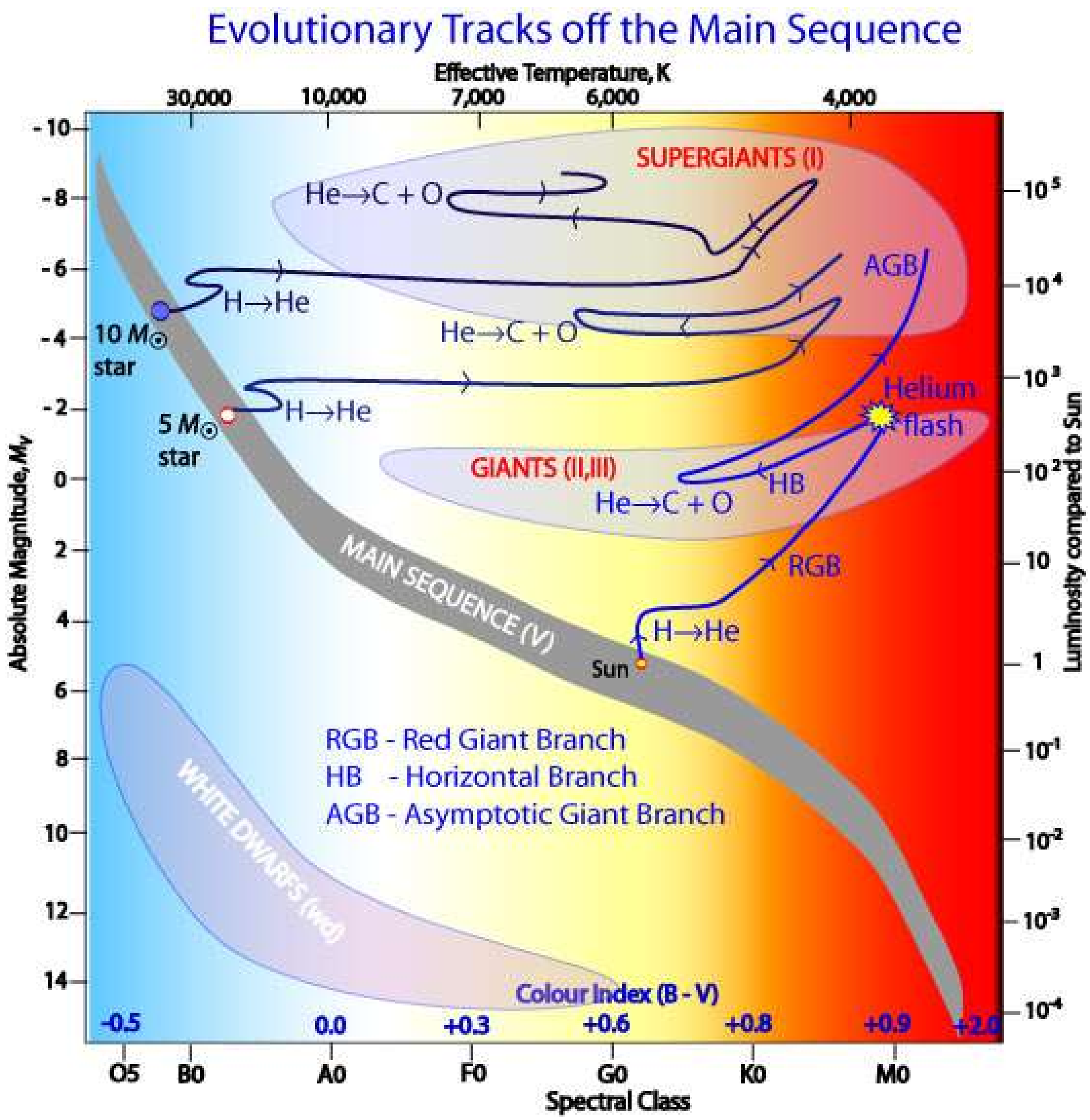
Heavier elements can be generated in He shell through so-called ***s-process***

The Fate of the Earth

- The Sun has enough hydrogen to steadily burn for another 5 billion years as a main-sequence star
- However, theoretical models predict that the luminosity will rise considerably before this time
- The Earth will experience a runaway greenhouse effect at some point in the next 1-4 billion years
- Certainly by the AGB-phase, the Sun's radius will be ~ that of Earth's orbit…



Life Track Exiting Main Sequence



For a Solar Mass Star:

