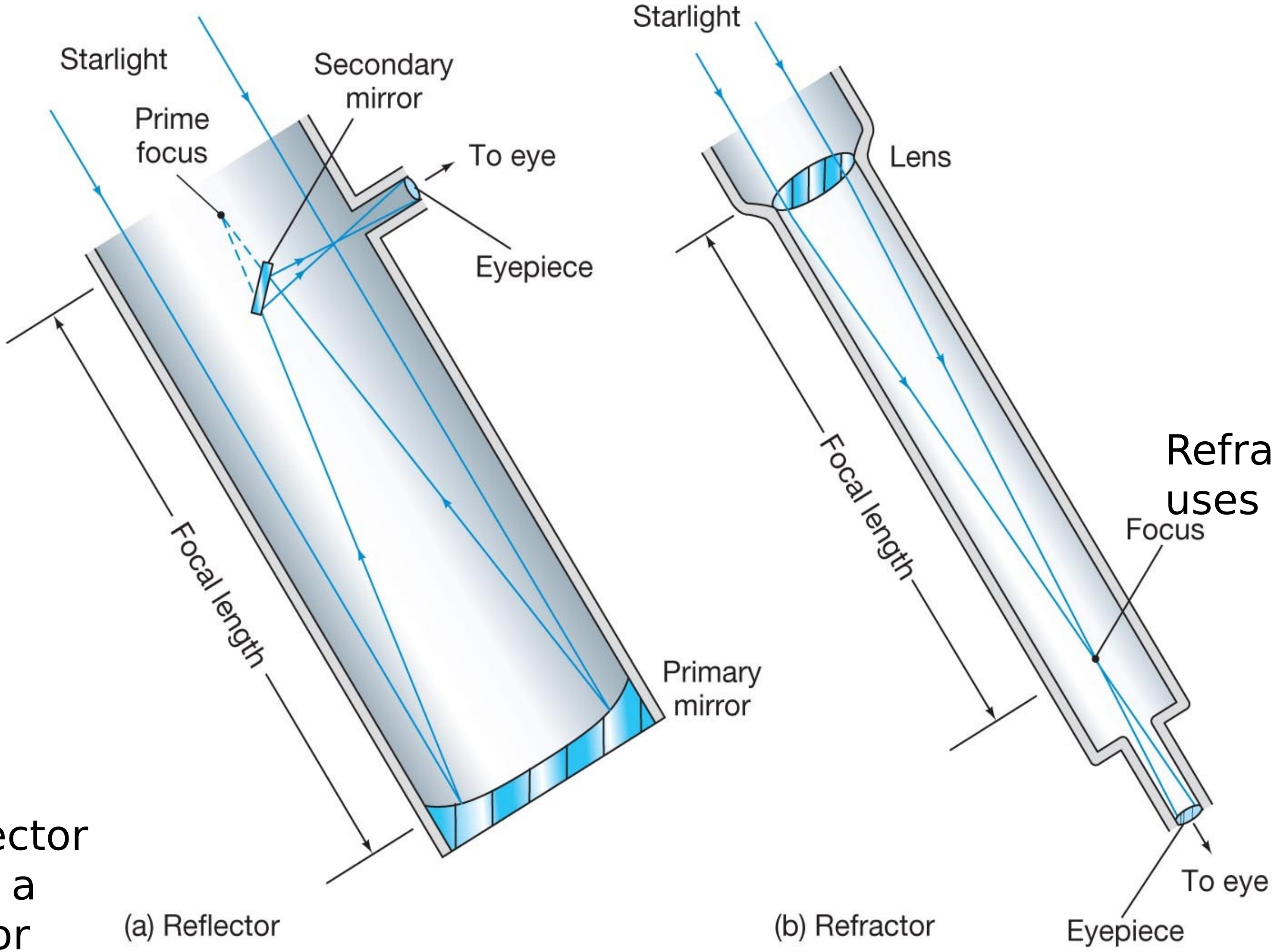
Announcements

- Midterm 1 grades are on D2L
    - Average 69%
    - Answers are posted on D2L (Content -> Handouts)
    - Scantrons here if you want them
    - Remember that lowest midterm grade is dropped
- Quiz 5 due on Monday,
  Problem Set 5 for practice
- Today we start Chapter 9, The Sun

Two types of optical telescopes: Reflecting and refracting telescopes

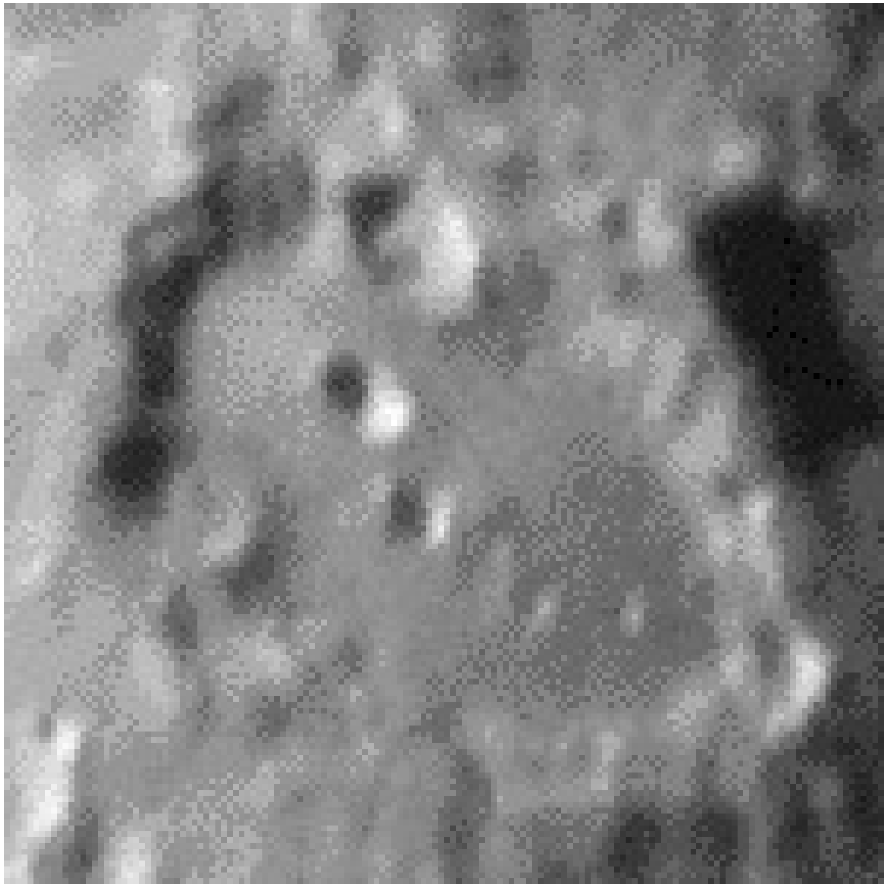


Refractor uses a lens

Reflector uses a mirror

The atmosphere limits how clearly we can see from Earth. Ways to solve this problem:

1) Avoid it as best as possible – put telescopes on mountains
2) Get lucky
3) Fix it
4) Go to space



Source: Philipp Salzgeber [1] -
http://salzgeber.at/astro/moon/seeing.html

Go to space: Hubble Space Telescope

One of the main advantages of a telescope in space is that its images are not blurred by the atmosphere

Why do we put telescopes on mountains?

A Because the sky is usually less cloudy

B To get closer to the stars

C To see wavelengths of light we can’t see from sea level

D To avoid some of the blurring effects of the atmosphere

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Why do we put telescopes on mountains?

- **A** To avoid some of the blurring effects of the atmosphere
- **B** To get away from the lights of cities and other populated areas
- **C** To find cold, dry conditions for infrared and radio observations
- **D** All of the above

Why do we put telescopes on mountains?

A To avoid some of the blurring effects of the atmosphere

B To get away from the lights of cities and other populated areas

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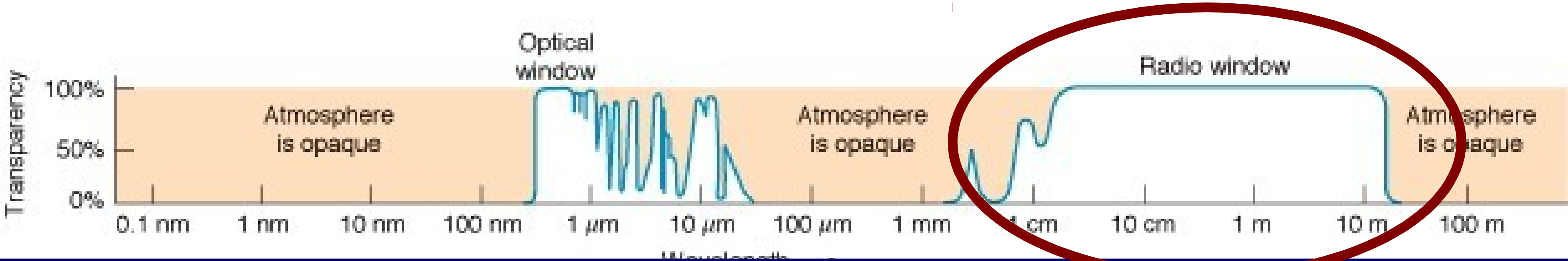
[✓ **D** All of the above]

So far we have been talking about optical telescopes that observe visible light. We also observe other parts of the electromagnetic spectrum.

The atmosphere is opaque to light of most wavelengths, marked by tan shading in the diagram. Optical and radio wavelengths can be seen from the ground. For γ-rays, X-rays, most ultraviolet and most infrared light, one uses satellite telescopes.



γ-rays X-rays UV visible infrared microwave RADIO

Radio telescopes

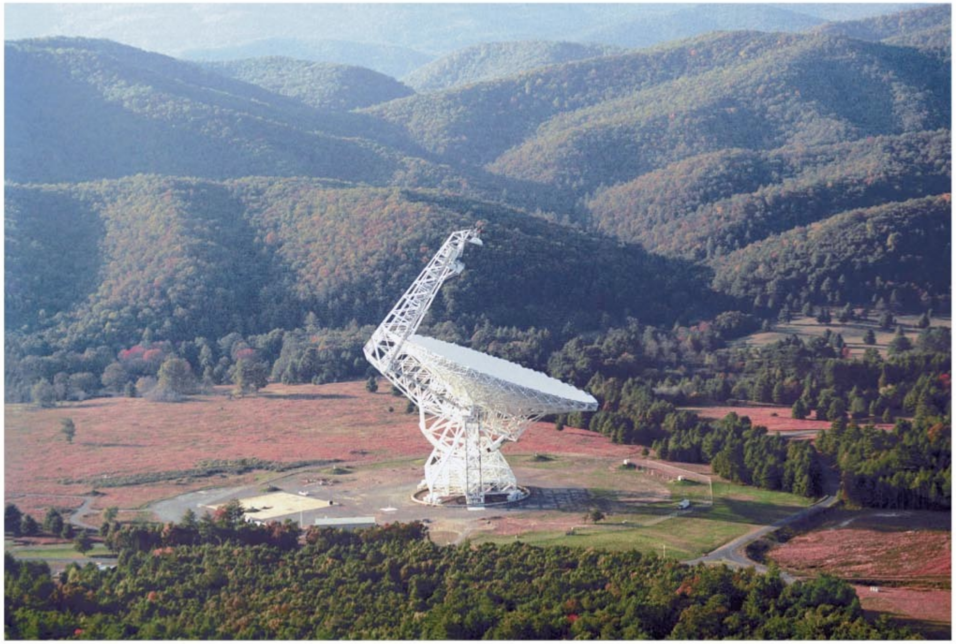
Similar to optical reflecting telescopes

Less sensitive to imperfections due to longer wavelengths – surface has to be smooth on the scale of wavelengths of light observed

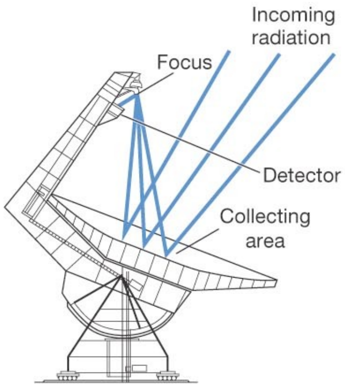
Can be made very large

Green Bank Telescope, 105 m diameter

National Radio Astronomy Observatory, West Virginia



(a)



(b)

Longer wavelength means poorer angular resolution

- Atmospheric blurring isn't an issue in radio
- The **diffraction limit** is
  - Ultimate limit in angular resolution comes from diffraction, the spreading of light as it passes a corner or opening

$$\text{angular resolution (arc seconds)} = 0.25\,\frac{\text{wavelength }(\mu\text{m})}{\text{mirror diameter (m)}}$$

  - Longer wavelength: poorer resolution
  - Larger telescope: better resolution

We’re observing 0.2 m radio waves with the Green Bank Telescope. What’s our angular resolution?

$$\text{angular resolution (arc seconds)} = 0.25\,\frac{\text{wavelength } (\mu\text{m})}{\text{mirror diameter (m)}}$$

What’s our wavelength?
→ 1 μm = 10^{-6} m, so 0.2 m = 2 x 10^{5} μm

What’s the diameter of the GBT?
→ 105 m

$$\text{angular resolution (arc seconds)} = 0.25\,\frac{2\times10^{5}}{105}$$

$$= 476 \text{ arc seconds}$$

We’re observing 0.2 m radio waves with the Green Bank Telescope. What’s our angular resolution?

$$\text{angular resolution (arc seconds)} = 0.25\,\frac{2\times10^{5}}{105}$$

$$= 476 \text{ arc seconds}$$

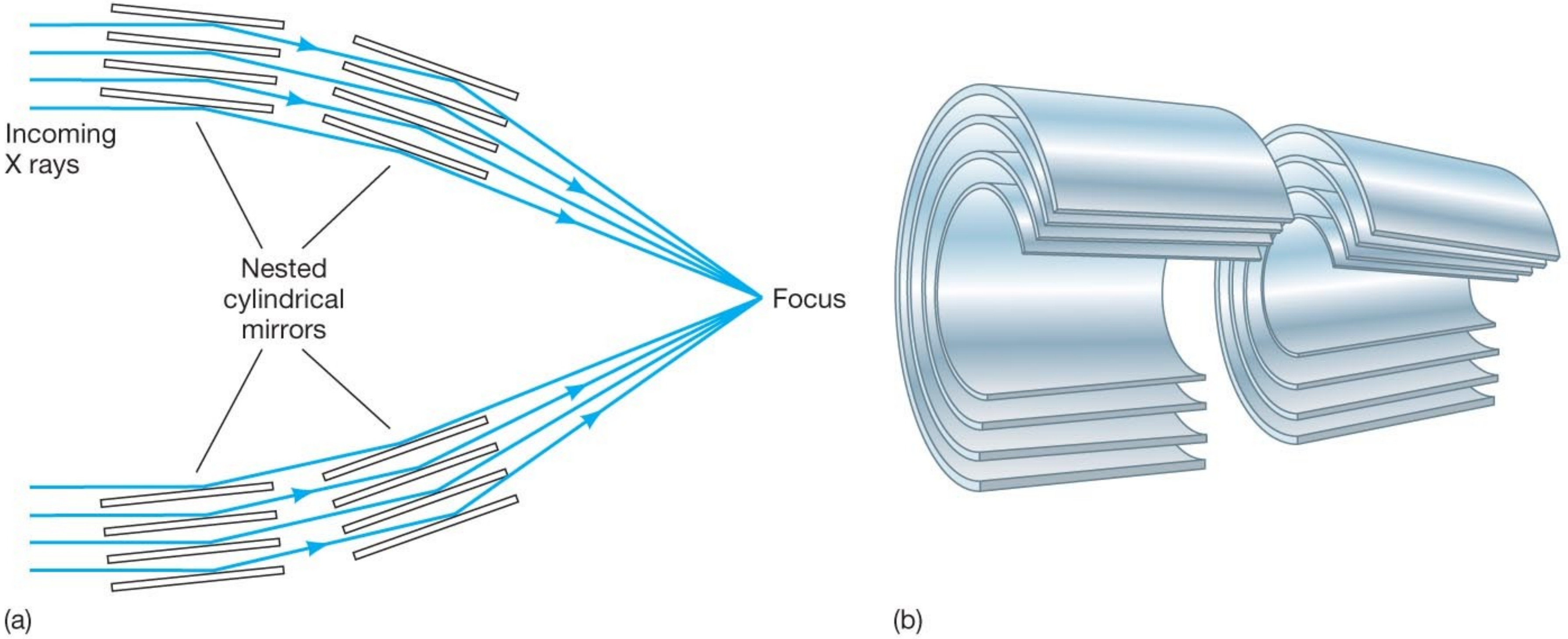
What does this mean?

