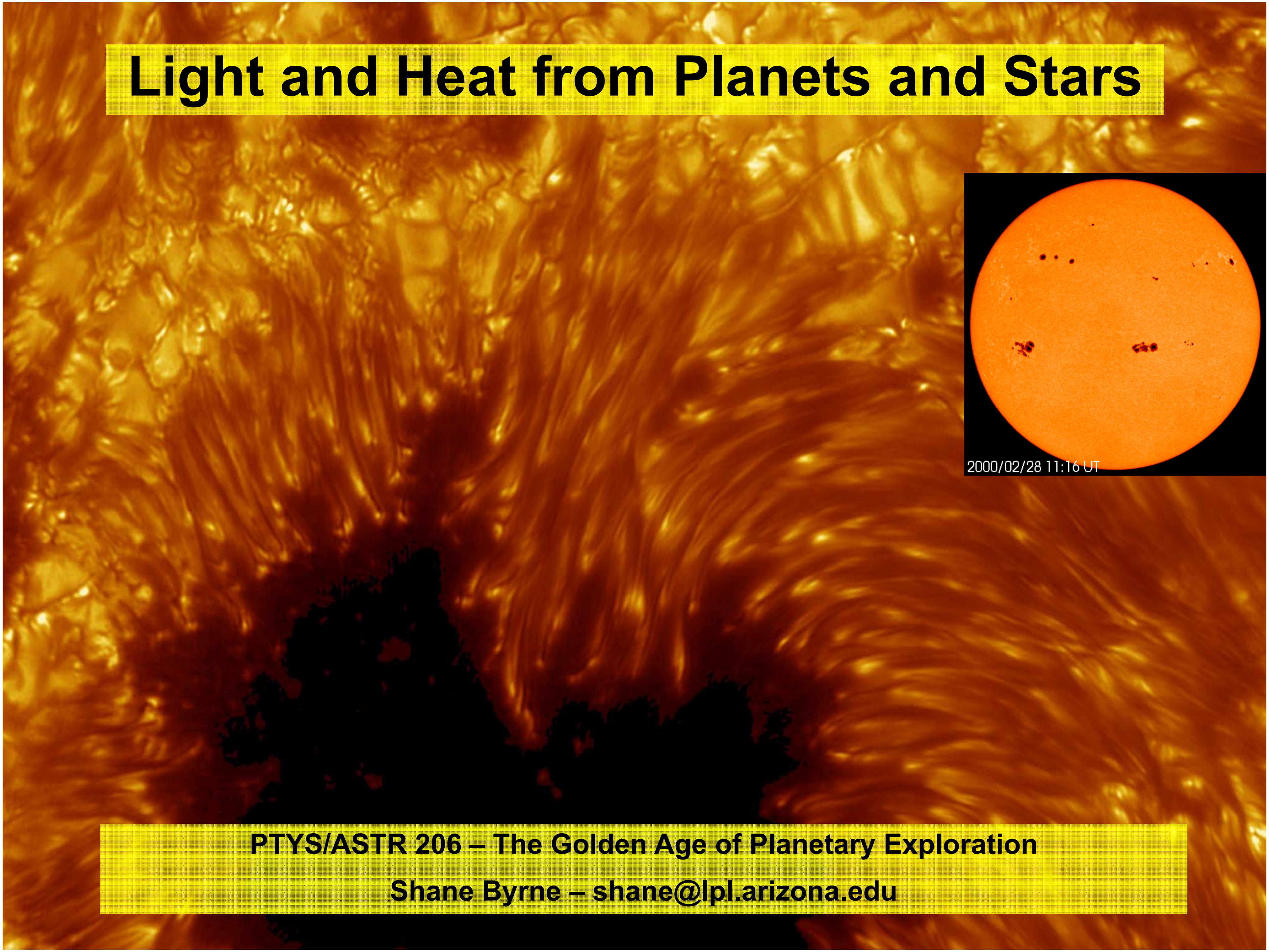
- **Announcements**
  - **Homework due this Thursday.**
  - **Everyone should have (at least) looked at it by now.**

Light and Heat from Planets and Stars



PTYS/ASTR 206 – The Golden Age of Planetary Exploration

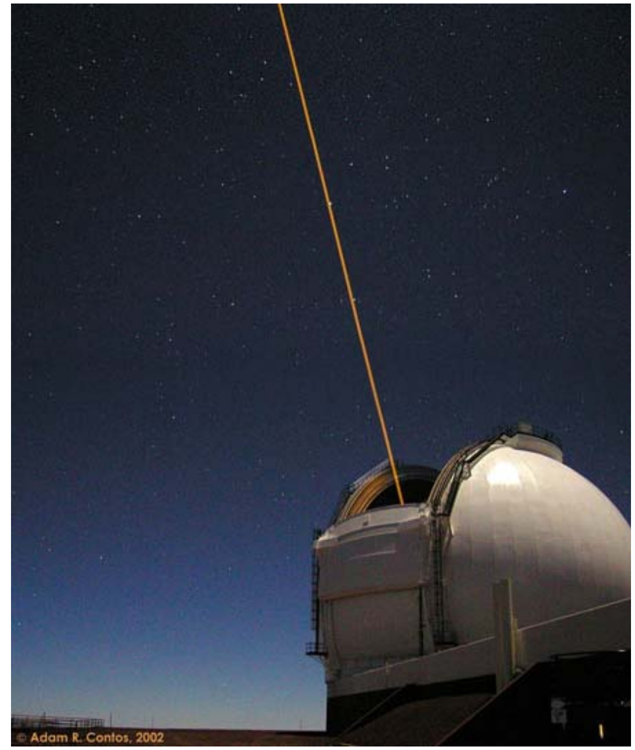
Shane Byrne – shane@lpl.arizona.edu

In this lecture…

- What is radiation?
- Blackbody radiation
  - Temperature and radiation
  - Emissivity
- Sunlight and starlight
  - Energy for planetary surfaces
- Reflection
  - Albedo and color
  - Scattering
- Emission and absorption lines
  - Atomic structure
  - Emission and absorption spectra
- The Doppler effect

What's radiation?

- **Visible light is *electromagnetic* radiation**
  - **<u>Not</u> the same as radioactivity**
    - **Mostly sub-atomic particles**



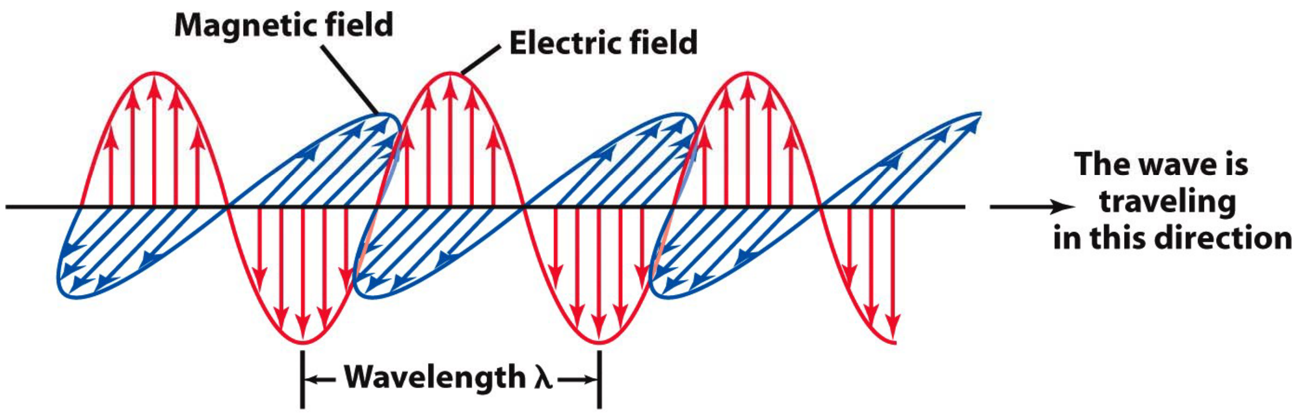


Figure 5-6
Universe, Eighth Edition

- Changing electric field produces the magnetic field
  - And vice-versa
  - These fields vary in one place – but the disturbance travels
  - Waves described by:
    - Wavelength
    - Frequency (waves passing by per sec.)
    - Speed
    - Amplitude
  - These are related:
    - Speed = wavelength * frequency
    - E.g. for blue light
      - Wavelength ~ $3*10^{-7}$ m
      - Speed ~ $3*10^{8}$ m/s
      - How many wave per sec?
      - Freq. = speed/wavelength
      - Freq. = 10^{15} Hz
      - 1,000,000,000,000,000 waves per second!

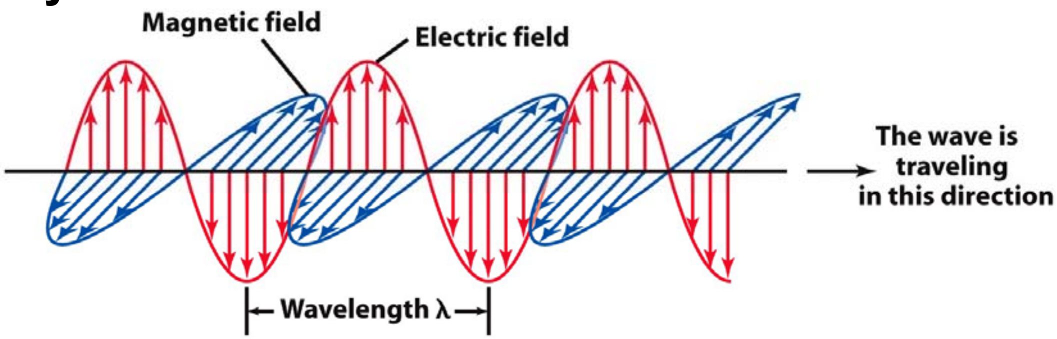
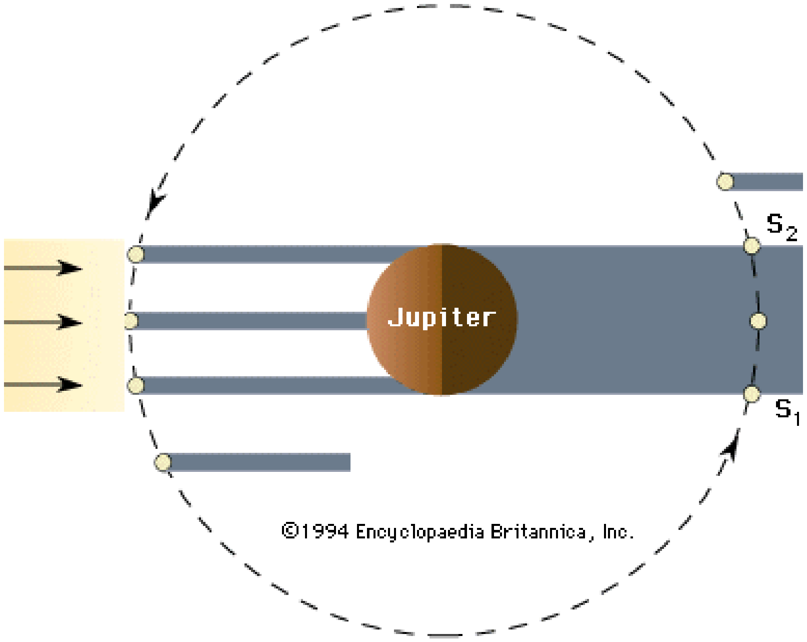


Figure 5-6
Universe, Eighth Edition

- Radiation (light) travels fast
  - Faster than anything else in the universe… but not infinitely fast.
  - Exactly 299,792,458 m/s (called ‘c’) in a vacuum
    - It’s exact because it defines what a meter is
    - Slower when going through material



- Romer studied the timing of Jupiter eclipsing its moons
  - Observations in 1676
  - Made possible with telescopes
  - Io enters Jupiter’s shadow earlier or later than expected.

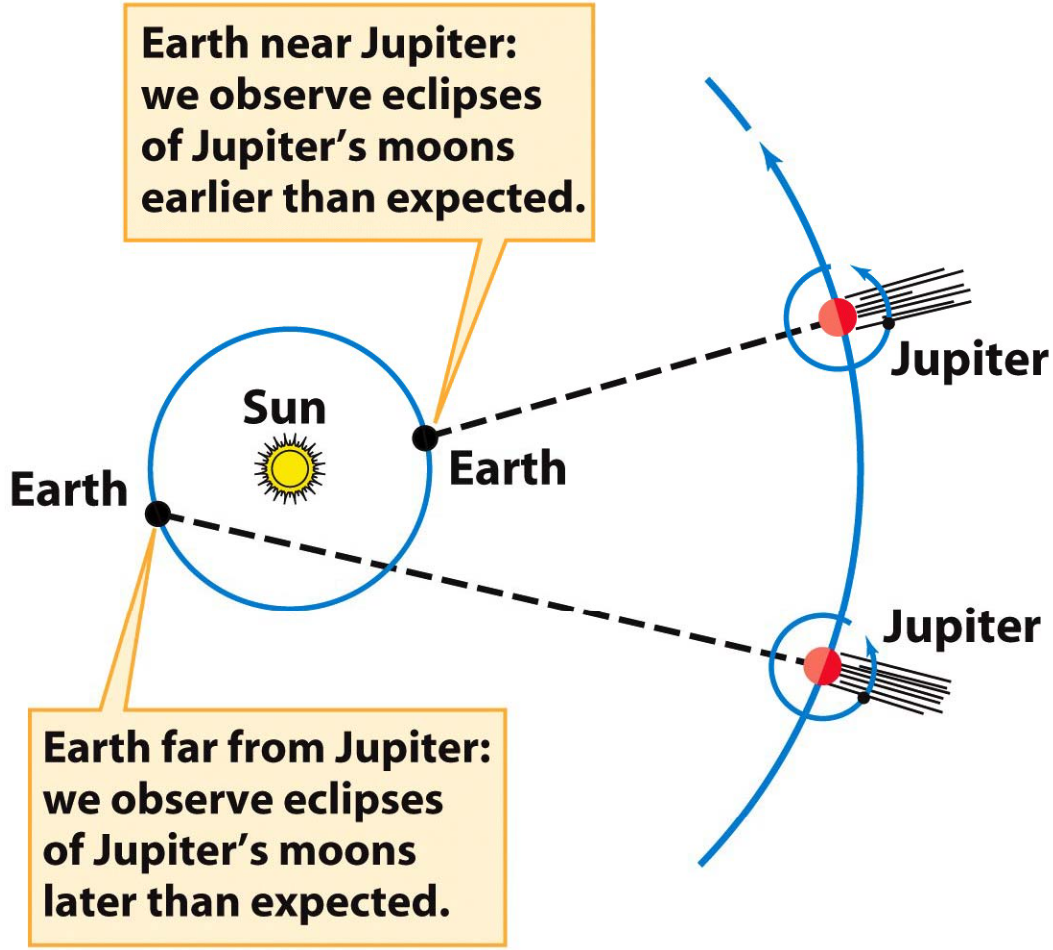


Figure 5-1
Universe, Eighth Edition

- These are all the same phenomena
  - The wavelength determines – what we call it & how energetic it is

