Astronomy 1 – Fall 2019

Announcements

1. Please use homework boxes in front of the Physics Study Room, not those in the Broida 1640 lobby (as originally stated).
2. Please use GauchoSpace to check that your HW 1 score was uploaded to the Gradebook.
3. Please also check that you got credit (1 point) for taking the Knowledge Assessment.
4. I will start awarding participation points for using your iClicker *today*. So don't worry if you joined the class late. You must register your iClicker; see the iClicker block on GauchoSpace.

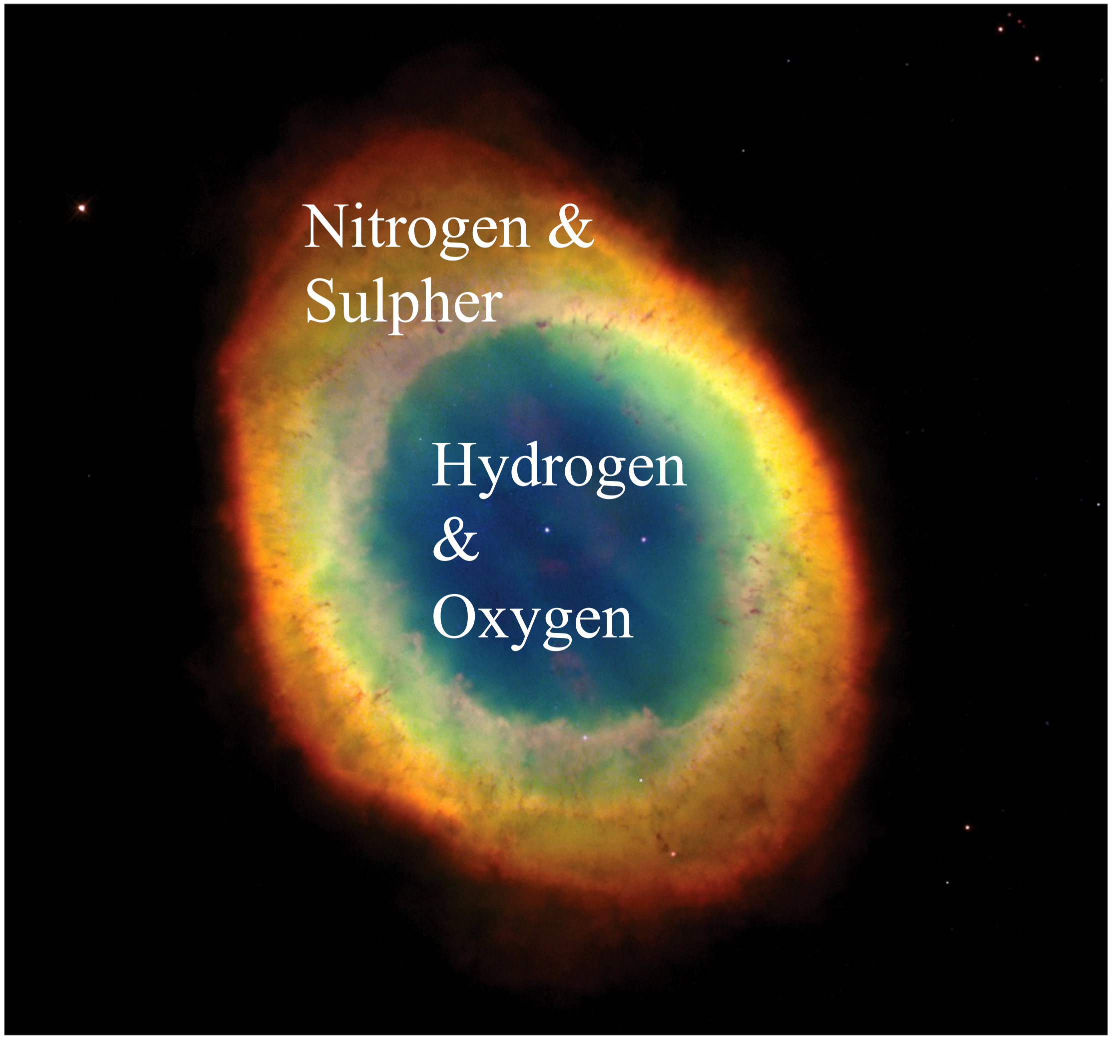
Lecture 4; October 14, 2019

Previously on Astro-1

- Newton's Laws of Motion:
  1. Inertia
  2. Force is proportional to acceleration; defines inertial mass
  3. Action/Reaction
- Newton's Law of gravity; defines gravitational mass
- The orbits of planets
- Tides

Today on Astro-1

- The nature of light.
- Properties of light emitted by opaque sources.
- Spectral lines



Chapter 5 Opener
Universe, Tenth Edition
Hubble Heritage Team, AURA/STScI/NASA

Iclicker Question:
What is the Energy of a Photon?

Example: DNA molecules are easily broken when hit with ultraviolet light at 260 nm. How much energy does a single photon at this wavelength have?

A. 7.6×10^{-19} J
B. 7.6×10^{-17} J
C. 7.6 J
D. 5.7×10^{-49} J
E. 7.6×10^{19} J

Planck's constant = 6.625×10^{-34} J s
speed of light = 2.9979×10^{8} m / s

Planck's Law:
Describes light in terms of particles called photons

$$E = \frac{hc}{\lambda}$$ or $$E = h\nu$$

E = Energy of a photon
h = Planck's constant = 6.625×10^{-34} J s
c = speed of light
λ = wavelength of light
ν = frequency of light

Iclicker Question: What is the Energy of a Photon?