If two objects are closer than about 480 arc seconds on the sky, we won’t be able to separate them.

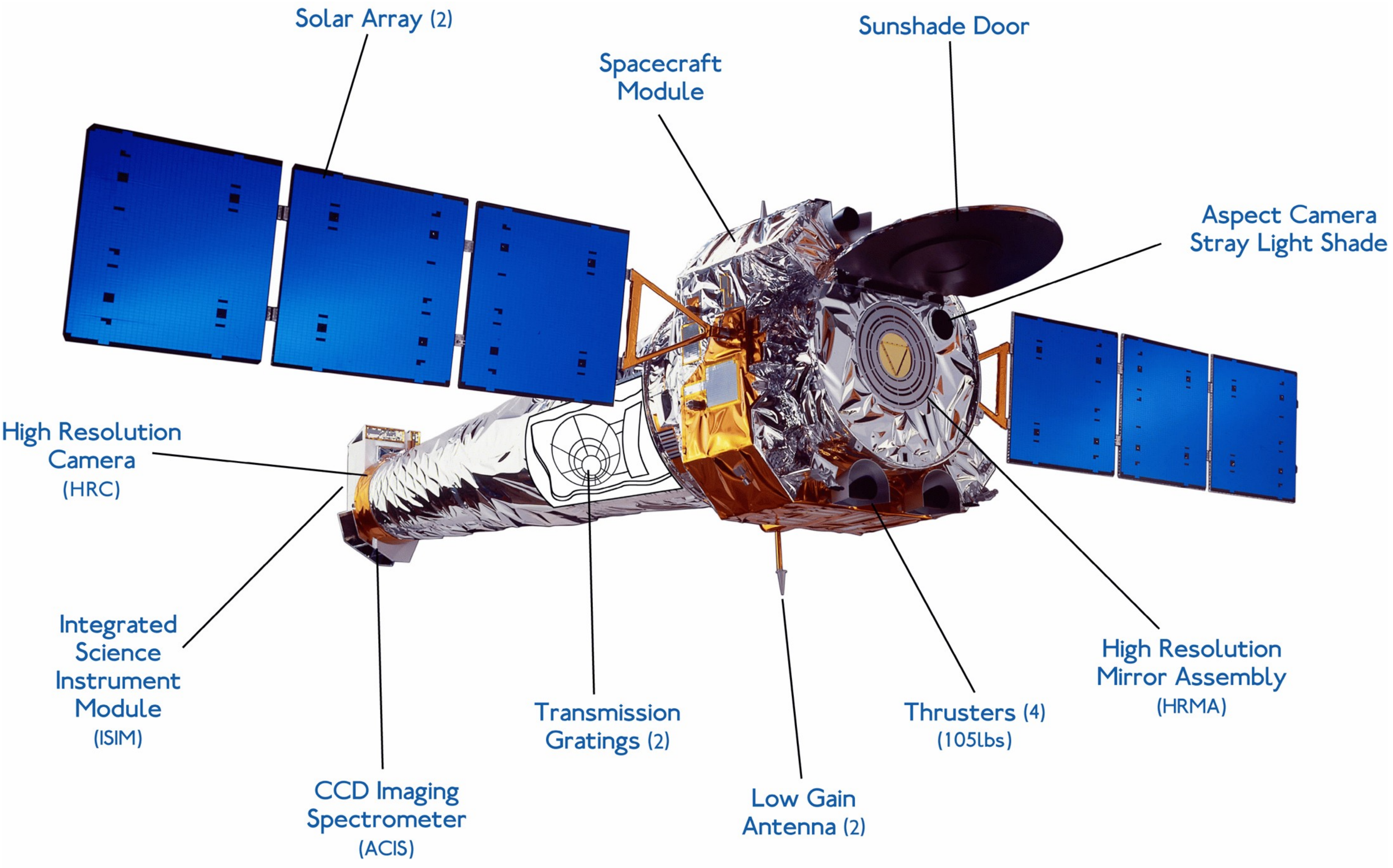
What about shorter wavelengths?

X-rays and gamma rays will not reflect off mirrors as other wavelengths do; need new techniques.

X-rays will reflect at a very shallow angle, and can therefore be focused.



The Chandra X-ray Observatory



The Fermi Gamma Ray Telescope

Fermi
Gamma-ray
Space Telescope

Gamma rays can't be focused. We just put a detector in space and wait for them.

Why do we put telescopes in space?

A To see wavelengths of light we can’t see from the ground

B To continuously observe for more than 24 hours, avoiding sunlight

C To avoid the blurring effects of the atmosphere

D All of the above

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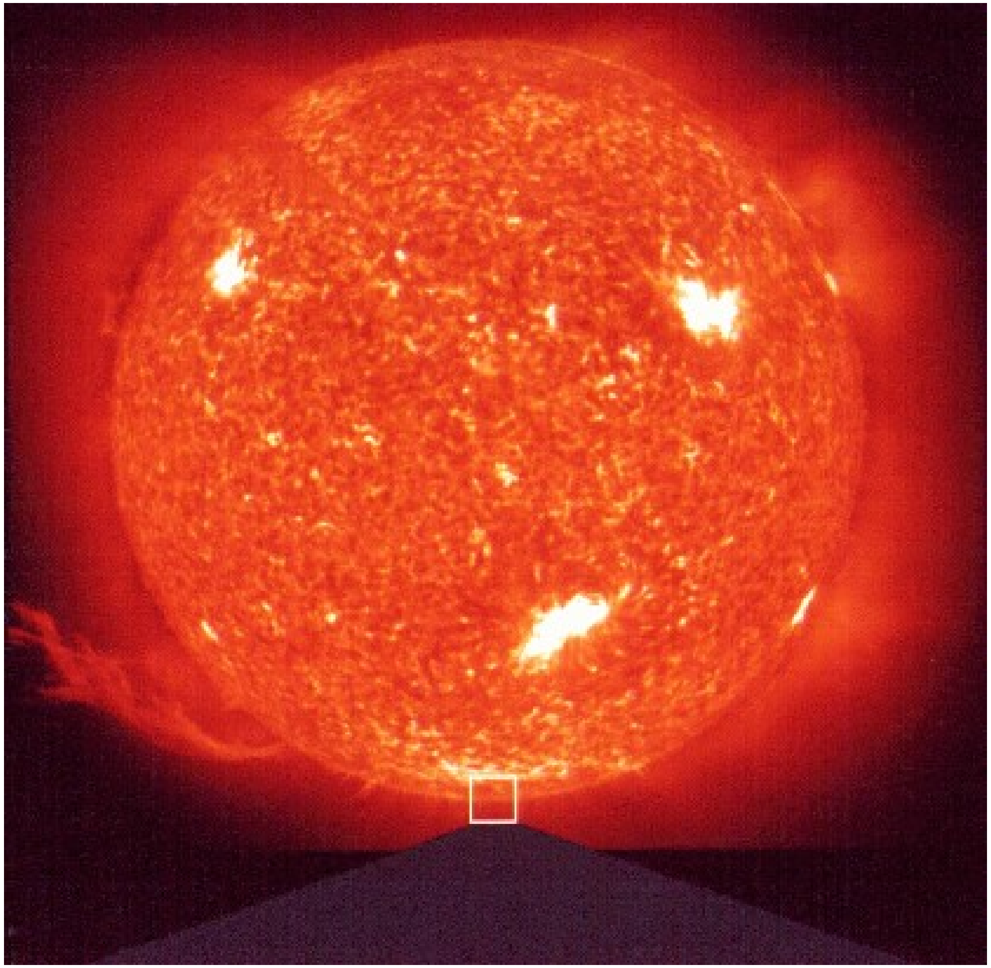
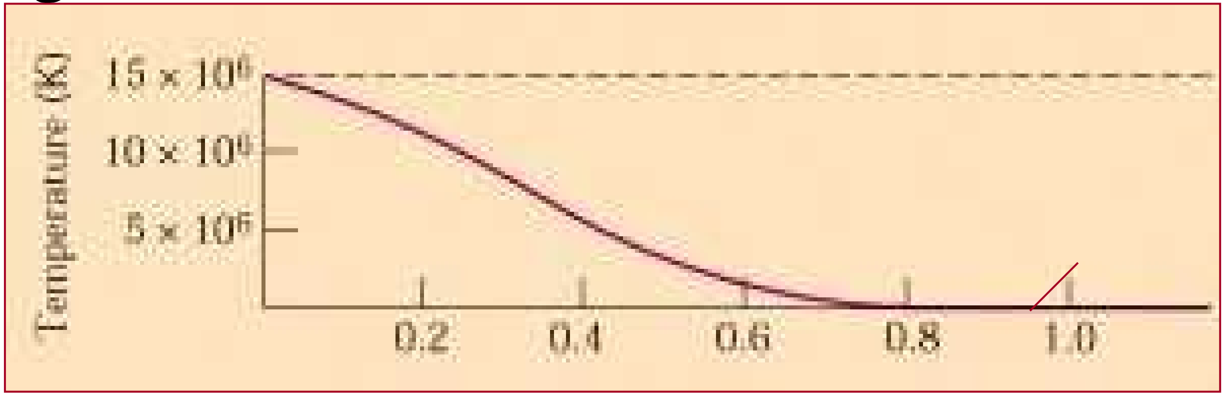
The Sun



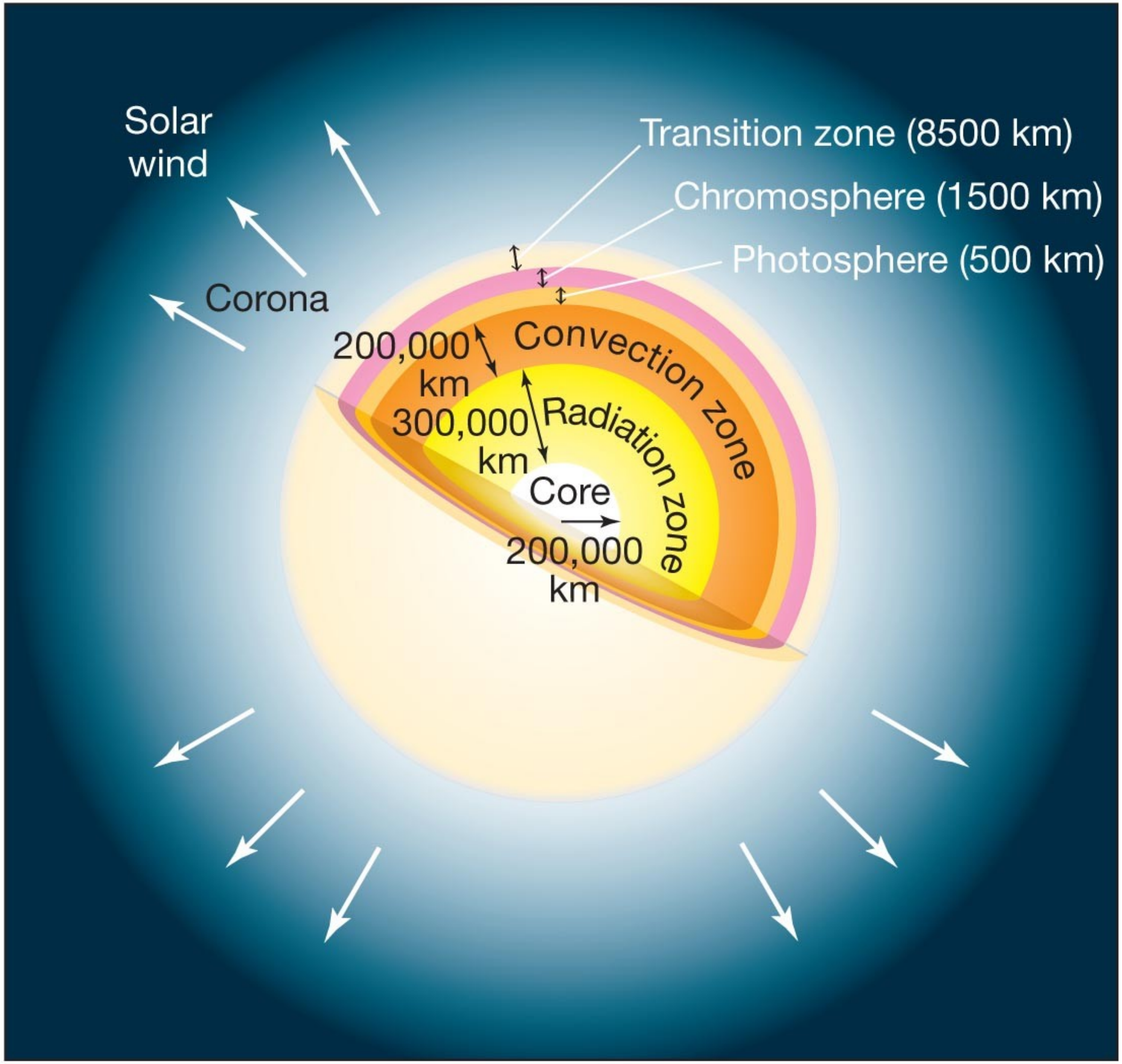
The Sun is a star – the closest and most important star to us.

General Features

- Radius about 700,000 km, **100 times radius of Earth**
- Composition: **3/4 hydrogen**, about 1/4 helium by mass (90% of the atoms are hydrogen)
- Density: **Roughly the density of water ice** (1.4 times the density of water: 1.4 g/cm^3 or 1400 kg/m3)
- Temperature very high at center (over 15 million K), dropping to 6,000 K near surface



Structure of the Sun



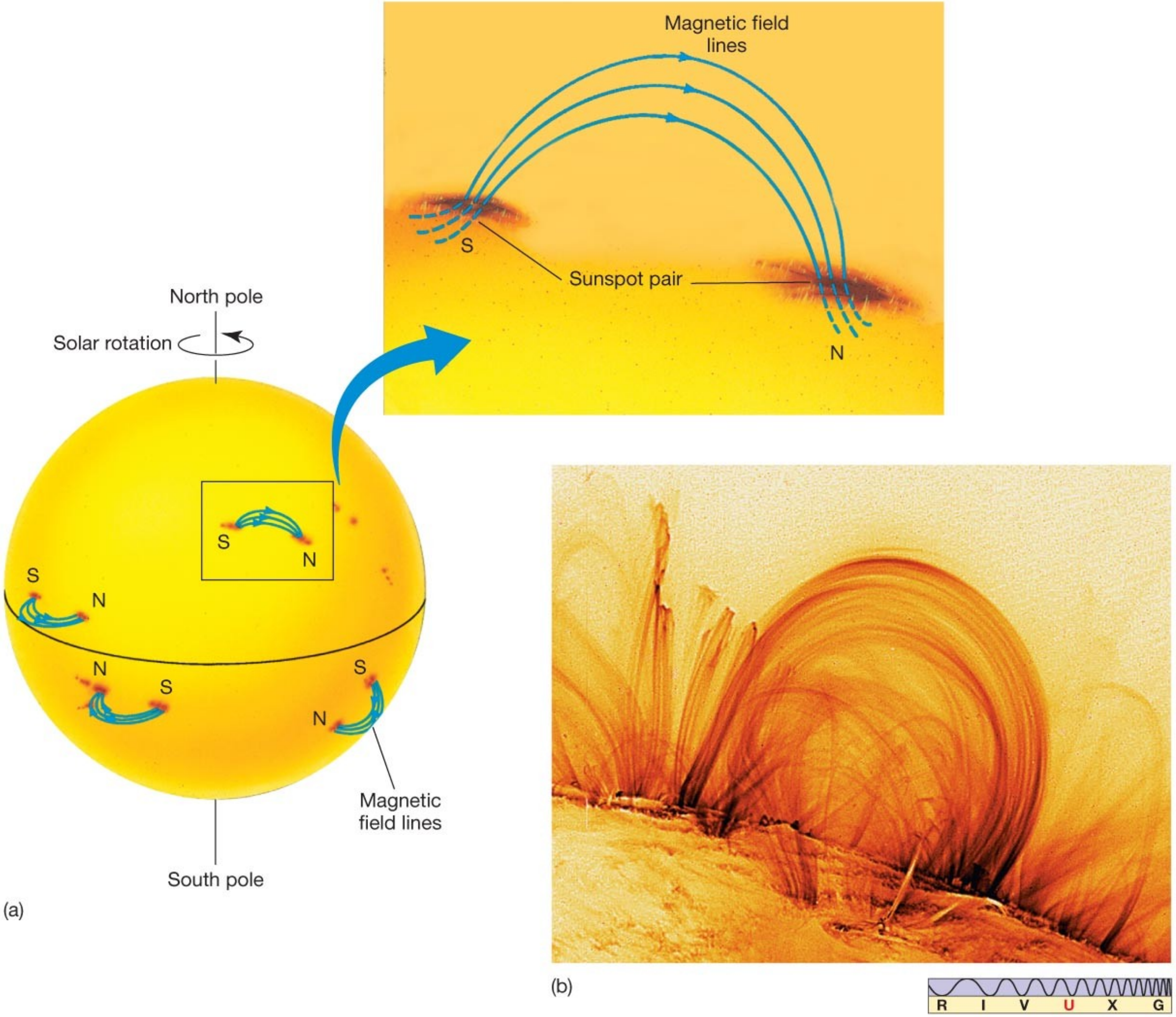
The Solar Atmosphere

(photosphere, chromosphere, corona)

- The Sun is mostly hydrogen; about 10% of its atoms are helium and there is a much smaller amount of heavier elements.
- Most light from the Sun leaves from the photosphere. This is what we see as the “surface” of the Sun, although it has no solid surface.
- Its average wavelength (green) corresponds to the 6000 K temperature of the photosphere.