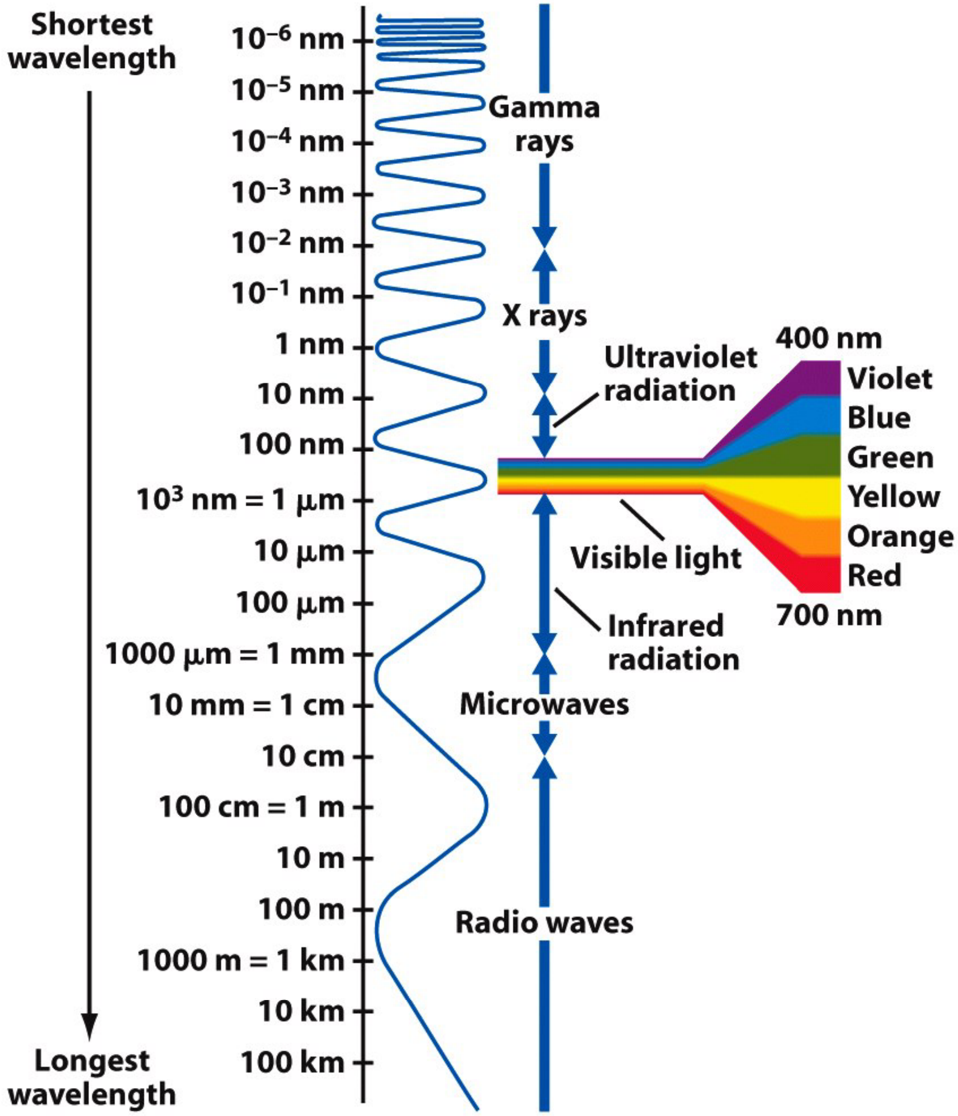
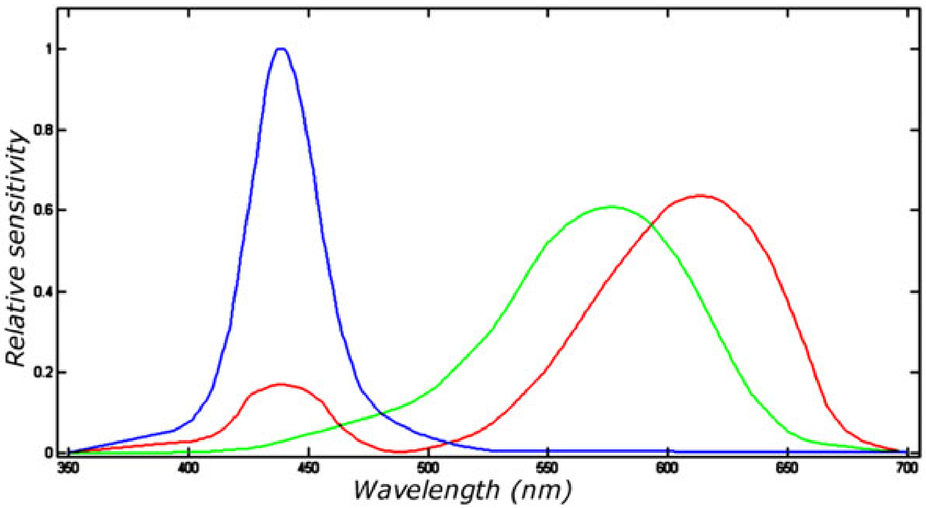


Figure 5-7
Universe, Eighth Edition

Figure 5-8
Universe, Eighth Edition

- White light is a mix of different wavelengths (colors)
  - Three types of cone cell in eyeball
    - Each detects different wavelengths
    - Not too sensitive
  - Only one kind of rod cell
    - Very sensitive – used for night vision
    - Only one kind so no color vision at night
    - These cells don't detect other wavelengths



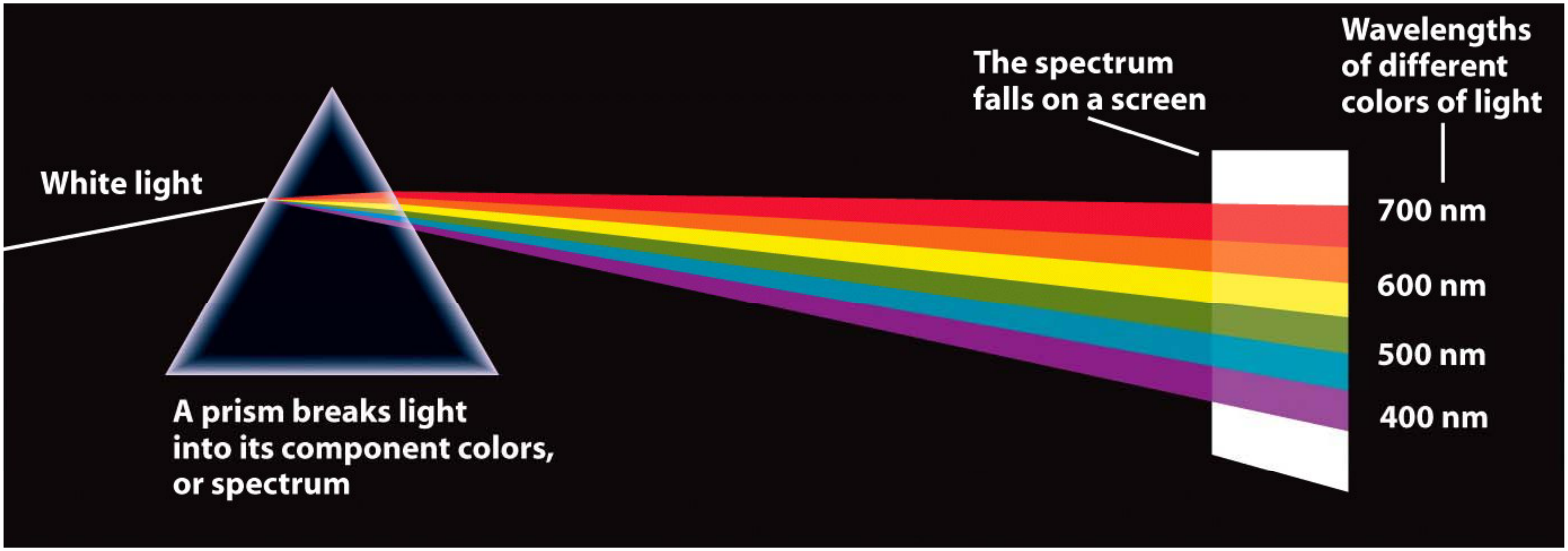
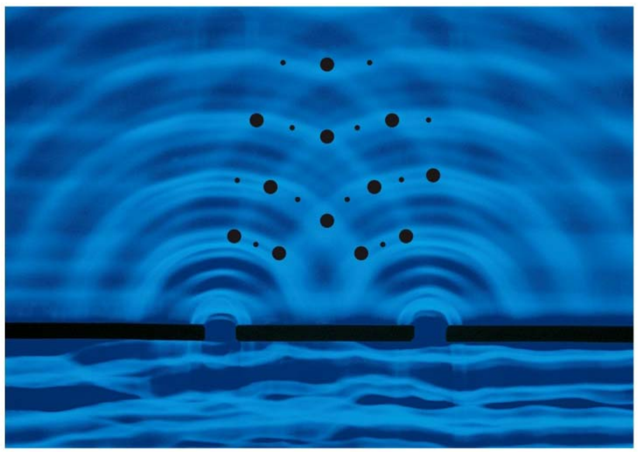


Figure 5-3
Universe, Eighth Edition

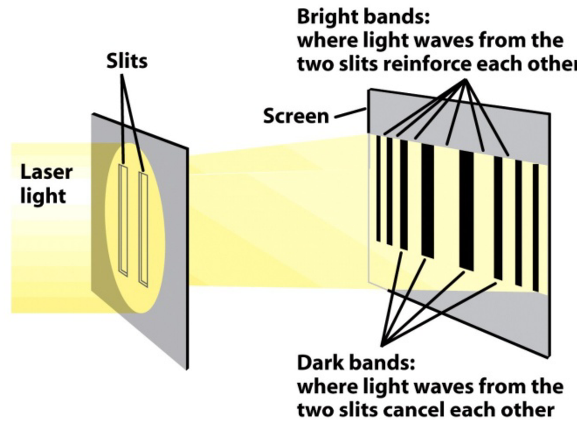
Waves or particles?

- Both – depends on the situation
  - Diffraction – light bends around corners – like a continuous wave
  - Interference – light adds together and cancels out – like a continuous wave



An analogous experiment with water waves

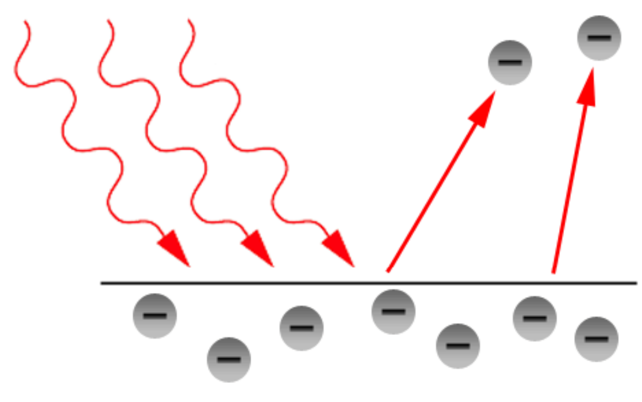
Figure 5-5b
Universe, Eighth Edition



An experiment with light

Figure 5-5a
Universe, Eighth Edition

- Photoelectric effect - Einstein
  - Light travels in discrete packages
    - Called photons
  - Photon energy depends on frequency
    - A single photon removes an electron from a metal
    - …if its energy is high enough…
    - The number of photons doesn't matter



Waves or particles?