Red Giant Branch

- **Inert (degenerate) helium core, hydrogen fusion in shell**

Helium Flash

- **Helium begins fusion (triple-alpha process), degeneracy is removed**

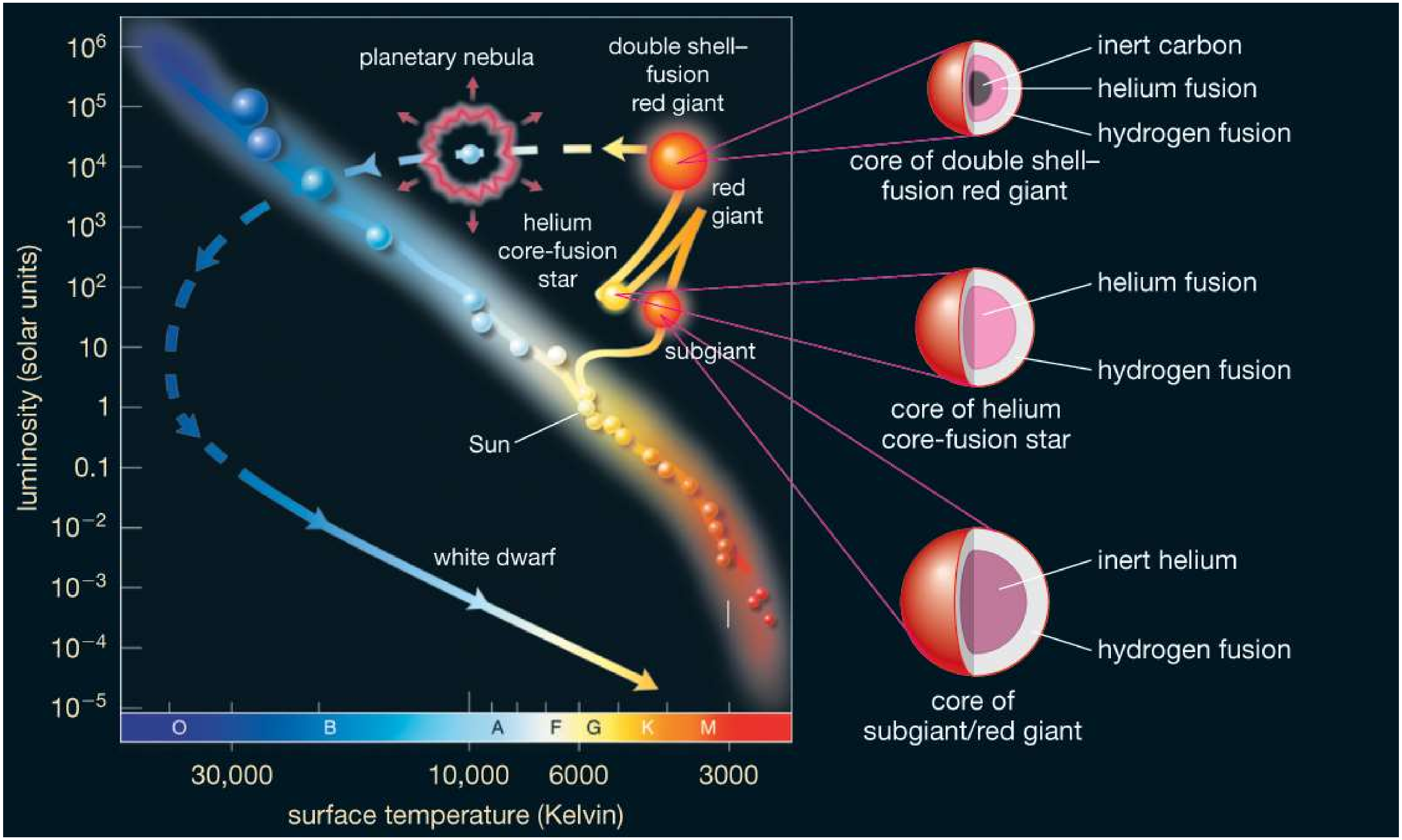
Horizontal Branch

- **Helium fusion in core with hydrogen shell**
- **Moves towards main sequence**
- **Smaller, but hotter star…**