What are Sunspots?

- Sunspots come and go, typically in a few days.
- Sunspot pairs are linked by magnetic field lines, which drain energy from the photosphere
- They are dark because they are cooler than the surrounding photosphere

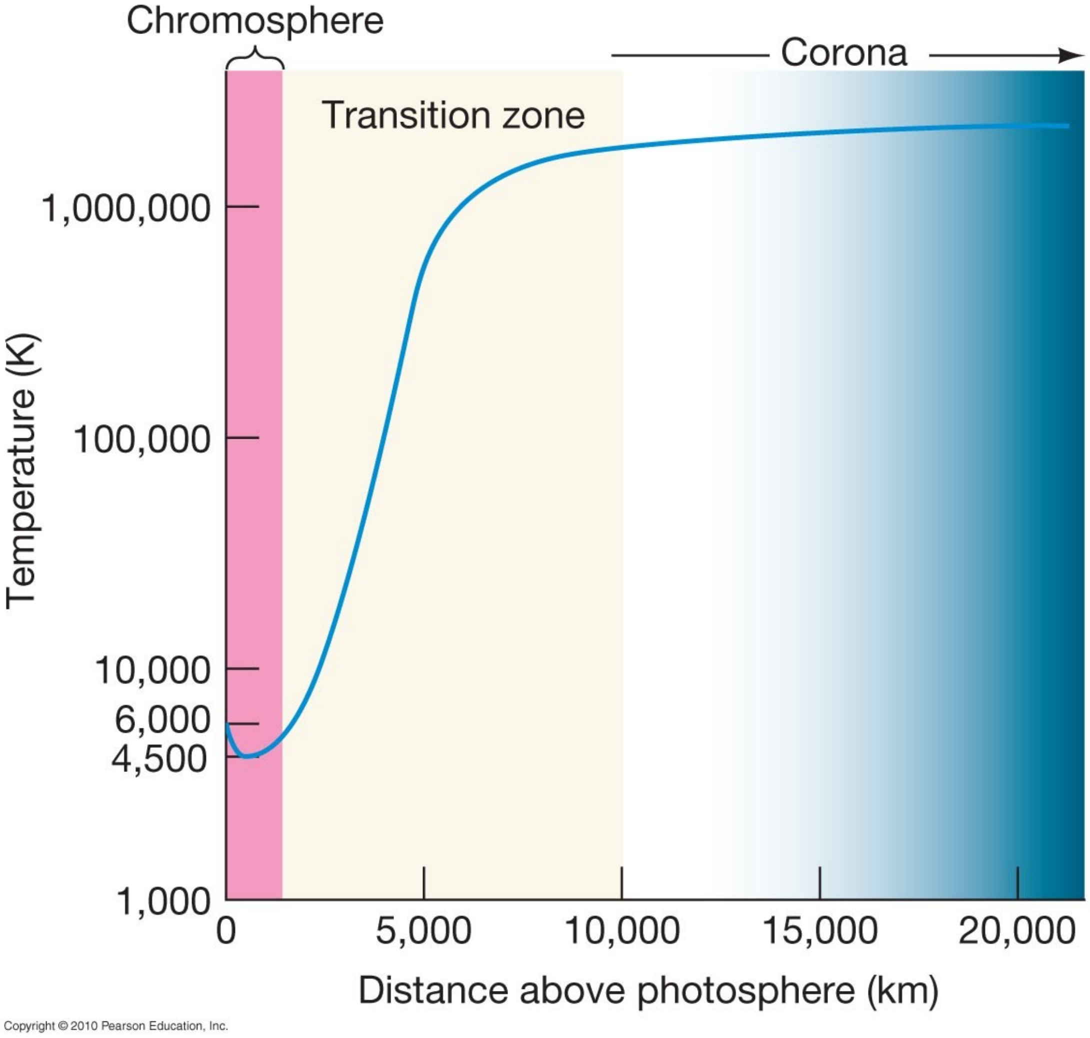


Summary: Features of the Photosphere

- Heat from the interior moves by **convection** (hot hydrogen gas rising) to the photosphere
- The tops of convection cells are called **granules**
- **Sunspots** are the result of strong magnetic fields going in or out of the Sun's surface
- The magnetic field drains energy from the surrounding photosphere, cooling it; because the cooler gas is darker, it is seen as a **dark spot**.

Photosphere and Corona

- The temperature of the photosphere is about **6,000 K**.
- But outside the photosphere, the temperature (surprisingly) increases, reaching **3 million K** in the Corona.



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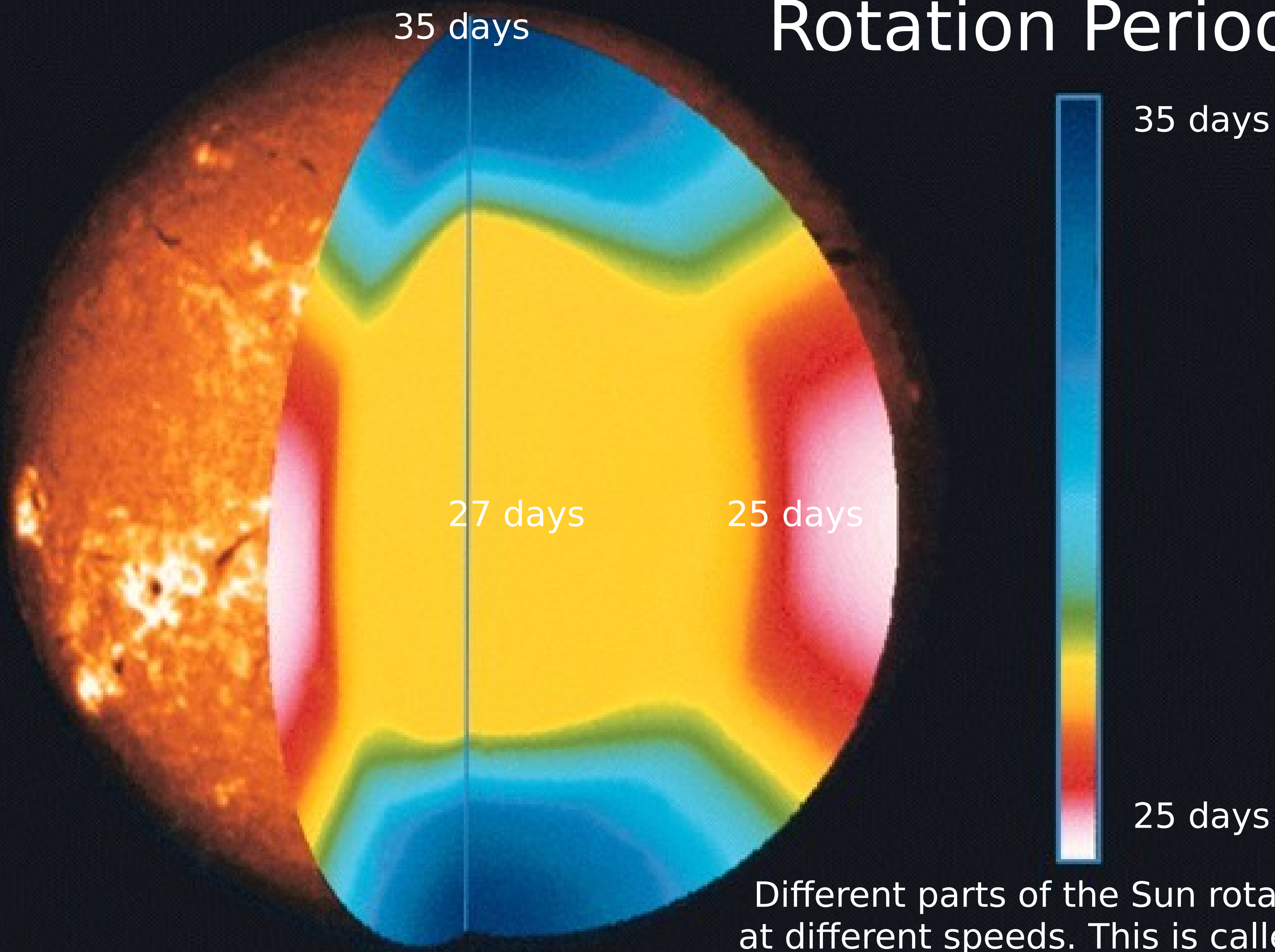
Rotation Period



Different parts of the Sun rotate at different speeds. This is called **differential rotation**.

Why does the Sun shine?

Only one known process can account for the huge amount of energy generated by the Sun:

Conversion of mass into energy via nuclear fusion

$$E = mc^2$$

Energy = mass x (speed of light)^2

$E=mc^2$

- Mass m given in kg
- Speed of light c is $3\text{x}10^8$ meters/second

Example: How much energy do you get if you can change 1 kg of matter entirely to energy?

$$\begin{aligned} E &= mc^2 = (1)\,(3\text{x}10^8)\,(3\text{x}10^8) \\ &= 9 \text{ x } 10^{16} \text{ watt-seconds} \end{aligned}$$

Example: Luminosity of the Sun

If the Sun changes 4 x10^9 kg to energy each second, how much energy does it produce each second?

E = mc2 = ($4\mathrm{x}10^9$) ($3\mathrm{x}10^8$) ($3\mathrm{x}10^8$)
= 4x3x3 x $10^9\mathrm{x}10^8\mathrm{x}10^8$ = 36 x 10^{27}
= 4 x 10^{28} watt-seconds

This is the luminosity of the Sun! Also notice that we've given the answer with the same precision (the same number of digits) we were given in the question.

Example: Luminosity of a star

If the luminosity of a star is 9 x 10^{26} watts, how much mass does it change into energy each second?

$$E = mc^2 \qquad m = \frac{E}{c^2}$$

$$m = \frac{9x10^{26}}{\left(3x10^{8}\right) x \left(3x10^{8}\right)} = \frac{9x10^{26}}{9\,x\,10^{16}} = 1x10^{10}\,kg$$

Luminosity measures energy per second, so a star with a luminosity of 9 x 10^{26} watts produces 9 x 10^{26} watt-seconds of energy every second

The Energy of Starlight

The Sun turns hydrogen into helium, and the mass of a helium atom is slightly less than the mass of 4 hydrogen atoms (by 0.7%=0.007)

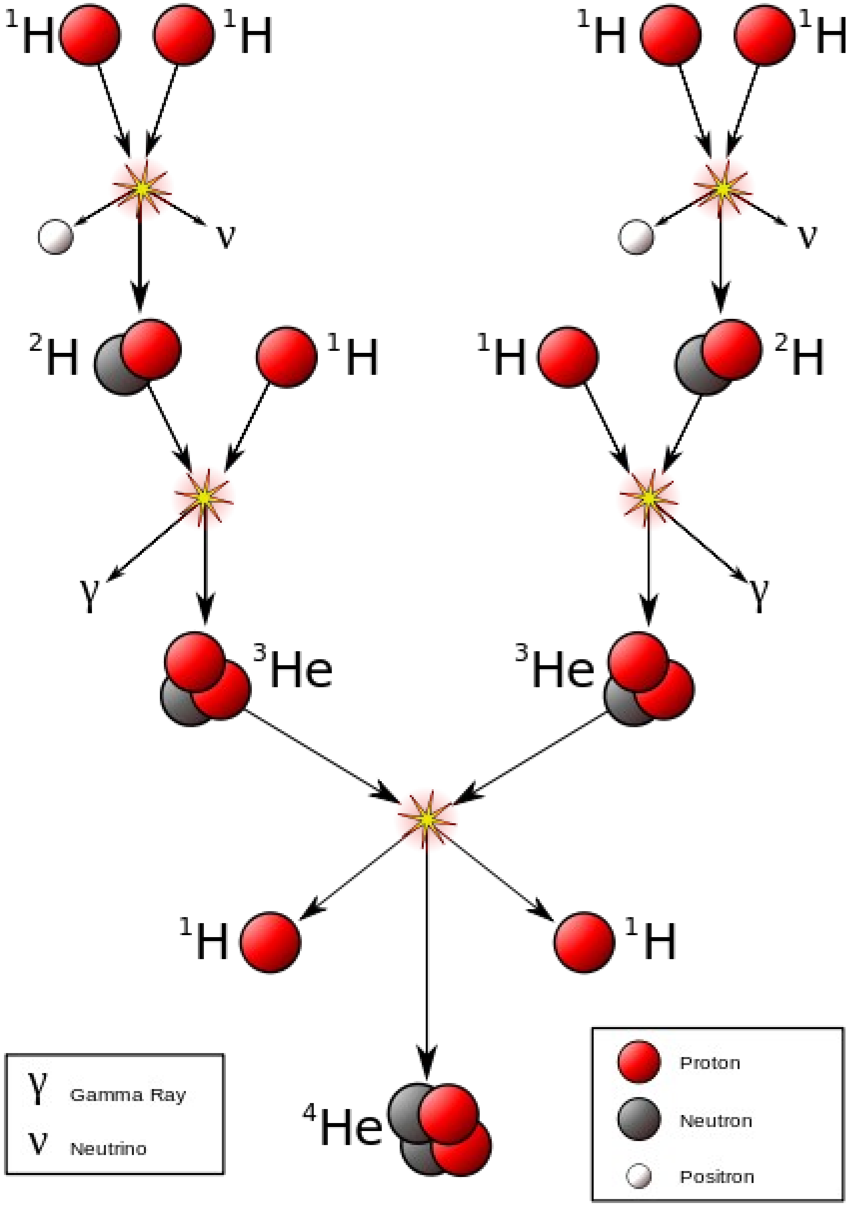
$$4m_H - m_{He} = .007\, m_H$$

Arthur Eddington (1920): Hydrogen can turn into helium, and when it does, 0.7% of its mass changes to energy, and **that energy powers the Sun**

Fusion of H to He in stars like the Sun

Basic process, neglecting intermediate steps:

4 protons → ^{4}He + 2 neutrinos + energy



Evidence of fusion in the Sun

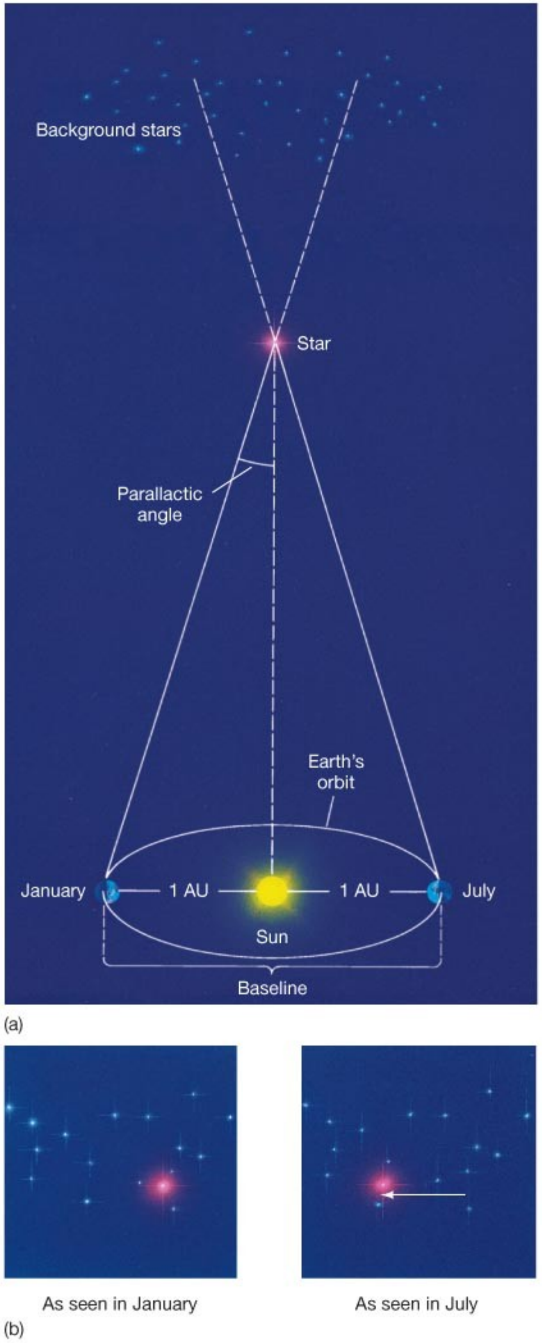
- Light
  - Gamma rays produced in the center are absorbed and re-emitted many many times before they reach the surface of the Sun, more than 10,000 years later
  - As they pass through cooler outer layers blackbody spectrum shifts to lower temperatures
  - We finally see visible radiation from the photosphere – this is not direct evidence of fusion
- Neutrinos

Distances – Method I: Stellar Parallax

For the very closest stars we can measure how much they shift against more distant stars over the course of six months – the time it takes for the earth to move from one side of its orbit to another.