- Long-wavelengths usually described as waves
  - Radiowaves, microwaves
- Shorter-wavelengths usually described as particles
  - Photon energy depends on frequency – ‘blue’ photons are more energetic than ‘red’ photons
  - …but total energy also depends on the number of photons
- Not a hard rule
  - x-rays still show diffraction
  - Radiowaves can still be described by photons

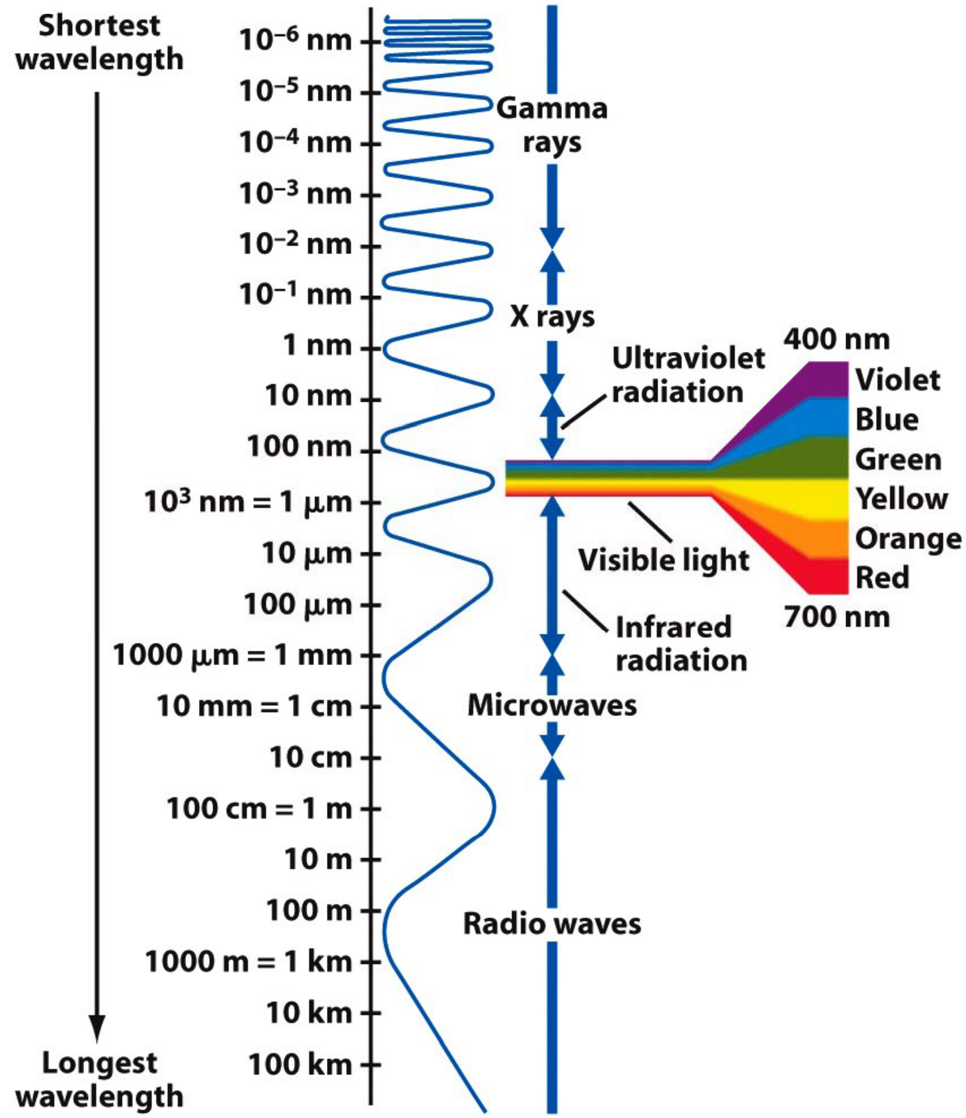
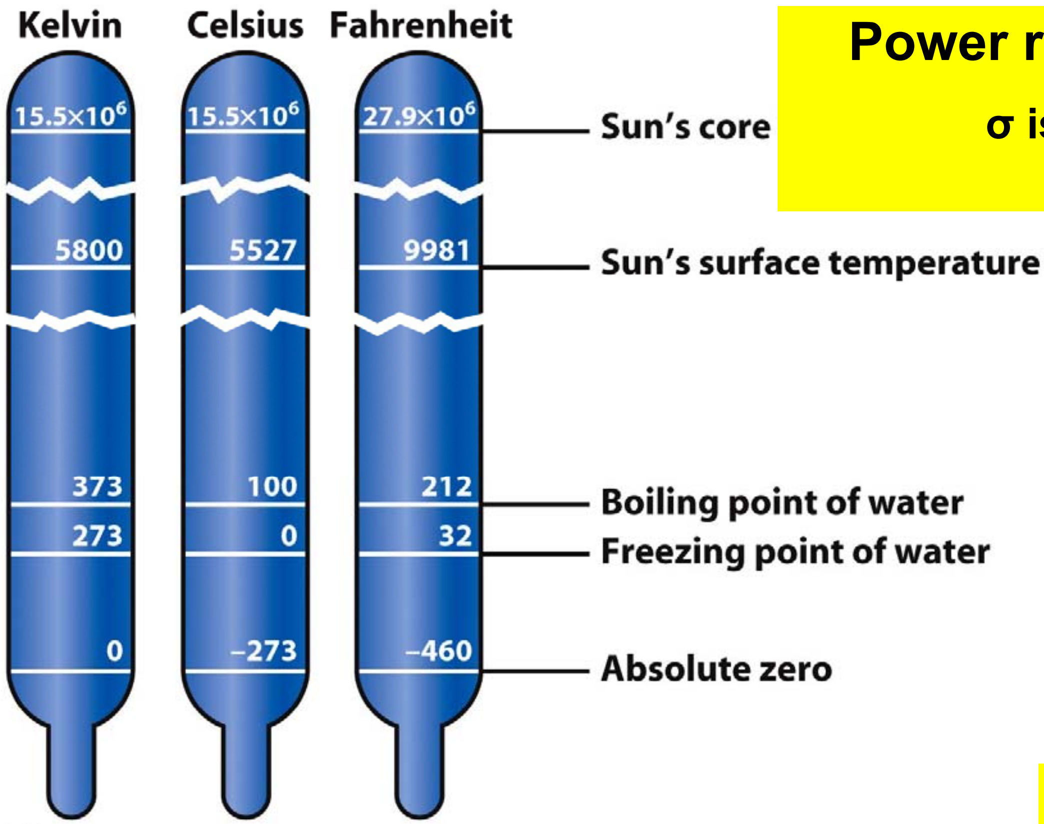


Figure 5-7
Universe, Eighth Edition

Blackbody radiation

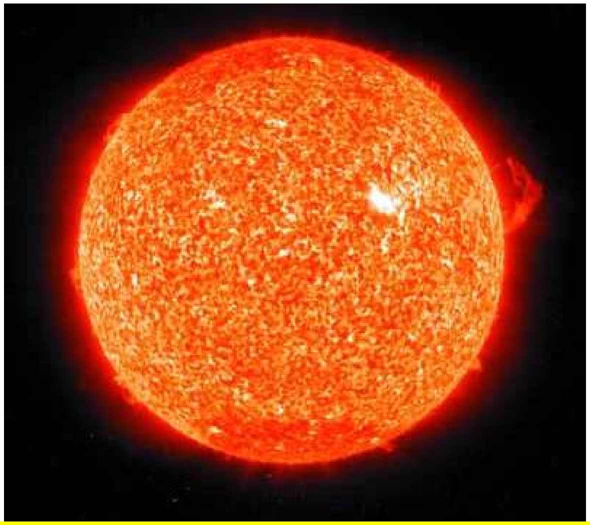
- Anything with heat (and that's everything) glows
  - Temperature in Celsius or Fahrenheit are conveniences
  - Temperature in Kelvin directly measures how much heat a material has
    - Temperature in Kelvin is always positive
    - Nothing actually has a temperature of absolute zero
  - The amount of radiation released depends on this temperature



Box 5-1
Universe, Eighth Edition

Power radiated per square meter = σT^4

σ is the Stefan-Boltzmann constant
5.67×10^{-8} W m^{-2} K^{-4}



Hot things radiate a lot of energy

- Some things emit radiation more efficiently than others
  - Measured by emissivity ε (from 0 – terrible to 1 – perfect)
  - A perfectly efficient (ε=1) material is called a black body
  - Emissivity and absorptivity are the same
    - A blackbody (perfect emitter) is also a perfect absorber

Total Power radiated per square meter = $\varepsilon \sigma T^4$

- Blackbodies radiate at all wavelengths – with perfect efficiency
  - They radiate at some wavelengths more than others
    - Planck curve
    - Blackbody curve
  - The sun radiates most at visible wavelengths
    - That's not a coincidence!

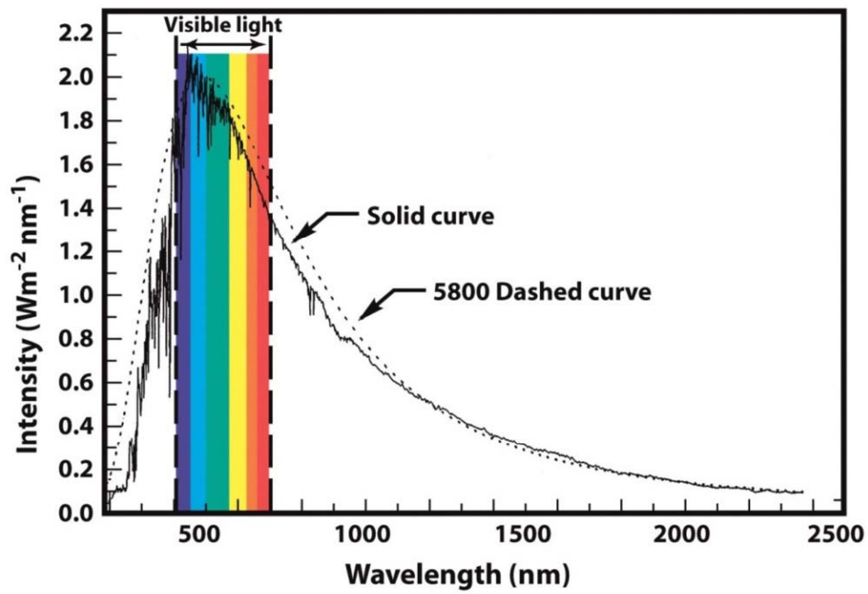


Figure 5-12
Universe, Eighth Edition

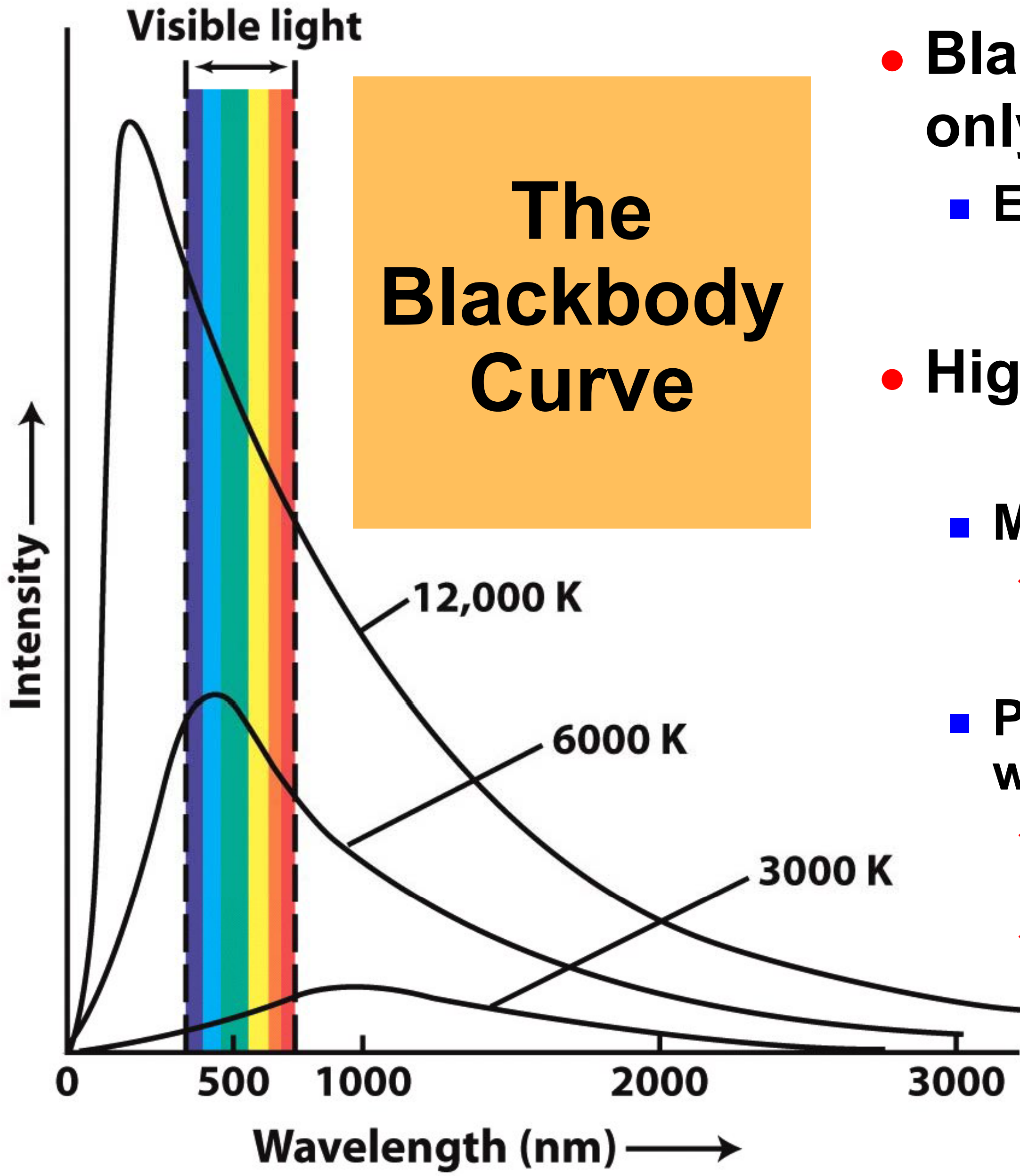
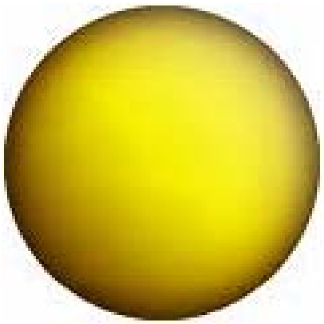
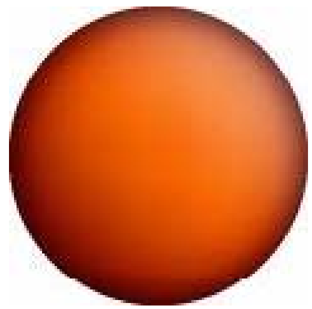


Figure 5-11
Universe, Eighth Edition

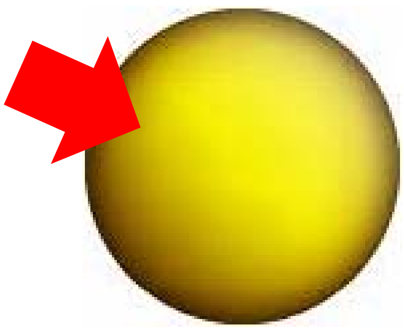
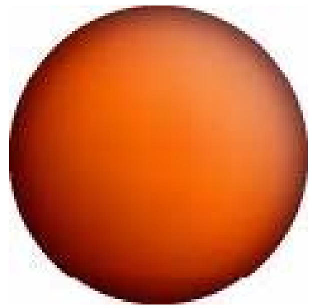
- **Blackbody radiation depends only on temperature**
  - **Emissivity=1**
- **Higher temperature means:**
  - **More radiation…**
    - **Power radiated per square meter = σT^4**
  - **Peak radiation at shorter wavelengths**
    - **A star with a surface at 3000 K radiates in the infrared**
    - **A star with a surface at 6000K (like the Sun) radiates in the visible part of the spectrum**

