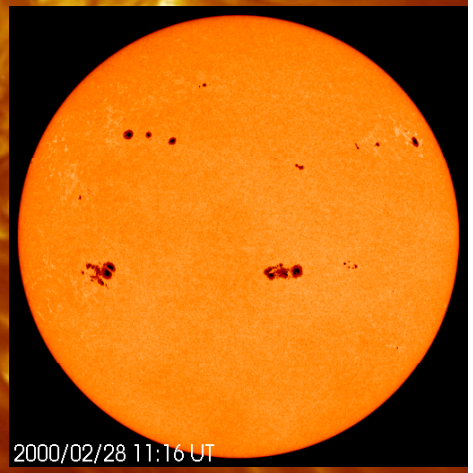
- **Announcements**
  - **Late homework #1 due now (50% credit)**
  - **Homeworks returned on Thursday**
    - **Grades were well distributed – Average was a high C**

The Sun



PTYS/ASTR 206 – The Golden Age of Planetary Exploration

Shane Byrne – shane@lpl.arizona.edu

In this lecture…

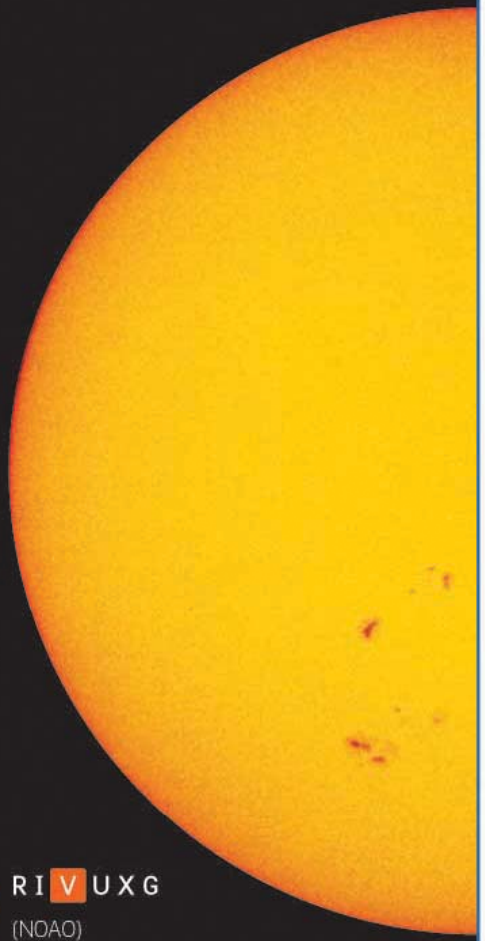
- Introduction to the Sun
- Powering the Sun
  - The core and nuclear fusion
- Solar interior
- Photosphere and Solar Atmosphere
- Magnetic effects
  - Sunspots, flares etc…
- Sunspots
  - 11 year cycle
  - Longer cycles and climate
- Comparing the Sun to other stars
  - Hertzsprung Russell Diagram

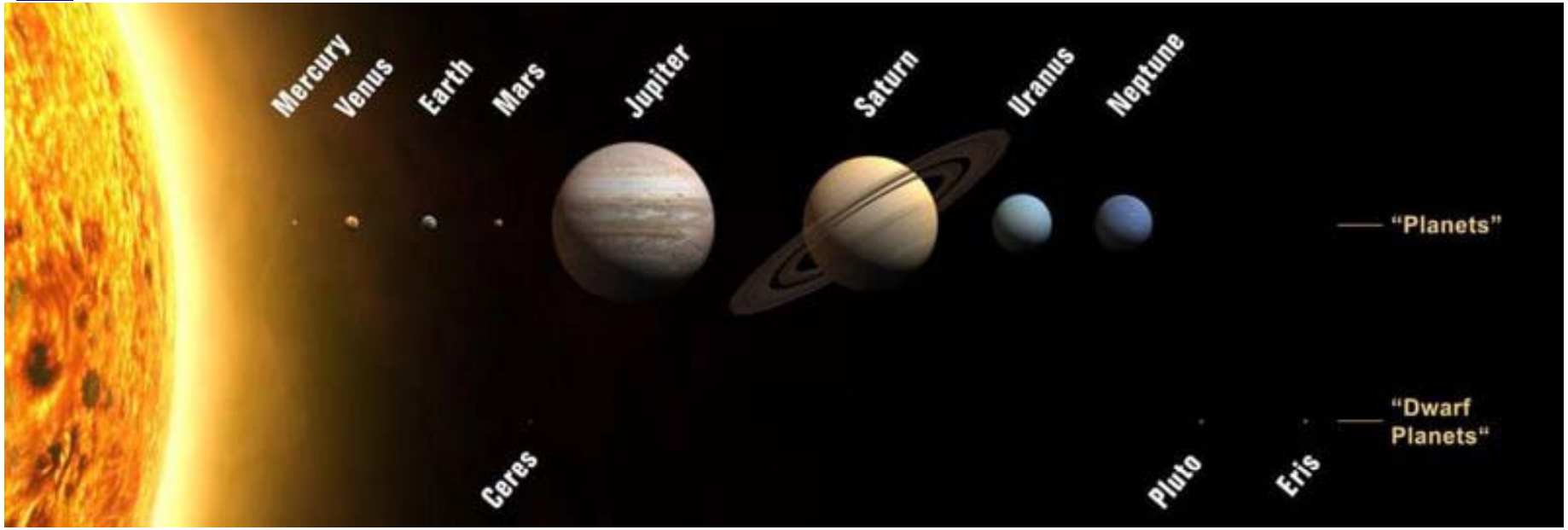
Introduction

- **The sun contains ~98-99% of all the material in the solar system**

Table 16-1 Sun Data

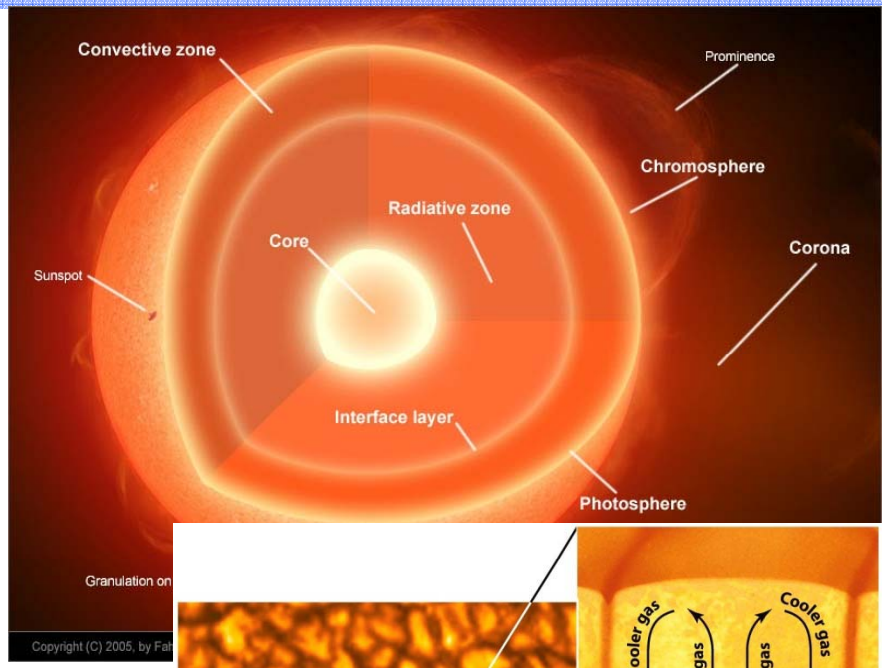
Distance from the Earth:	Mean: 1 AU = 149,598,000 km
	Maximum: 152,000,000 km
	Minimum: 147,000,000 km
Light travel time to the Earth:	8.32 min
Mean angular diameter:	32 arcmin
Radius:	696,000 km = 109 Earth radii
Mass:	1.9891×10^{30} kg = 3.33×10^5 Earth masses
Composition (by mass):	74% hydrogen, 25% helium, 1% other elements
Composition (by number of atoms):	92.1% hydrogen, 7.8% helium, 0.1% other elements
Mean density:	1410 kg/m^3
Mean temperatures:	Surface: 5800 K; Center: 1.55×10^7 K
Luminosity:	3.90×10^{26} W
Distance from center of Galaxy:	8000 pc = 26,000 ly
Orbital period around center of Galaxy:	220 million years
Orbital speed around center of Galaxy:	220 km/s





- The sun dominates the solar system
  - Contains almost all the mass
  - Is huge compared to any other object
  - Supplies almost all the energy
    - Other sources – contraction of planets e.g. Jupiter
    - Other sources – Radioactive elements e.g. Earth's interior
  - Dominates the orbits of almost all solar system objects
    - Except those of planetary Moons
- Long argument about where the sun's energy comes from

- **The sun can be divided up into…**
  - **Interior**
    - Nuclear fusion reactions
    - Energy transported radiation and convection
    - Temperatures up to 15 million degrees (Kelvin)
  - **"Surface"- photosphere**
    - Not solid – really part of the atmosphere
    - About 6000K
    - Magnetic field effects
    - Sunspots, flares etc
    - Energy transported convection
  - **"Atmosphere"**
    - Chromosphere and Corona
    - Very thin
    - Up to 1 million degrees
    - Energy transported radiation
    - Solar wind



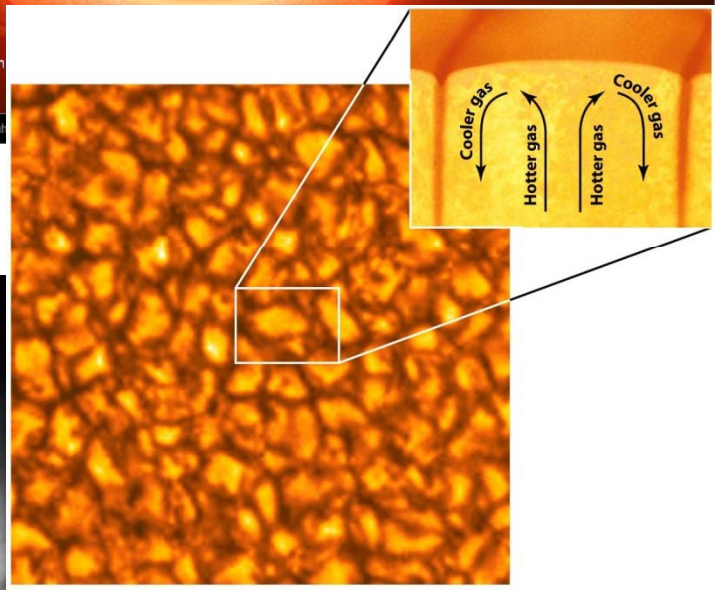


Figure 16-9
Universe, Eighth Edition
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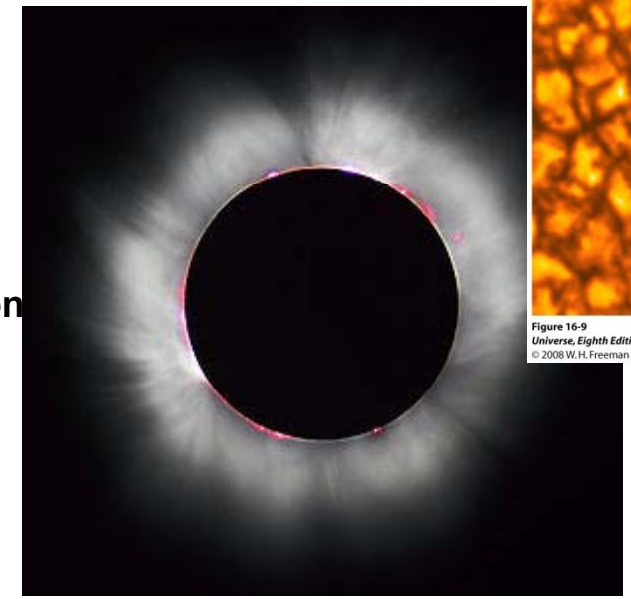


Solar interior – Powering the Sun

- Atoms have nuclei surrounded by electron clouds
- Atomic nuclei contain protons (with a + electric charge) and neutrons
  - Held together by the 'strong' nuclear force
  - Repelled from other nuclei by electromagnetic forces
  - If you can get two nuclei close enough then the strong nuclear force will win
- How do you force two nuclei together?
  - High temperatures
    - A lot of energy
    - Nuclei move fast
  - High pressures
    - Atoms are closely packed
    - Nuclei collide often

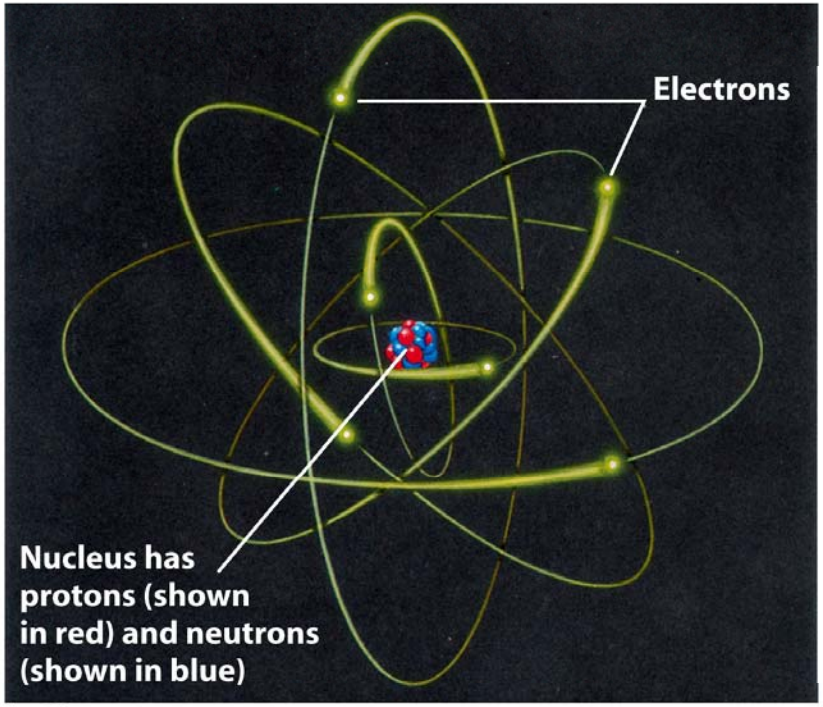
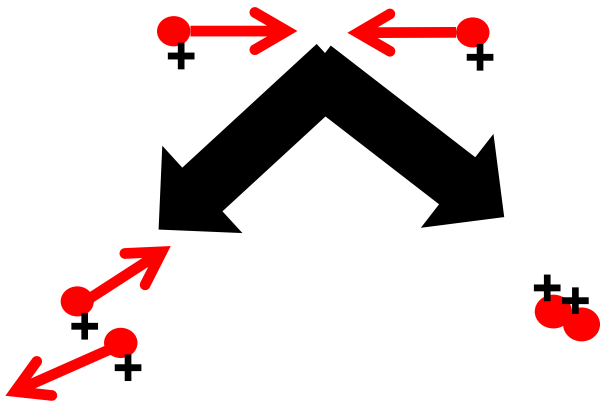


Figure 5-20
Universe, Eighth Edition



Low energy – nuclei repel each other

High energy – nuclei combine

- **Temperature and density are very (very very) large in the center of the sun**