That tiny shift can tell us the distance to that star. So tiny that no one saw it until 1838.

- Shift is about 1/3600 of a degree or 1 arcsecond.



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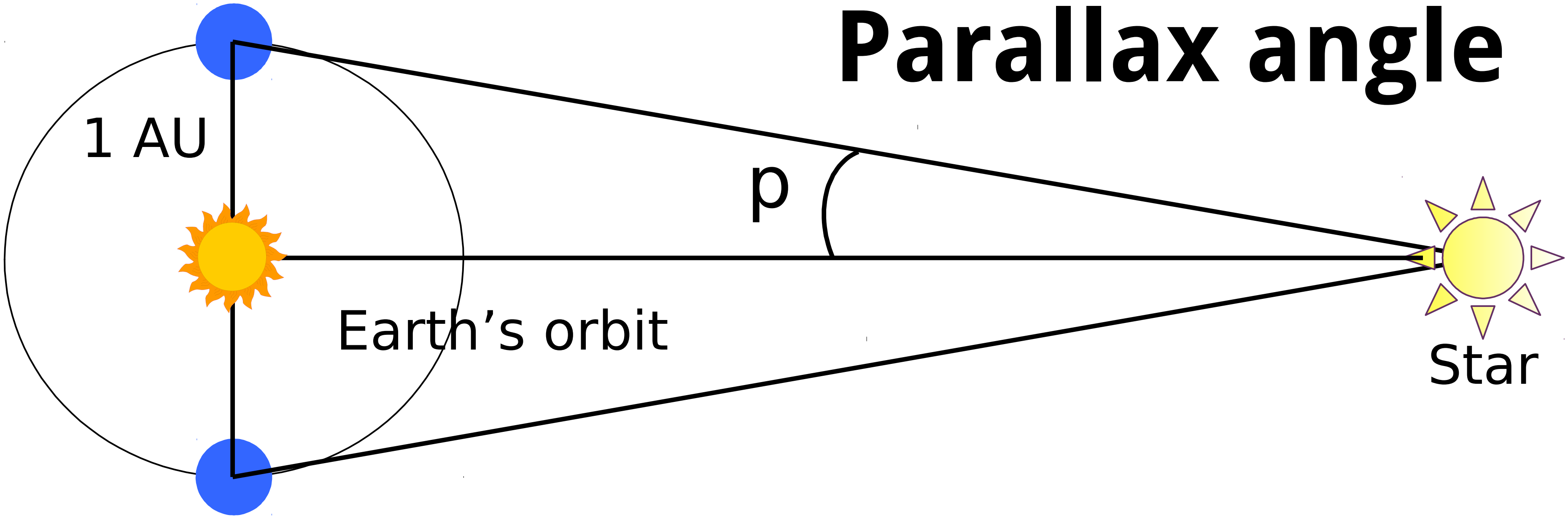
Parallax angle



- The parallax angle p of a star is the angle formed by the star and the radius of the Earth's orbit. (i.e. the angle subtended at a star by the radius of the Earth's orbit is the parallax angle, p, of the star)
- This is the apparent shift in the star's position due to the Earth's motion about the Sun.
- When the angle is 1 arc second, the star's distance is 1 parsec (for parallax second, abbreviated pc)
- 1 pc ~ 210,000AU ~ 3.26 ly ~ 3.09 x10^{13} km.

Method 2: **Spectroscopic Parallax**

How bright something seems depends on its distance

$$\text{apparent brightness} = \text{luminosity}/(4\pi\ d^2)$$

How bright
it seems

How bright
it is

How far
away it is

$$B \text{ proportional to } 1/\mathrm{d}^2$$

or

$$B_2 = B_1 \times \frac{d_1^2}{d_2^2}$$

- Example: The brightness of sunlight at the Earth is 1400 watts/meter^2. What is the brightness of sunlight at Saturn, 10 AU from the Sun?

A few more examples

1) What is the brightness of the sun at 40 A.U. if it is 1400 watts/m^2 at 1 A.U?

$$B_2 = B_1 \times \frac{d_1^2}{d_2^2}$$

$$= 1400 \times \frac{1^2}{40^2} = 0.875 \text{ watts/m}^2$$

A few more examples

1) What is the brightness of the sun at 40 A.U. if it is 1400 watt/m2 at 1 A.U?

2) How about at 100 A.U.?

$$B_2 = B_1 \times \frac{d_1^2}{d_2^2}$$

$$= 1400 \times \frac{1^2}{100^2} = 0.14 \text{ watts/m}^2$$

Another example: If the Sun has an apparent brightness of 0.0014 watts/m^2, how far away is it?

$$B_2 = B_1 \times \frac{d_1^2}{d_2^2}, \text{ so}$$

$$d_2^2 = d_1^2 \times \frac{B_1}{B_2}$$

$$= (1 \text{ A.U.})^2 \times \frac{1400}{0.0014} = 10^6 \text{ A.U.}^2 \text{ and}$$

$$d_2 = \sqrt{10^6} = 1000 \text{ A.U.}$$

Stellar Spectra and Classification

The classification of a star is its spectral type.

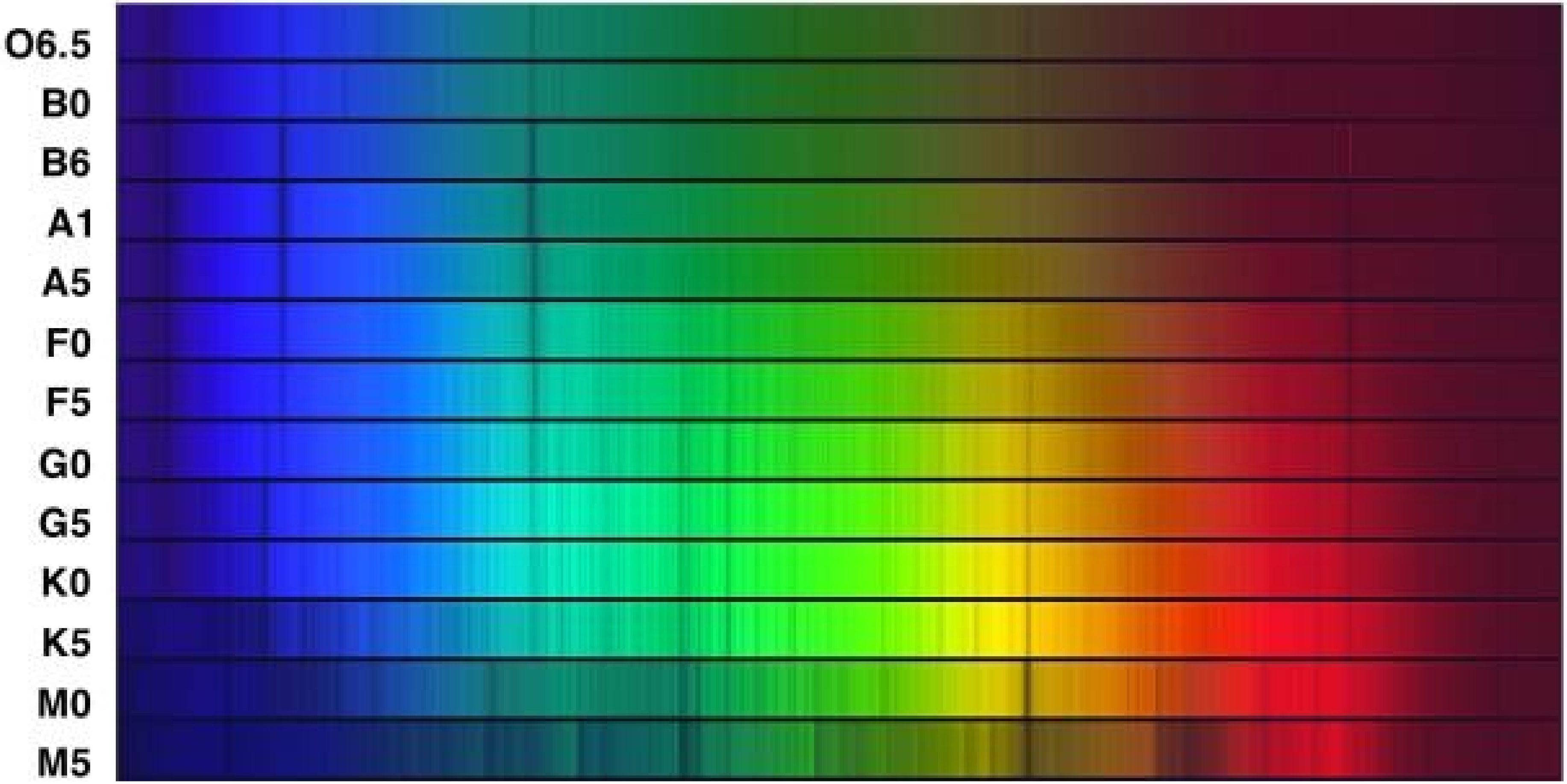
Ordered from hottest to coolest, the spectral types are:

O, B, A, F, G, K, M (L, T)

(Use the mnemonic Oh, Be A Fine Guy/Girl Kiss Me,
or make up your own!)

- O stars are hottest with surface temperature > 25,000 K.
- G stars (like the Sun) have surface temperature of approximately 6000 K.
- M stars are coolest (Betelgeuse for example) with surface temperatures approximately 3000 K.

Stellar Spectra and Classification



Stellar Sizes

So if you know the spectral type, you know the temperature. How do you know how luminous a star is?

The relation between temperature and luminosity is:

$$L = 4\pi\sigma T^4 R_*^2$$

Some constants we won't worry about

Temperature

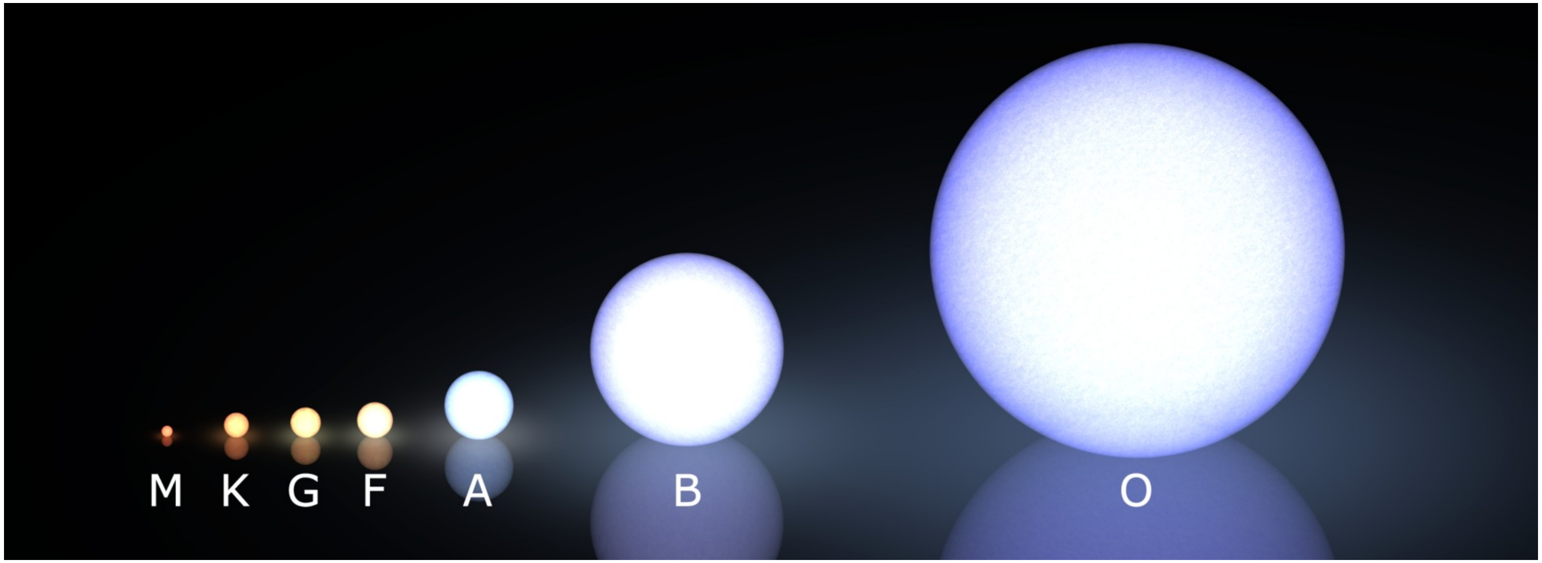
Radius (size) of star

This relationship is for continuous, blackbody radiation.