- **Which of these stars is hotter:**

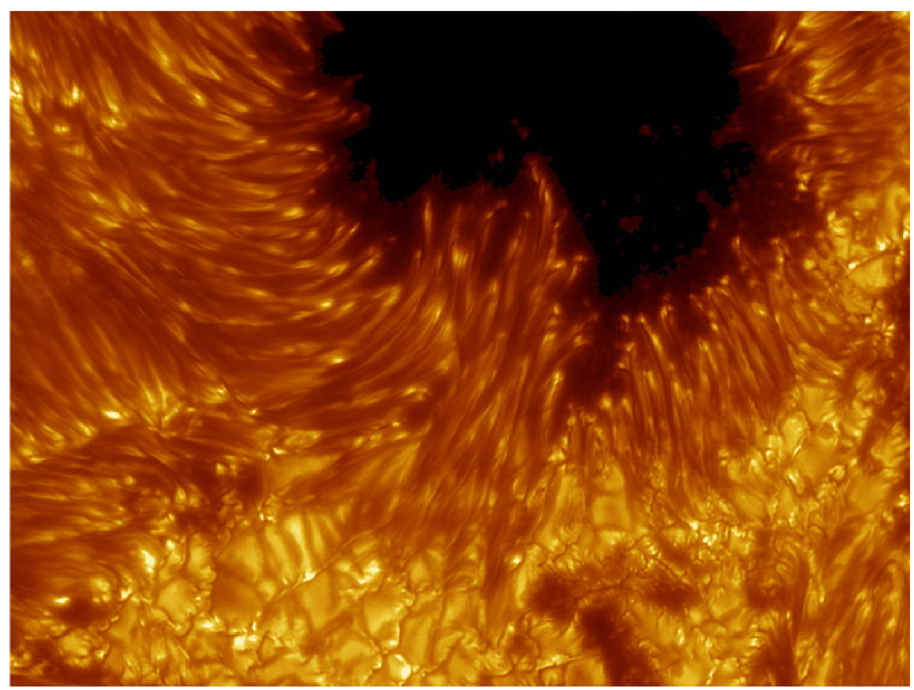




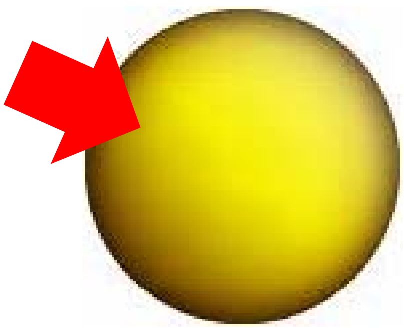
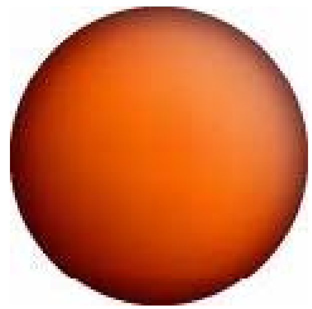
- **Which of these stars is hotter:**

- **Are the inside of sunspots hotter or cooler than the rest of the Sun's surface ?**



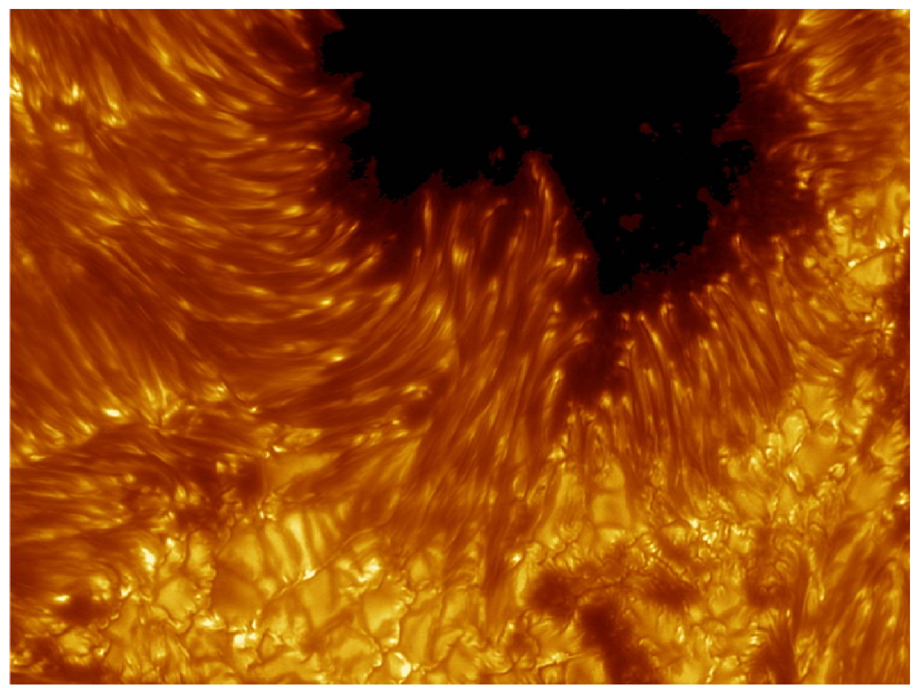
- **Which of these stars is hotter:**

- **Are the inside of sunspots hotter or cooler than the rest of the Sun's surface ?**

  - **Darker means less radiation means cooler!**

    (But not by much still ~4500 K)



- **Wavelength of peak emission**
  - **Wien's law**

$$\lambda_{max} = \frac{0.0029 \text{ K m}}{T}$$

λ_{max} = wavelength of maximum emission of the object (in meters)

T = temperature of the object (in kelvins)

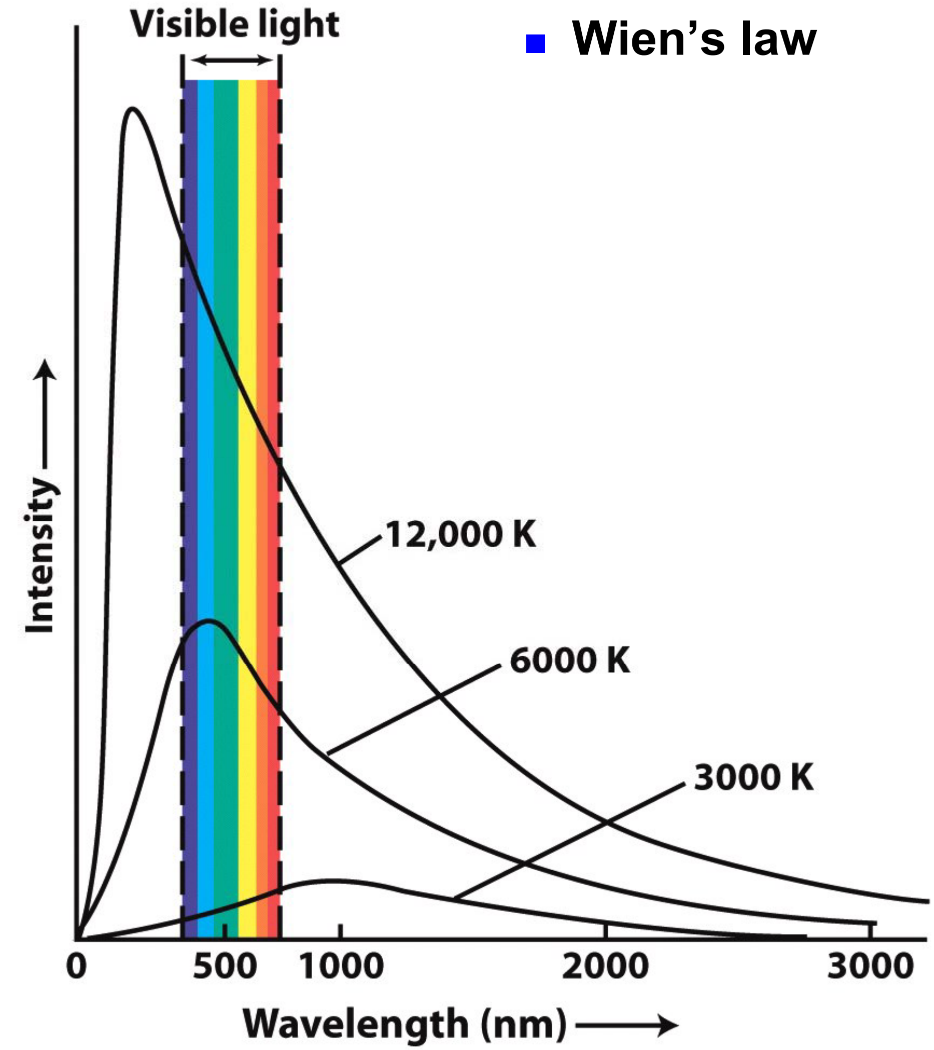
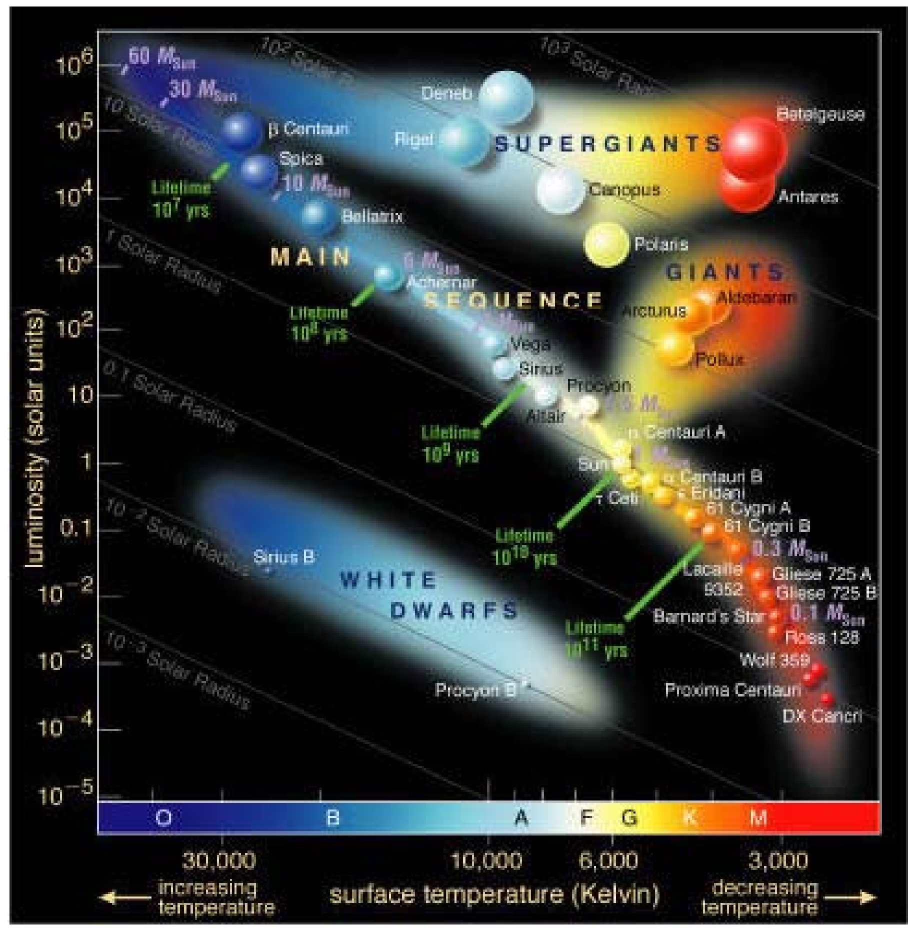


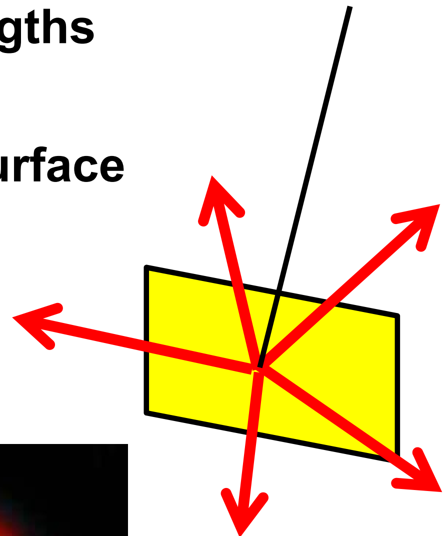
Figure 5-11
Universe*, *Eighth Edition



Davedarling.com

Solar power

- Add up all the energy emitted by the Sun
  - Over all wavelengths
  - In all directions
  - Over its entire surface