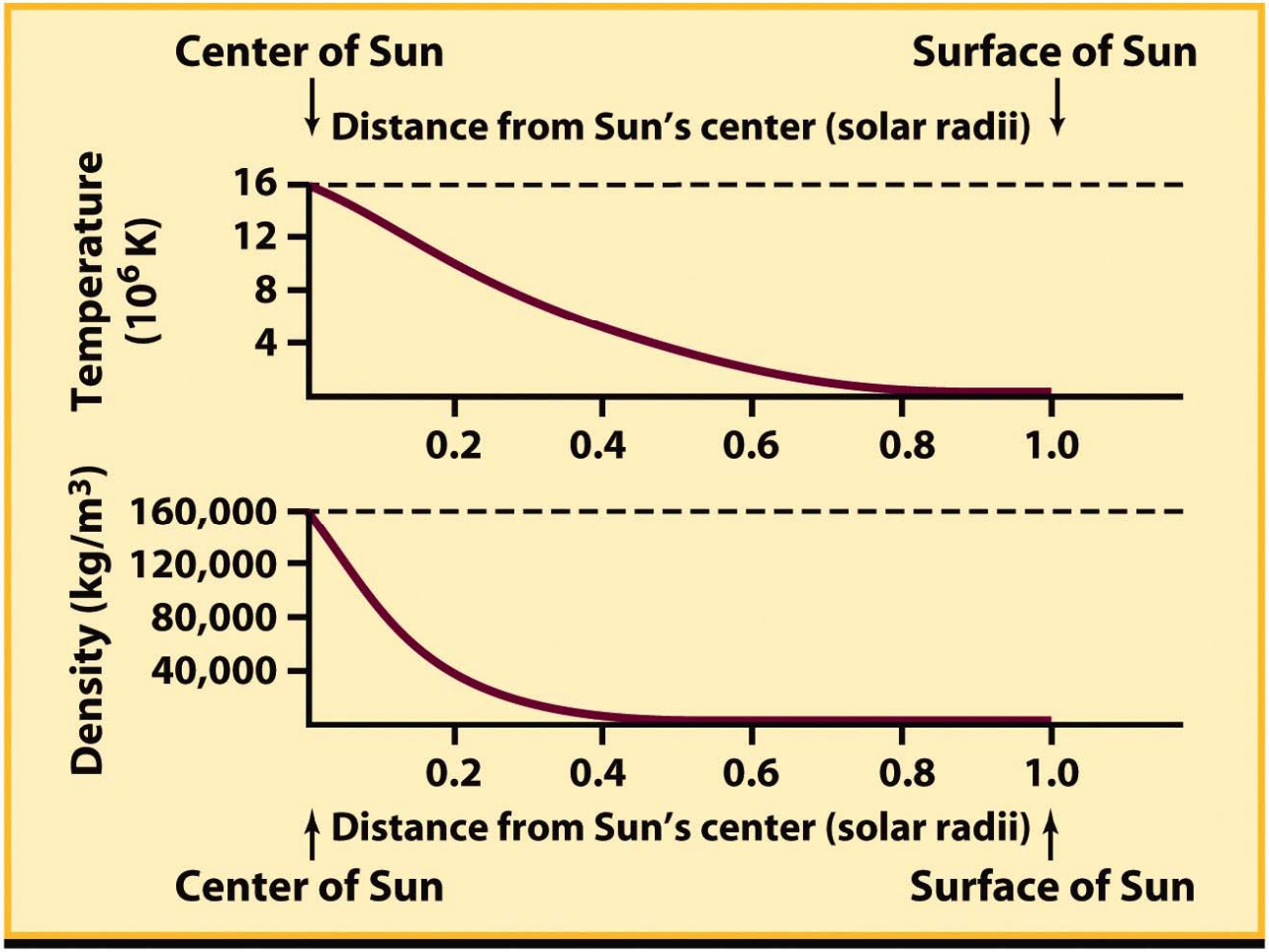


Figure 16-3 part 2
Universe, Eighth Edition

- **How dense is the sun on average?**

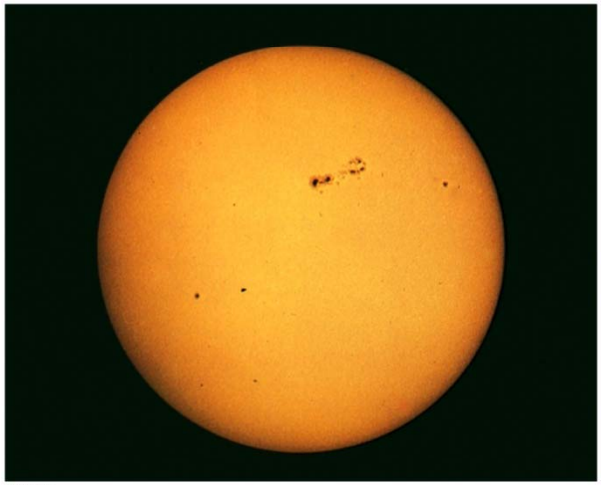


Figure 16-7
Universe, Eighth Edition

The Sun

The Earth

A rock

- How dense is the sun on average?

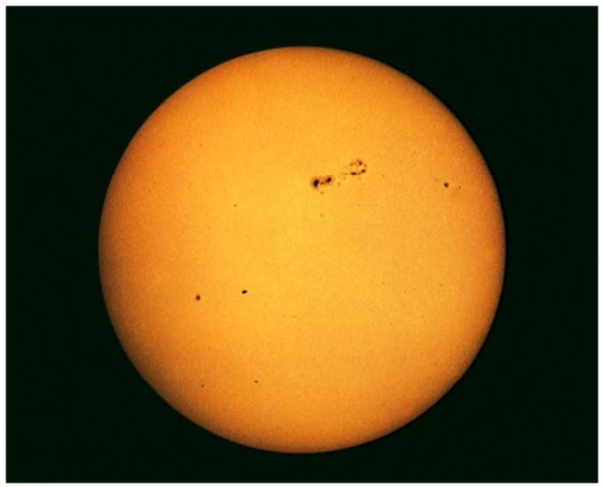


Figure 16-7
Universe, Eighth Edition

The Sun

1400 Kg m^{-3}

The Earth

5500 Kg m^{-3}

A rock

~3000 kg m^{-3}

- Average density of the Sun is low!
- It's the <u>enormous mass</u> of the Sun (330,000 Earth Masses) that generates the high pressures at its center
  - Gravity does the work
  - Gravity is weak so stars need to be big to make this work

- **All the energy is produced in the dense, hot, core**

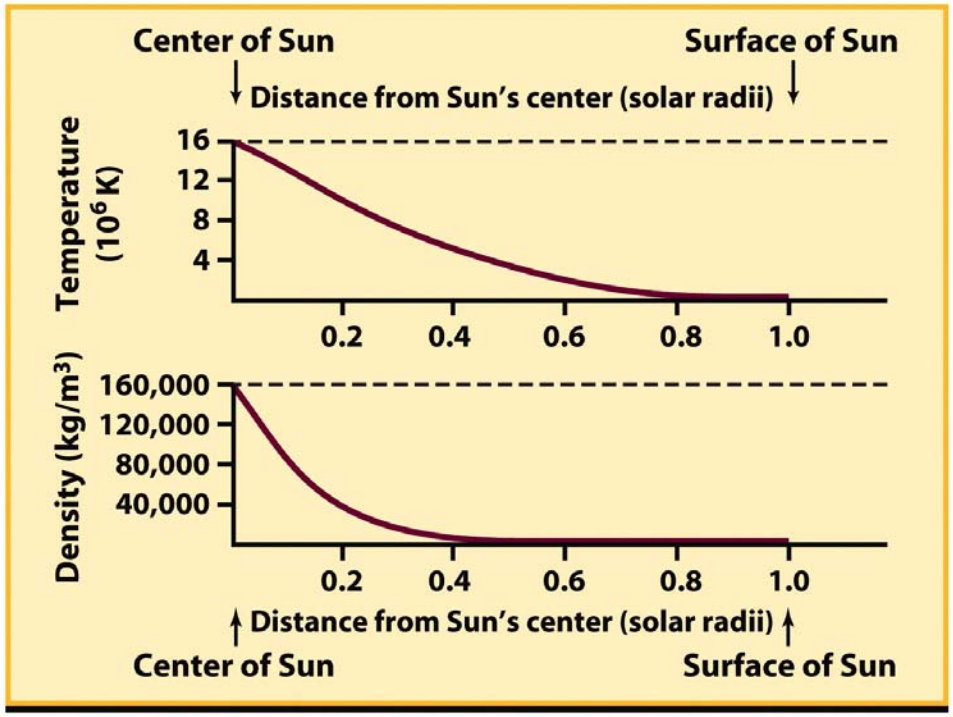


Figure 16-3 part 2
Universe, Eighth Edition

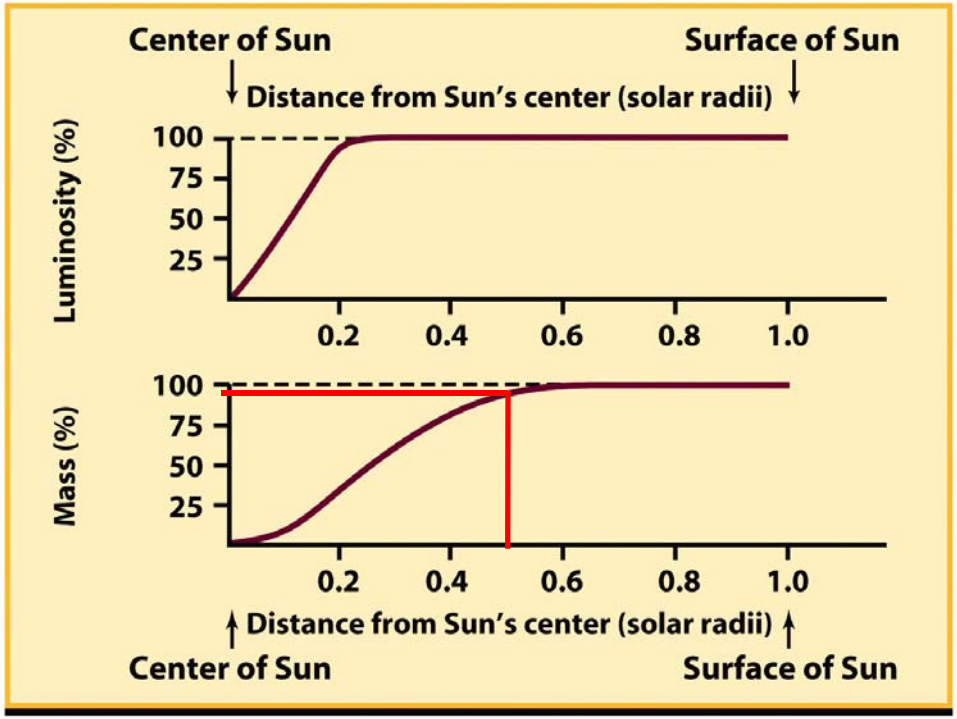
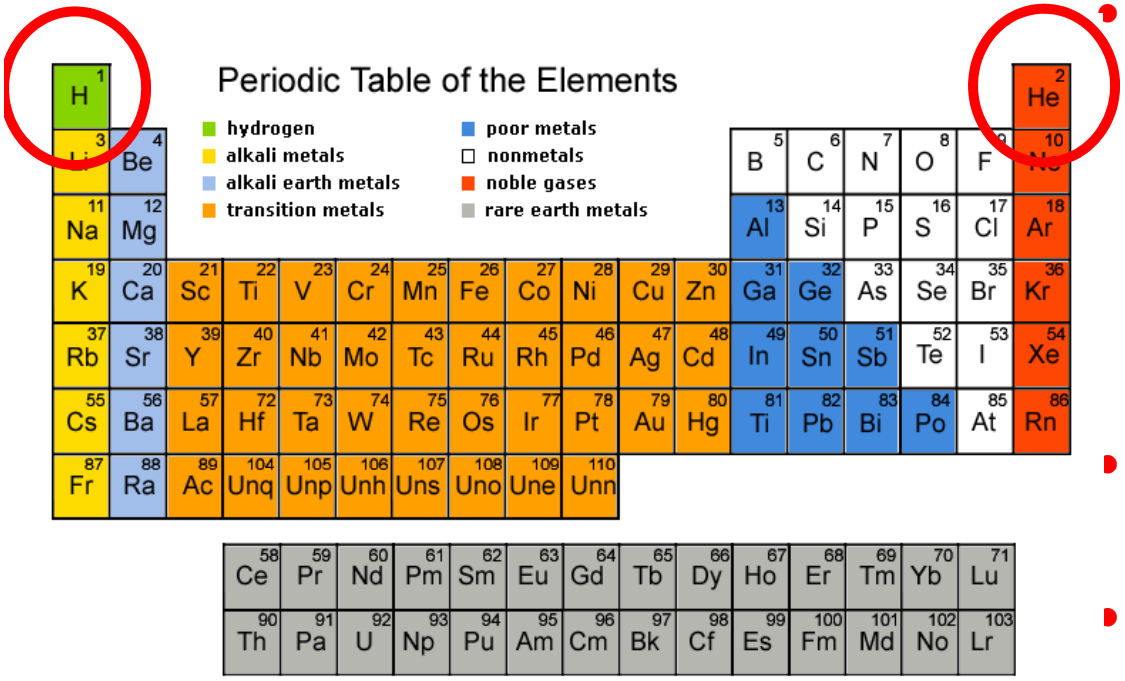


Figure 16-3 part 1
Universe, Eighth Edition

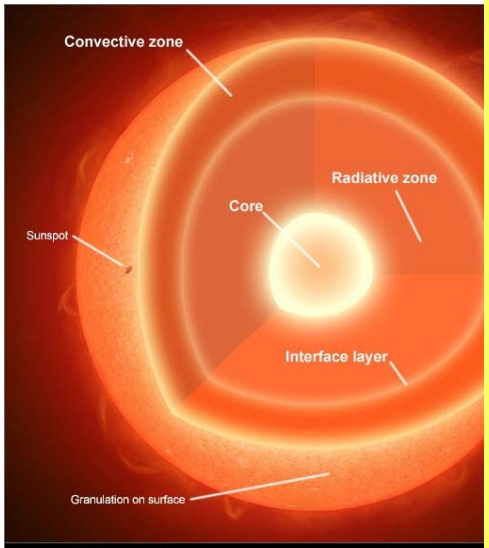
- **>90% of the sun's mass is in the central half**

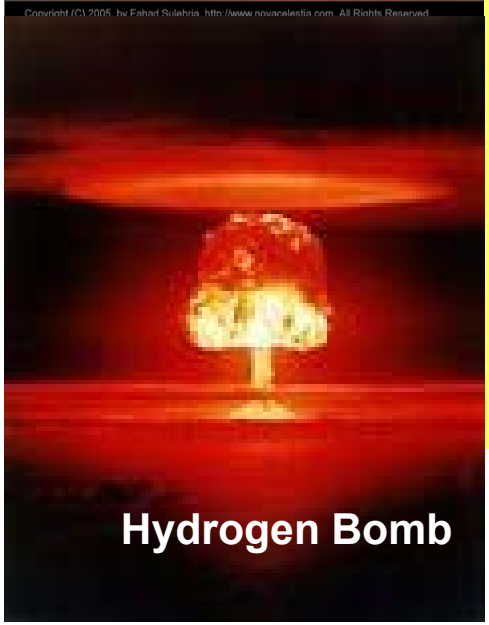


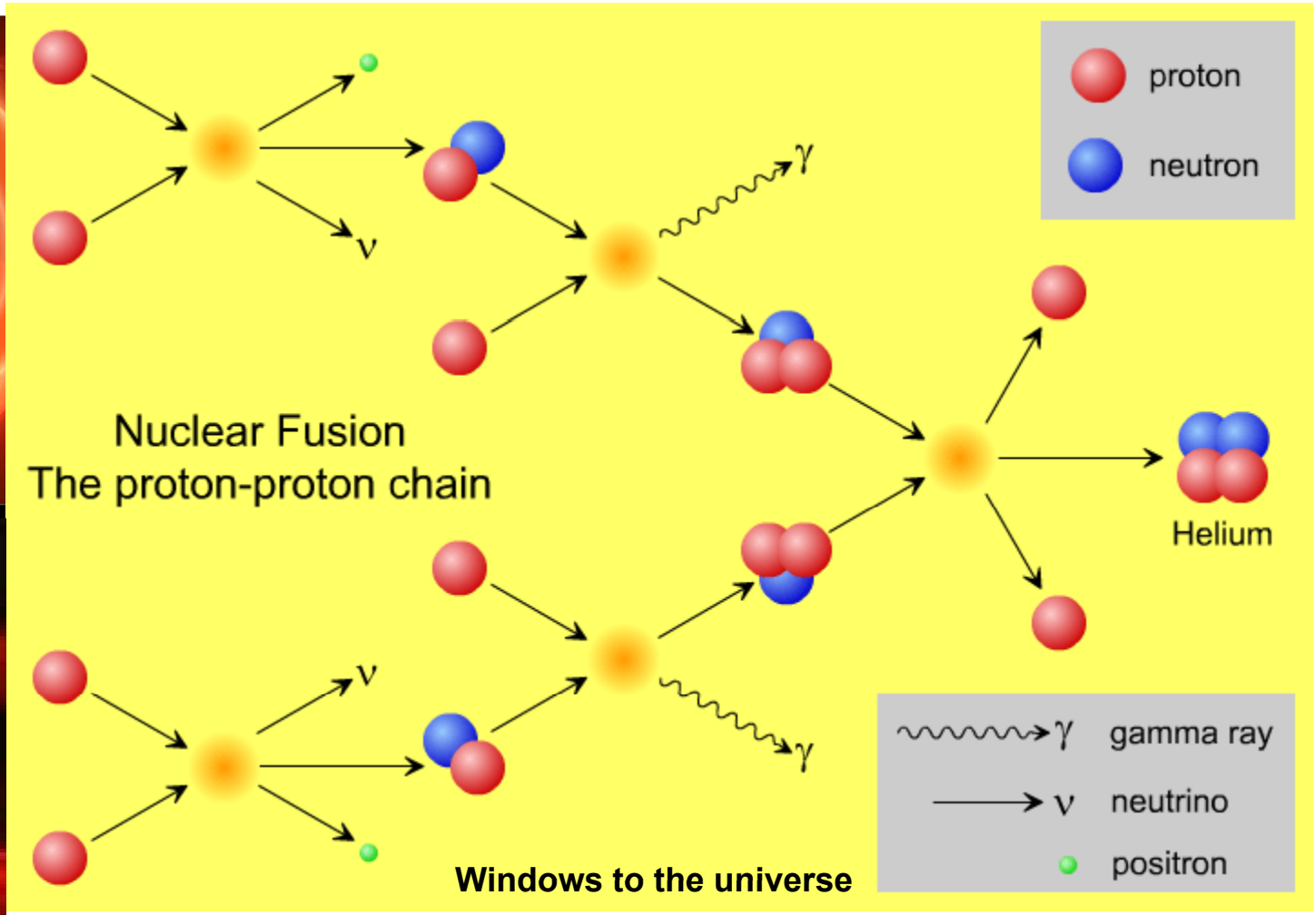
- **Two main players to think about**
  - **Hydrogen**
  - **Helium**
  - **99.9% of the atoms in the Sun**
- **Number of protons decides what the element is**
- **Number of neutrons decides the isotope**