Two ways stars can be luminous

$$L = 4\pi\sigma T^4 R_*^2$$

- Either very high temperature – big T
- Or very big – big R



Size, Temperature and Luminosity

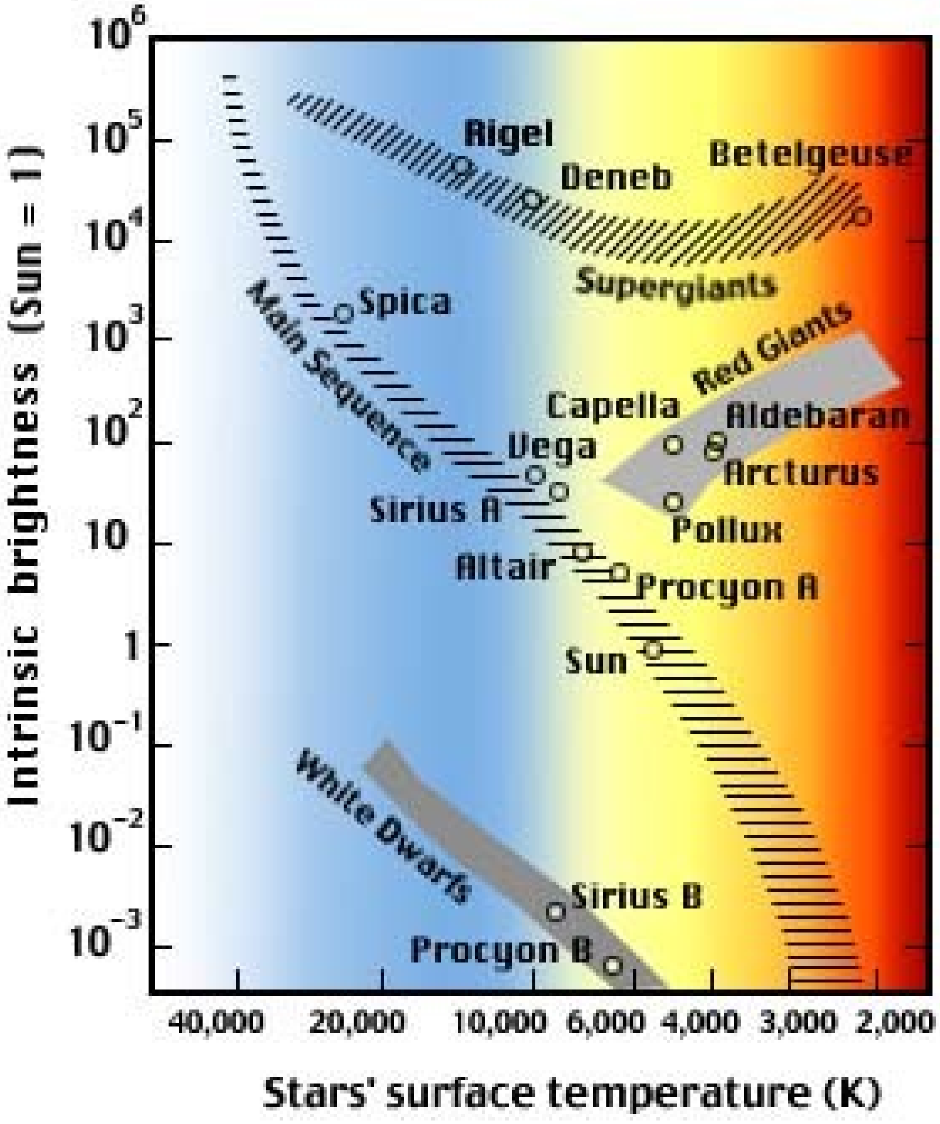
- This means that you can find the size of a star if you know its luminosity and its temperature.
- Temperature you know by spectral type – O,B,A,F,G,K,M (you tell this by taking a spectrum of the star)
- Luminosity if you know its distance

H-R Diagram: Summary

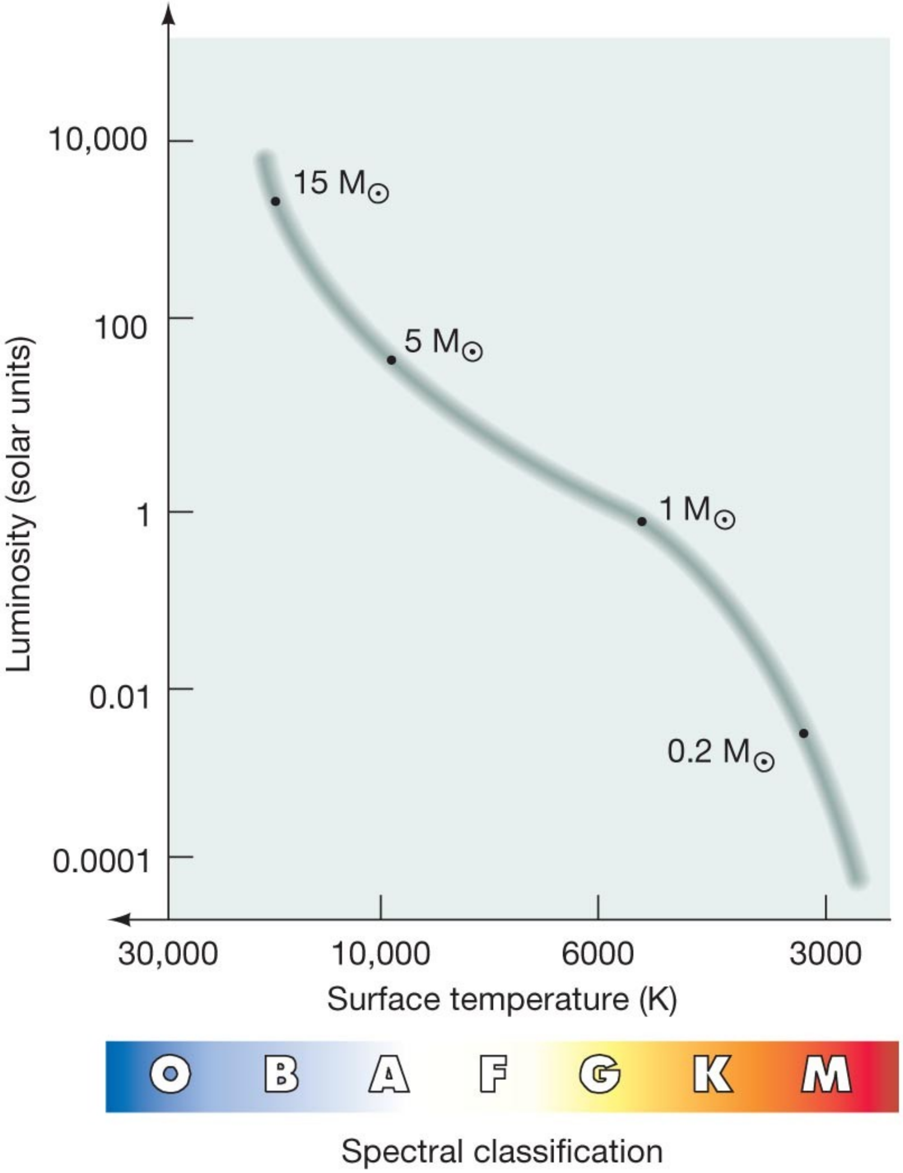
The H-R diagram plots **luminosity** versus **surface temperature**

More than 90% of all stars lie on the **main sequence**.

The hottest stars on the **main sequence** are also the brightest stars, and the dimmest are also the coolest.



The Main Sequence



Stars with small masses are the stars that are low on the main sequence. They burn much more slowly, so they are much dimmer and their surfaces are cooler. Stars with larger masses burn much more quickly and have hotter surfaces (and hotter interiors).

The Main Sequence

Stars don’t move along the main sequence – that would require them to change their mass.

Instead they just sit on the main sequence until their time there is up.

The main sequence is a waystation, where stars spend MOST of their lives.

Lifetimes of other stars

The lifetime of a star can be summarized as the following formula:

$$\text{lifetime of star} = 10^{10}\,\text{years} \times \frac{M}{L}$$

Here is an example:
A main sequence star has mass 5M$_\odot$ and luminosity 1000 L$_\odot$ What is the star’s lifetime? The calculation is again

$$\text{lifetime of star} = 10^{10}\,\text{years} \times \frac{5}{1000} = 5 \times 10^{7}\,\text{years}$$

Gas in the ISM

Gas in the ISM is mostly hydrogen.
It is in **three phases:**

- Cold (10-100s K)
- Warm (around 8000 K)
- Hot (10^6 K)

Most of the volume is hot, but hot gas is very diffuse – most of the gas is warm or cold. This cold gas is important because it is found in clouds that form stars. Cold gas clouds are what stars come from.

Gas cool enough that its hydrogen is in the form of atoms is called **HI**.

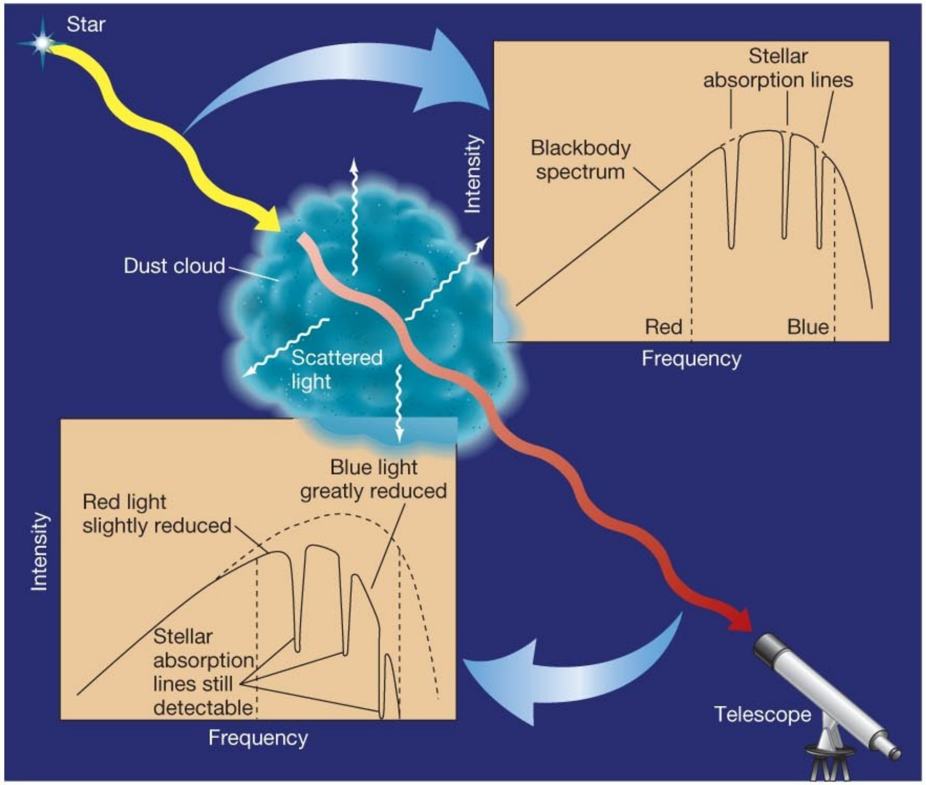
HI ("H one") is astronomer-speak for neutral hydrogen.

Neutral hydrogen gas cannot be seen in visible light. This is a **radio** image of HI gas in the constallation of Orion.

Some of these cold clouds have formed hot, massive stars that have heated up the gas hot enough for the hydrogen to be ionized. These regions of hot gas are called **HII regions**.

HII (“H two”) is astronomer-speak for ionized hydrogen.

Cool clouds emit little visible light and are observed as dark nebulae, dark clouds that block the light from the stars behind them.
Dust within these clouds scatters light of wavelengths shorter than the size of a typical dust grain, reddening and dimming the light that goes through
it.



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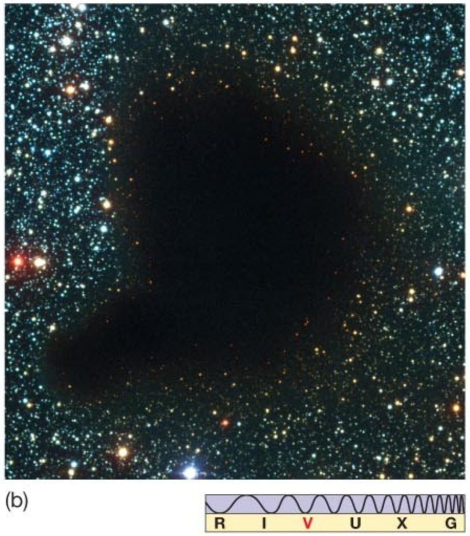


(b)

Dusty clouds become transparent in infrared light.

Star Formation

Star formation is the process of clouds of gas and dust collapsing to form a star. Pretty simple, but we still don't understand all the details.

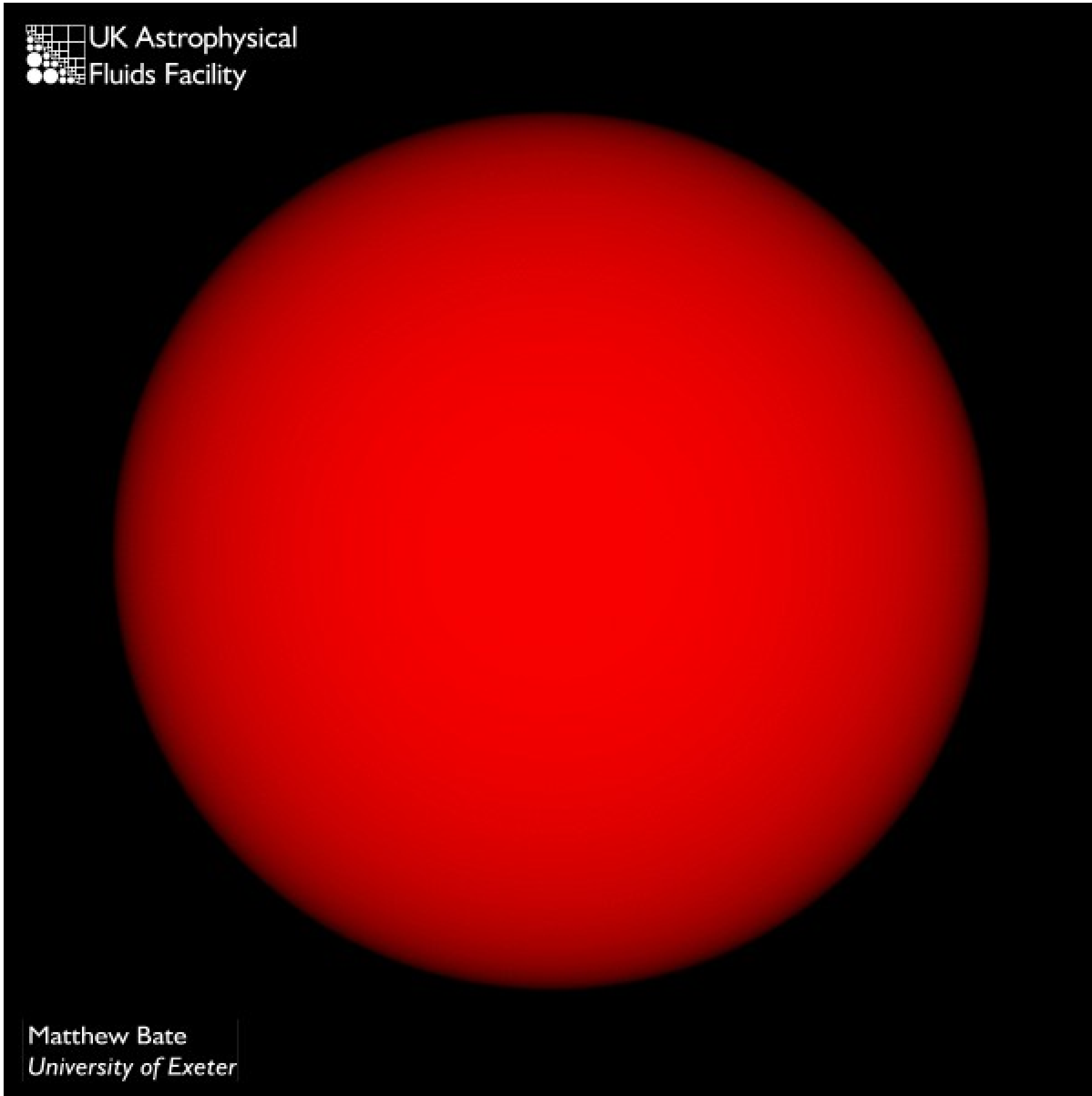
Your book has it broken into 7 stages, which are phases in a single process:

The collapse of molecular gas and formation of stars (textbook stages 1-6)

Stage 1 – A molecular cloud begins to collapse. Usually we see this from spectral lines of molecules. Stars form in cold, dense molecular gas.

Molecular Cloud Collapse

0 yr: We begin with such a gas cloud, 2.6 light-years across, and containing 500 times the mass of the Sun. The images measure 1 pc (3.2 lightyears across).