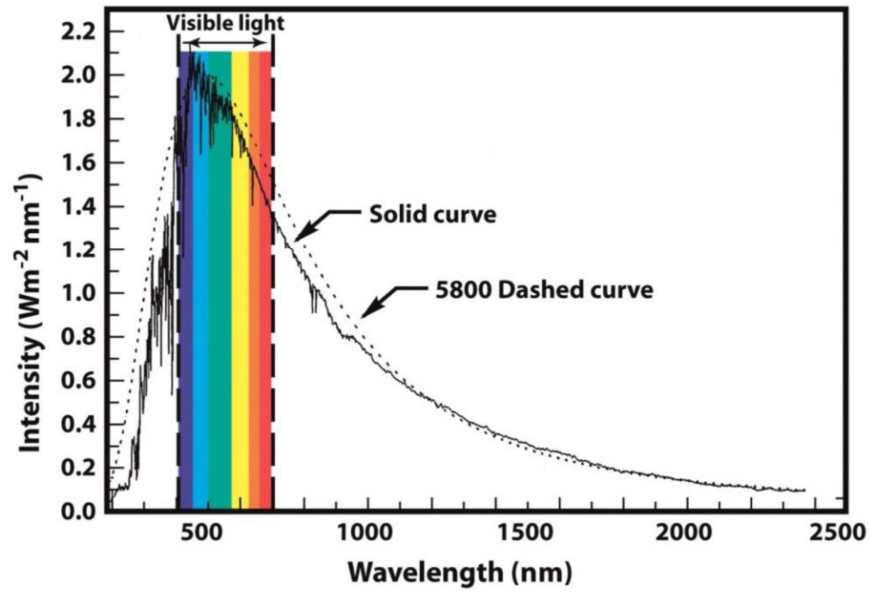


Figure 5-12
Universe, Eighth Edition
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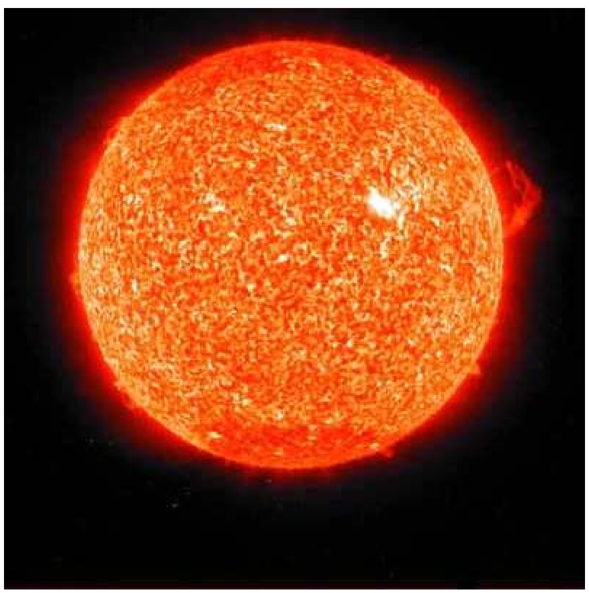
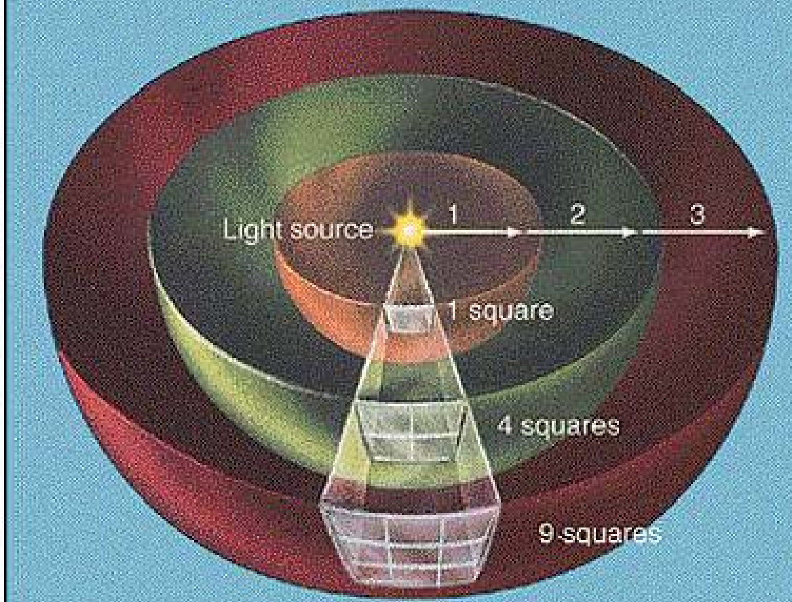


$$= 4 * 10^{26} \text{ Watts}$$

The US generates about 1.5 * 10^{19} Joules/year (in 2007)
The sun does this 27 million times every second

- That energy gets spread over a large area…
  - More spread out further from the Sun



Area increases with distance squared

- At the Earth @ 1AU distance

$$4 * 10^{26}\ \mathrm{W}$$

becomes

$$1367\ \mathrm{W\ m^{-2}}$$

- What about at 2 AU?
  - Area that sunlight is spread over is 4 times larger
  - Power at 2AU is: $1367\ \mathrm{W\ m^{-2}} / 4 = 342\ \mathrm{W\ m^{-2}}$
- In general…

$$\text{Solar power} = 1367\ \mathrm{W\ m^{-2}}\ /\ R^2$$

  - Where R is the distance from the Sun in AU

- Another example.
  - Mars is 1.52 AU from the Earth
  - How much solar power does it receive per square meter?

Solar power = 1367 W m^{-2} / R^2

Solar power = 1367 W m^{-2} / 1.52^2

Solar power = 592 W m^{-2}

Planet	Perihelion - Aphelion distance (AU)	Solar radiation maximum and minimum (W/m²)
Mercury	0.3075 - 0.4667	14,446 - 6,272
Venus	0.7184 - 0.7282	2,647 - 2,576
Earth	0.9833 - 1.017	1,413 - 1,321
Mars	1.382 - 1.666	715 - 492
Jupiter	4.950 - 5.458	55.8 - 45.9
Saturn	9.048 - 10.12	16.7 - 13.4
Uranus	18.38 - 20.08	4.04 - 3.39
Neptune	29.77 - 30.44	1.54 - 1.47

- Distant planets receive less sunlight
  - Colder temperatures
  - Material behaves differently
  - A gas on Earth (e.g. CO_2) is solid ice on the outer solar system

Reflection

- **Surface temperature of a planet is much lower than the Sun**
  - **What wavelengths does it emit radiation at?**
  - **Let's take Earth for example – temperature is about 300 K**
    - **Remember Wien's Law**

$$\lambda_{max} = \frac{0.0029 \text{ K m}}{T}$$

λ_{max} = wavelength of maximum emission of the object (in meters)

T = temperature of the object (in kelvins)

  - **Plugging in the temperature gives ~10^{-5} m (10 μm)**
    - **i.e. In the infra-red**
  - **We can't see Earth glowing with our eyes**
    - **We see only reflected solar light**

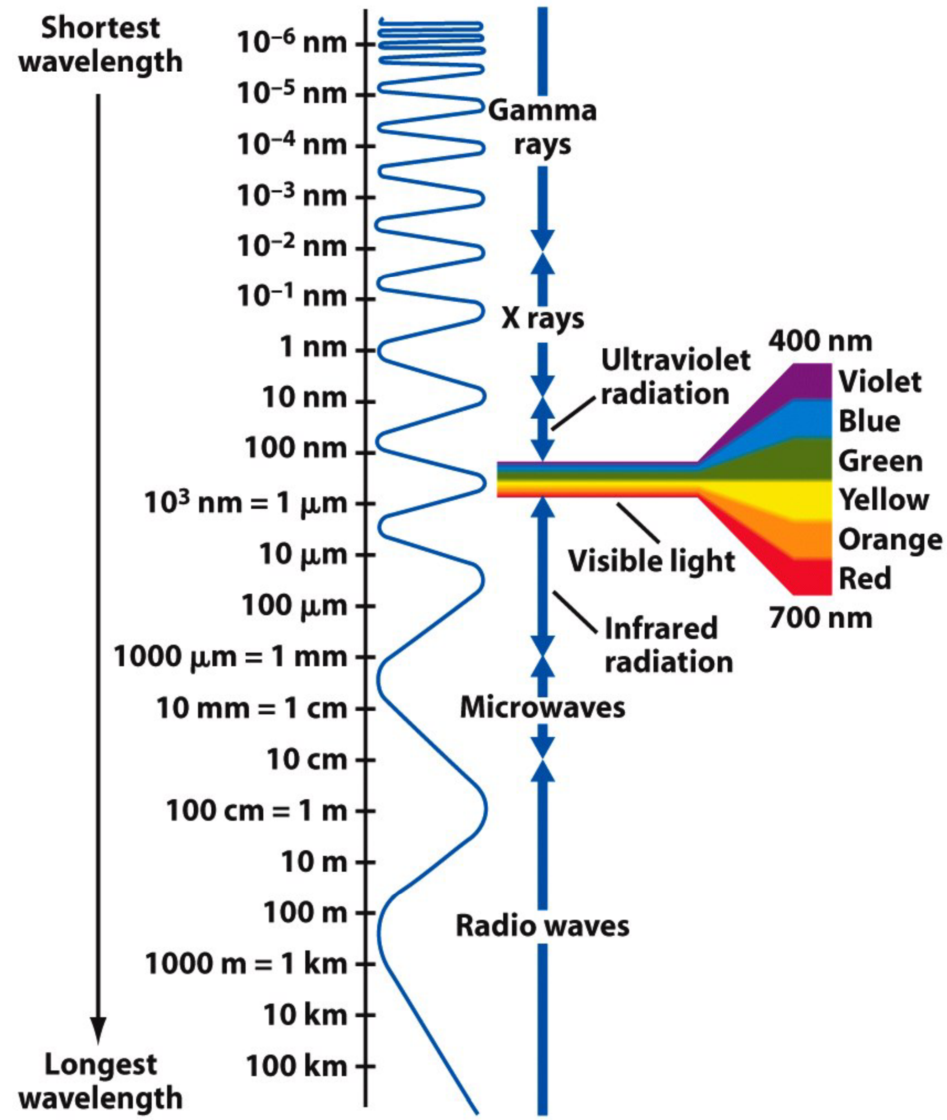


Figure 5-7
Universe, Eighth Edition

- **Most of the radiation we detect in planetary astronomy is generated by the Sun**
  - **The signal of the solar spectrum is stamped on the light being reflected**
- **Spectrum from a planet depends on:**
  - **The solar spectrum**
  - **What wavelengths the planet reflects best**

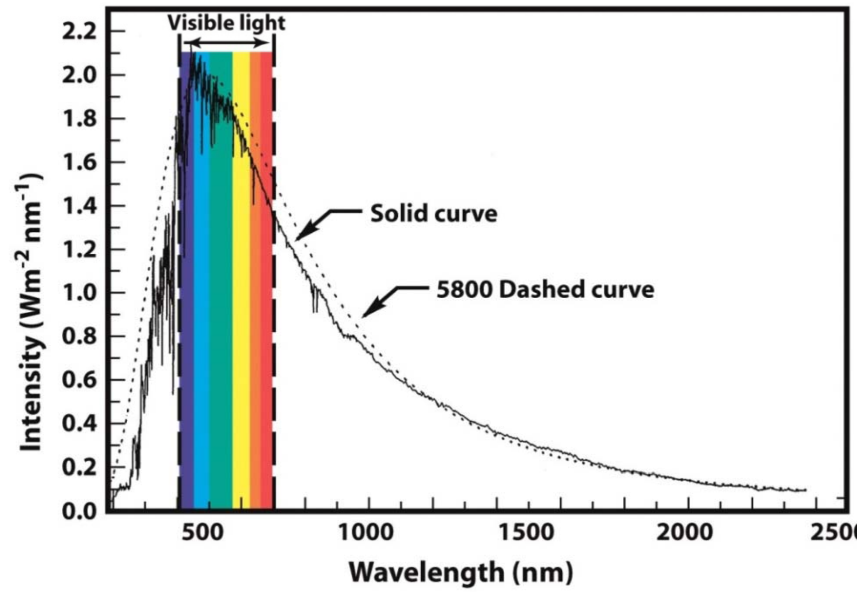
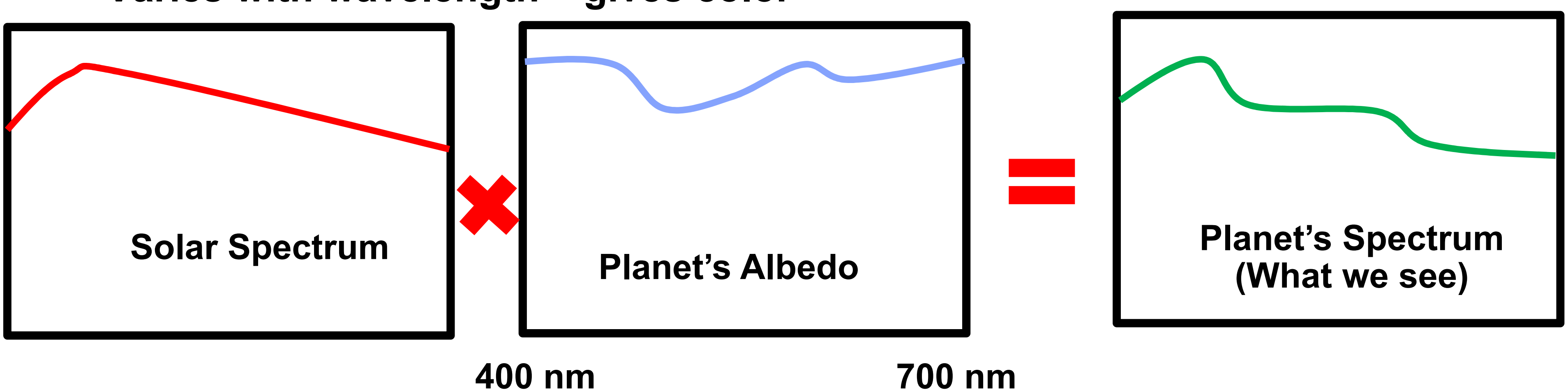
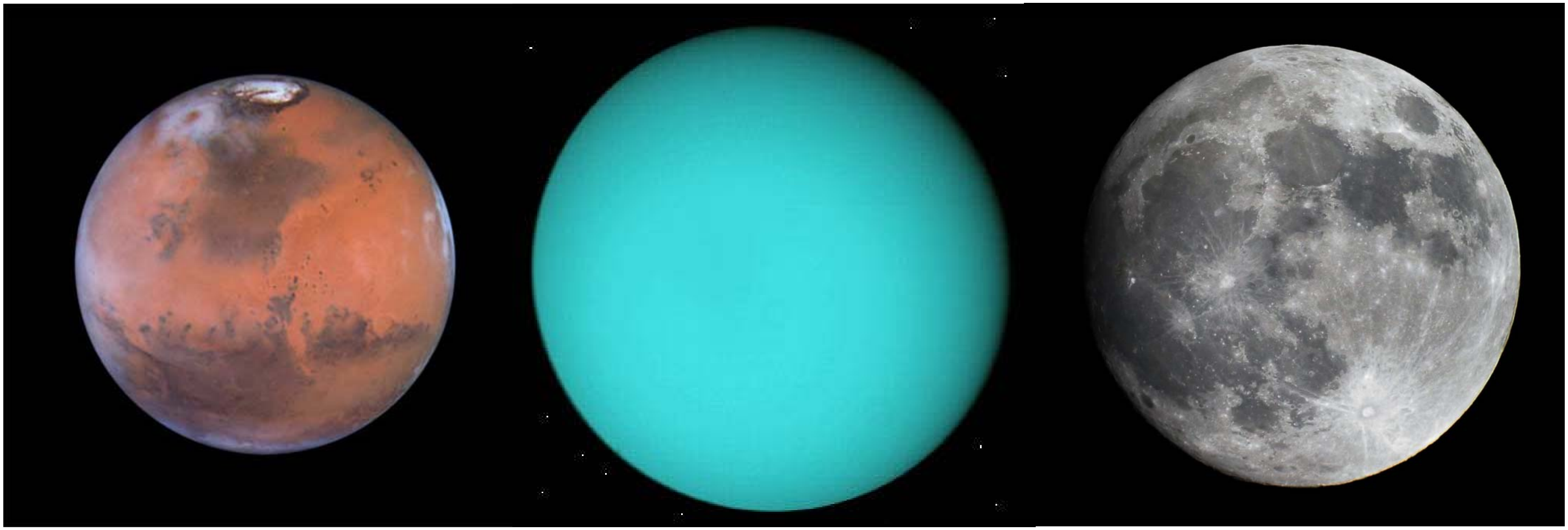