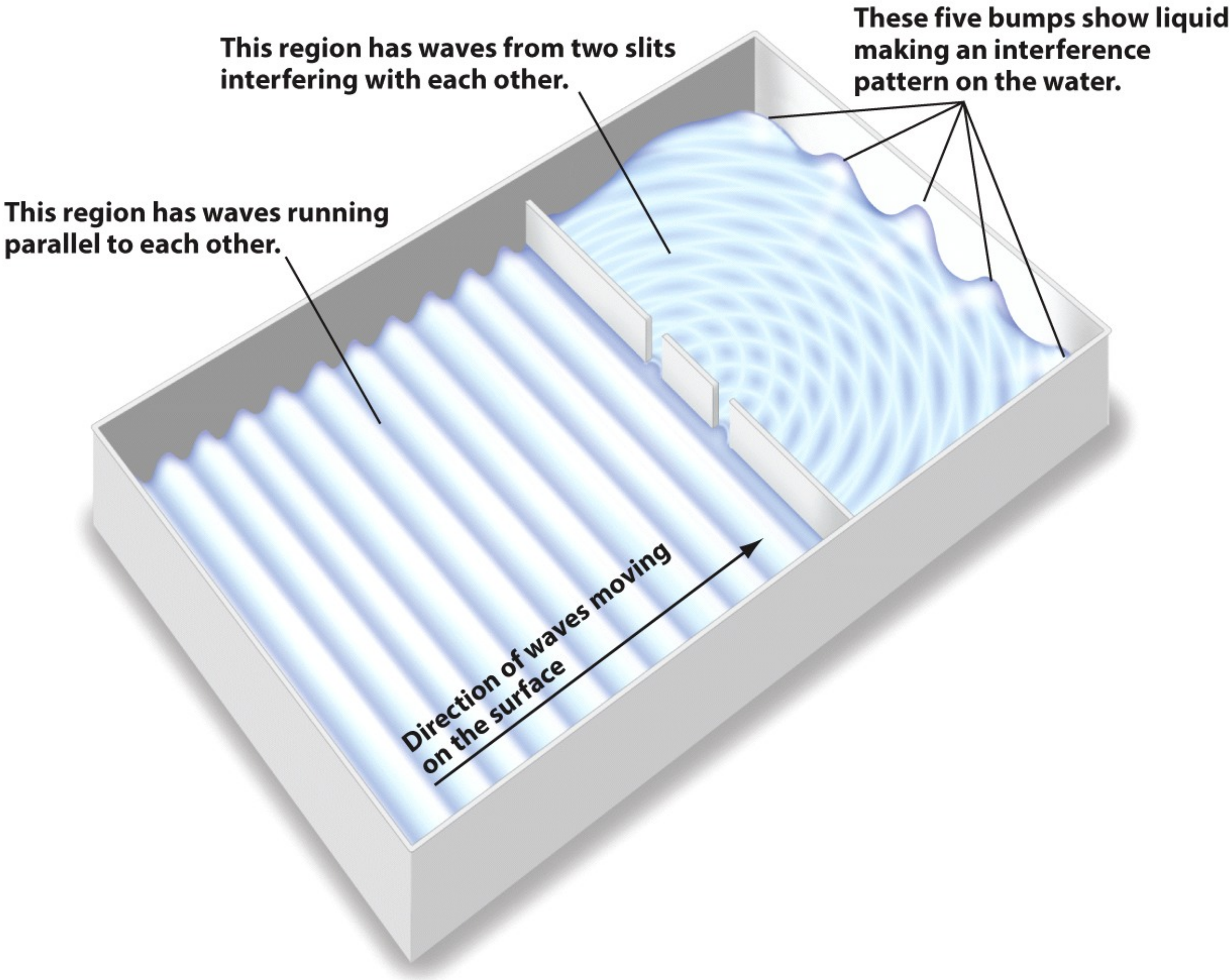
Example: DNA molecules are easily broken when hit with ultraviolet light at 260 nm. How much energy does a single photon at this wavelength have?

A. 7.6×10^{-19} J
B. 7.6×10^{-17} J
C. 7.6 J
D. 5.7×10^{-49} J
E. 7.6×10^{19} J

$$E = \frac{hc}{\lambda} = \frac{(6.625 \times 10^{-34}\,Js)(3.00 \times 10^{8}\,m/s)}{2.60 \times 10^{-7}\,m} = 7.64 \times 10^{-19}\,J$$

Light is also a Wave

Properties of Waves
Example: Interference



This region has waves from two slits interfering with each other.