	Zero Neutrons	One Neutron ●	Two Neutrons ●●
Hydrogen (H) 1 – proton ●	H^1 Regular Hydrogen ●	H^2 Deuterium ●●	H^3 Tritium ●●●
Helium (He) 2 – protons ●●		He^3 Helium 3 ●●●	He^4 Regular Helium ●●●●

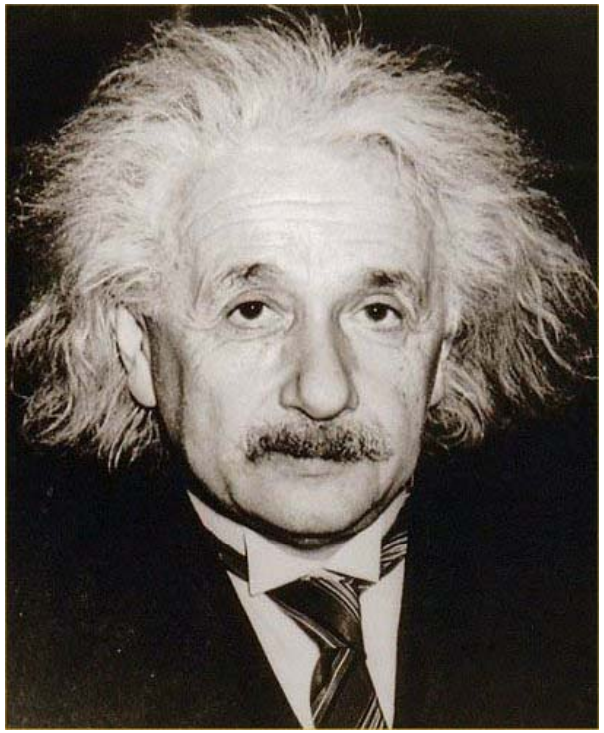
- **Nuclear fusion releases energy**
  - **The proton-proton chain – Hydrogen nuclei fuse into a helium nucleus**







- **Other reaction chains exist in bigger stars**

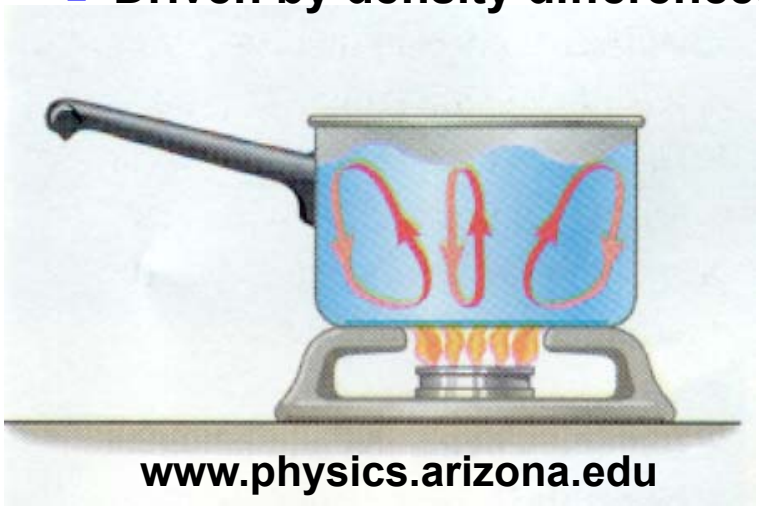


- **Net effect?**
  - 4 hydrogen nuclei go in…
  - …1 helium nuclei comes out
    - With some other sub-atomic junk
  - But…. 4 x H^1 has more mass than 1 x He^4
  - What happened to the extra mass?

    It was converted to energy…
    - $E = m c^2$

- **Nuclear fusion – small atoms fusing together**
- **<u>NOT</u> nuclear fission – big atoms splitting apart**
  - Plutonium, Uranium etc…
  - Nuclear fission is used in power plants (and bombs)
  - Nuclear fusion will be used in power plants in the near-future (and bombs)

- **Nuclear fusion produces the energy…. Now what?**
  - **Energy is transported through the sun**
- **Radiative zone**
  - **No organized gas motion**
  - **Photons carry the energy**
    - **Zig-zag path due to collisions with atoms**
- **Convective zone**
  - **Organized gas motion**
  - **Many convection cells**
  - **Extends up to the 'surface'**
  - **Driven by density differences**



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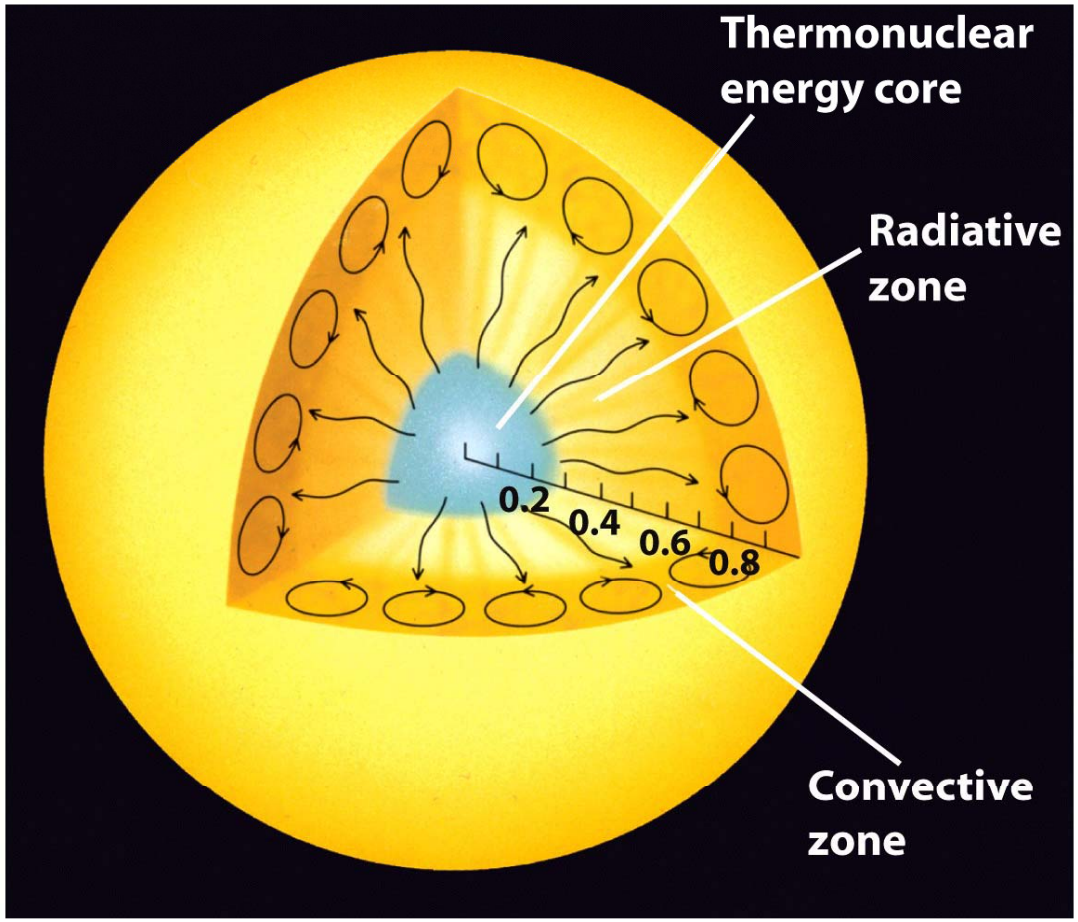

Figure 16-4
Universe, Eighth Edition

Solar "surface" – the photosphere

- Hot gases convected up from below
  - Hot – 6000K
  - Tenuous – Density of 0.01% of room air
  - Radiates like a blackbody in the visible portion of the spectrum
  - We can't see through the photosphere with light
  - Photosphere is about 400km thick
    - Very thin compared to the solar radius 700,000km

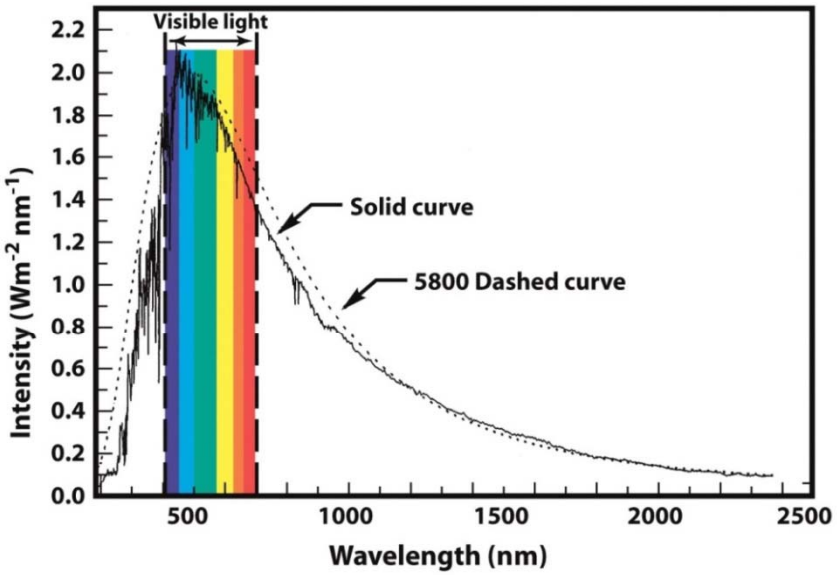

Figure 5-12
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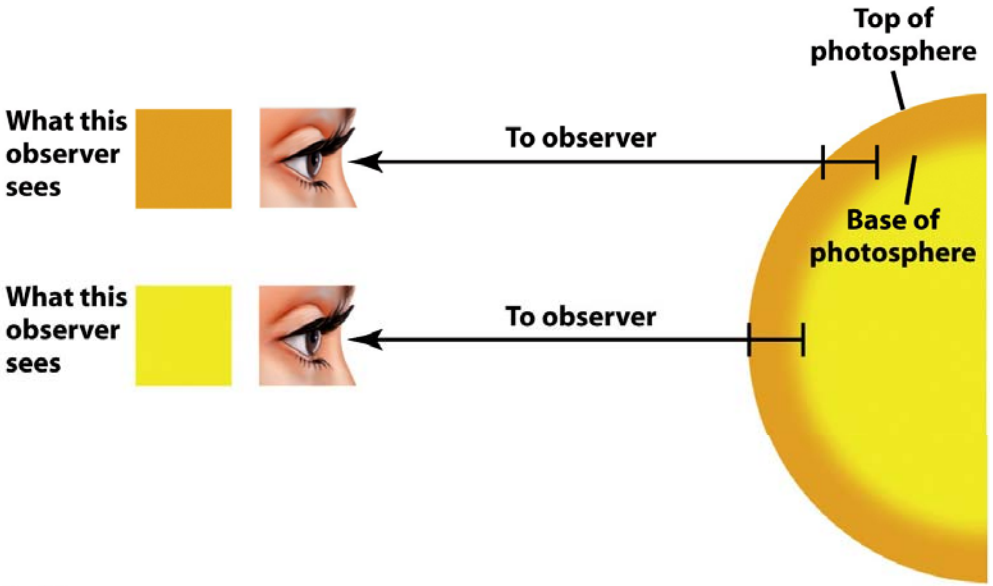

Figure 16-8
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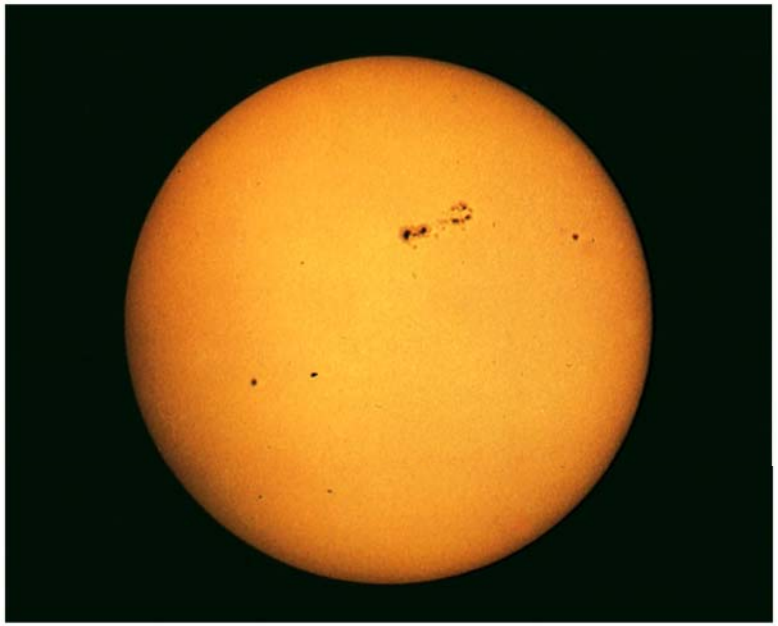

Figure 16-7
Universe, Eighth Edition
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- **Convection cells create granules**
  - **~1000 km across, lasts a few minutes**
  - **Larger collections of cells exist - supergranules**
    - **35,000km across, lasts 1 day**