Source: Matthew Bate, U. Exeter: http://www.astro.ex.ac.uk/people/mbate/Cluster/cluster3d.html

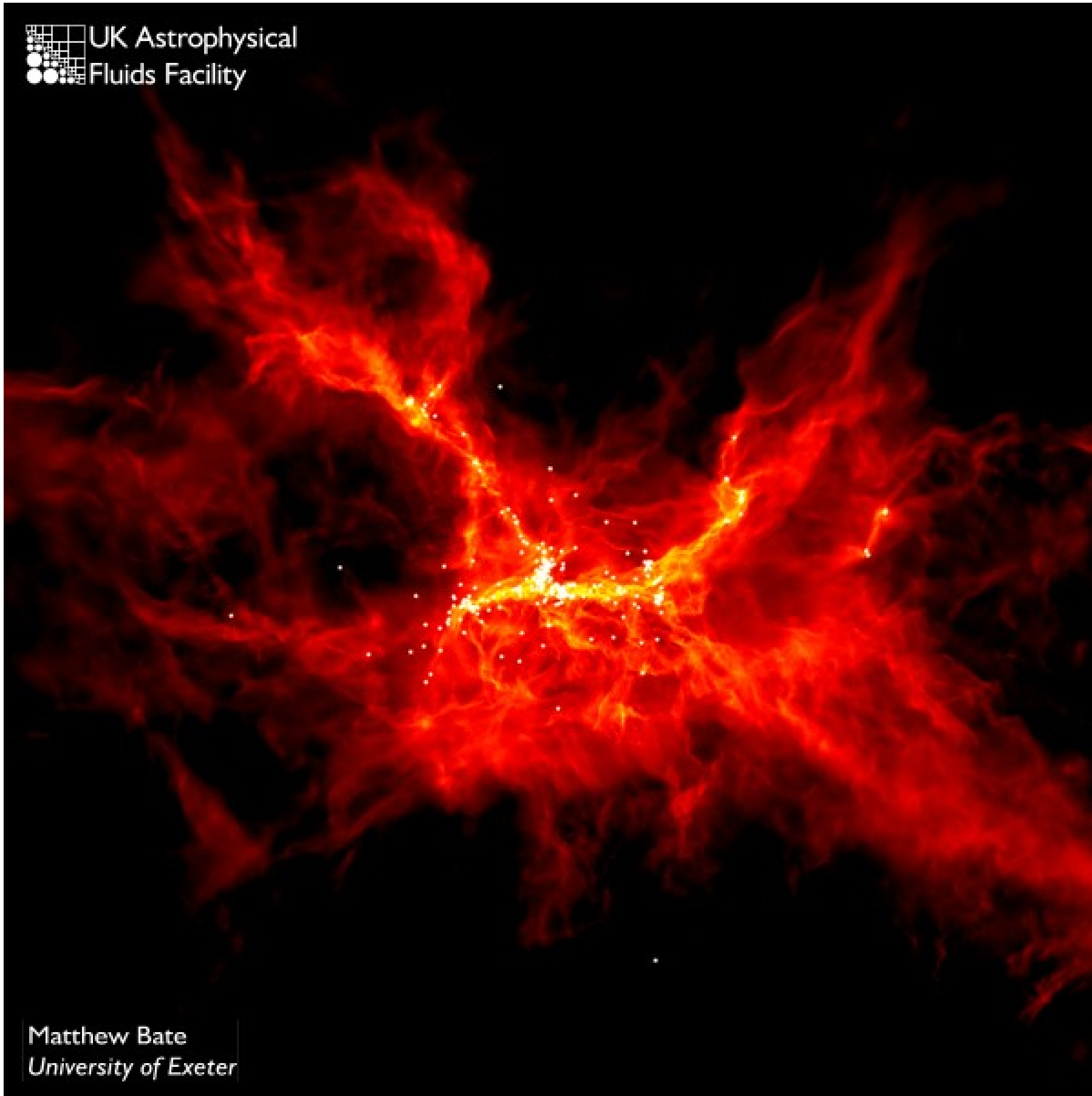
Molecular Cloud Collapse

152,000 yr: When enough energy has been lost in some regions of the simulation, gravity can pull the gas together to form dense "cores".

Source: Matthew Bate, U. Exeter: http://www.astro.ex.ac.uk/people/mbate/Cluster/cluster3d.html

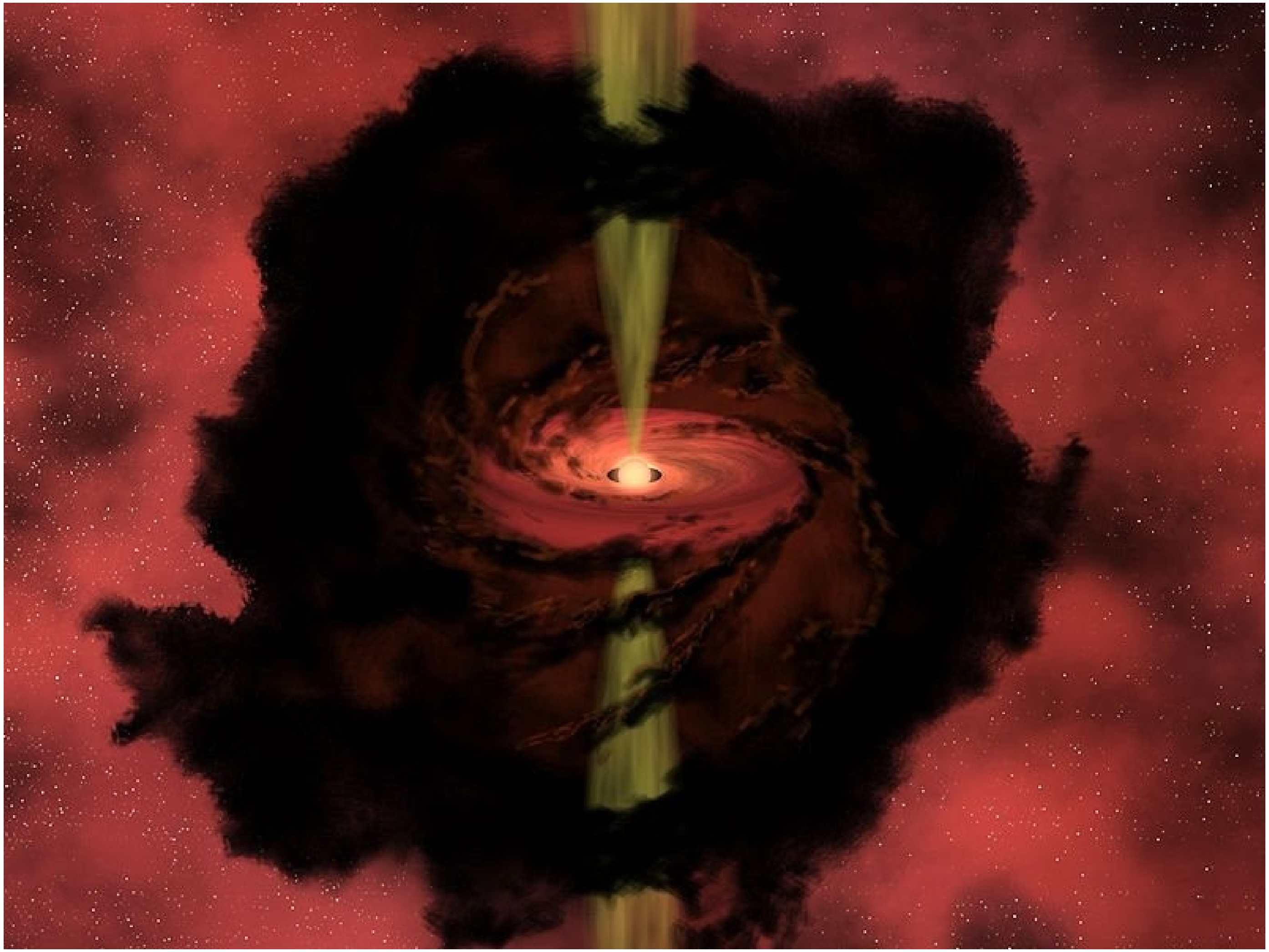
Molecular Cloud Collapse

The cloud and star cluster at the end of simulation (which covers 210,000 years so far). Some stars and brown dwarfs have been ejected to large distances from the regions of dense gas in which the star formation occurs.



Source: Matthew Bate, U. Exeter: http://www.astro.ex.ac.uk/people/mbate/Cluster/cluster3d.html

Stage 4: The protostar



The star is still forming, but the cloud has a hot central thing that can be considered a star already.
It is surrounded by a disk of gas.

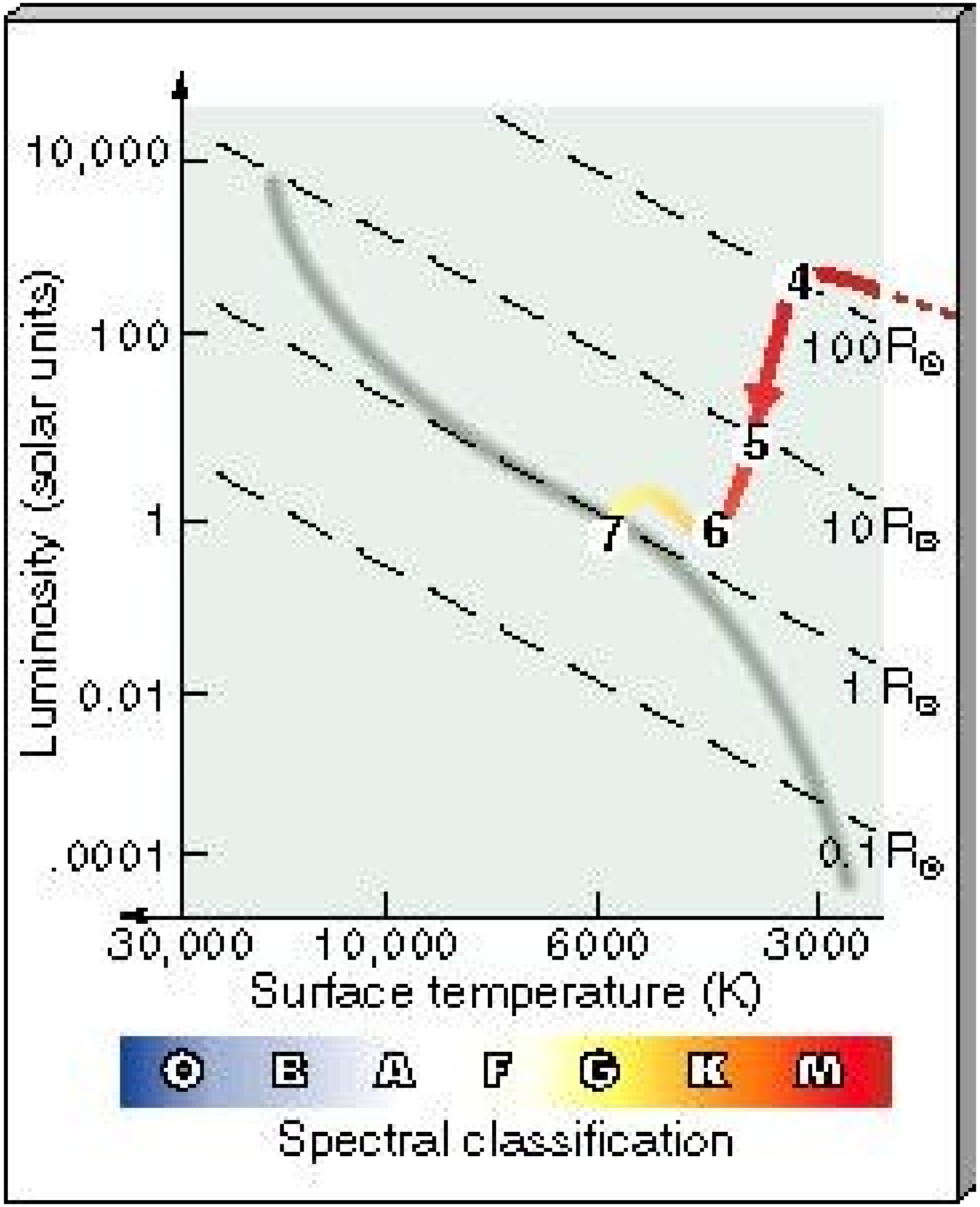
Stage 6/7: A star is born.

A star is born once it stars fusing hydrogen to helium at its core.

Roughly half of all stars are not born alone, but in a binary system.

Where the star lands on the ZAMS is where it is **stuck**.

Stars don’t move along the main sequence, but they will eventually leave it.

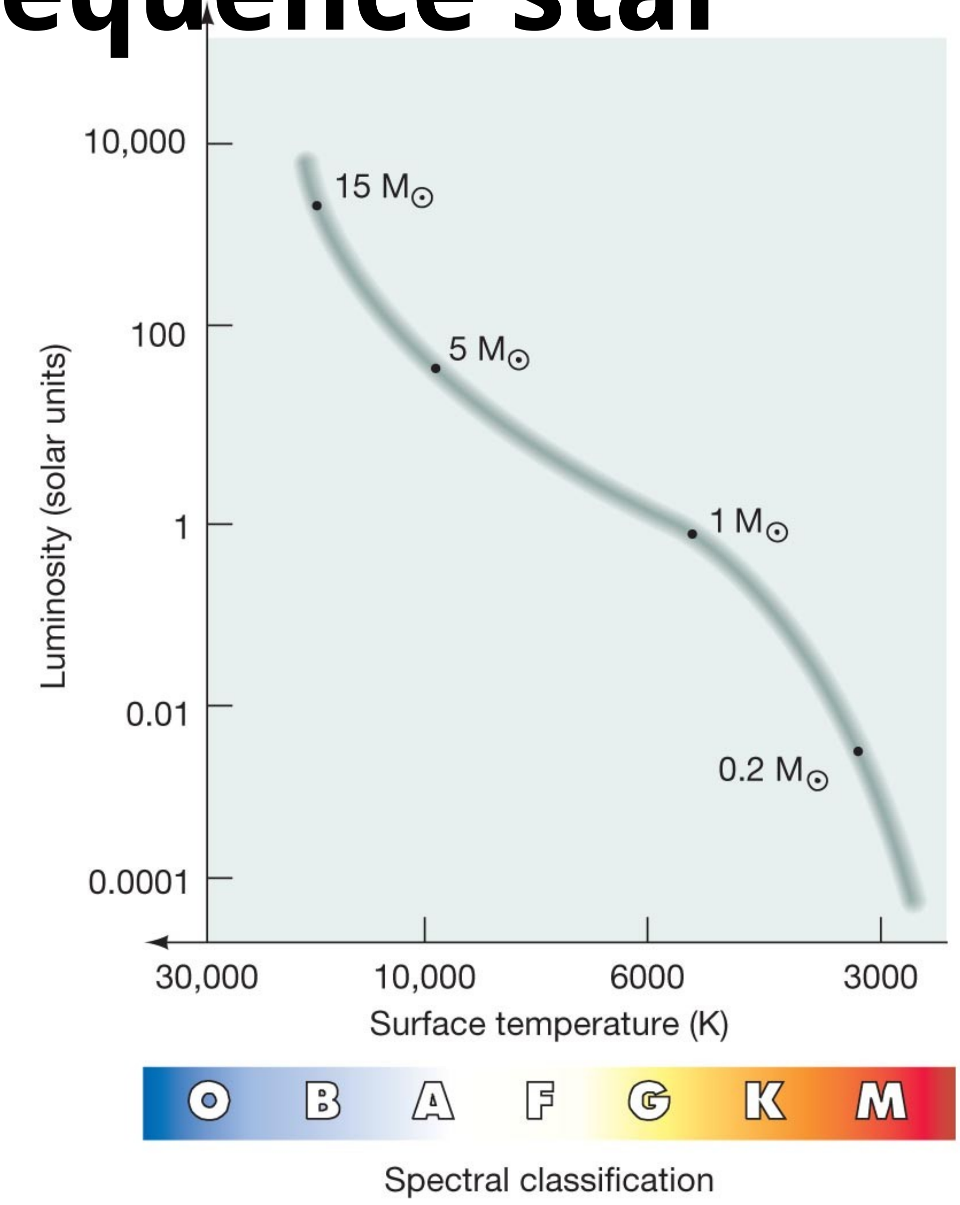


I. Main sequence star

The main sequence is boring – H fuses in the core to make He, but not much else happens

As we have seen, where a star sits on the main sequence depends on its mass.

It stays on the main sequence until it converted all hydrogen in its core into helium.