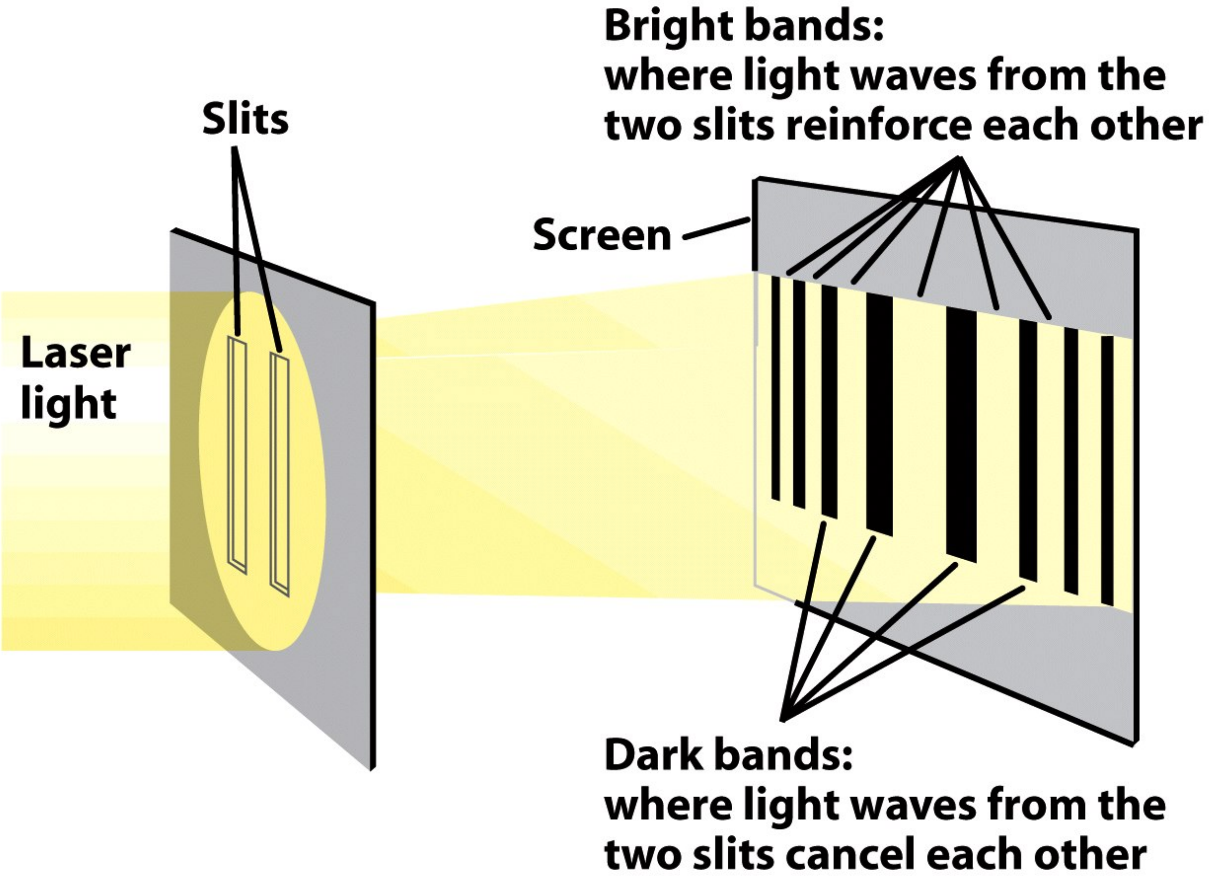
These five bumps show liquid making an interference pattern on the water.

This region has waves running parallel to each other.

Direction of waves moving on the surface

Figure 5-5b
Universe, Tenth Edition
© University of Colorado, Center for Intergrated Plasma Studies, Boulder, CO

Young's Double-Slit Experiment Illustrates that Light is a Wave



An experiment with light

Figure 5-5a
Universe, Eighth Edition

Light is Electromagnetic Radiation

But what "wiggles" to make the wave? In 1860 James Clerk Maxwell showed that all forms of light consist of oscillating electric and magnetic fields that move through space at a speed of 3.00 × 10^5 km/s or 3.00 × 10^8 m/s. This figure shows a "snapshot" of these fields at one instant.

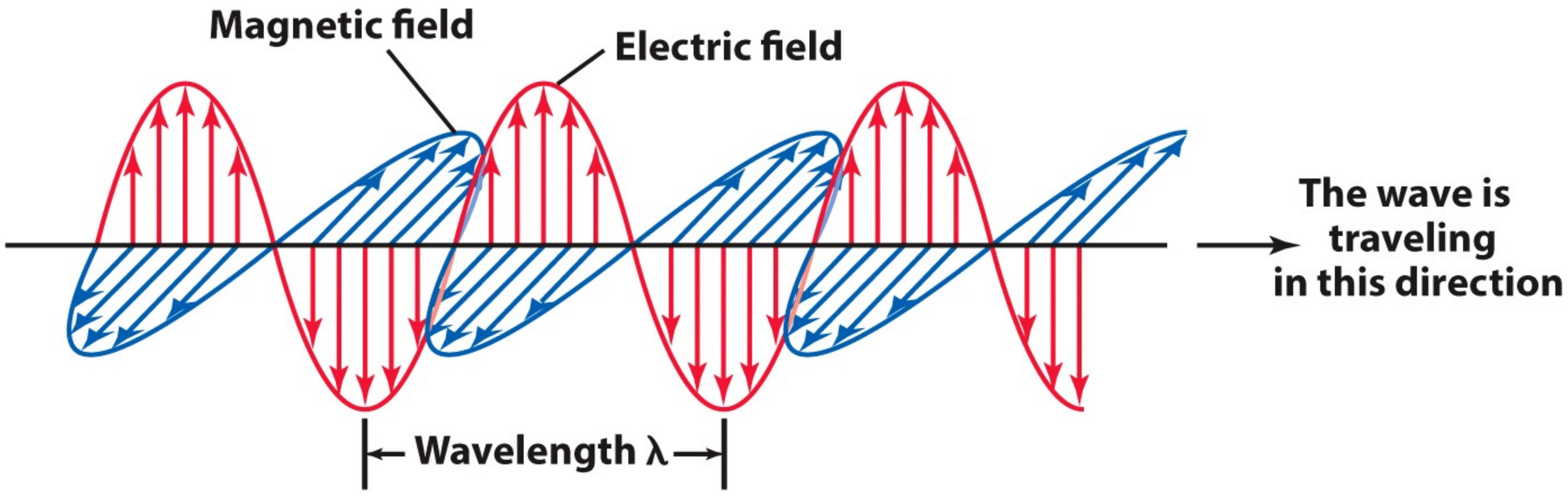


Figure 5-6
Universe, Tenth Edition

Frequency and Wavelength of an Electromagnetic Wave

$$\nu = \frac{c}{\lambda}$$

ν = frequency of an electromagnetic wave (in Hz – a Hertz is one cycle per second)
c = speed of light, 3×10^{8} m/s
λ = wavelength of the wave (in meters)