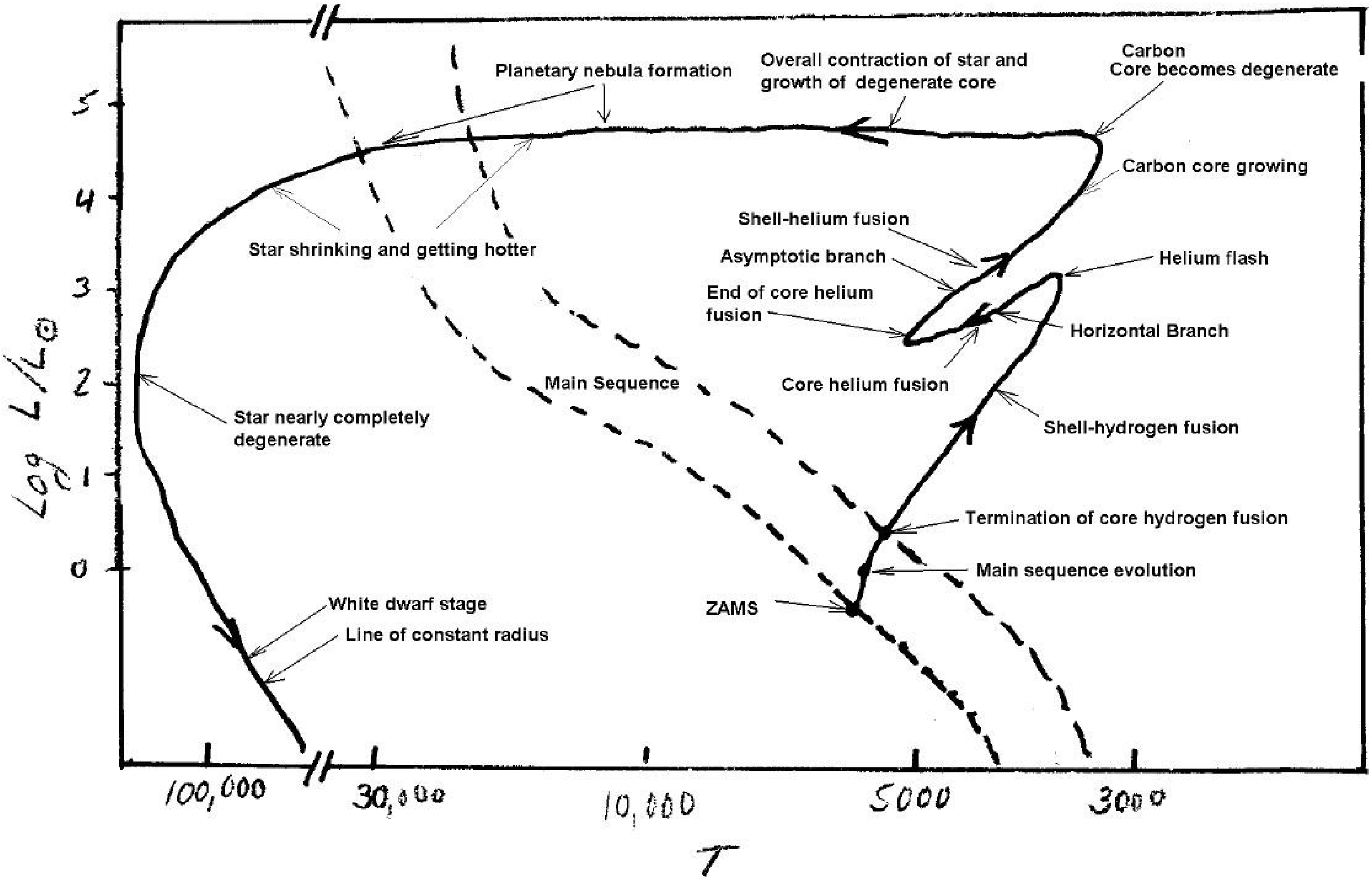
Asymptotic Giant Branch

- **Carbon/Oxygen core**
- **Helium and hydrogen fusion shells**

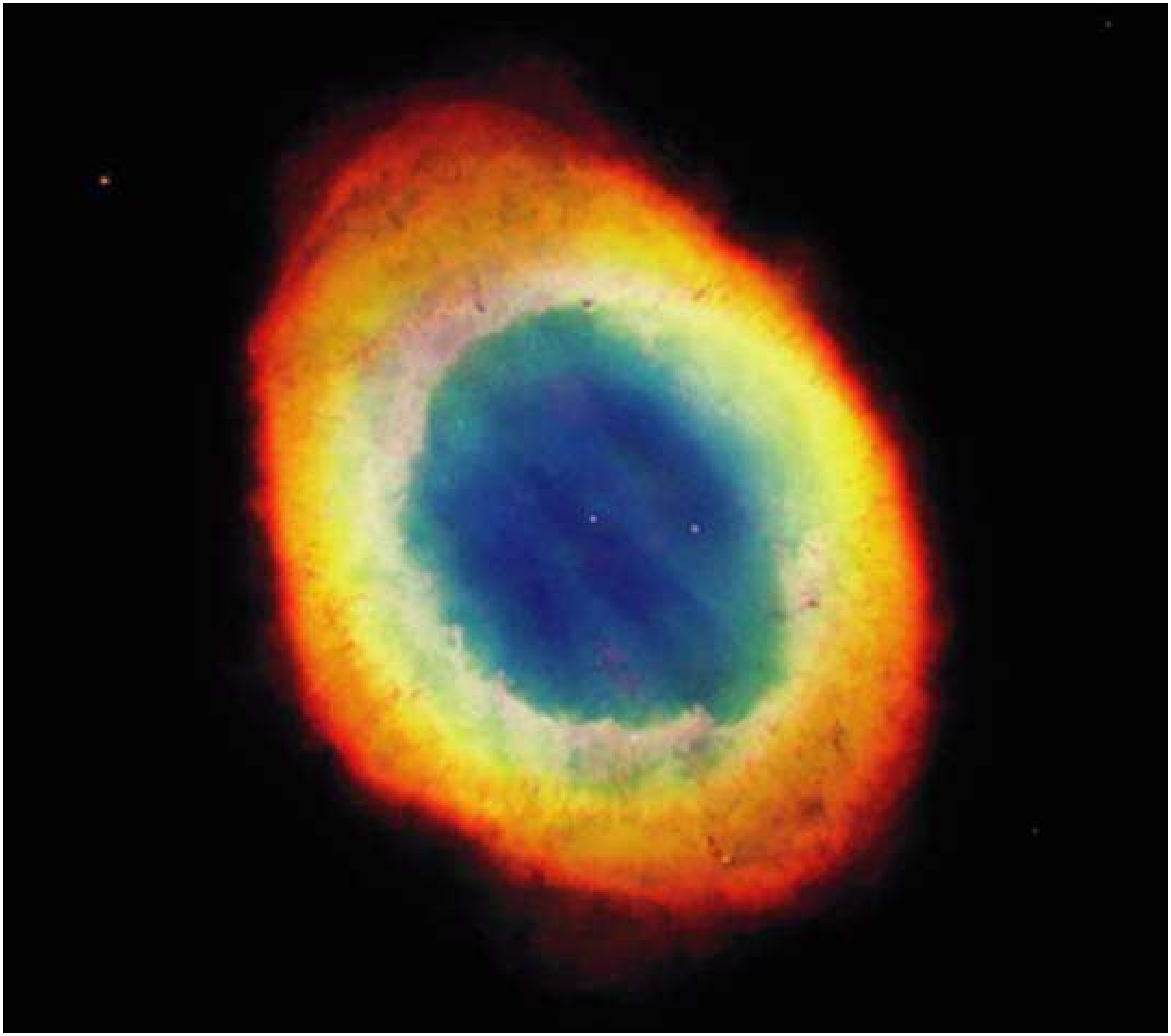
Life Track of a Sun-Like Star



Life Track of a Sun-Like Star (slightly more accurate)



What Happens Next?



A star like our sun dies by puffing off its outer layers, creating a *__planetary nebula__*.