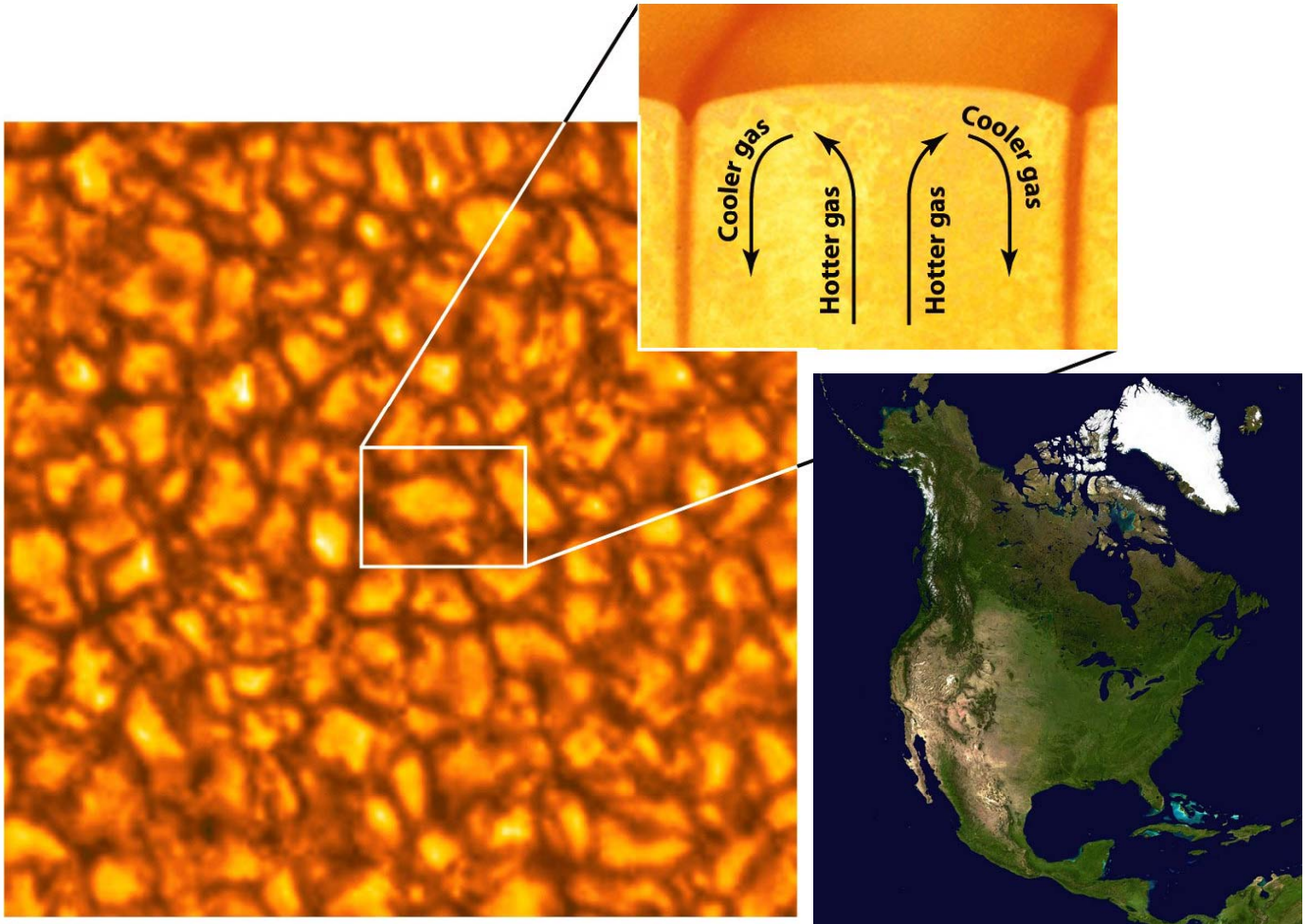

Figure 16-9
Universe, Eighth Edition

Solar Atmosphere

- Divided into the:
  - Chromosphere
  - Corona

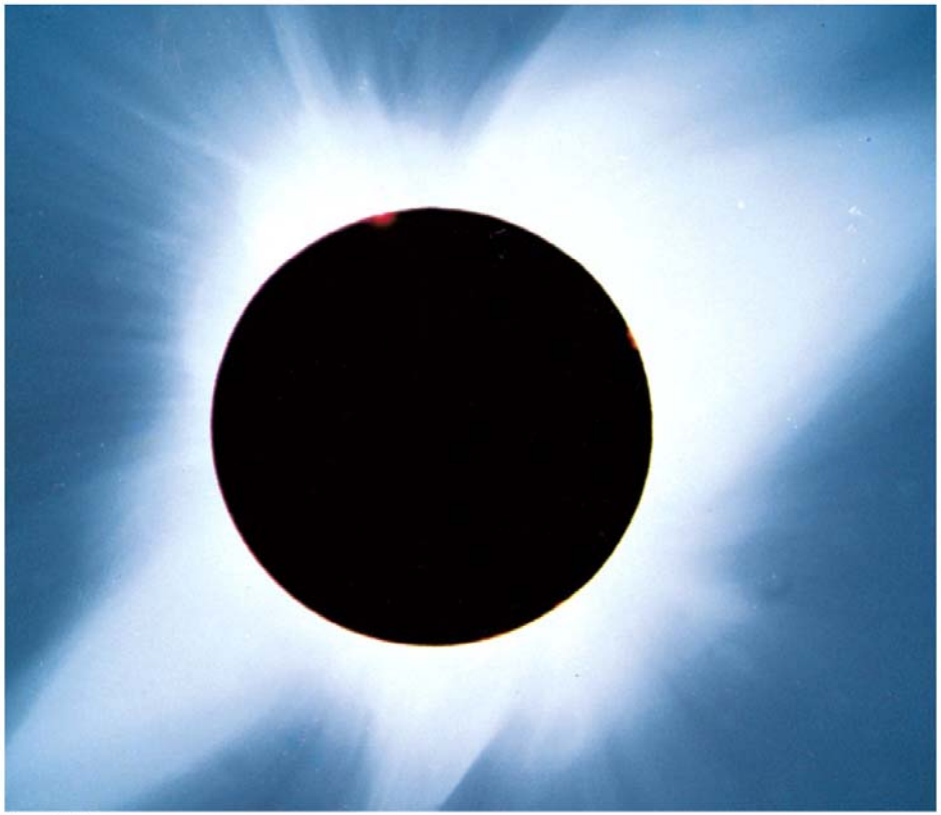

Figure 16-13
Universe, Eighth Edition

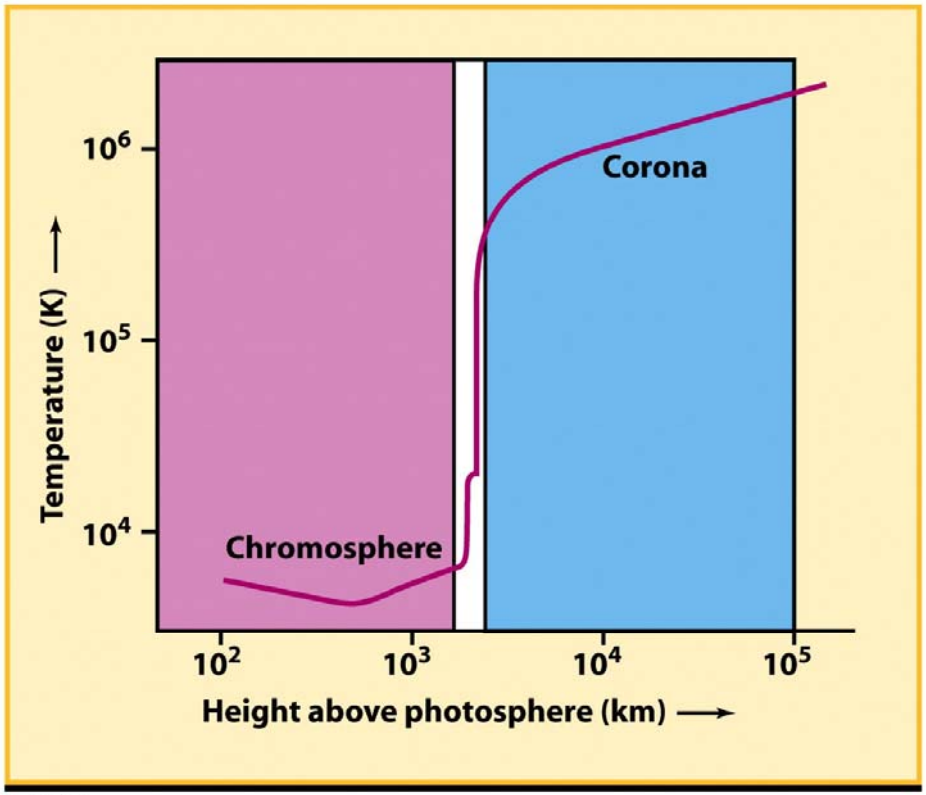

Figure 16-14
Universe, Eighth Edition

- **Chromosphere**
  - **2000km thick**
  - **Temperature inversion**
    - **Heated from below – photosphere**
    - **Heated form above – Corona**
  - **Much more tenuous than photosphere**
    - **1/10,000th of the density**

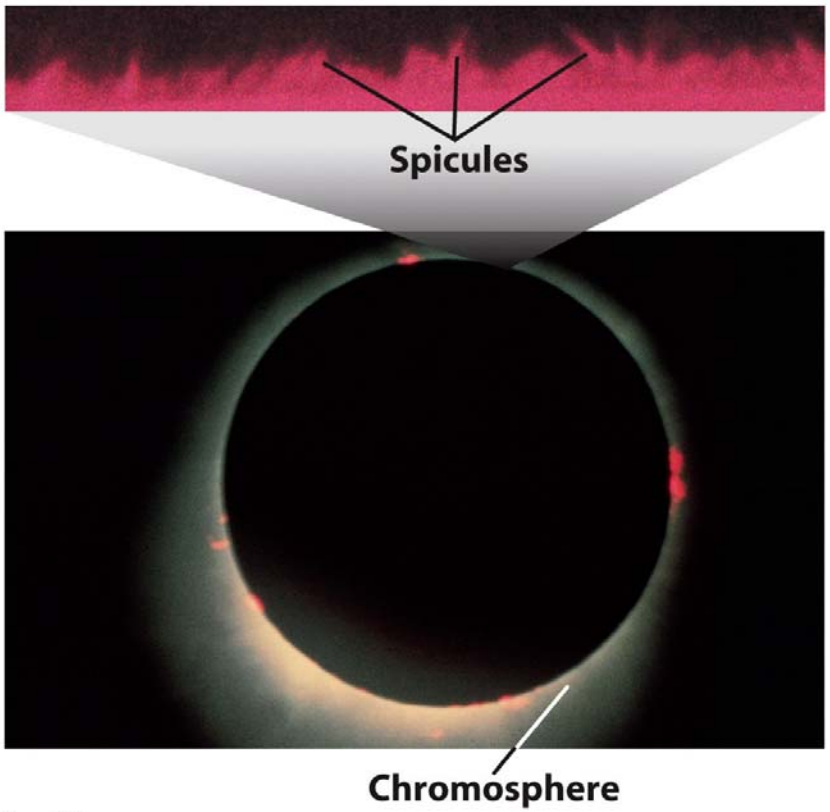

Figure 16-11
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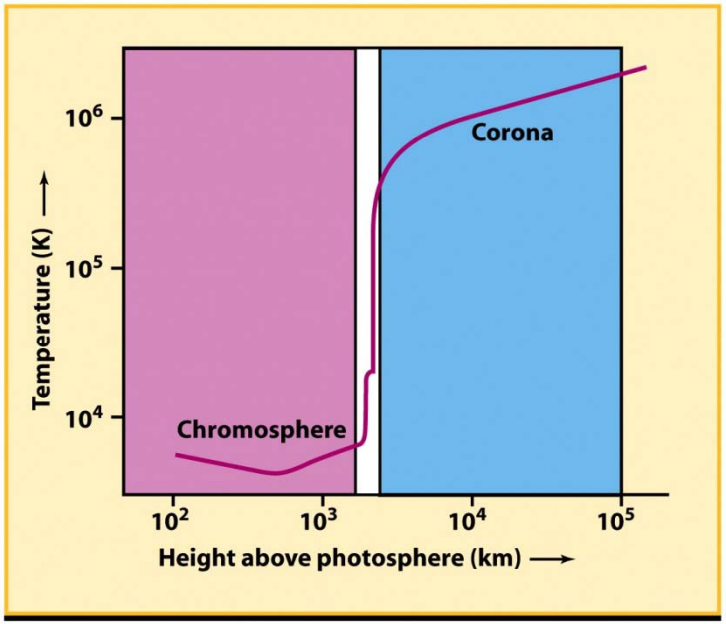

Figure 16-14
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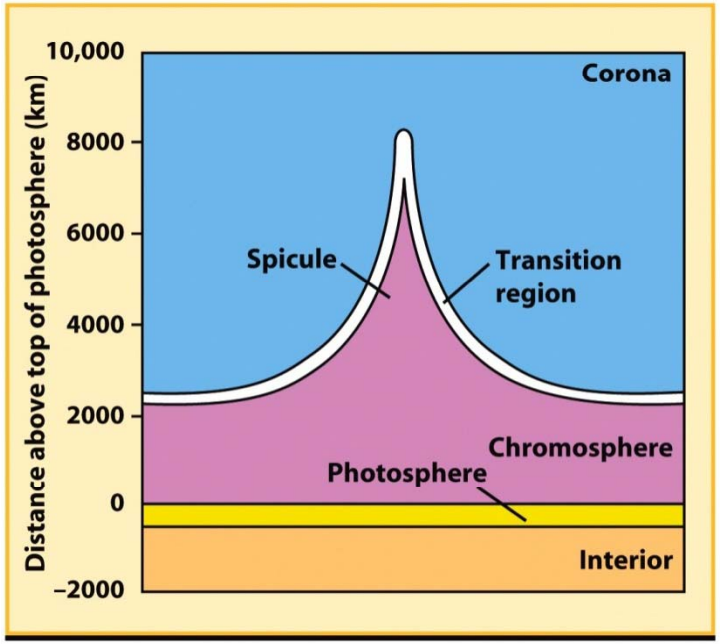

Figure 16-12
Universe, Eighth Edition

- **Corona**
  - **Starts 2000km above the photosphere**
  - **Extremely hot – 2 million degrees**
  - **Very Tenuous**
    - **10^{11} atoms per cubic meter**
    - **1,000,000,000,000 times less dense than the photosphere**
  - **No upper edge**
    - **Gradually fades into interplanetary medium**
  - **How is the Corona heated ??**
    - **Magnetic field effects**

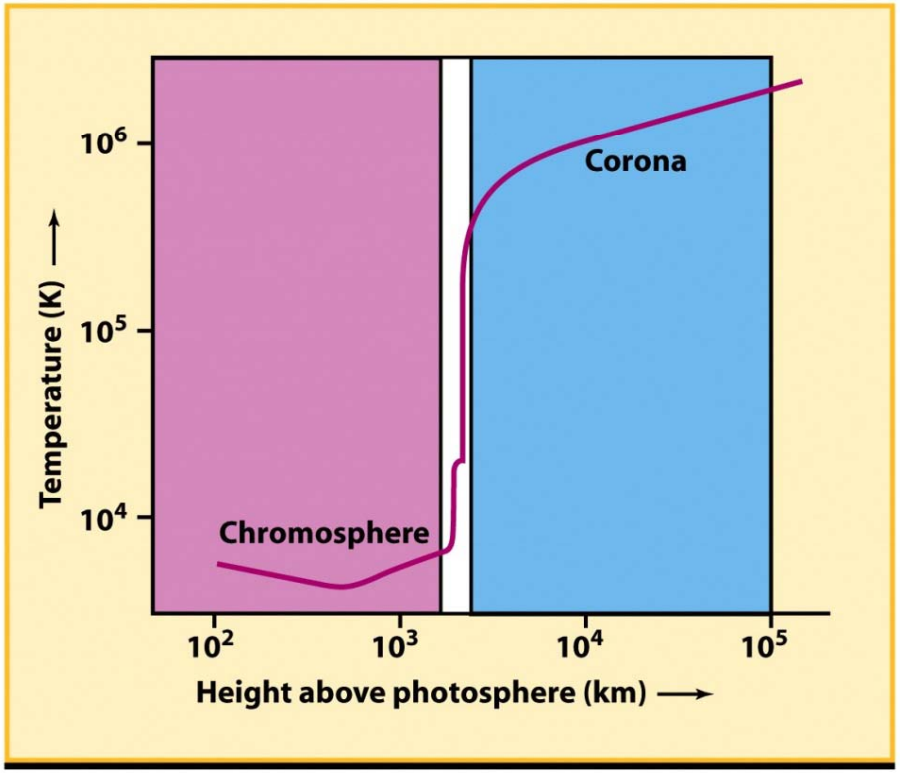

Figure 16-14
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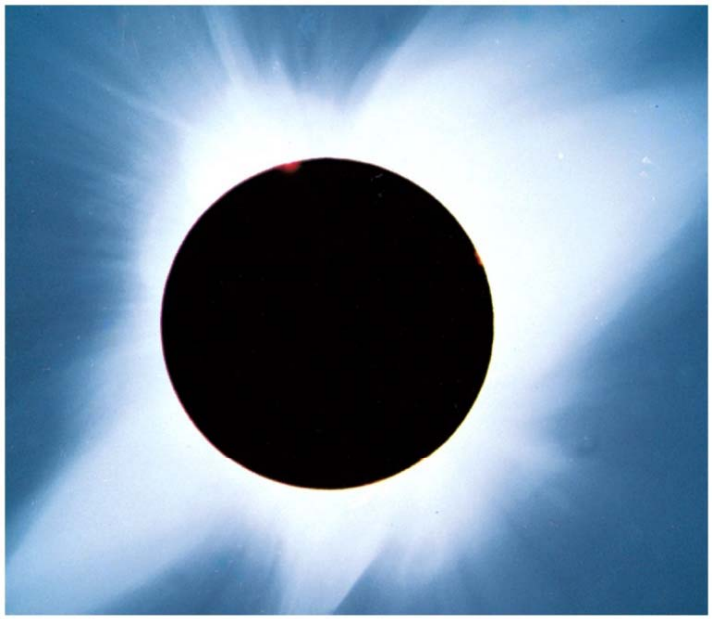

Figure 16-13
Universe, Eighth Edition

- **Recap the different parts of the Sun**
  - **Solar radius 700,000km**

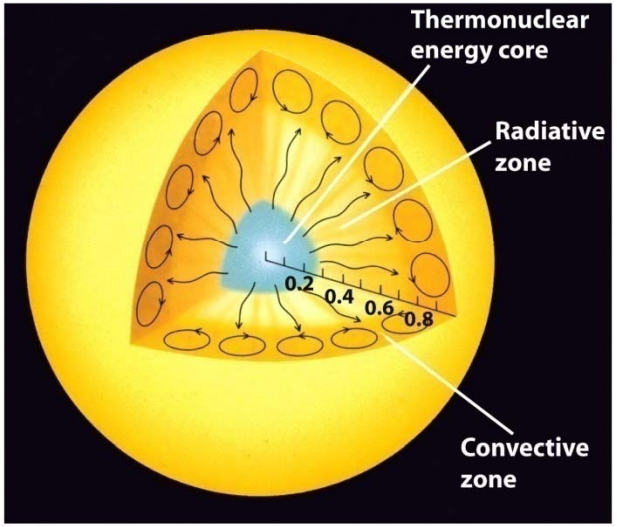

Figure 16-4
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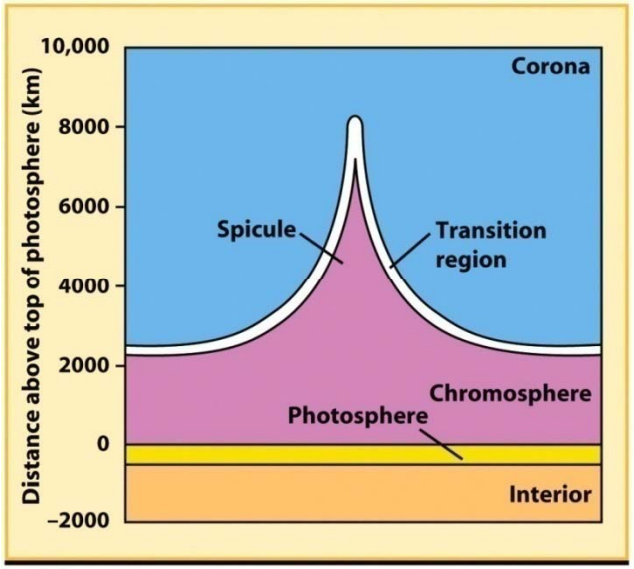