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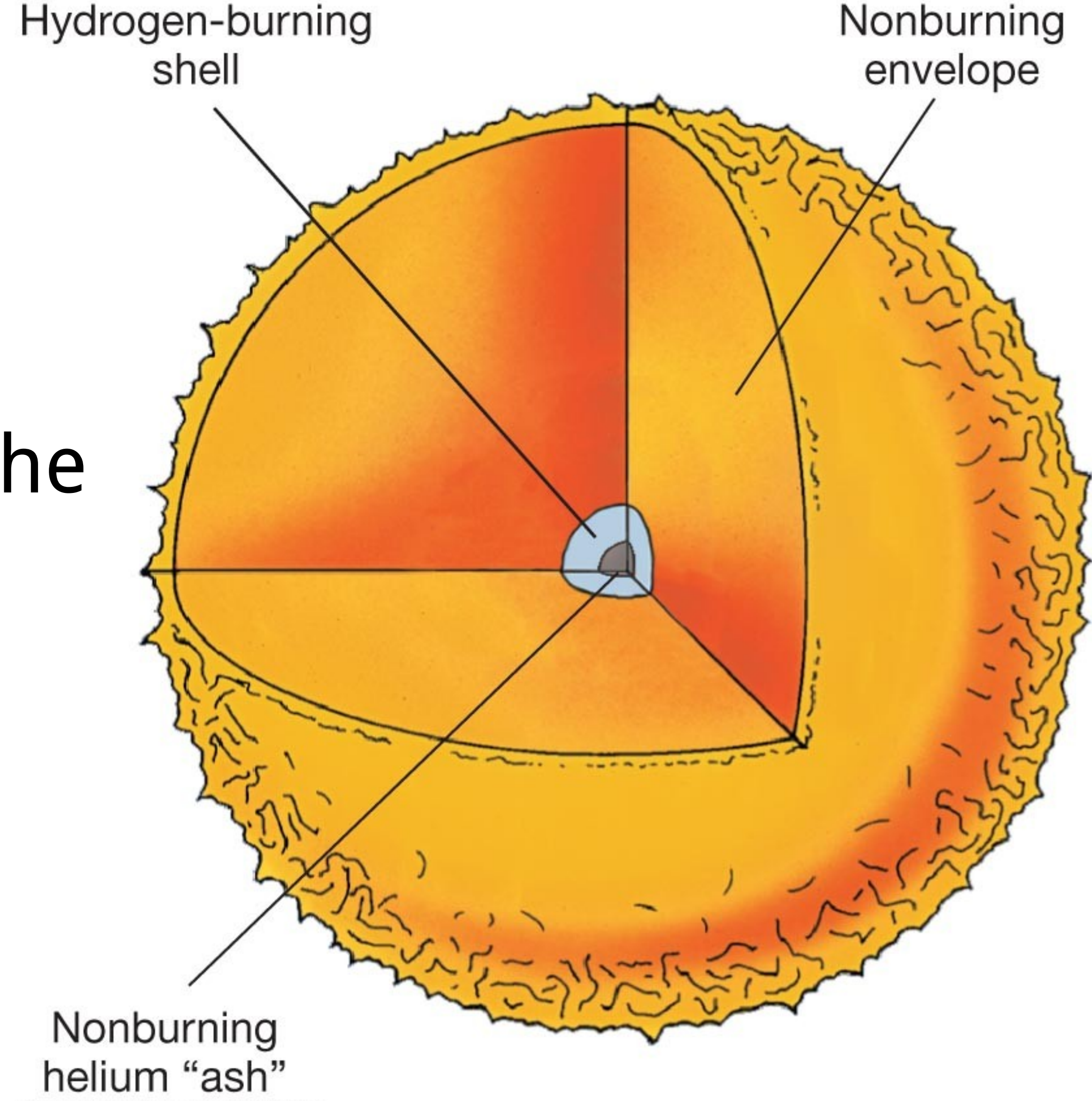
II. Red Giant

Eventually the star gets hot enough to burn hydrogen in the outer layer around the He core.

This is called *hydrogen shell burning.*

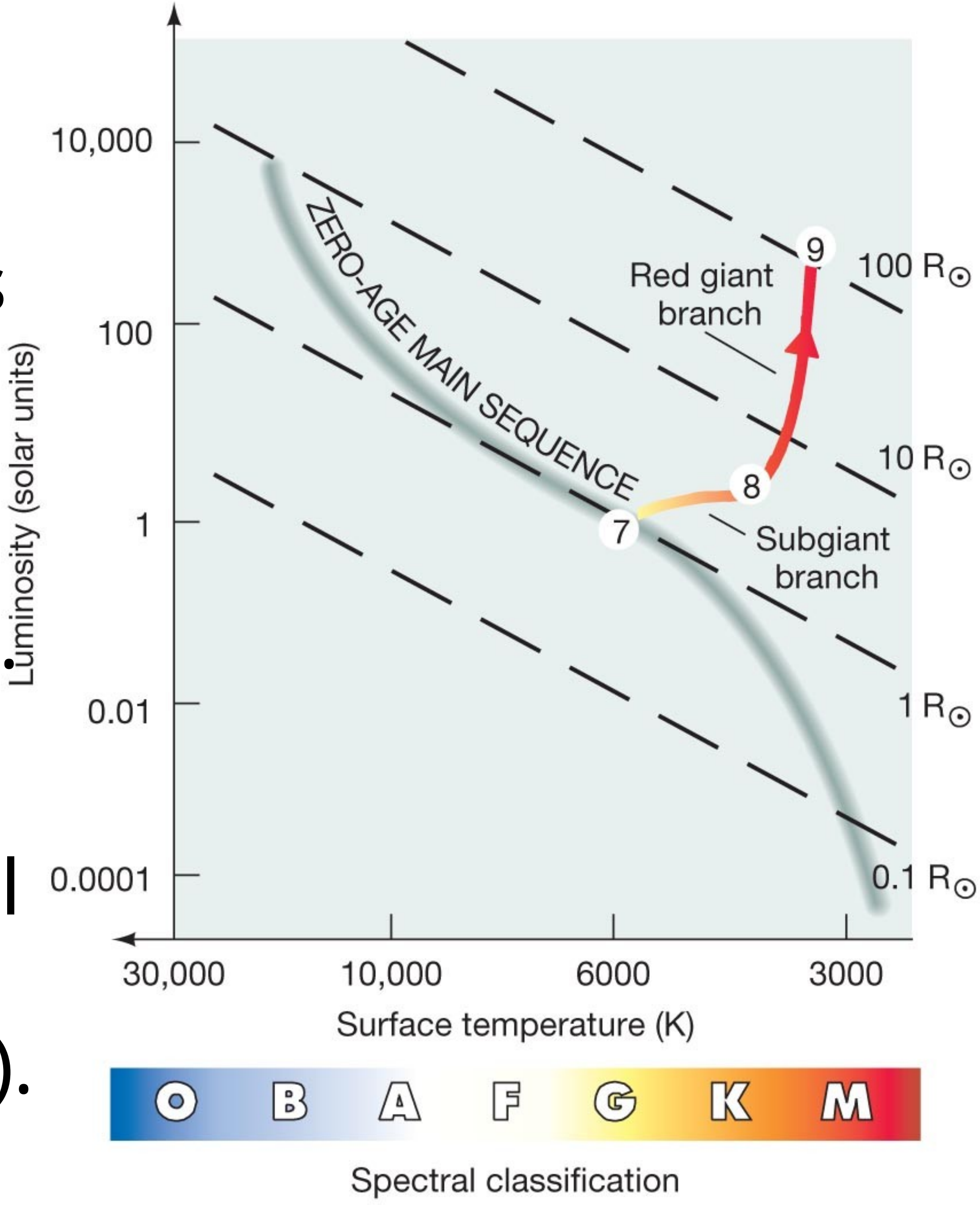
This is the **Red Giant stage.**



II. Red Giant

At first the star cools with the luminosity staying roughly constant—core contraction (stage 8).

Later, hydrogen shell burning makes the star expand (stage 9).



IV. Helium flash (stage 10)

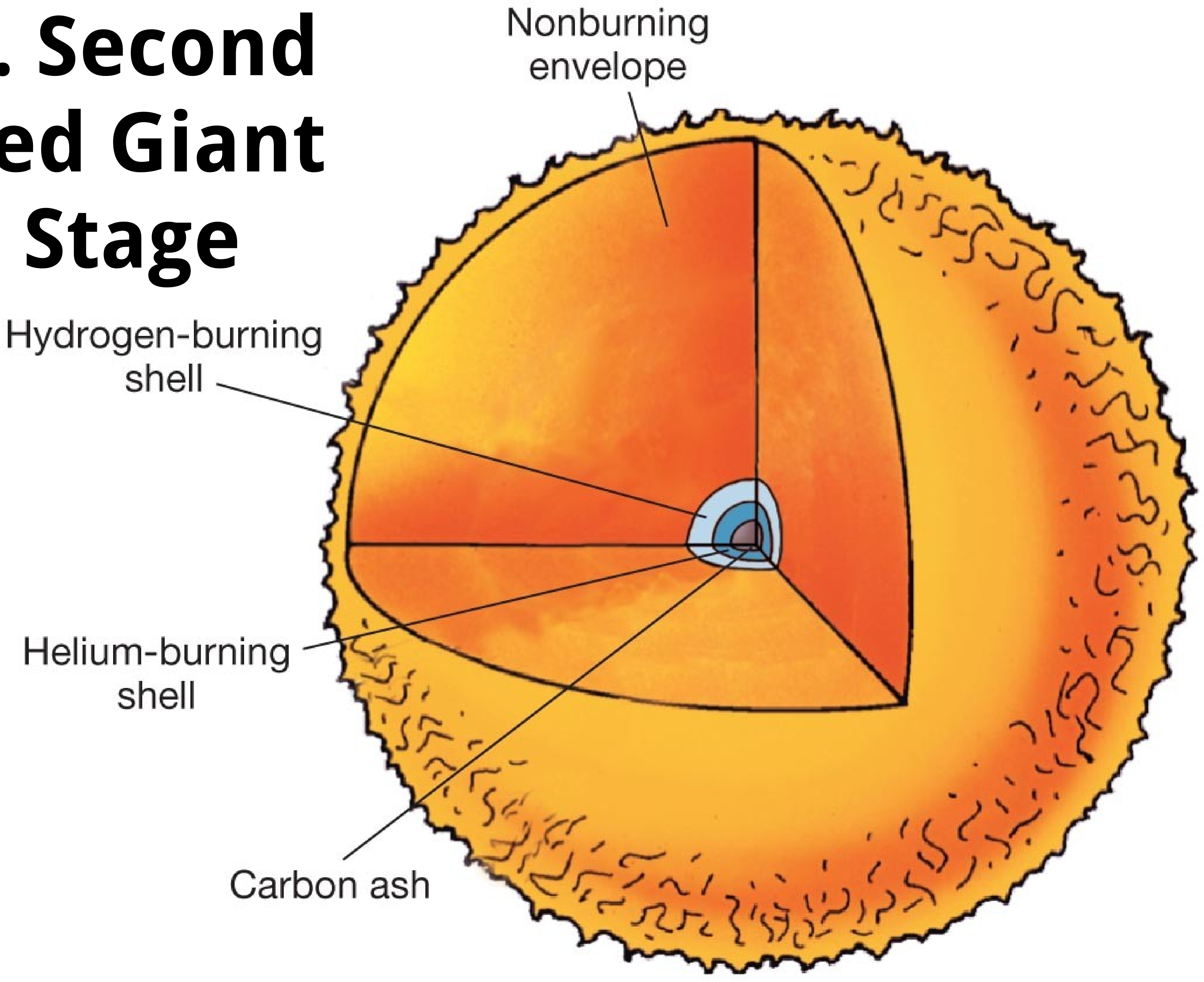
For stars with M > 0.4 Msun, the temperature will reach 100 million K, hot enough to ignite the fusion of He in the core to produce C.

Three helium nuclei combine to form a carbon nucleus:

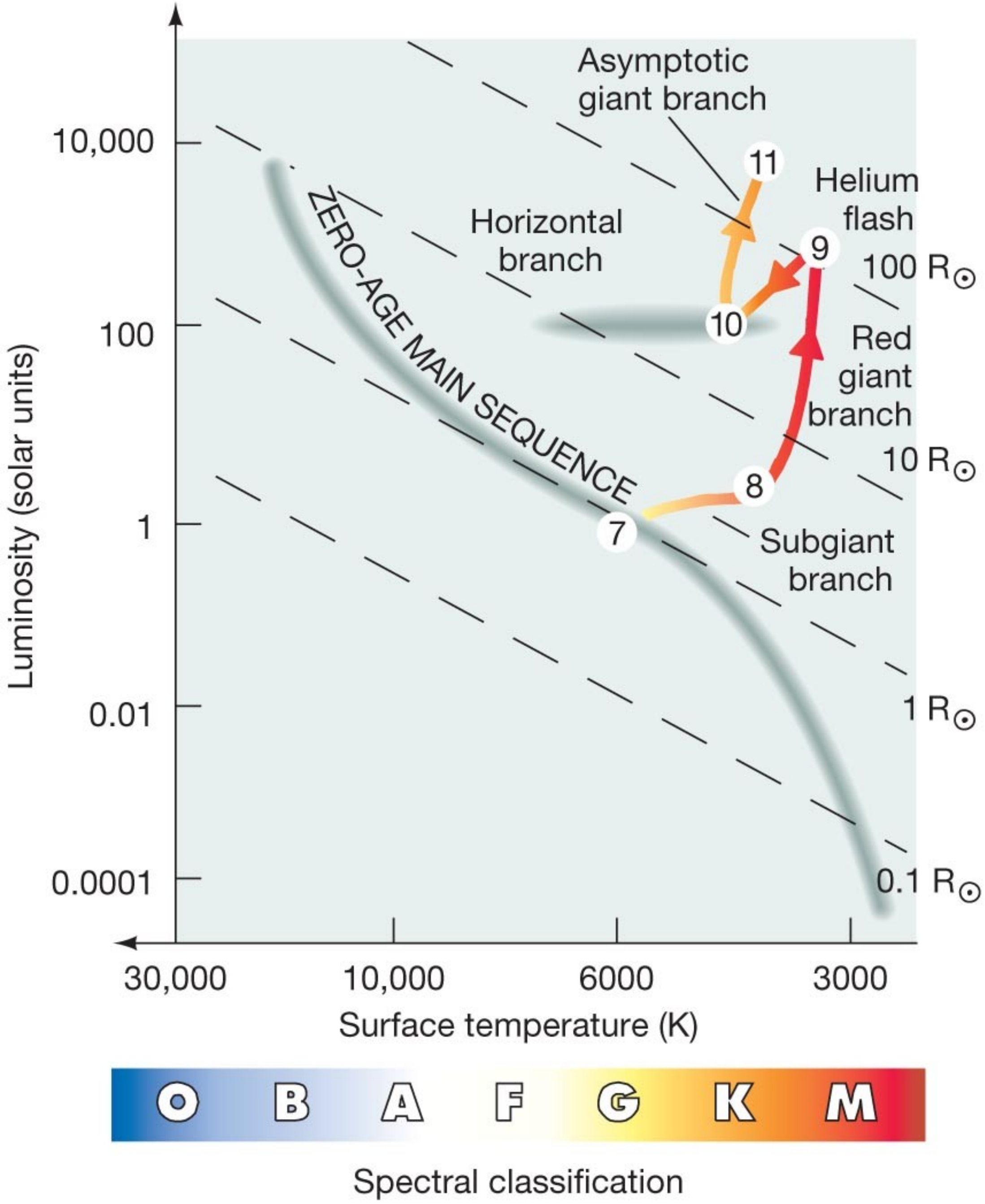
$$\mathbf{{}^{4}He + {}^{4}He + {}^{4}He \rightarrow {}^{12}C}$$

Fusion of helium to carbon begins explosively throughout the core, and the burst of energy released is called the **helium flash**. The core re-expands, the H burning in the shell slows because the shell is now cooler, and the outer layers of the star contract.

V. Second Red Giant Stage



Similar story as before: Lack of nuclear fusion at the center causes carbon core to contract, releasing energy, the overlaying layers fuse more rapidly, and the star expands again (11).