Figure 5-12
Universe, Eighth Edition

- **Reflectance is also called Albedo**
  - **From 0 (totally black) to 1 (very bright)**
  - **Varies with wavelength – gives color**

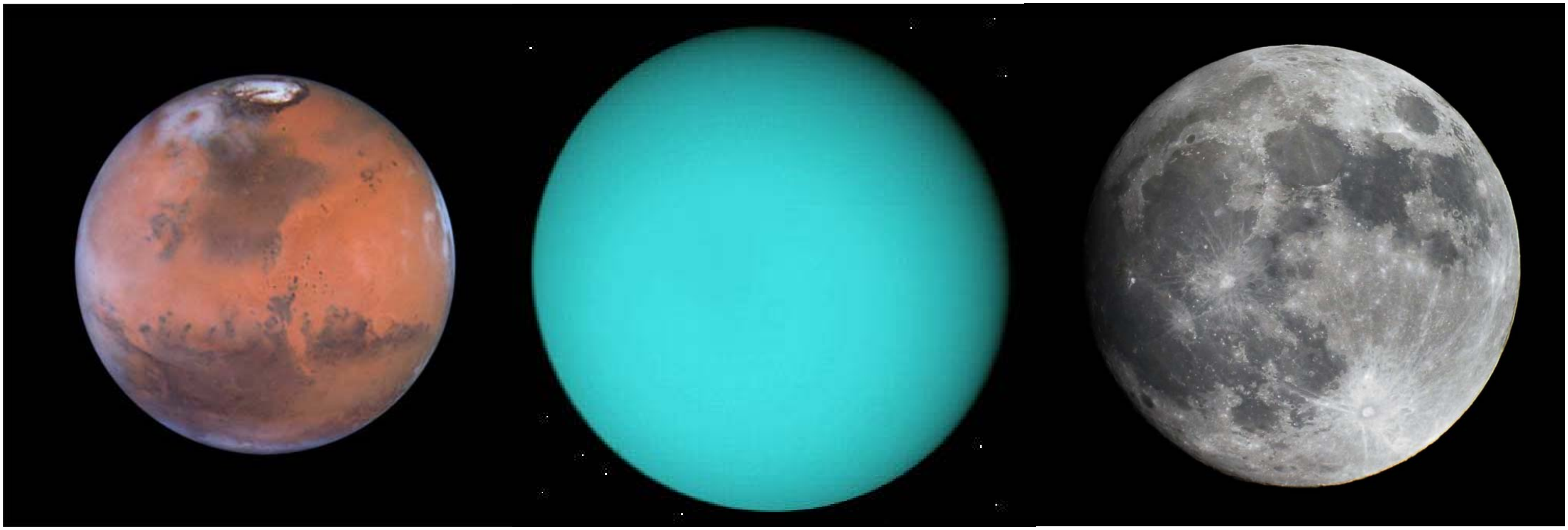


- **Different planets reflect light differently**

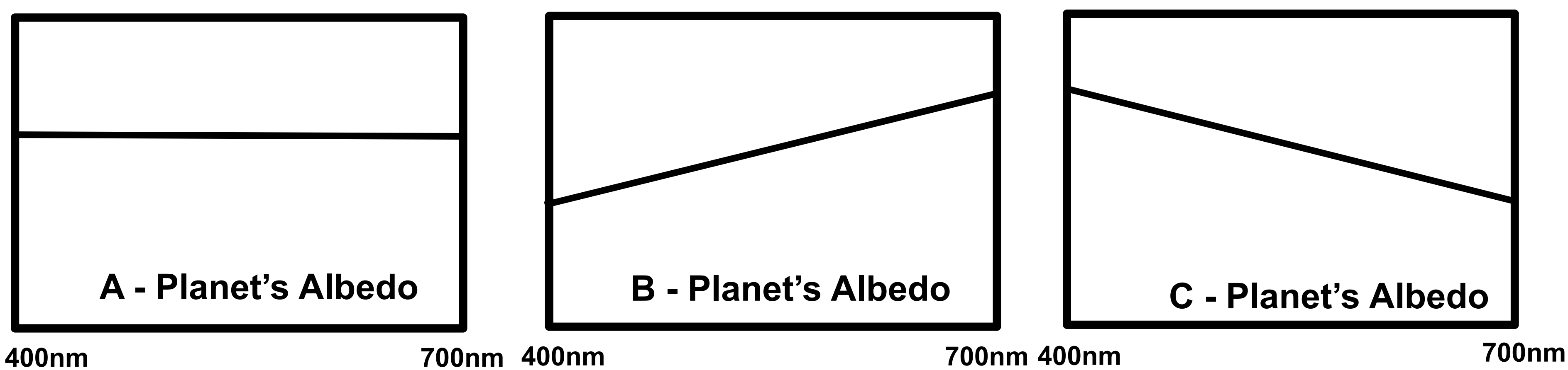


- **Compositional differences**
- **Grain size of the soil**
- **Clouds in the atmosphere**
- **Etc…**

- Different planets reflect light differently



- Match up the Albedo with the planet….



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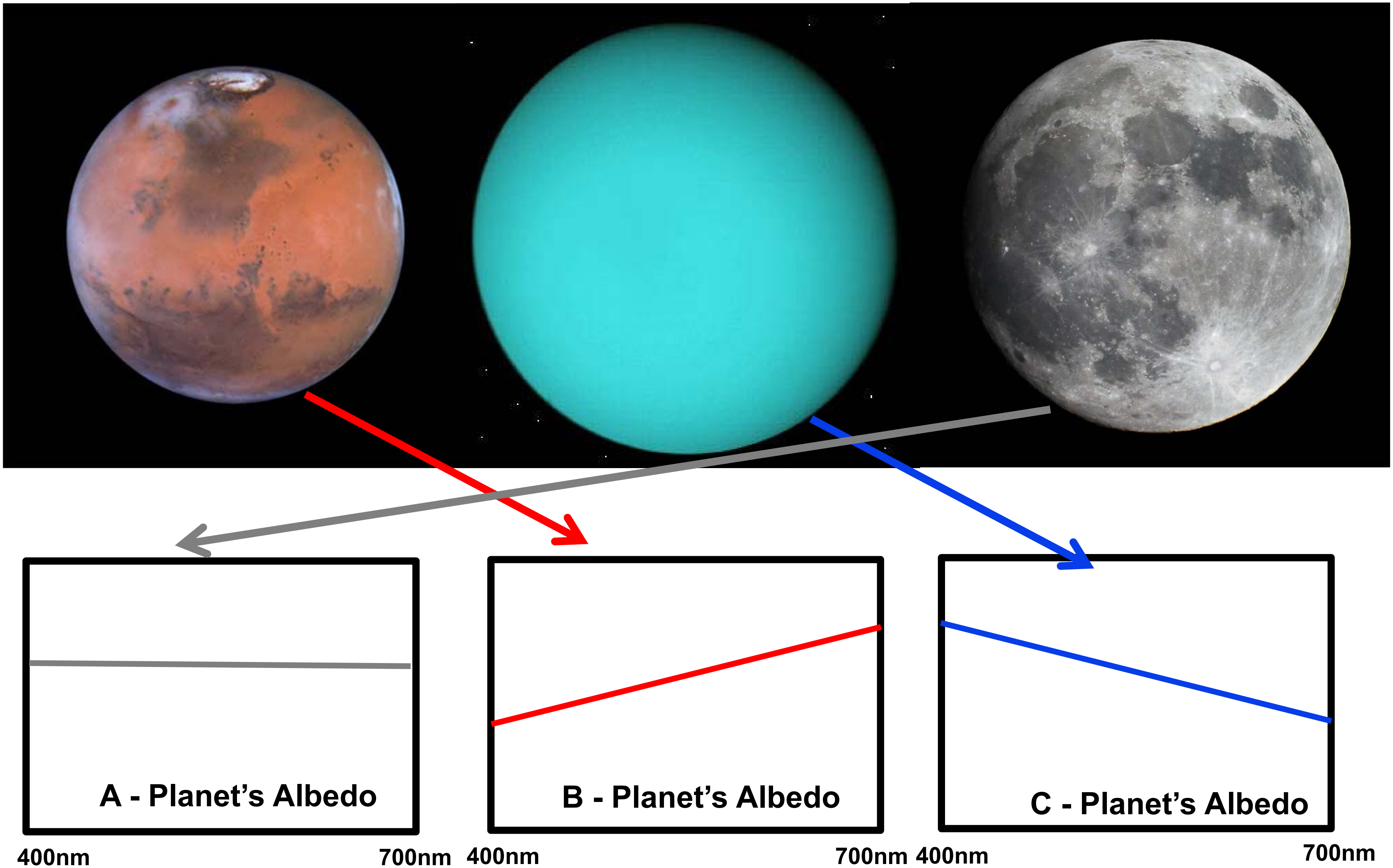
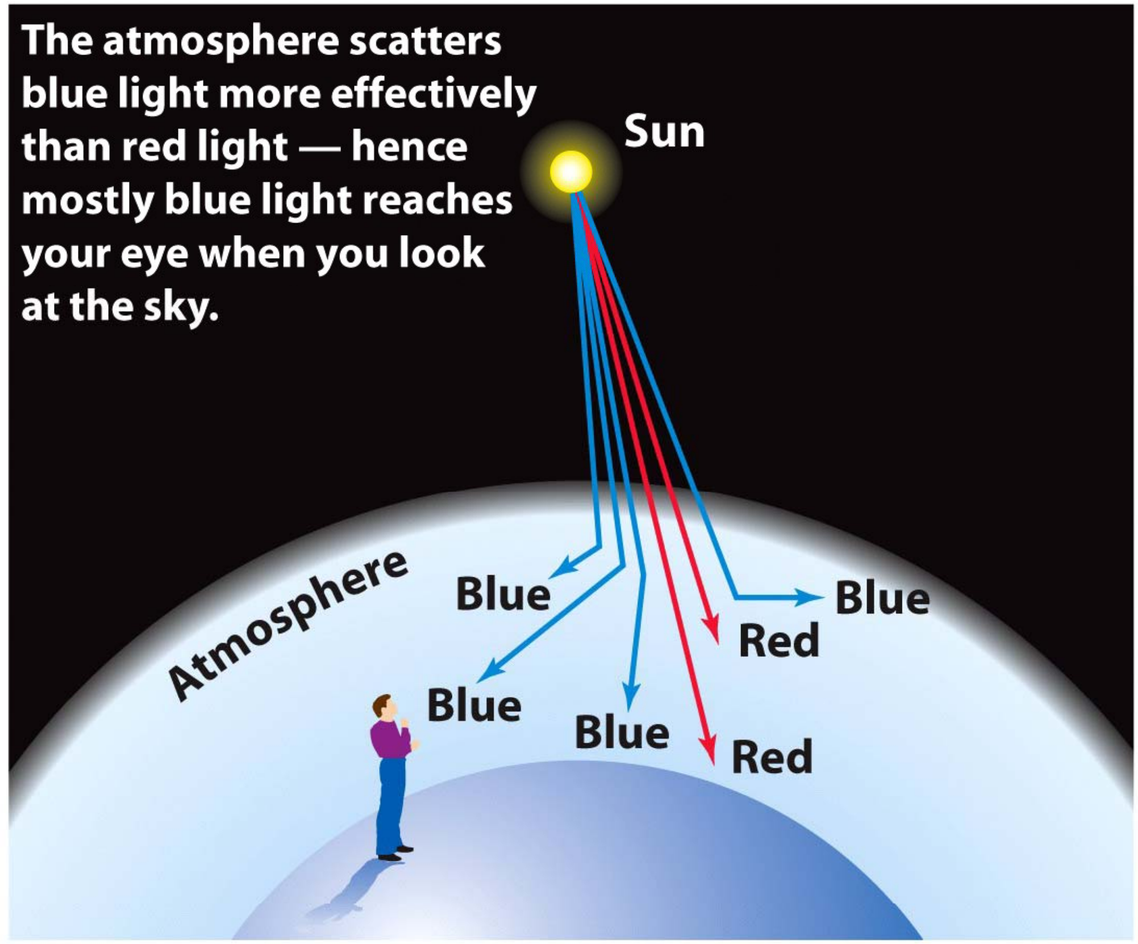


Scattering

- Light can bounce of particles without getting absorbed

- Earth's atmosphere is a good example
  - Look at a part of the sky away from the Sun
  - Where's that light coming from?