Figure 16-12
Universe, Eighth Edition
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Region	Position/Thickness	Temperature	Notes
Thermonuclear Core	0 - 0.25 Solar radii	15-8 million K	Fusion reactions
Radiative zone	0.25 – 0.7 Solar radii	8-2 million K	Energy transported by photons
Convective zone	0.7 - 0.999 Solar radii	2 million – 6000K	Energy transported by convection
Photosphere	400km thick	6000K	Opaque layer
Chromosphere	2000km thick	~6000K	Tenuous atmosphere
Corona	Extends outwards	2 million K	Very hot Very tenuous

Activity on the Sun – the solar dynamo

- Coronal loops, Prominences/filaments
- Solar flares and coronal mass ejections
- Sunspots and plages

- How do we explain all of these things?
  - Magnetic fields

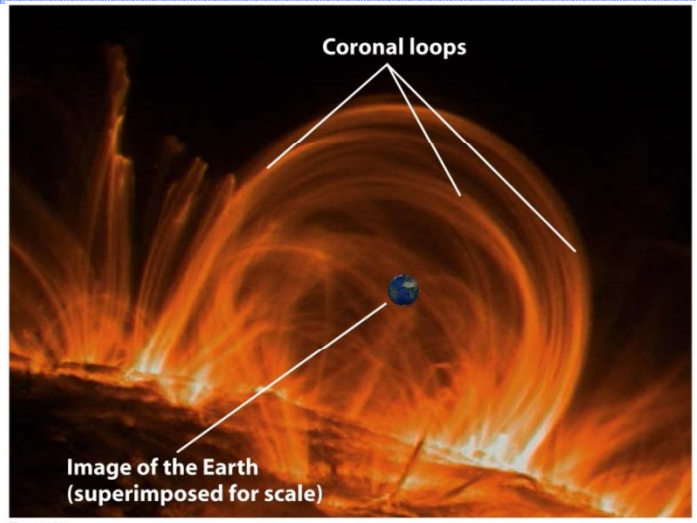


Figure 16-25a

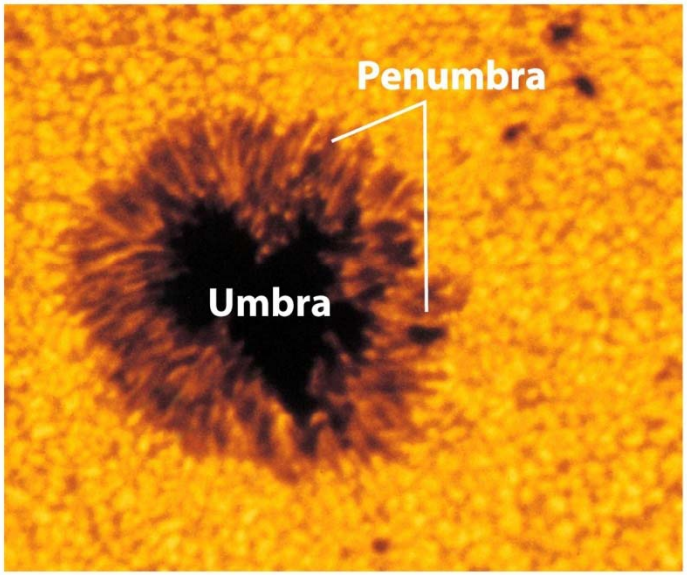


Figure 16-16a
Universe, Eighth Edition

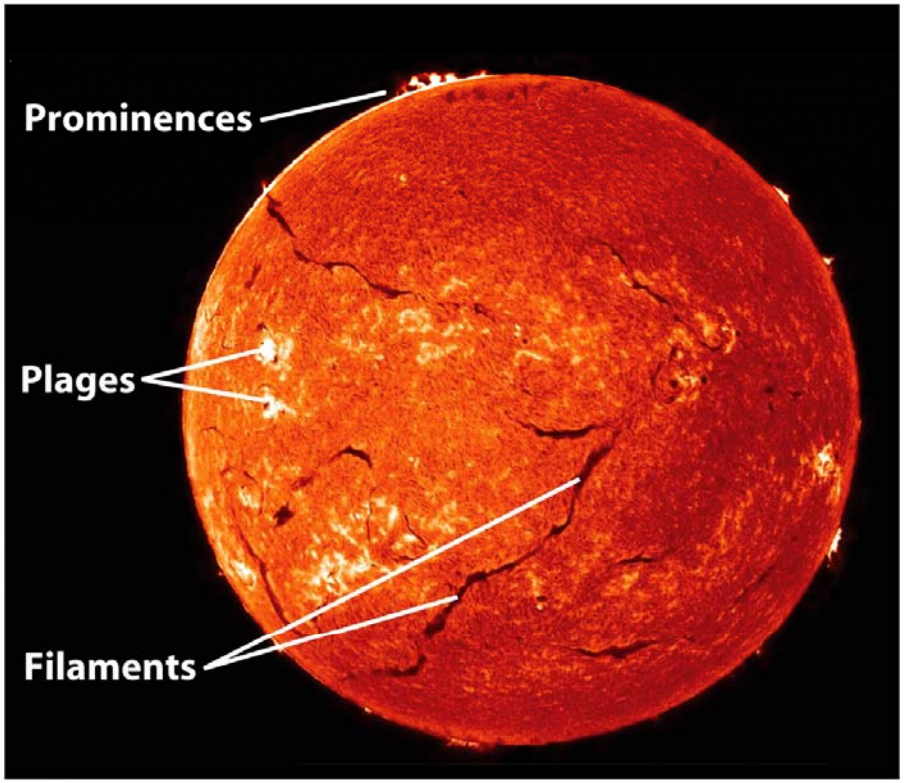
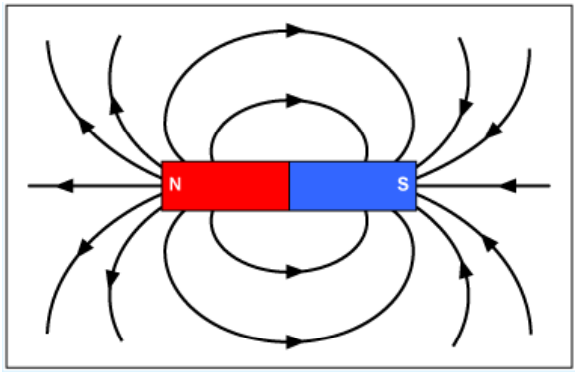
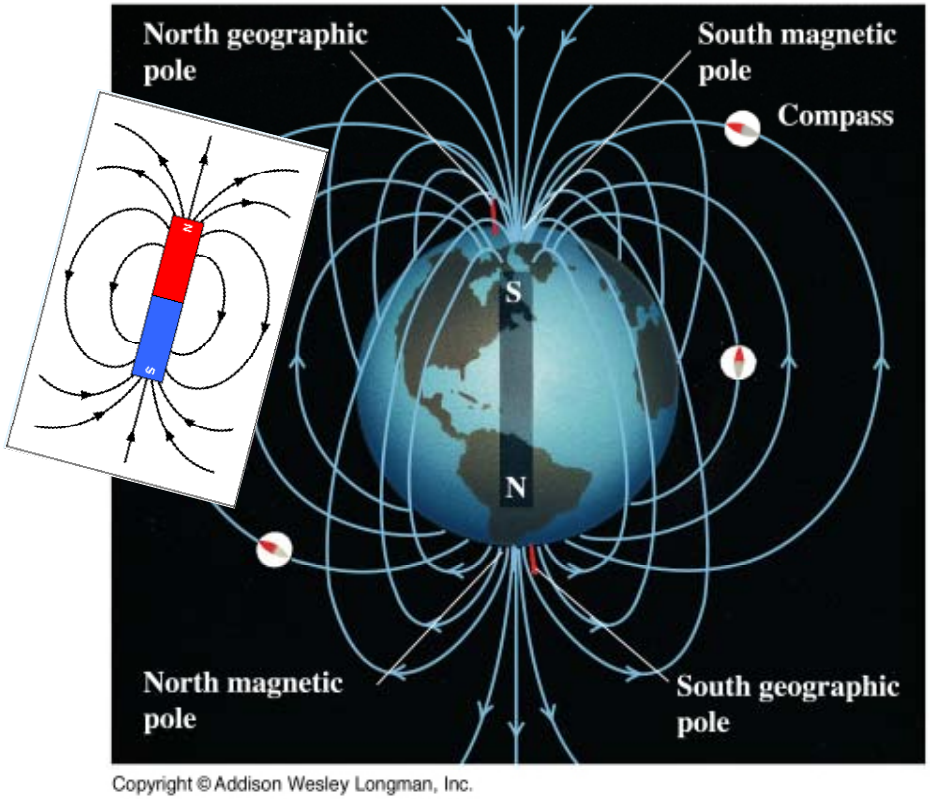


Figure 16-26
Universe, Eighth Edition

- Magnetized objects have magnetic field lines
  - There's always a north and south pole to a magnet



- Planets and stars are also magnetized



- Moving charged particles create magnetic fields

- Magnetic fields can change the course of moving charged particles

- …but the Sun doesn't spin like a rigid object
  - Radiative zone appears to spin like a rigid body
  - At the surface the equator spins faster
- The sun's gases are a plasma
  - i.e. electrons have been stripped off
  - The gas atoms are charged
  - They affect (and are affected by) the magnetic field
- What does that do to the magnetic field?

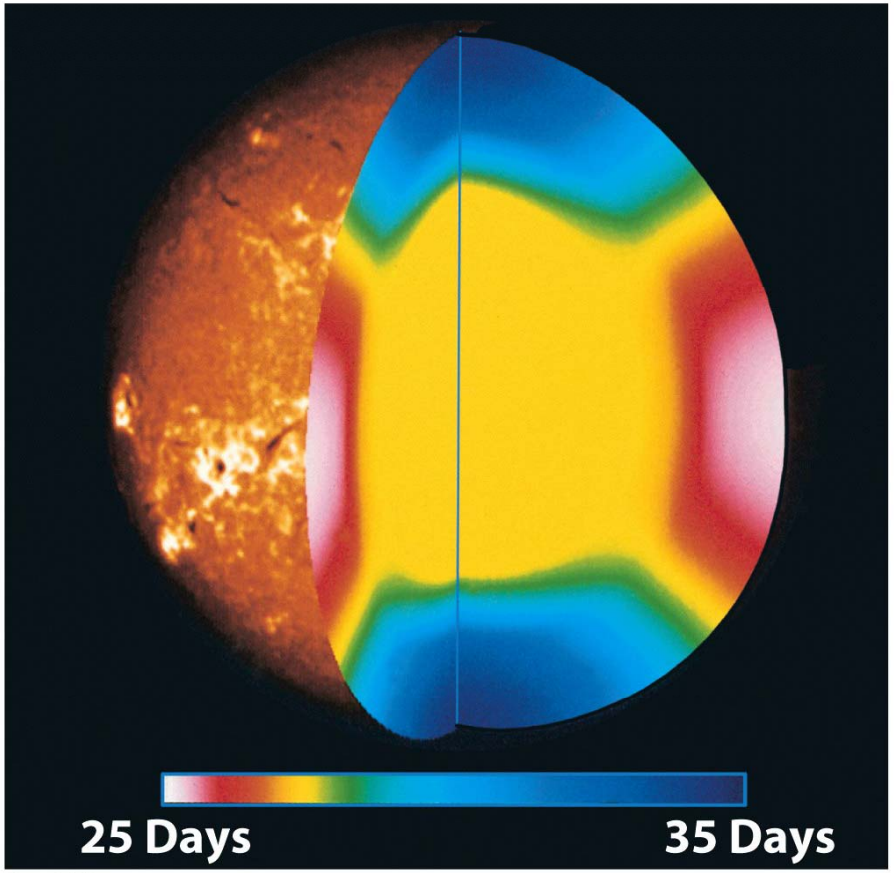


Figure 16-24
Universe, Eighth Edition

- The field lines start out looking like a bar-magnet
- Then they get stretched by the faster rotation near the equator
  - The field lines follow the charged particles as the sun rotates
  - Fields lines get wound up just under the surface

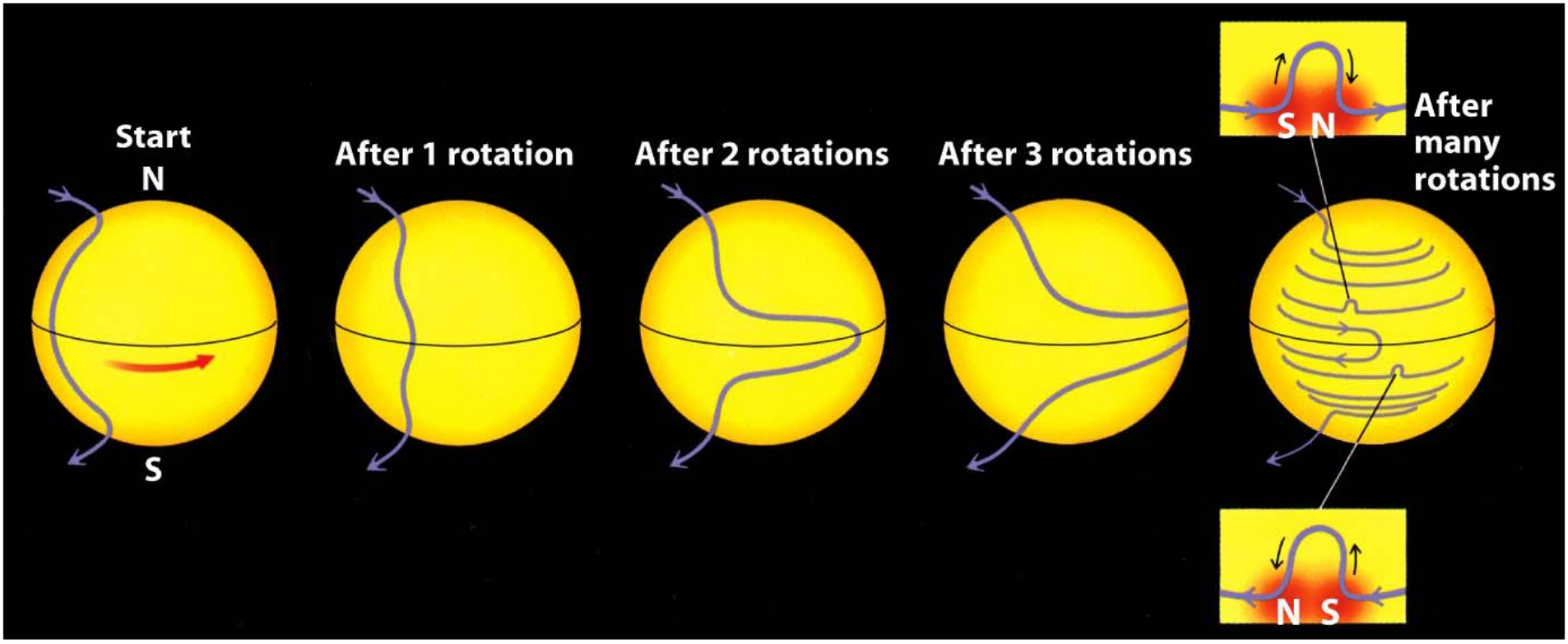
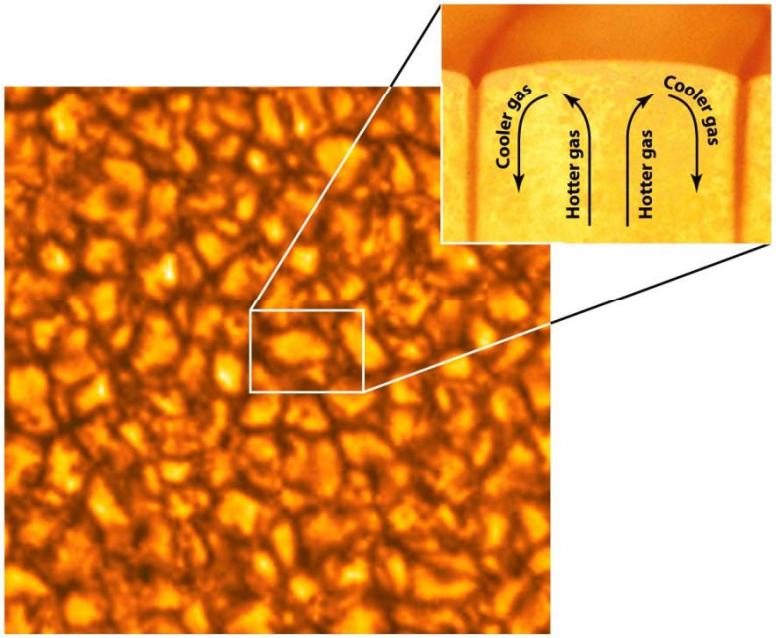