Example: What is the frequency of visible light at 540 nm?

$$540nm\left(\frac{1m}{10^{9}nm}\right) = 5.4\times10^{-7}m$$

$$\nu = \frac{3\times10^{8}m/s}{5.4\times10^{-7}m} = 5.6\times10^{14}Hz$$

Color of Light Depends on Its Wavelength

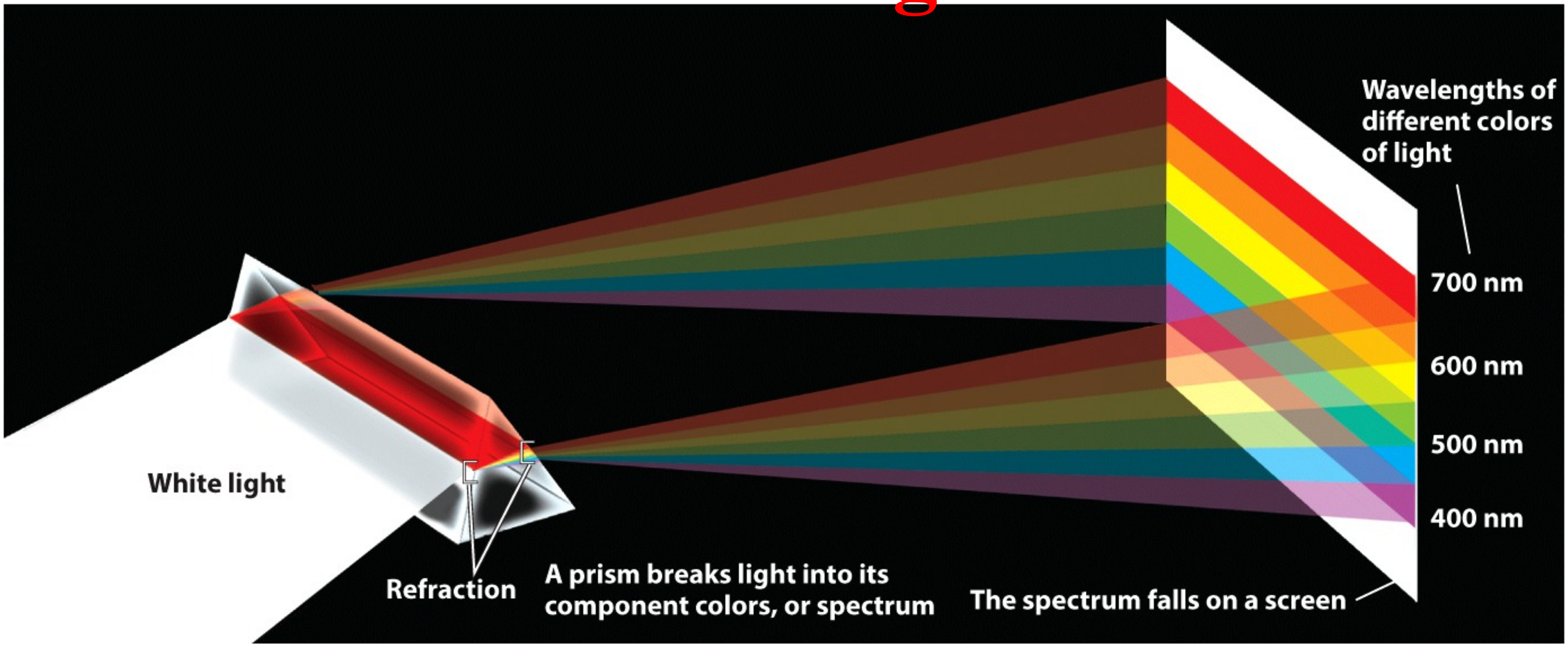


Figure 5-3
Universe, Tenth Edition

Newton used this experiment to prove that prisms do not add color to light but merely bend different colors through different angles. It also proved that white light, such as sunlight, is actually a combination of all the colors that appear in its spectrum.