Only a white dwarf is left behind

Examples of Planetary Nebula

Helix nebula

Cat's eye Nebula

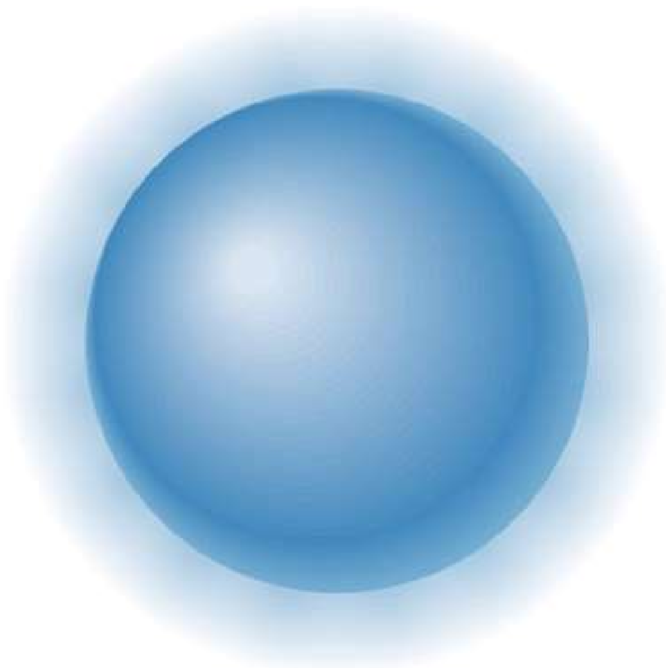
Eskimo Nebula

- The white dwarf core can still be millions of degrees kelvin in temperature (but cools off fast)

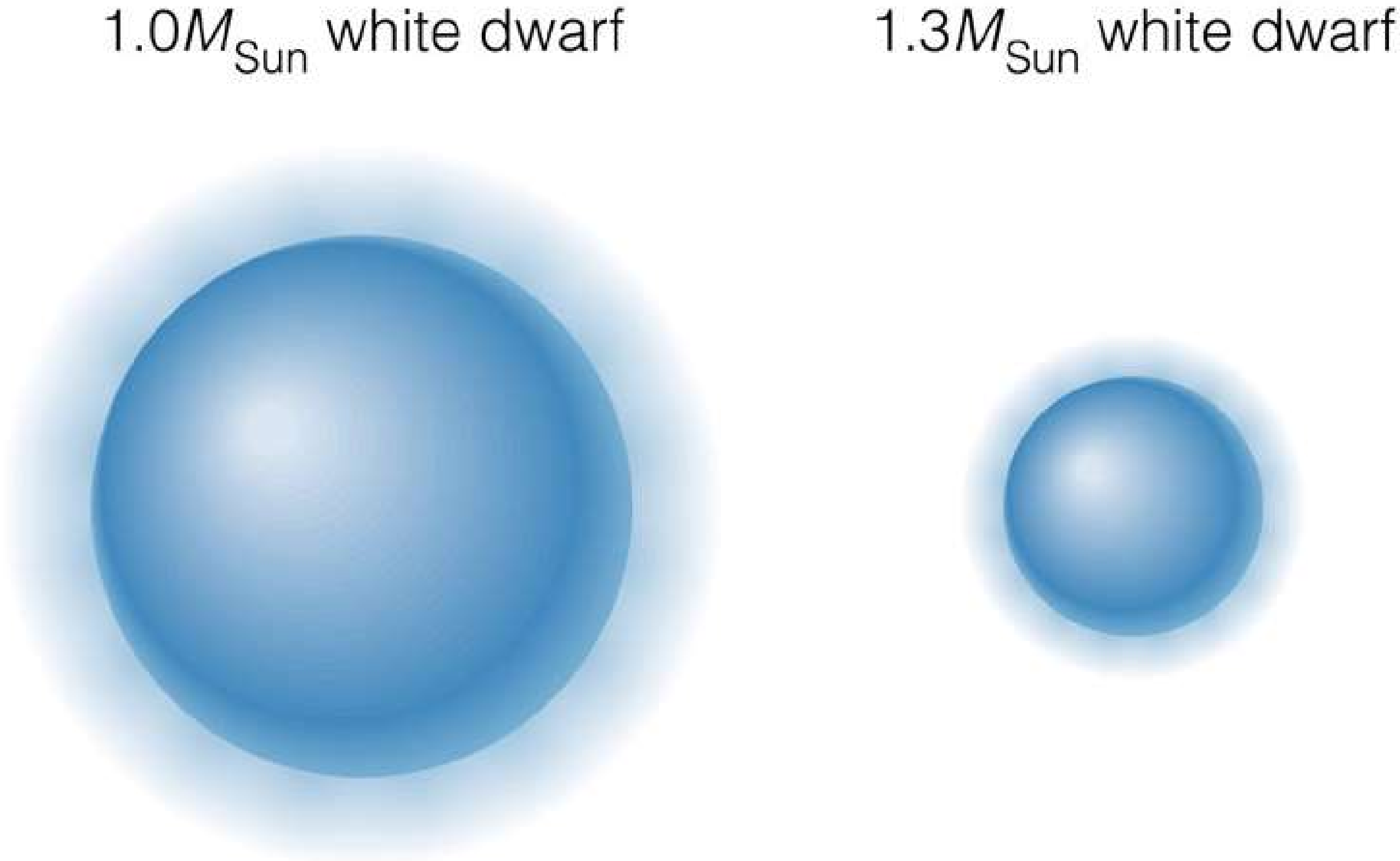
- Intense UV light ionizes the ejected outer layers of the star