Figure 16-23
Universe, Eighth Edition

- **Another complication… convection moves the gas as well**
  - **Puts a kink in the magnetic field lines**
  - **Pushes kink through the surface**
  - **Magnetic field lines inhibit convection where they intersect the surface**
  - **Surface cools off – sunspot forms**
    - **Sunspots are ~4500K**



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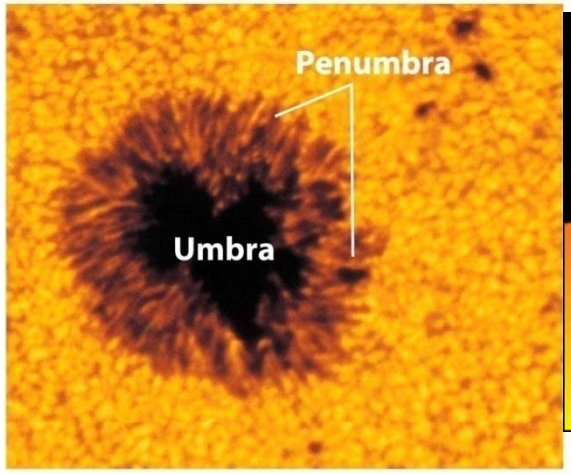

Figure 16-16a
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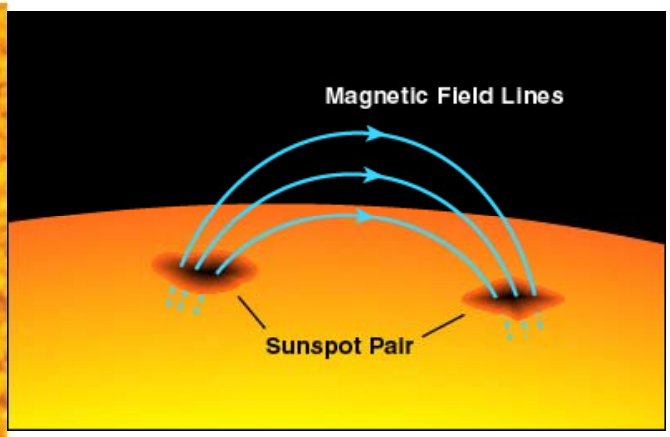

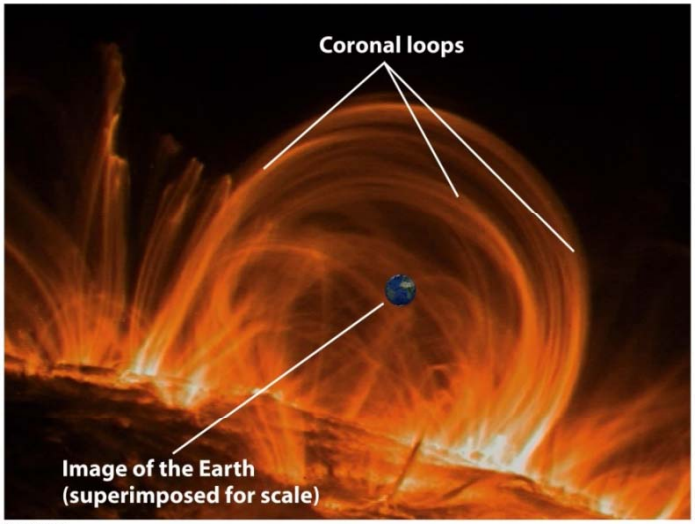

Figure 16-25a
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- **There's a huge amount of energy stored in these field loops**
  - **Field lines can 'snap' – but need to reconnect with another field line**
  - **Plasma can break free if field lines form closed loop**
  - **Known as 'magnetic reconnection'**

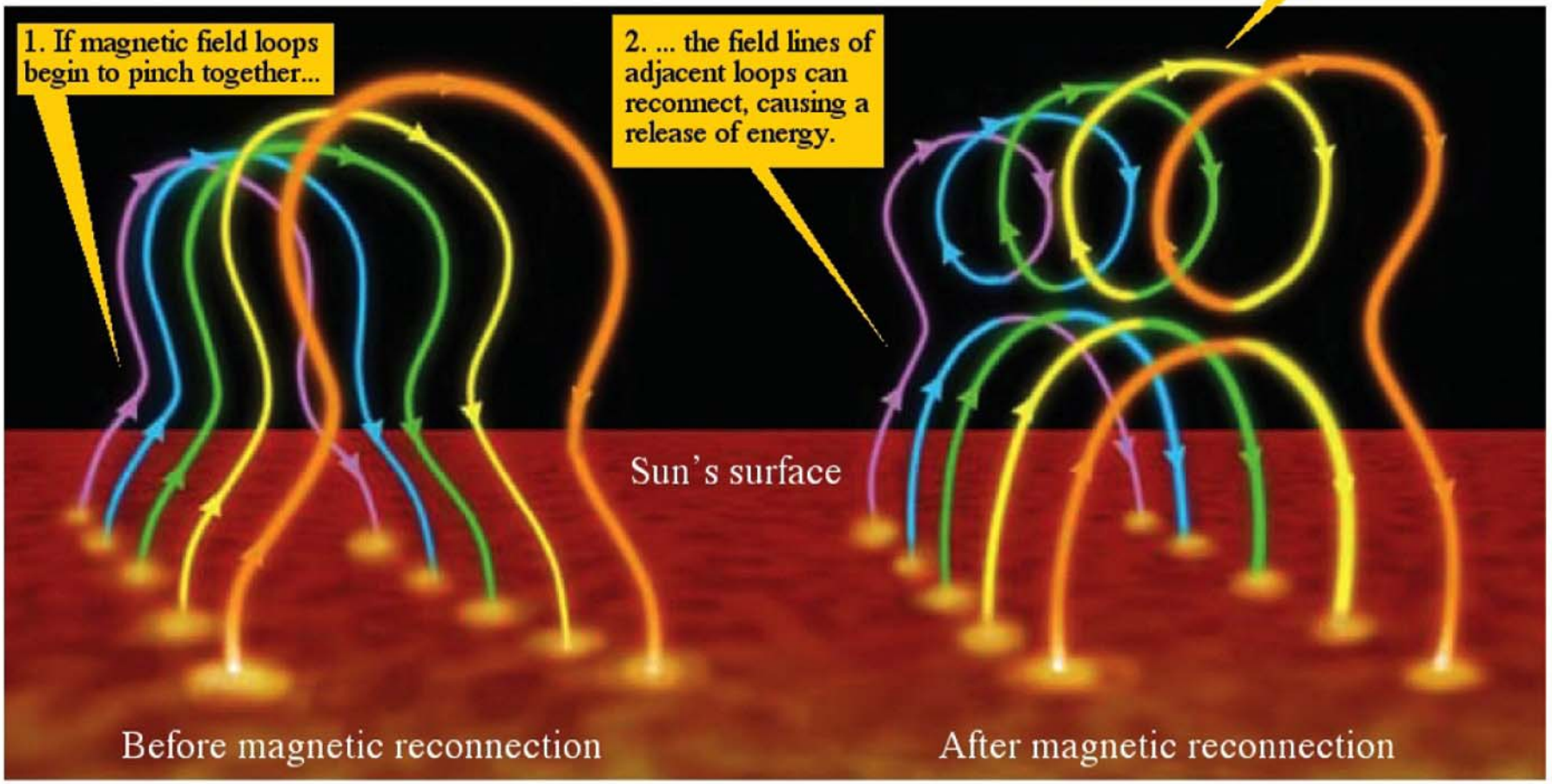

Figure 16-25b
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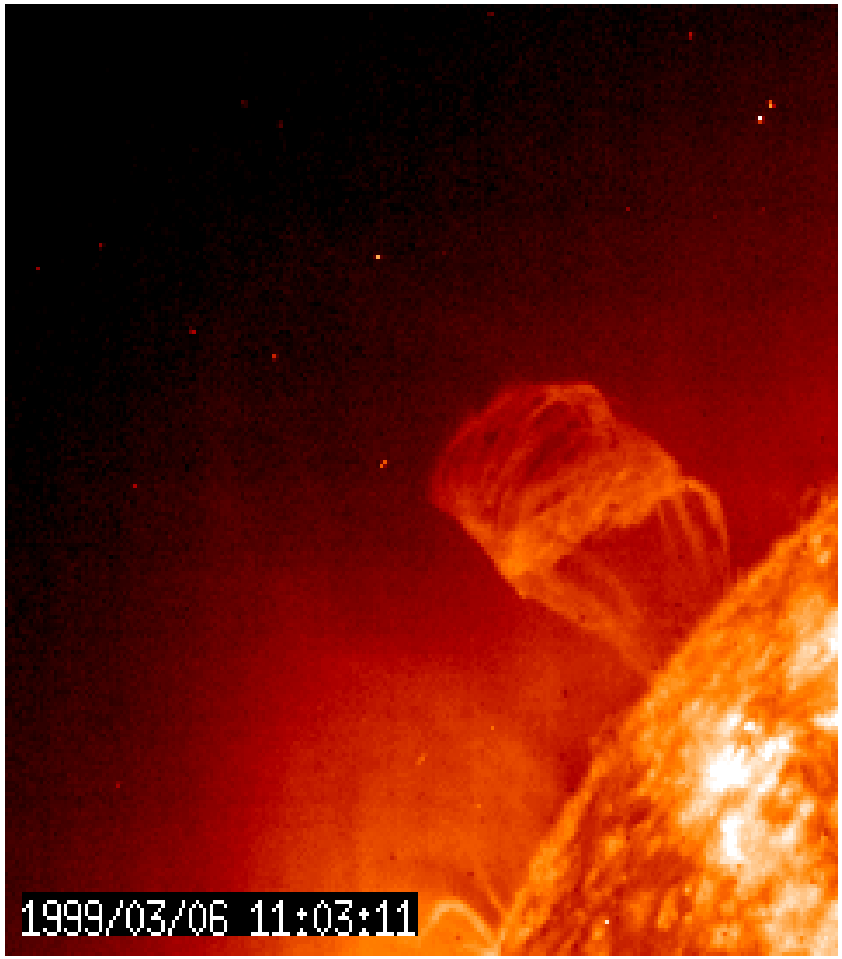
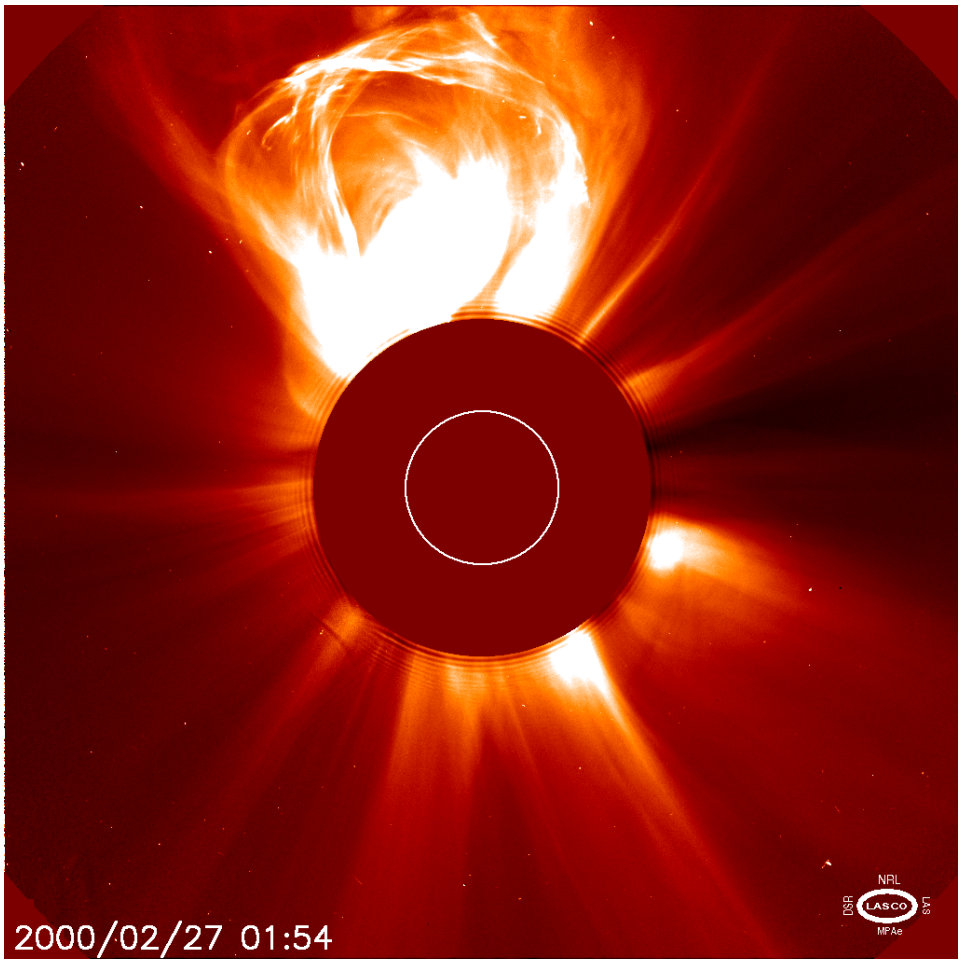
- **Flares (left) and Coronal mass ejections (right)**
  - **Eject large clouds of plasma from the Sun**
  - **Clouds may be aimed towards Earth and produce Aurora**





Solar cycles

- Sunspots were observed by the ancient Greeks
- They have an eleven year cycle
  - Connected to reversals in the Sun's magnetic field