- Scattering in Earth's atmosphere is mostly by gas molecules
  - Very small - smaller than the wavelength of light
  - Scatters blue light more easily than red



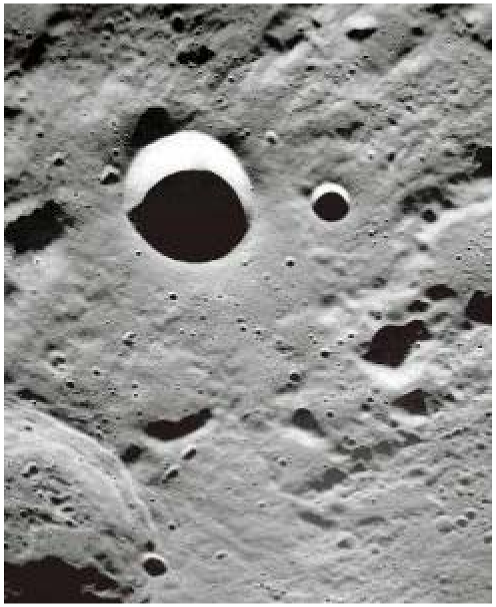
Why the sky looks blue

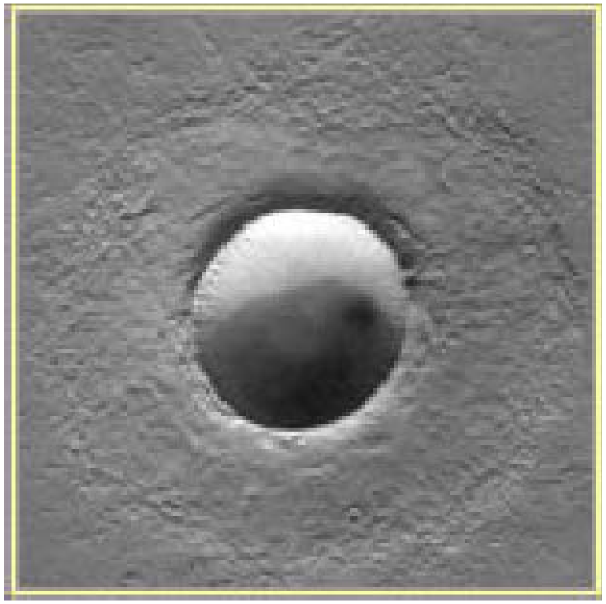
Box 5-4a
Universe, Eighth Edition

- **Why is the Sky on Mars not Blue?**

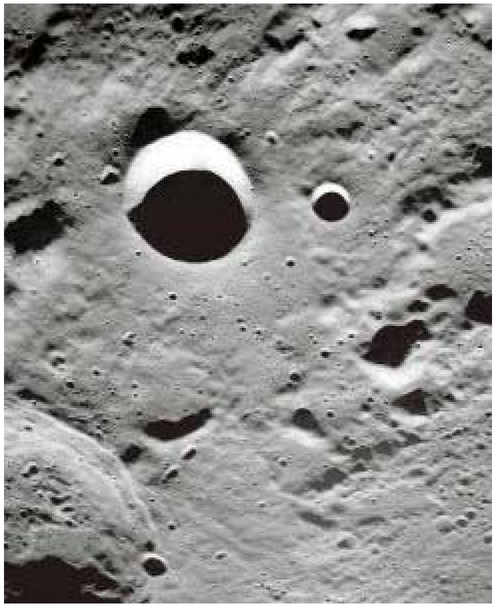
- **Why is the Sky on Mars not Blue?**
  - **Most of the scattering is from reddish dust**
  - **Dust is bigger than the wavelength of light**

- **Shadows on Mars vs the Moon**
  - **A difference from scattered light**
  - **Which is which?**

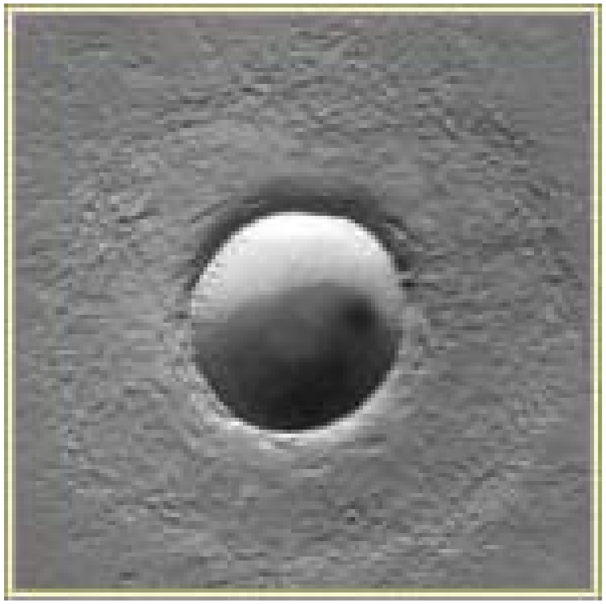




- **Shadows on Mars vs the Moon**
  - **A difference from scattered light**



Moon



Mars

Spectra

- **Atoms have small nuclei surrounded by orbiting electrons**
  - **Nuclei have almost all the mass**
  - **Occupy almost none of the volume**
  - **Electrons occupy orbits with only certain energies**

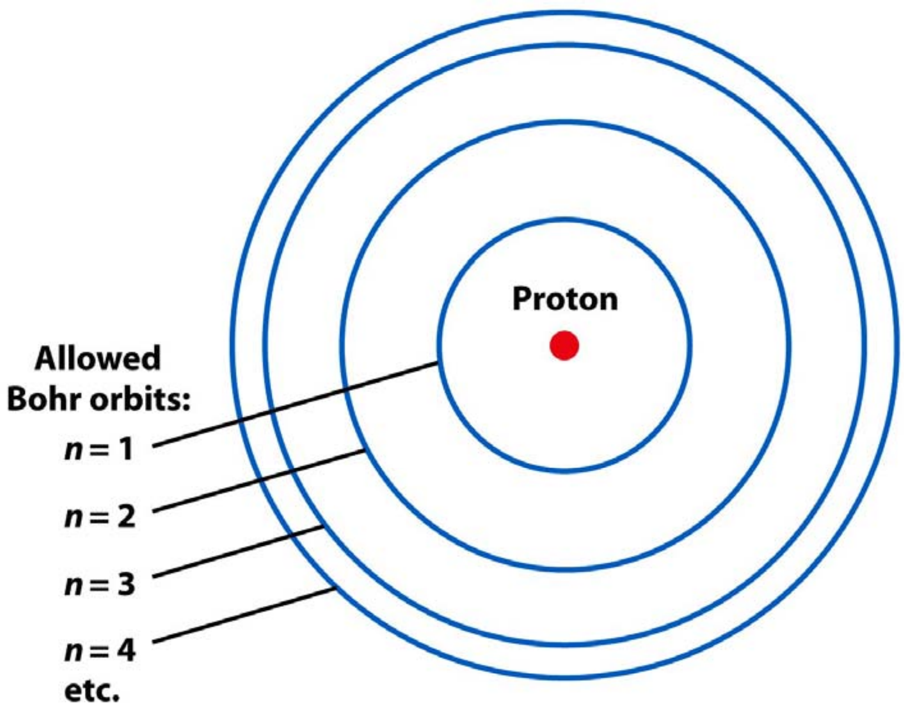


Figure 5-22
Universe, Eighth Edition

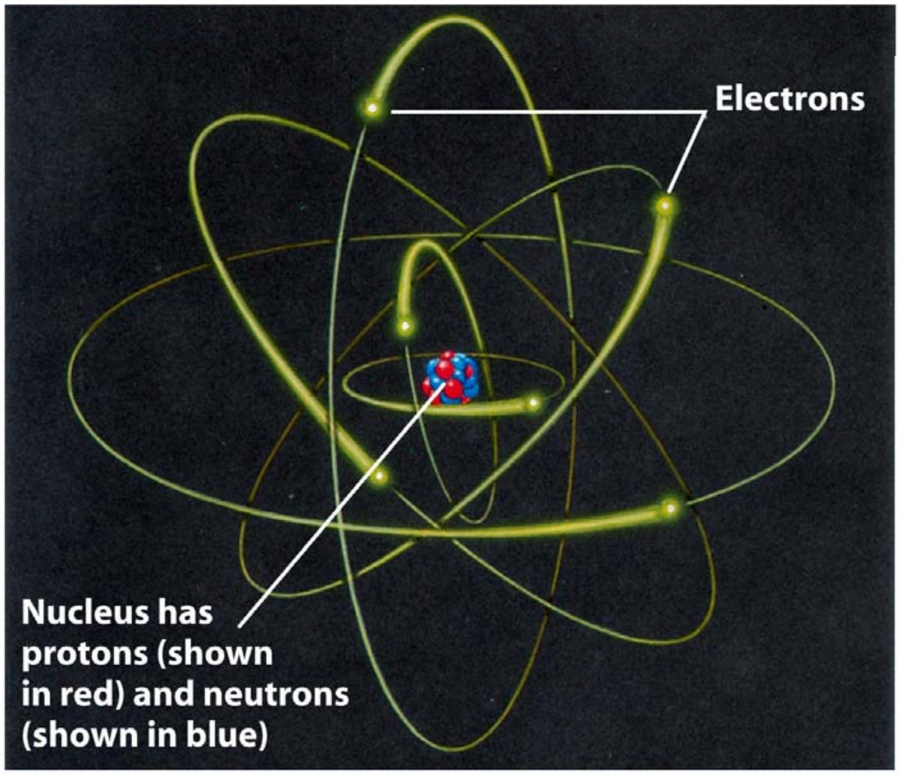
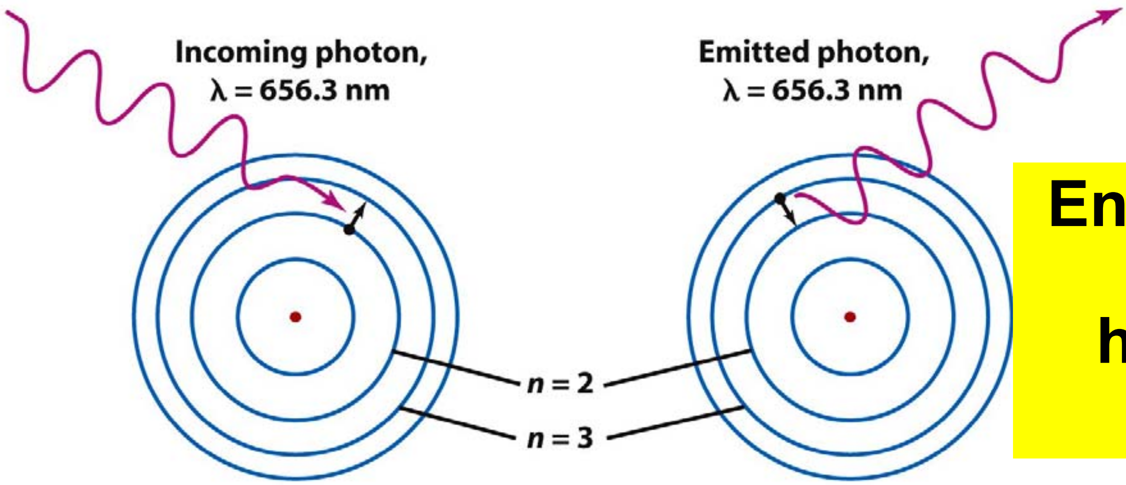


Figure 5-20
Universe, Eighth Edition

- Elections can jump from one orbit to another
  - Each jump requires a very specific amount of energy
  - Certain jumps are possible for some atoms, but not others
- Electromagnetic energy is…
  - Released when electrons go to a lower energy orbit
  - Absorbed when electrons go to a higher energy orbit
- Specific energies correspond to specific wavelengths



(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up to the $n = 3$ orbit

(b) Electron falls from the $n = 3$ orbit to the $n = 2$ orbit; energy lost by atom goes into emitting a 656.3-nm photon

Figure 5-23
Universe, Eighth Edition

Energy = h * c / wavelength

h is the planck constant 6.63×10^{-34} J s

- Usually there's roughly equal amounts of absorption and emission going on
  - But… emission is in all directions
  - Net absorption of background light as emission is weaker
  - No hot background – then all you see is the weak emission

- Different possibilities
  - Continuum
  - Adsorption spectra
    - Reflection from planet - surfaces
    - Solar atmosphere
  - Emission spectra
    - Planetary atmosphere limb views

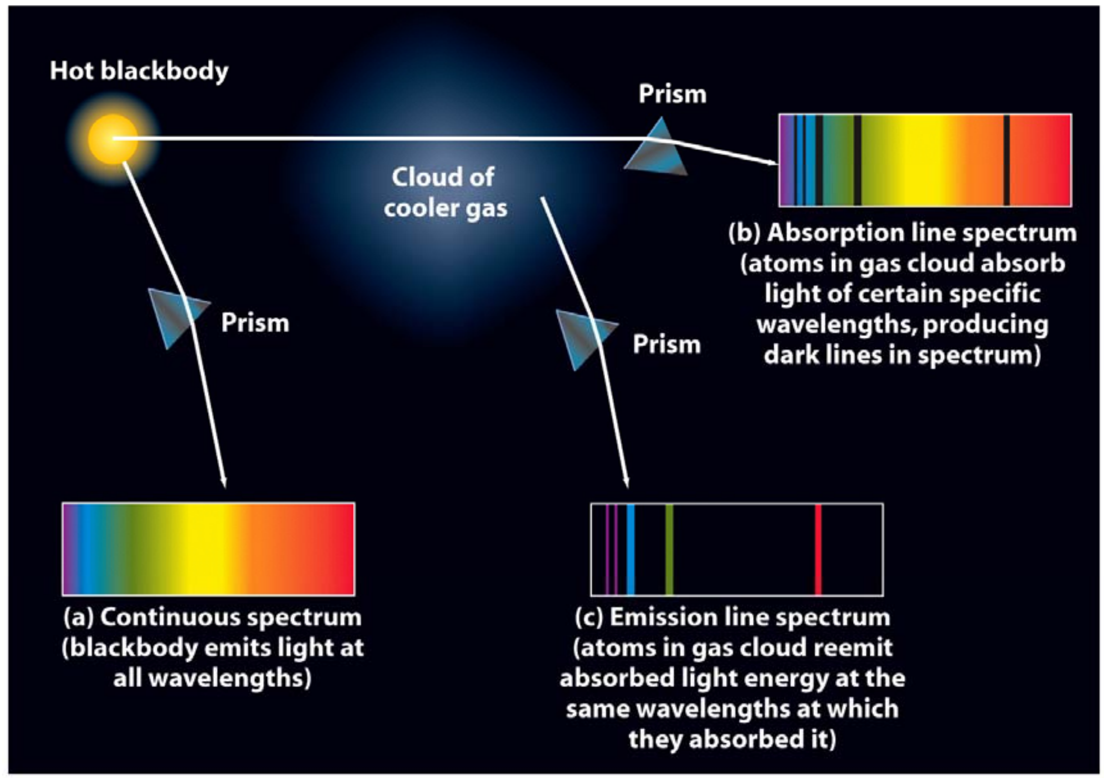


Figure 5-16
Universe, Eighth Edition

- **Each atom produces a very characteristic spectral fingerprint**
- **Molecules produce spectra lines from:**
  - **Bending and stretching of bonds between atoms**
  - **Changes in rotation of the molecule**