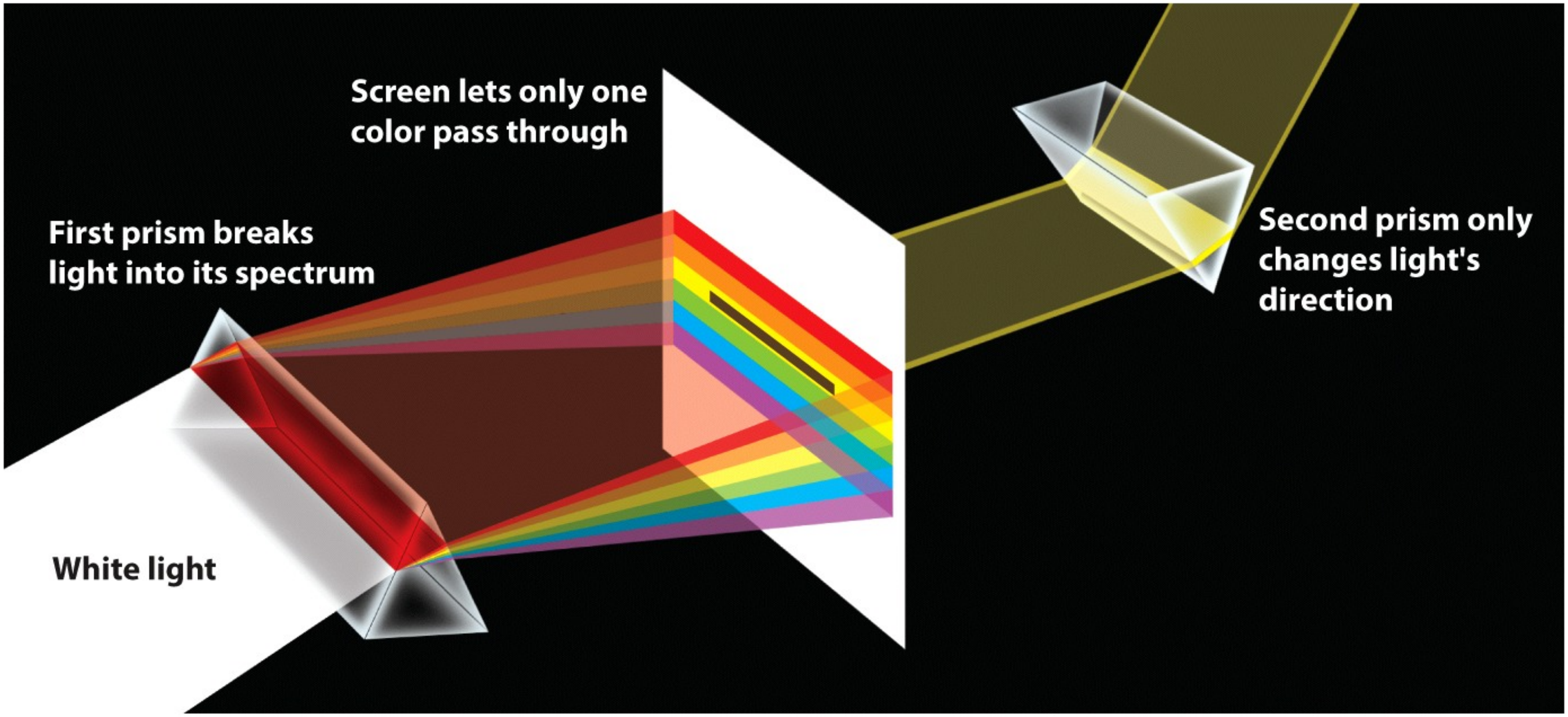


Figure 5-4
Universe, Tenth Edition

What about "invisible light?" Around 1800 British astronomer William Herschel passed sunlight through a prism and held a thermometer just past the red end of the visible spectrum. The thermometer registered a temperature increase, indicating there was "infrared" light that we could not see.