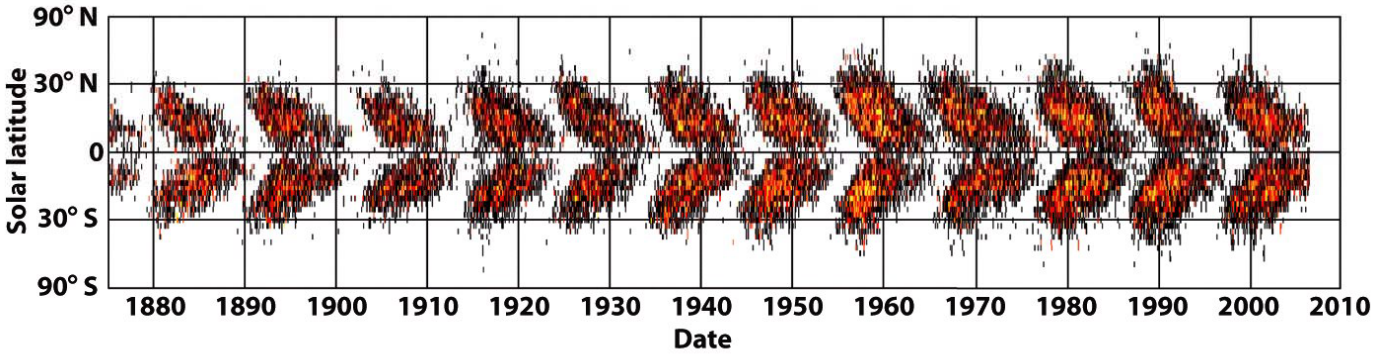


Figure 16-19
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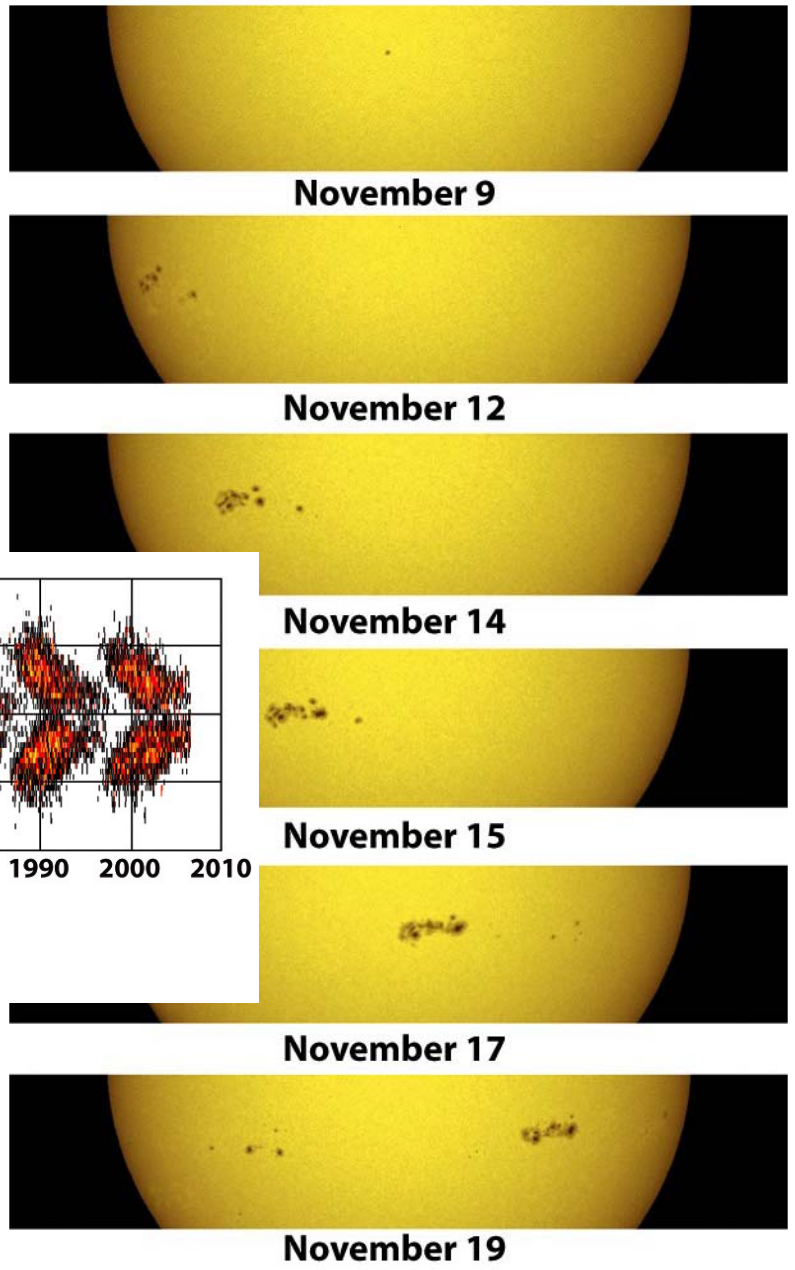

Figure 16-17
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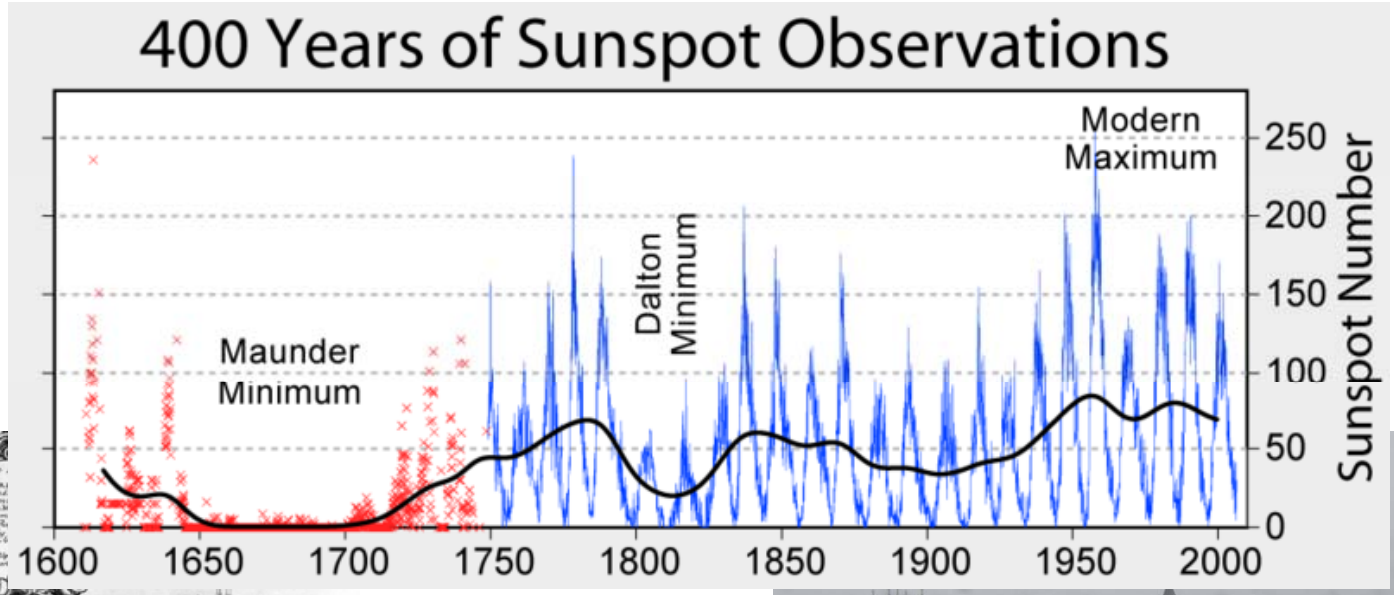
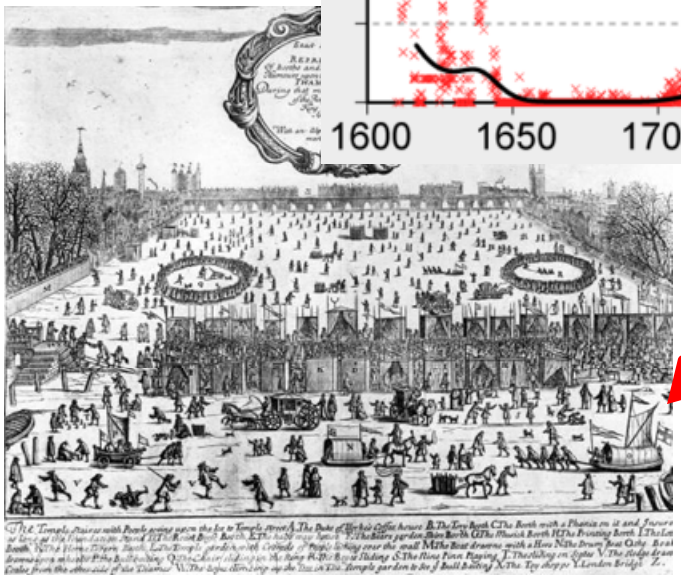
- **Sunspots have longer term variations**
  - **Not understood - Possibly influence climate on the planets**
  - **Maunder minimum is a period without much sun-spot activity**
  - **Corresponds to a period of anomalous climate in Europe and North-America**
    - **Little ice age in Europe – droughts in N. America**





Winter in London 1680 - today

Comparing the sun to other stars

- Pretty mediocre – fortunately for us

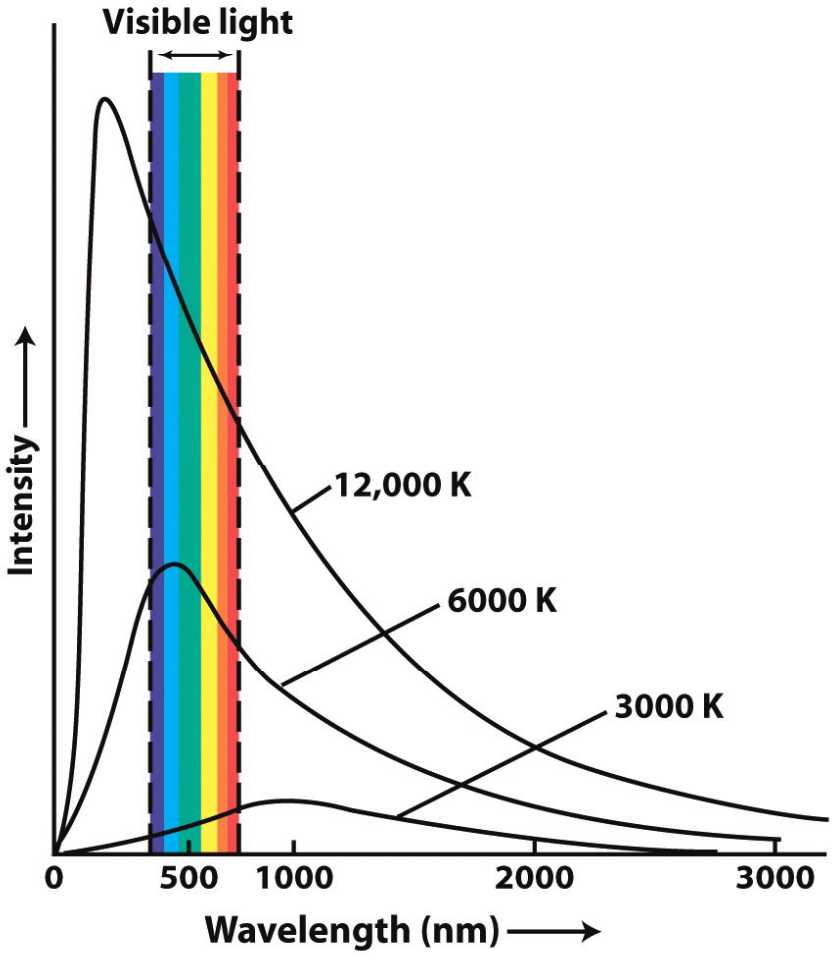


Figure 5-11
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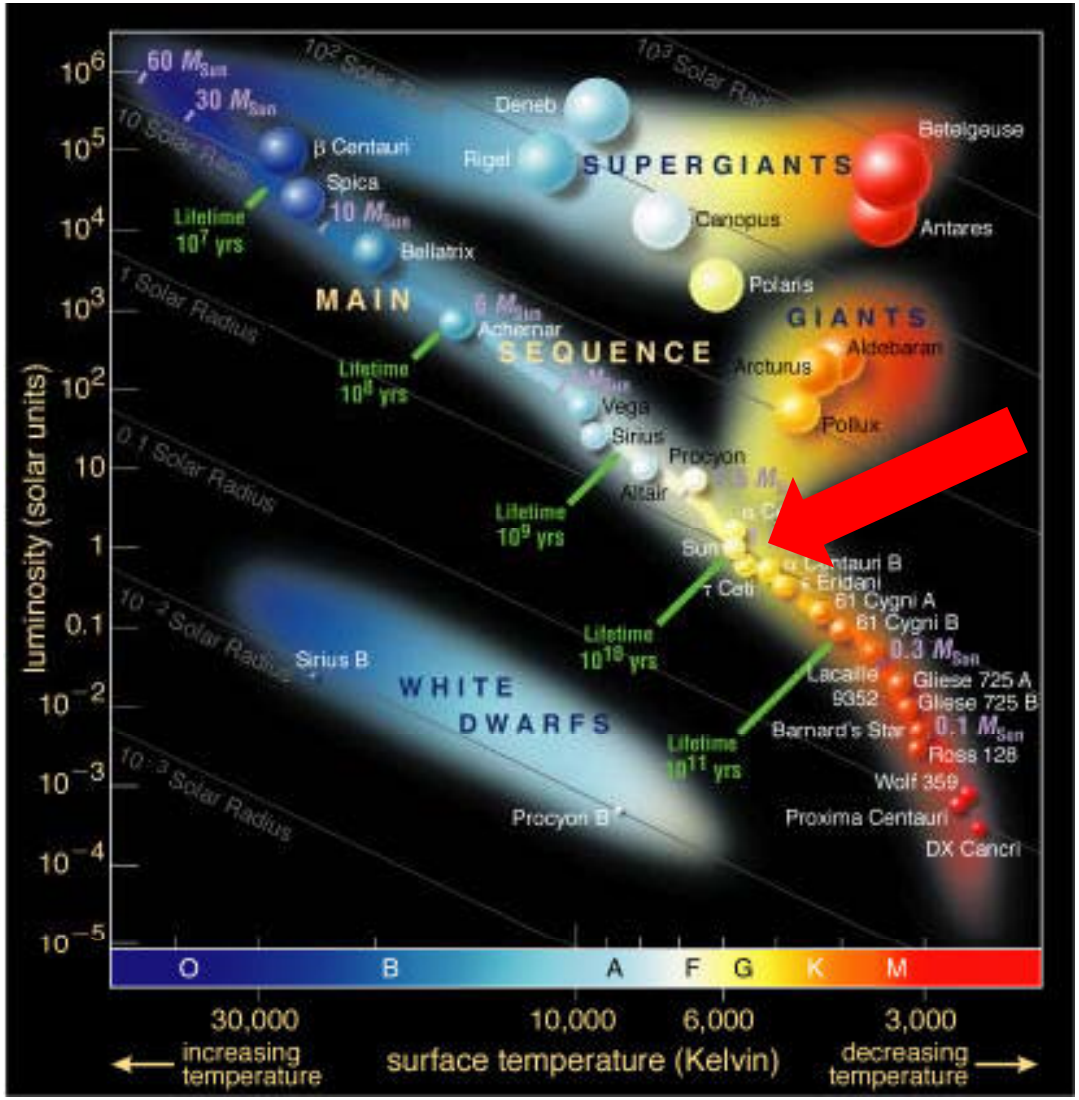
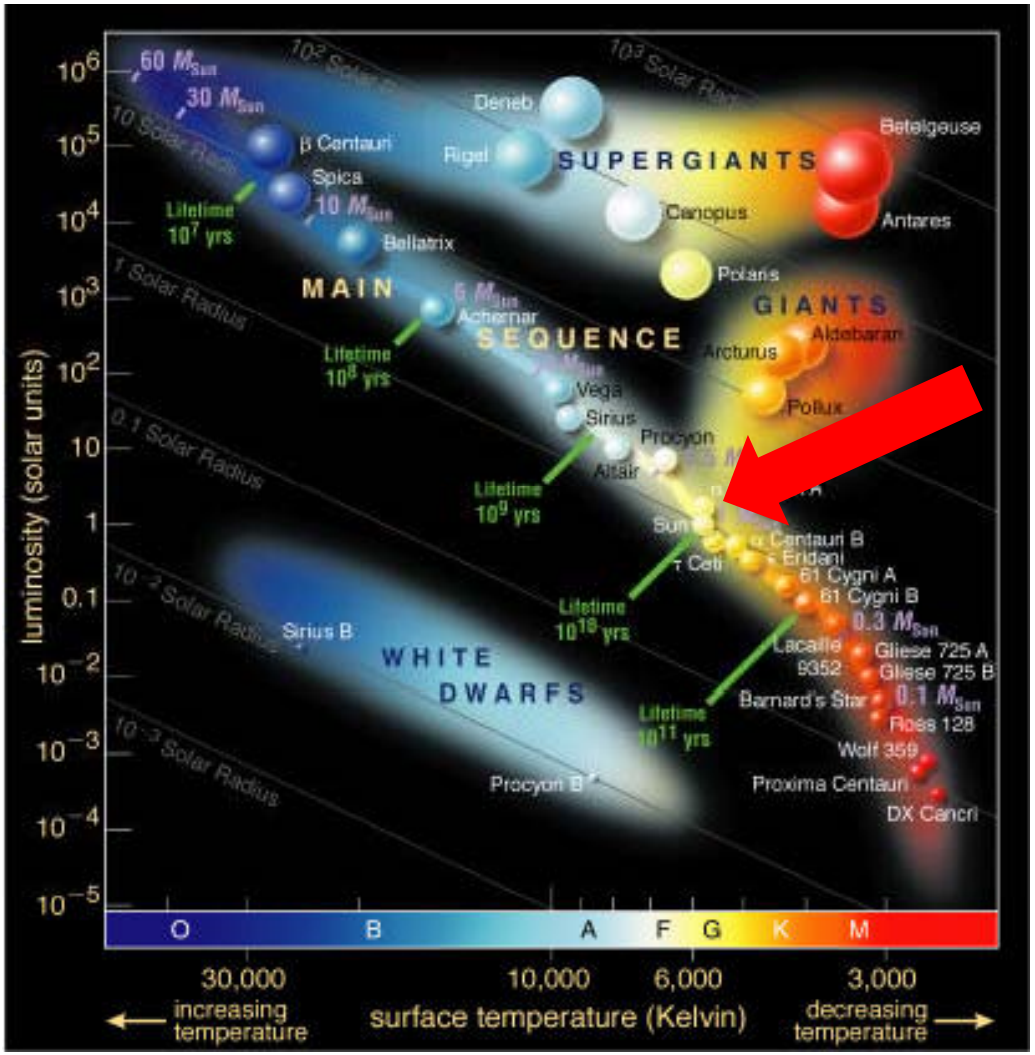