Leaving Behind a White Dwarf…

$1.0M_{Sun}$ white dwarf



- White Dwarf's are the remaining cores of low-mass stars
- A white dwarf is about the same size as Earth



White dwarfs shrink when you add mass to them because their gravity gets stronger

Shrinkage of White Dwarfs

- Quantum mechanics says that electrons in the same place cannot be in the same state
- Adding mass to a white dwarf increases its gravity, forcing electrons into a smaller space
- In order to avoid being in the same state some of the electrons need to move faster
- Is there a limit to how much you can shrink a white dwarf?

The White Dwarf Limit

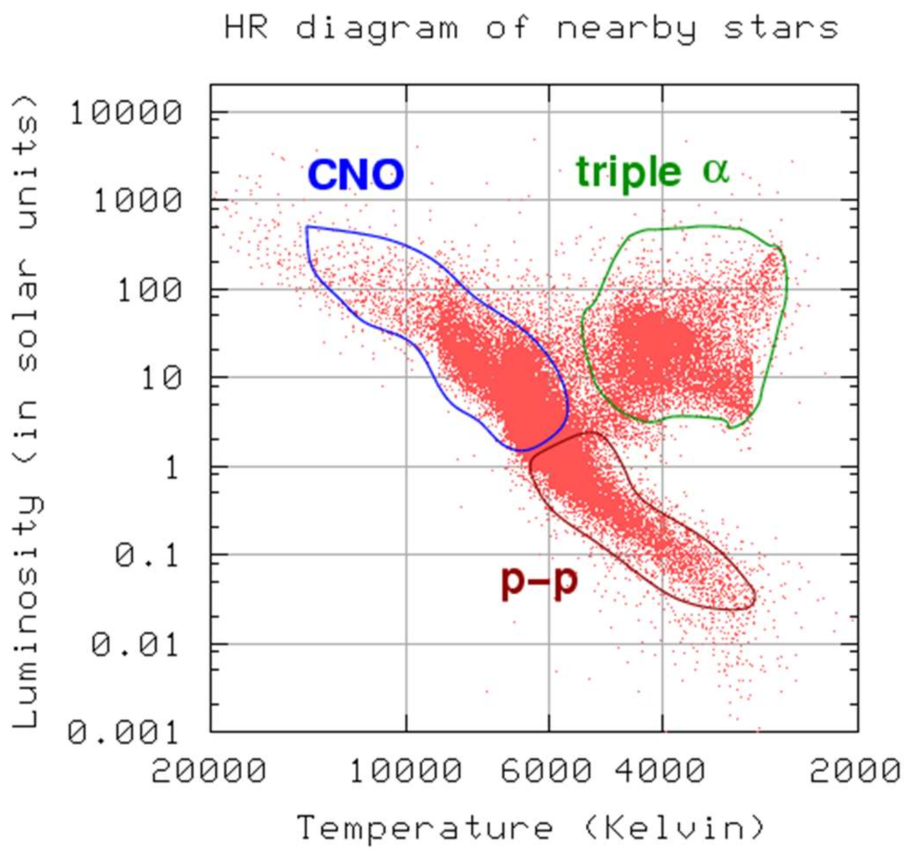
S. Chandrasekhar

- Einstein's theory of relativity says that nothing can move faster than light
- When electron speeds in white dwarf approach speed of light, electron degeneracy pressure can no longer support it
- Chandrasekhar found (at age 20!) that this happens when a white dwarf's mass reaches 1.4 M_{sun}
- He actually puzzled this out on the boat from India to England before he started his grad studies in physics. (Once at Cambridge his advisor told him he was crazy and to drop this work…. it won him the Nobel Prize)

What have we learned?

- What are the life stages of a low-mass star?
  - H fusion in core (main sequence)
  - H fusion in shell around contracting core (red giant; RGB)
  - He fusion in core (horizontal branch; HB)
  - Double shell–fusion (red giant; AGB)
- How does a low-mass star die?
  - Ejection of H and He in a planetary nebula leaves behind an inert white dwarf.

End of Todays Lecture



HR diagram of nearby stars
CNO
triple α
p–p
Luminosity (in solar units)
10000
1000
100
10
1
0.1
0.01
0.001
20000
10000
6000
4000
2000
Temperature (Kelvin)