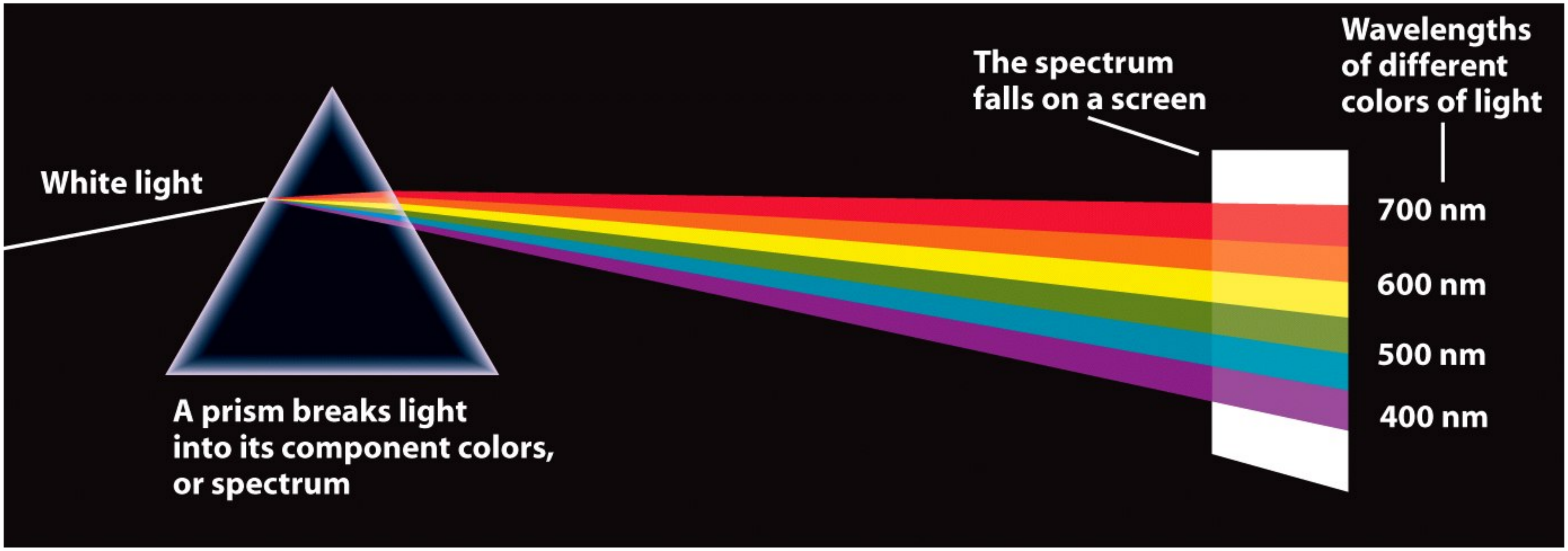


Figure 5-3
Universe, Eighth Edition
© 2008 W. H. Freeman and Company

Human Eye is Sensitive to a Small Part of the Electromagnetic Spectrum

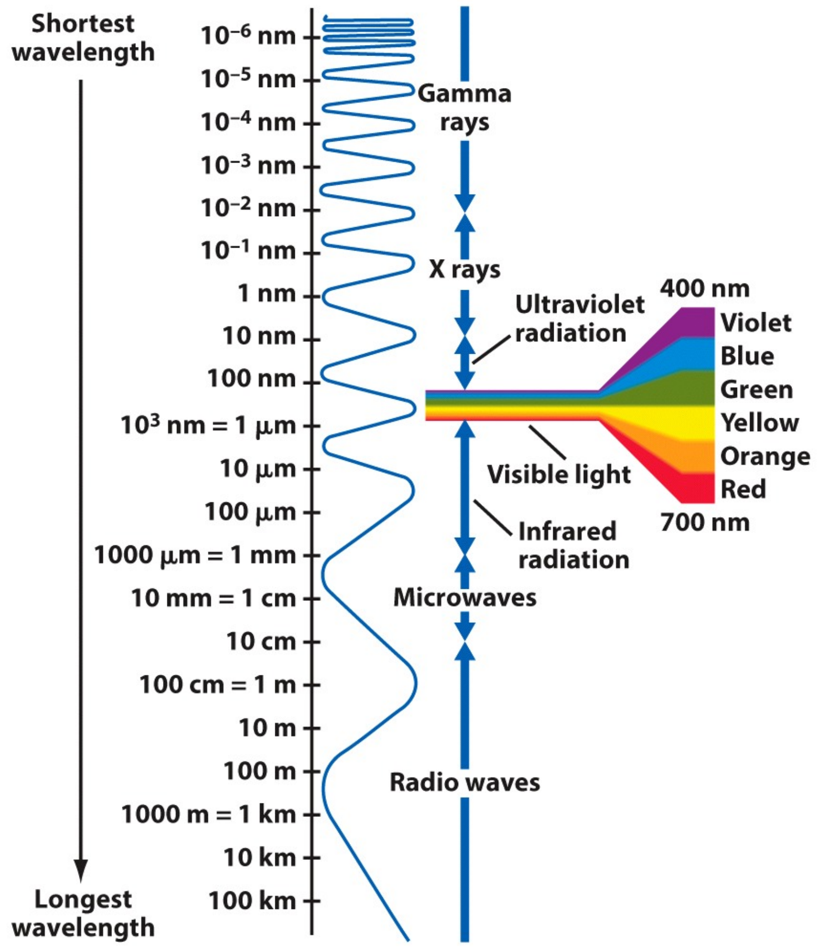
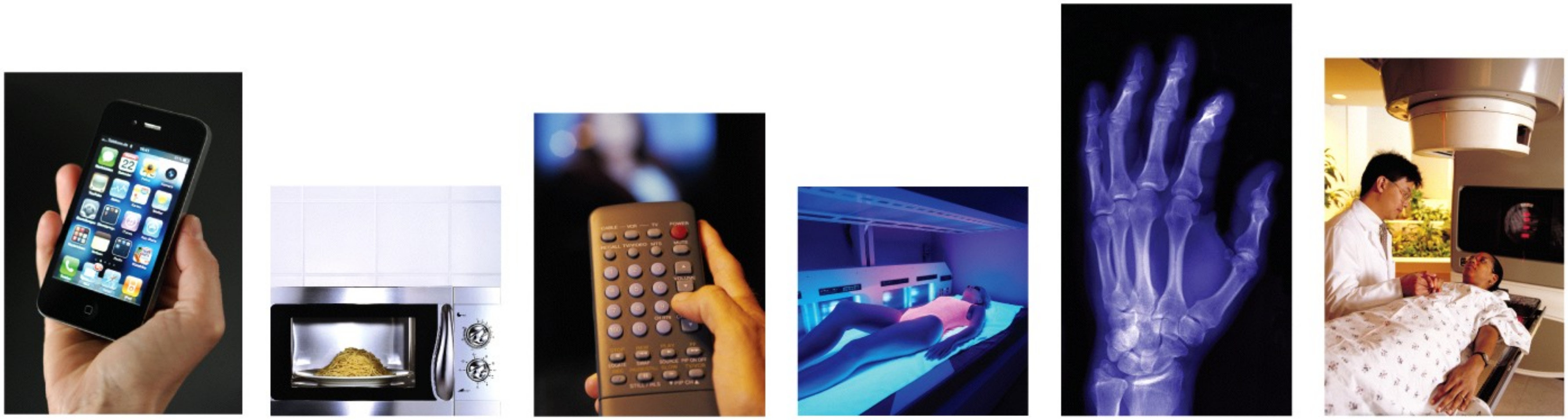


Figure 5-7
Universe, Tenth Edition

…but you are familiar with ‘invisible light’