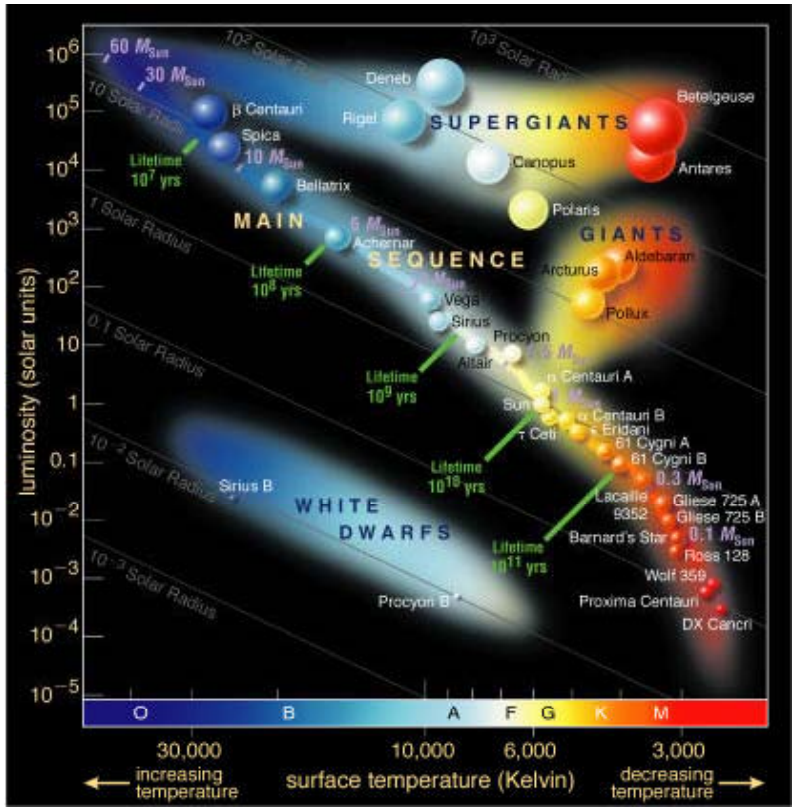
- When stars burn hydrogen
  - Bigger stars -> higher core pressures -> more energy produced
  - Bigger stars are hotter (and bluer)
    - This is the “main sequence”

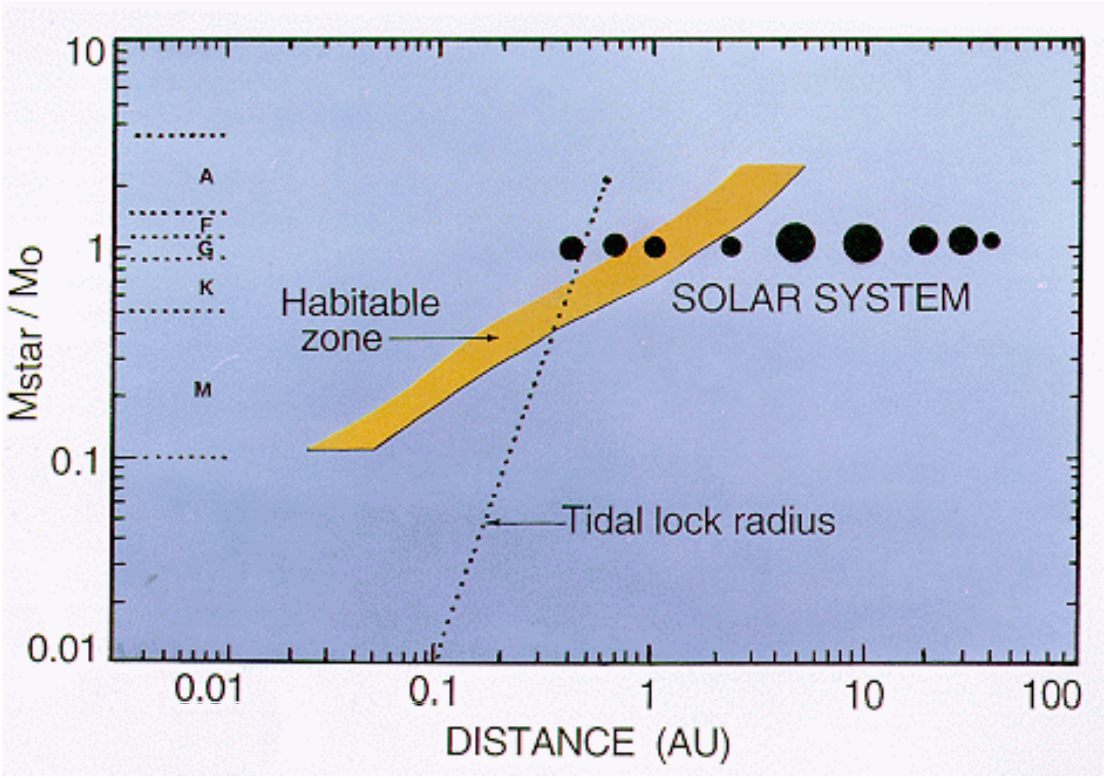
- The sun is a “main sequence” star

- Bigger stars burn hydrogen faster
  - Bigger = short-lived
  - Sun lasts ~10 billion years
  - We’re about half-way through



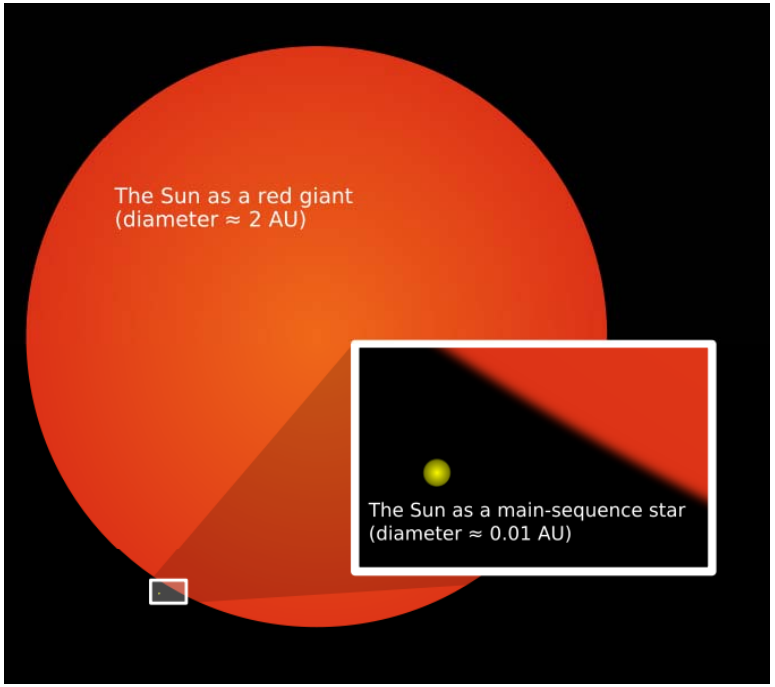
- **Implications for extra-solar planets and life**
  - **Big stars – too short-lived and too hot!**
  - **Very Small stars – Don't produce enough energy**
  - **Solar type stars are the best**





Death of the Sun (and Earth)

- In about 5 billion years
- Red giant phase
  - Helium core
  - Hydrogen burning in thin shell
  - Core collapses slowly
  - Core heats up and burns Helium
    - Forms carbon and Nitrogen
- Inner planets will be engulfed
- Sun will not burn carbon/nitrogen
- Outer layers cast off into a planetary nebula
- Core becomes a white dwarf



In this lecture…

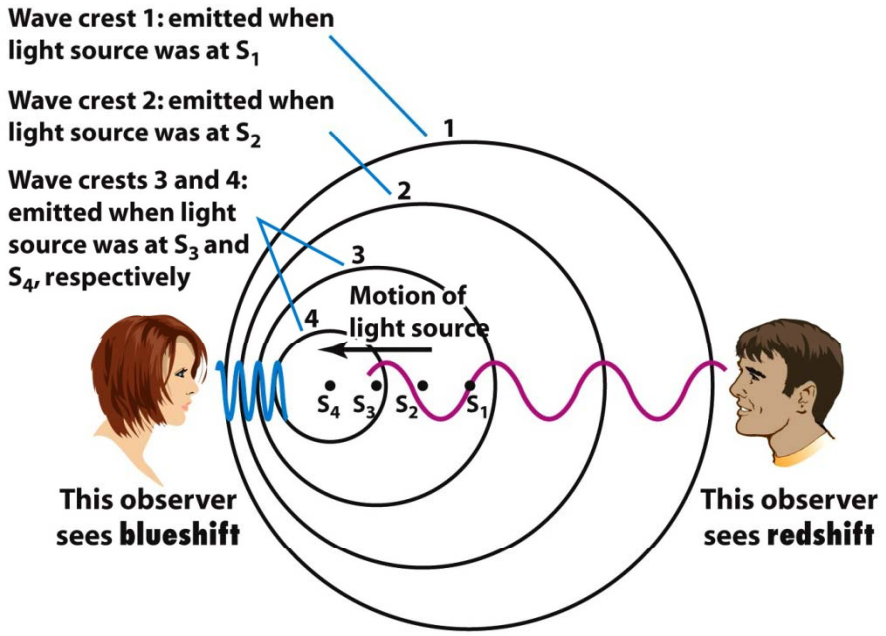
- Introduction to the Sun
- Powering the Sun
  - The core and nuclear fusion
- Solar interior
- Photosphere and Solar Atmosphere
- Magnetic effects
- Sunspots
  - 11 year cycle
  - Longer cycles and climate
- Comparing the Sun to other stars

Next: Craters

- Reading
  - Chapter 16 to revise this lecture
  - Chapter 7.6 for next lecture

The Doppler Shift

- **Wavelength of light appears to change when source is moving**
  - **Becomes redder when source moves away**
    - **Waves are spread out - longer**
  - **Becomes bluer when source approaches**
    - **Waves are bunched up - shorter**



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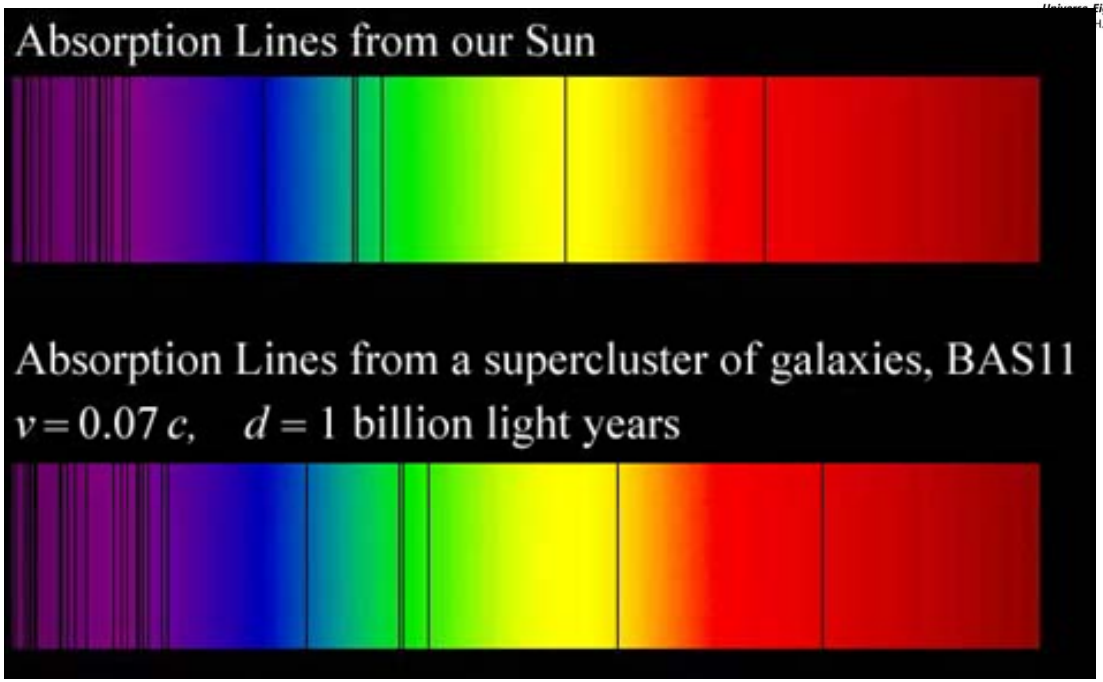
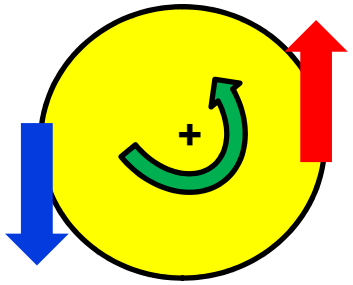
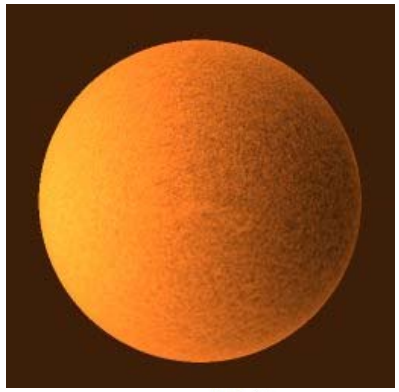


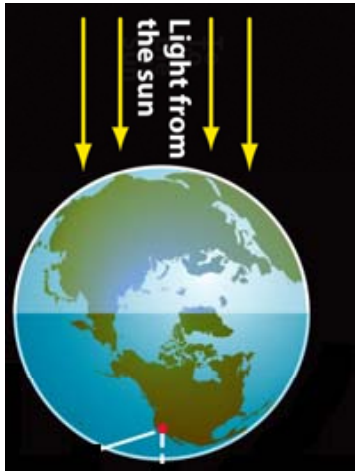
$$\lambda = \lambda_o \left(1 + v/c\right)$$

λ = Observed wavelength
λ_0 = original wavelength
v = velocity away from observer
c = speed of light

- **Redshifts/Blueshifts can be used to figure out how fast things are moving away/toward you.**
  - **Especially useful for the Sun**
  - **Map of radial velocities called a dopplergram**
    - **Solar rotation means one side is red-shifted and one blue-shifted**
  - **Small scale details provides info on rising and sinking of material**
    - **Granules**







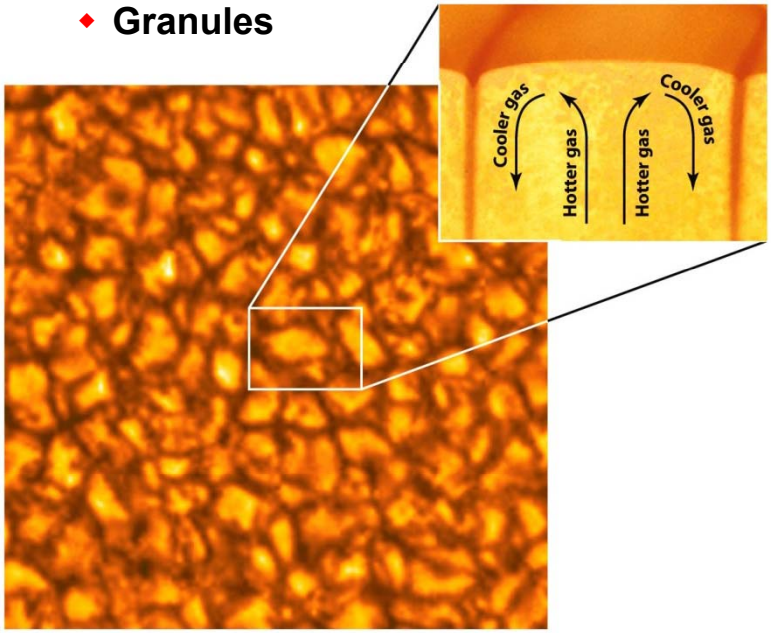


Figure 16-9
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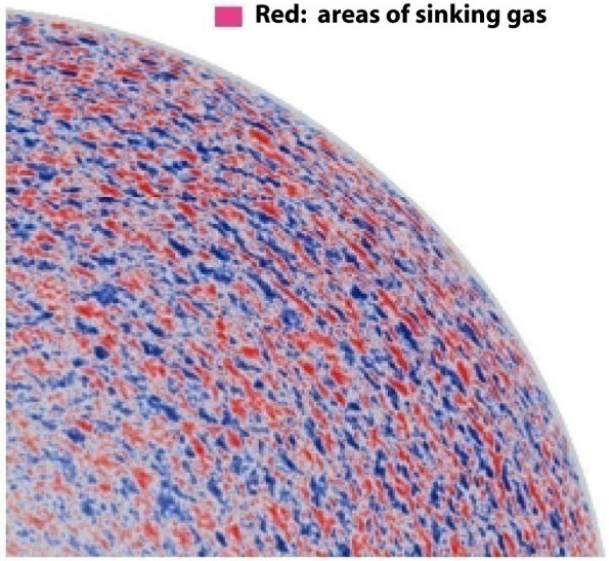

Figure 16-10
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