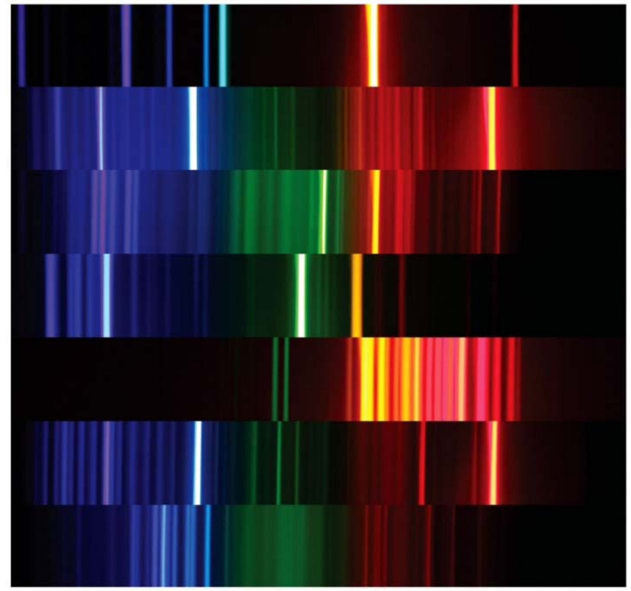
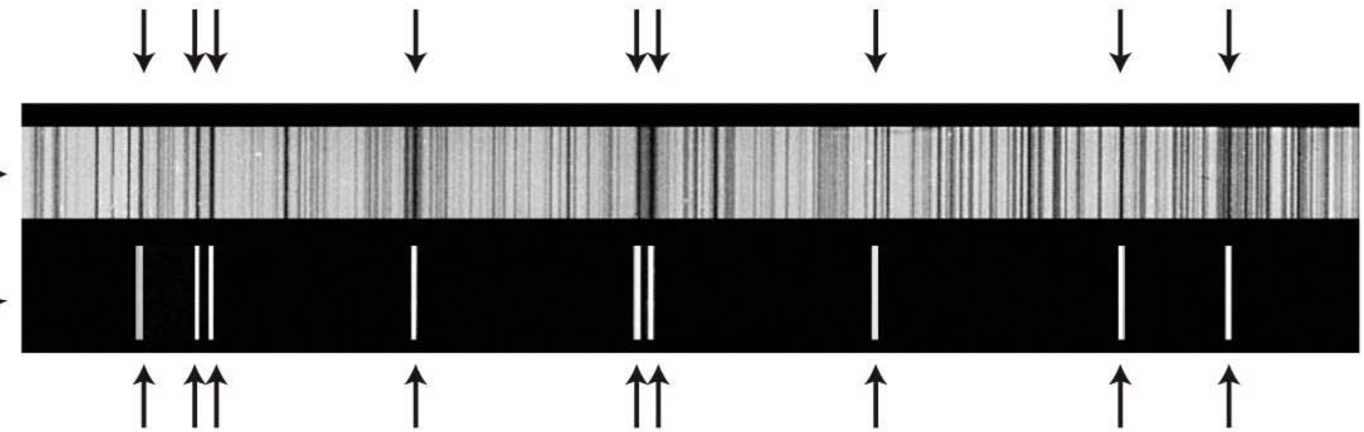


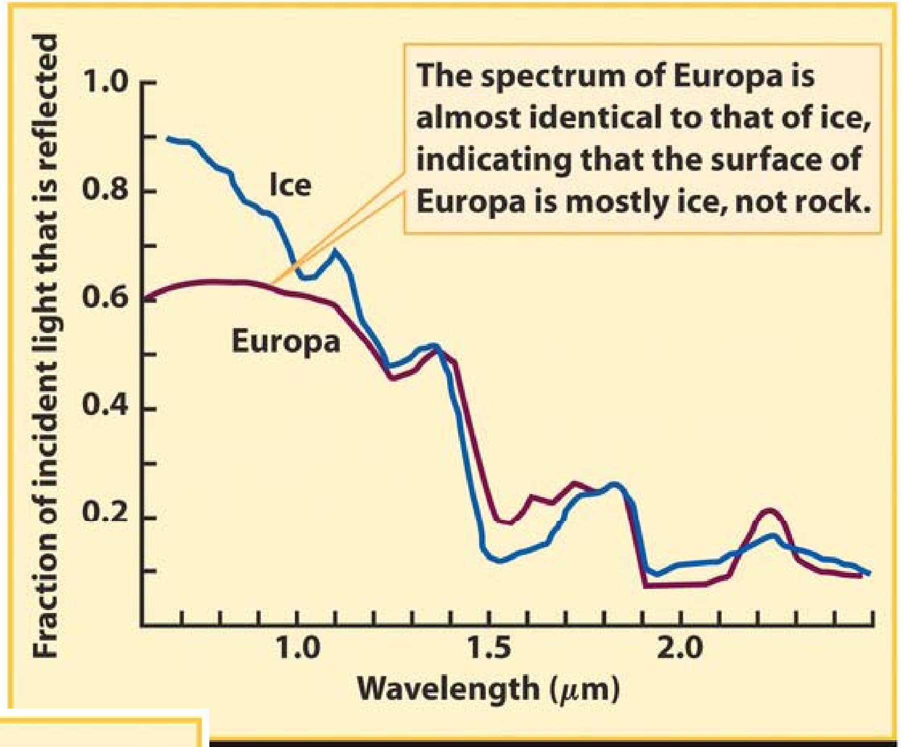
Figure 5-15
Universe, Eighth Edition

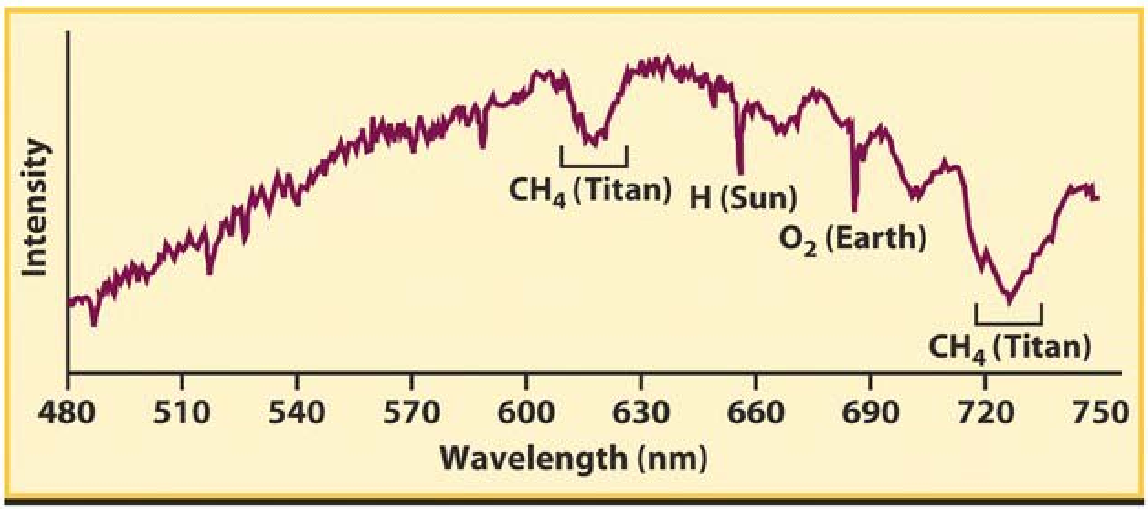


For each emission line of iron, there is a corresponding absorption line in the solar spectrum; hence there must be iron in the Sun's atmosphere

Figure 5-17
Universe, Eighth Edition

- **Matching Lab spectra to observations**
  - **Determine planetary composition remotely**
  - **Most telescopes are on the ground - be careful of absorptions from Earth's atmosphere**





(a) The spectrum of sunlight reflected from Titan

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**

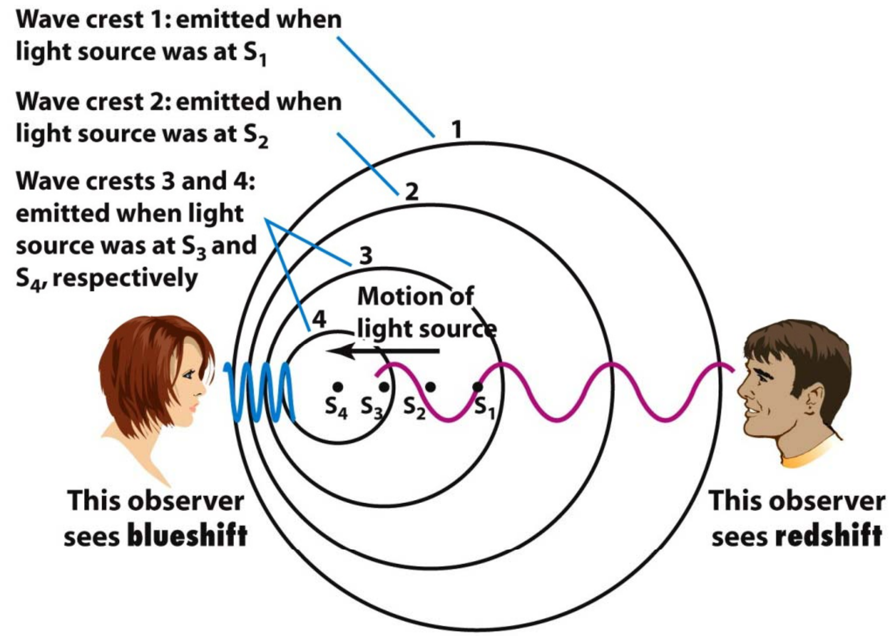
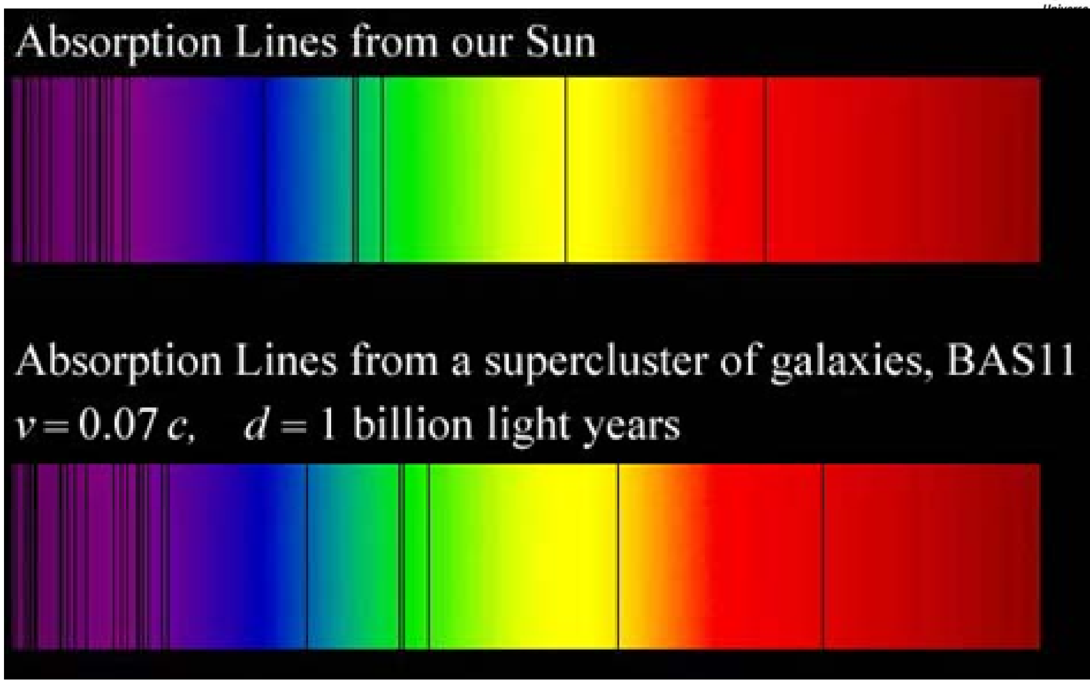


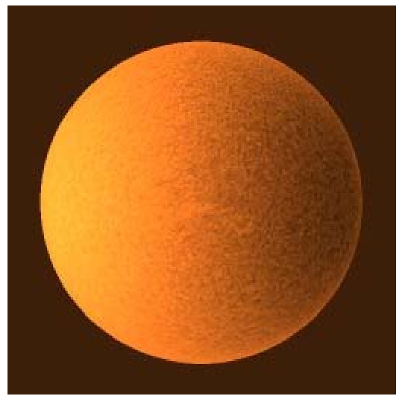
Figure 5-26
Eighth Edition
H. Freeman and Company

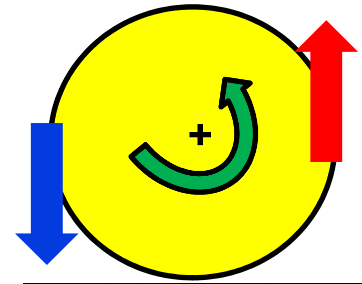


$$\lambda = \lambda_o \left(1 + {}^{v}\!/_{c}\right)$$

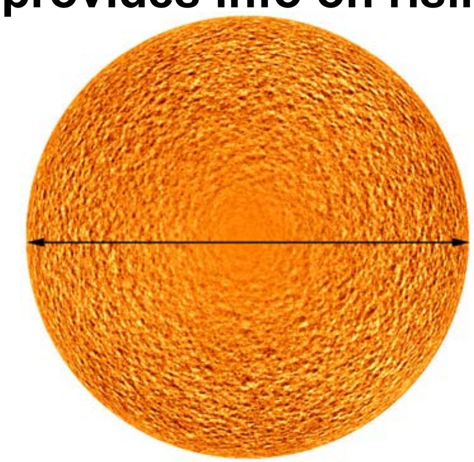
λ = Observed wavelength
λ_0 = original wavelength
v = velocity away from observer
c = speed of light

- 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



In this lecture…

- What's radiation?
- Blackbody radiation
  - Temperature and radiation
  - Emissivity
- Sunlight and starlight
  - Energy for planetary surfaces
- Reflection
  - Albedo, color & scattering
- Emission and absorption lines
  - Atomic structure
  - Emission and absorption spectra
- The Doppler effect

Next: Exploring the solar system from the Earth

- Reading
  - Chapter 5 to revise this lecture
  - Chapter 6 for next Tuesday