(a) Mobile phone: radio waves

(b) Microwave oven: microwaves

(c) TV remote: infrared light

(d) Tanning booth: ultraviolet light

(e) Medical imaging: X-rays

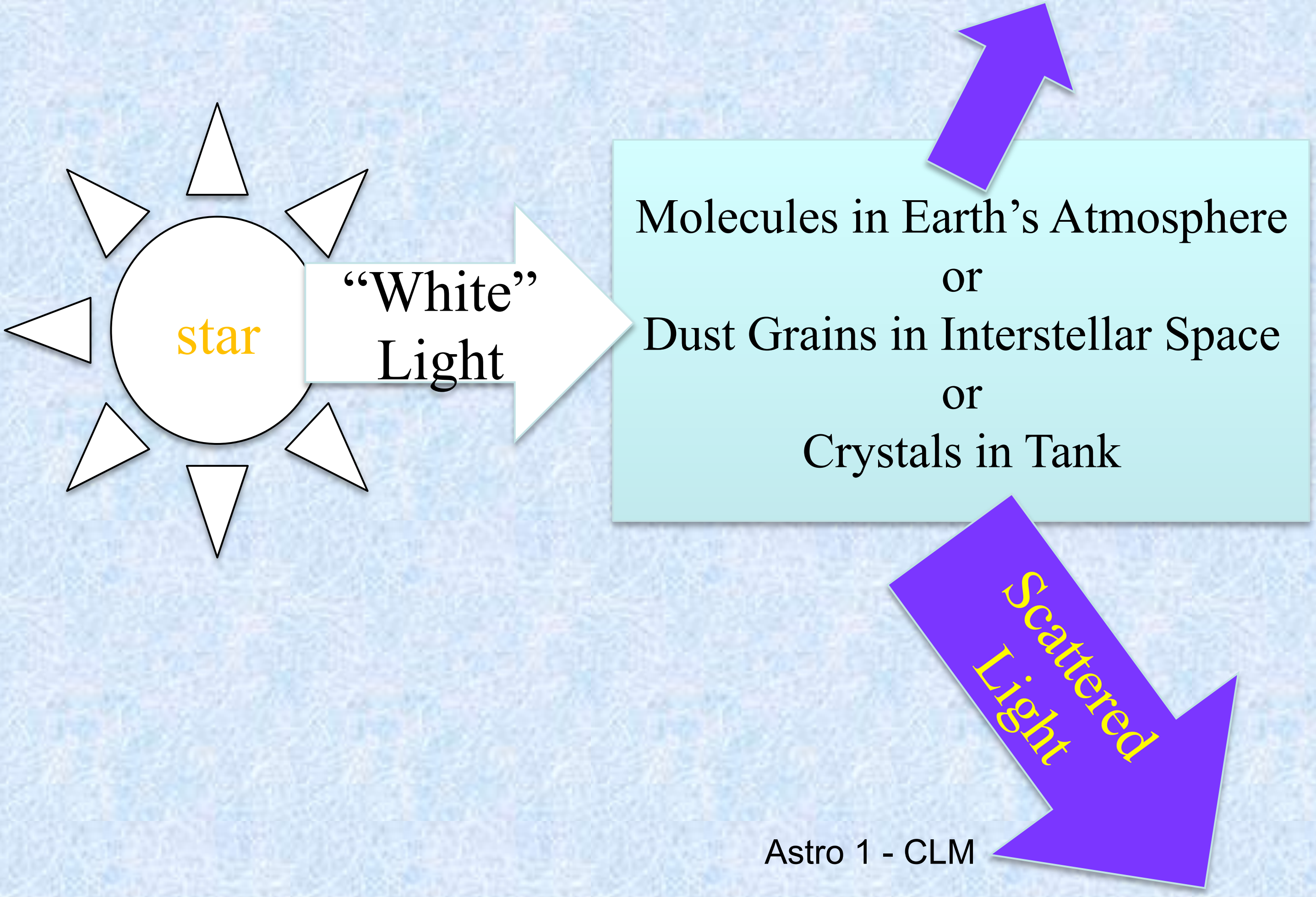
(f) Cancer radiotherapy: gamma rays

Figure 5-8
Universe, Tenth Edition
a: Maurizio Gambarini/dpa/Corbis; b: Michael Haegele/Corbis; c: Bill Lush/Taxi/Getty; d: Neil McAllister/Alamy; e: Ted Kinsman/Photo Researchers, Inc.; f: Will and Deni McIntyre/Science Source

It’s only invisible to the human eye.

Tabletop Sunset Demonstration

Short wavelength light scatters more than does long wavelength light.