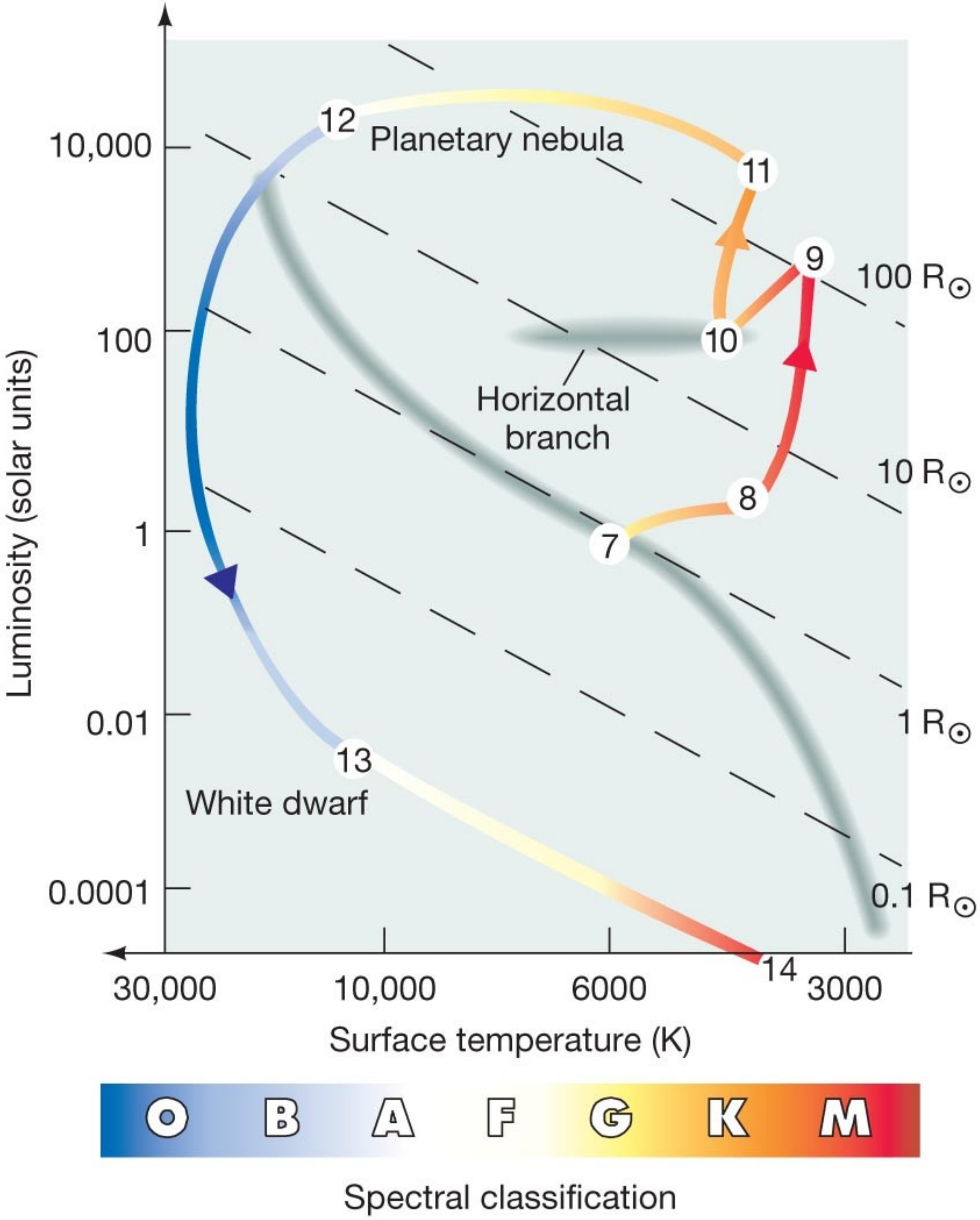


White dwarfs

The star burns so brightly that it sheds a planetary nebula—gas that travels away from the star (12).

Once the star runs completely out of nuclear fuel what remains of the star contracts and forms a white dwarf (13).

The star cools eventually becoming a black dwarf, too small and faint to see (14).



White dwarfs, planetary nebulae

- To support a star's core against gravity, the degeneracy pressure is much larger than it would be for any metal on earth. These stars that are supported by degeneracy pressure are called **white dwarfs.**
- The Sun itself will end as a white dwarf, compressed to about the size of the Earth. A typical white dwarf radius is then about the radius of the Earth. Its density is about **5 tons per teaspoon**.
- A star **smaller than 4 solar masses** ends its life by ejecting a planetary nebula and settling down to become a white dwarf.
- **Planetary nebulae are thus found around white dwarfs**.

Novae: H-bombs at the surface of white dwarfs

Some white dwarfs are in binary systems with another star.

In a close binary, or when the other star becomes a red giant and is sufficiently large, hydrogen from the surface of the other star falls onto the white dwarf.

Once enough hydrogen builds up on a white dwarf, it will suddenly fuse to helium. This is a **nova**, the sudden fusion of hydrogen to helium on the surface of a dwarf.

Type I Supernovae

If a white dwarf accretes too much mass from a companion, or if it merges with another white dwarf, its mass will exceed the Chandrasekhar limit. What happens then?

The immense gravity collapses the star, and all elements suddenly start fusing again.

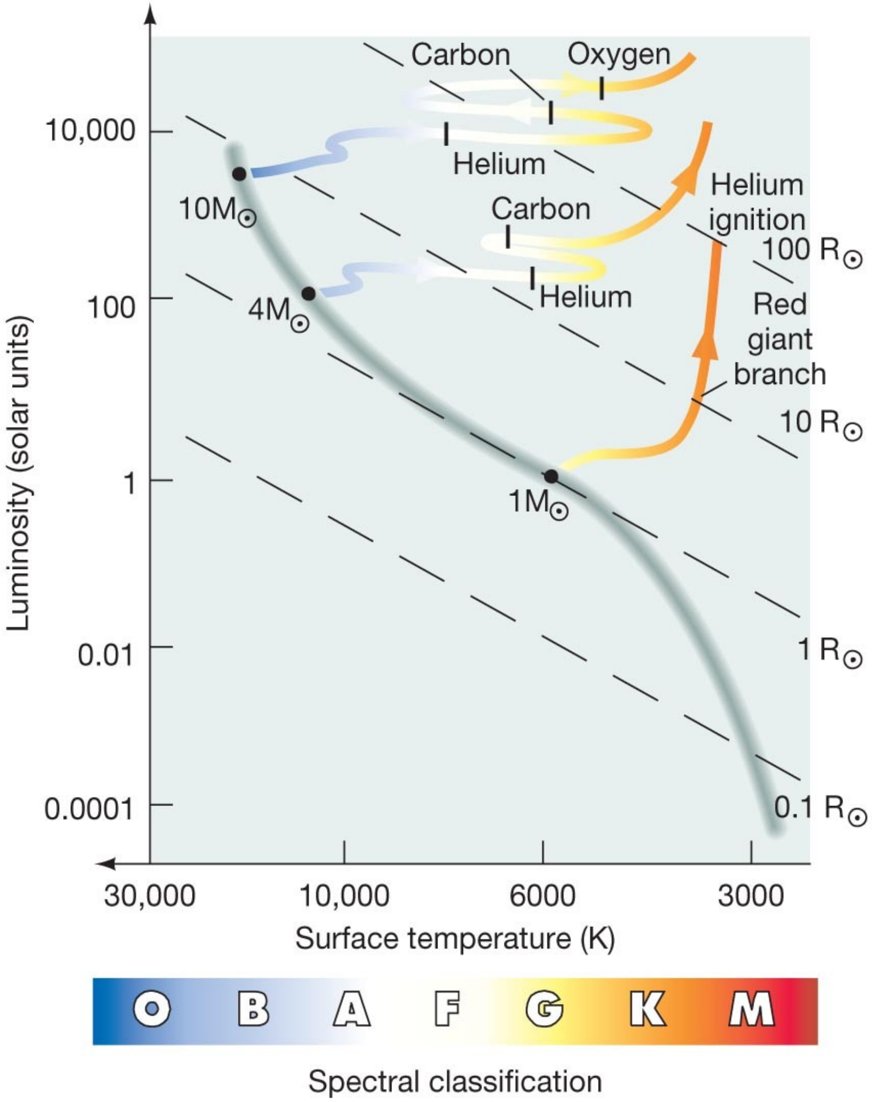
The dramatic increase in energy production disrupts the star, spewing the newly fused elements into the ISM, leading to a visible supernove Type I with a very characteristic lightcurve.

Left over is a supernova remnant without central star.

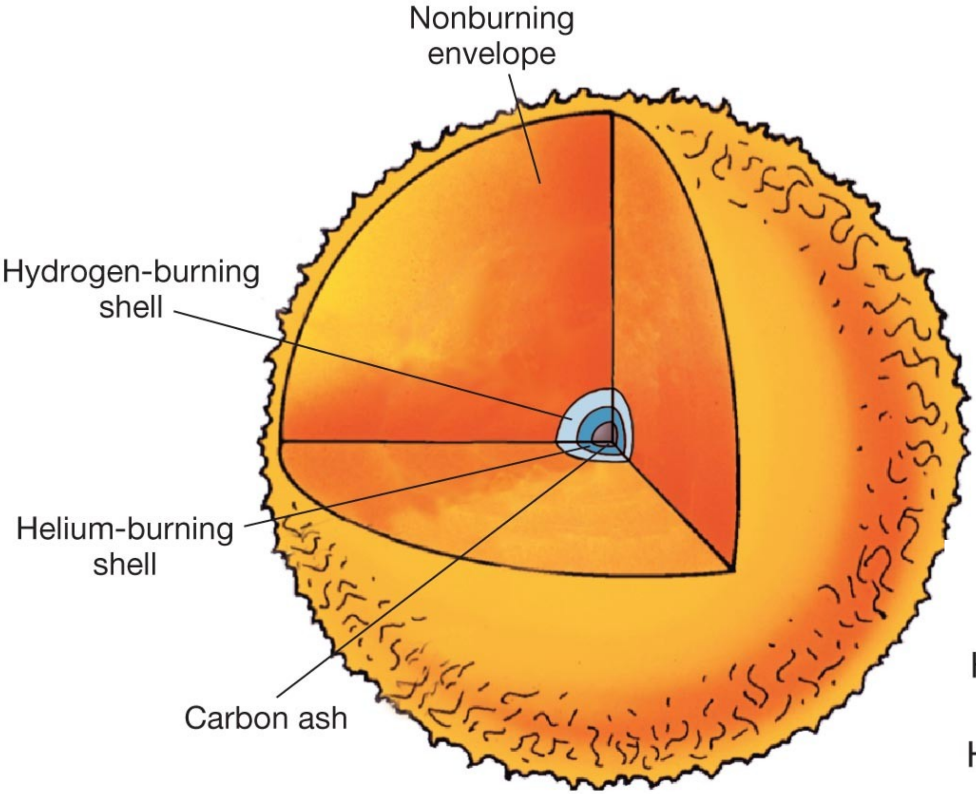
Evolution of Stars More Massive than the Sun

A star of more than 8 solar masses can fuse elements far beyond carbon in its core, leading to a very different fate.

Its path across the H–R diagram is essentially a straight line – it stays at just about the same luminosity as it cools off.



Stars with lower masses only produce Carbon



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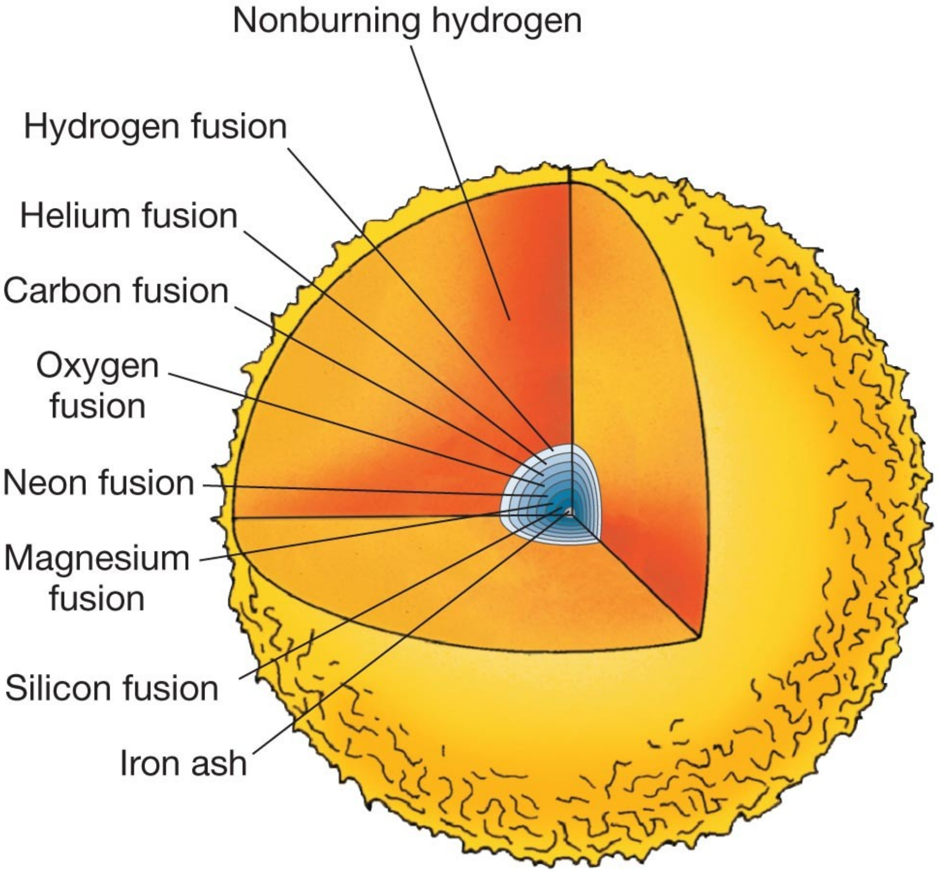
Stars with higher masses produce Iron



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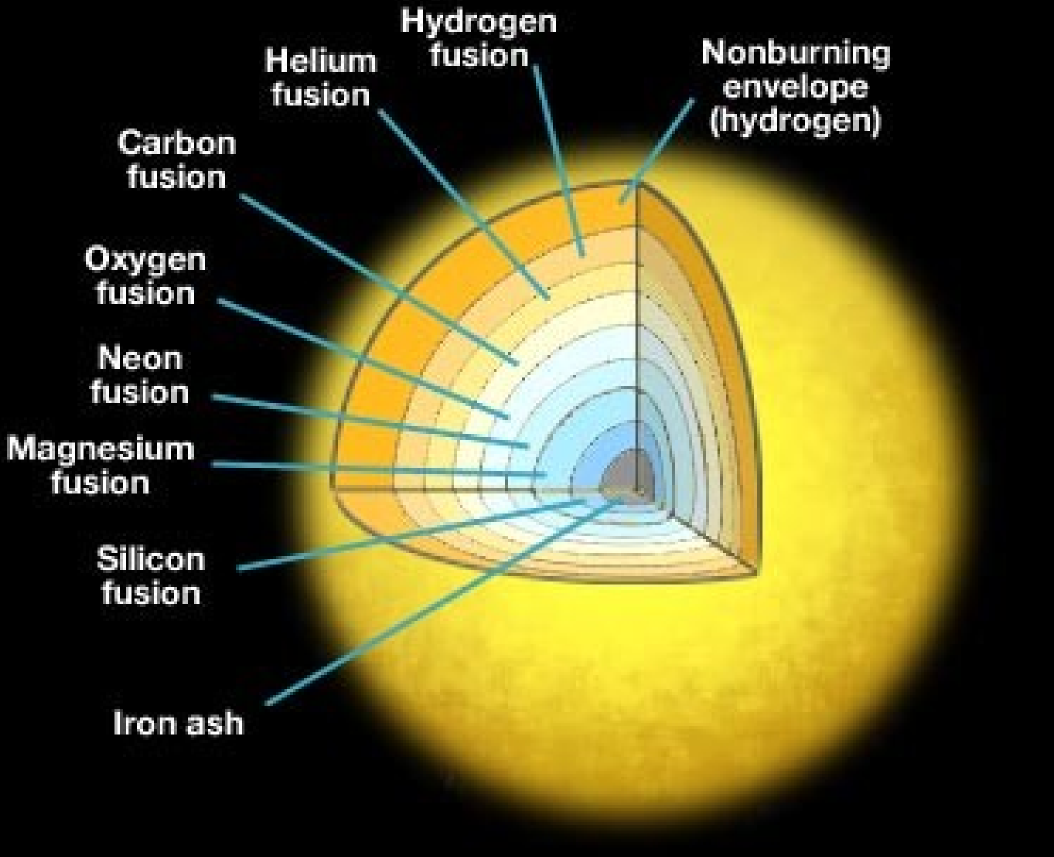
Evolution of the most massive stars

The most massive stars are hot enough to fuse heavier and heavier elements in their cores

Fusion of the heaviest element occurs in the center, surrounded by shells burning each of the lighter elements

Star has an "onion" structure

This happens until the core of the star has been fused into iron



Not to scale! The core containing the layers of fusion is only a small part of the star.

The Deaths of Massive Stars

- Elements that are formed in low mass stars stay inside the stars. Elements heavier than helium are distributed throughout the galaxy by the supernova explosions that blow apart the most massive stars.
- Nearly everything in you except hydrogen was once in a massive star that blew itself apart in a supernova.
- Supernovae are the way elements heavier than helium get out of the stars where they form and are distributed through the universe.

Summary: Two types of supernovae

- **Type I:**
  The collapse of an accreting white dwarf when its mass reaches 1.4 solar masses.
- **Type II:**
  The collapse of the iron core of a massive star when its mass reaches 1.4 solar masses. The energy of matter falling during the gravitational collapse (and then rebounding) is the energy that explodes the rest of the star. Remnant is a neutron star or black hole.