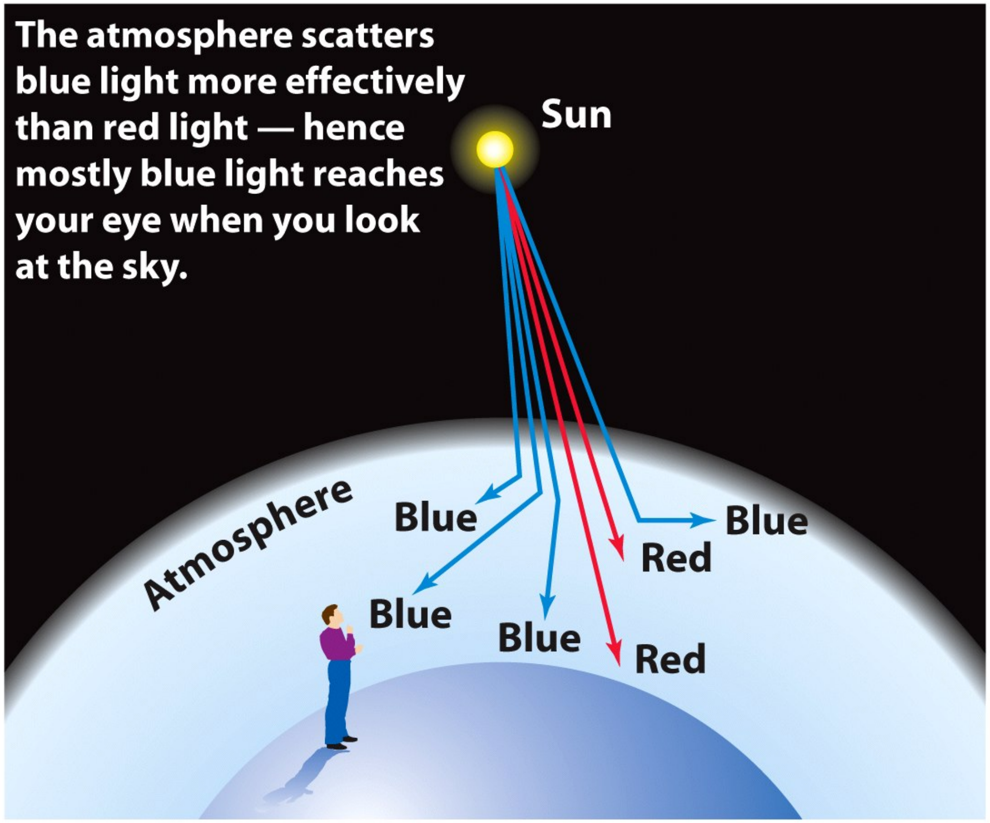
star

"White" Light

Molecules in Earth's Atmosphere
or
Dust Grains in Interstellar Space
or
Crystals in Tank

Scattered Light

Why is the Sky Blue?



The atmosphere scatters blue light more effectively than red light — hence mostly blue light reaches your eye when you look at the sky.

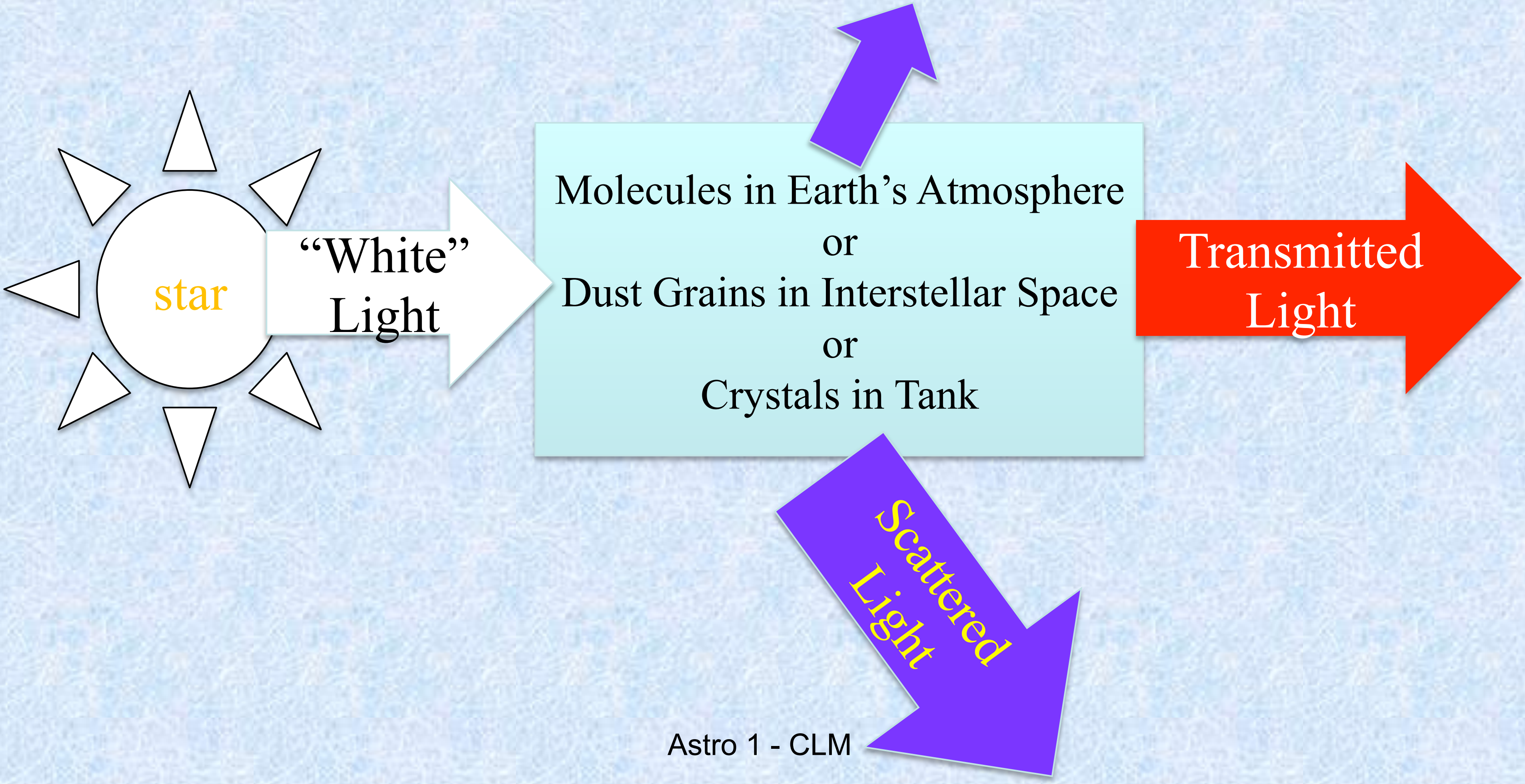
Why the sky looks blue

Box 5-4a

Universe, Eighth Edition

Tabletop Sunset Demonstration

If the long wavelength photons do not scatter,
then red light is transmitted.



star

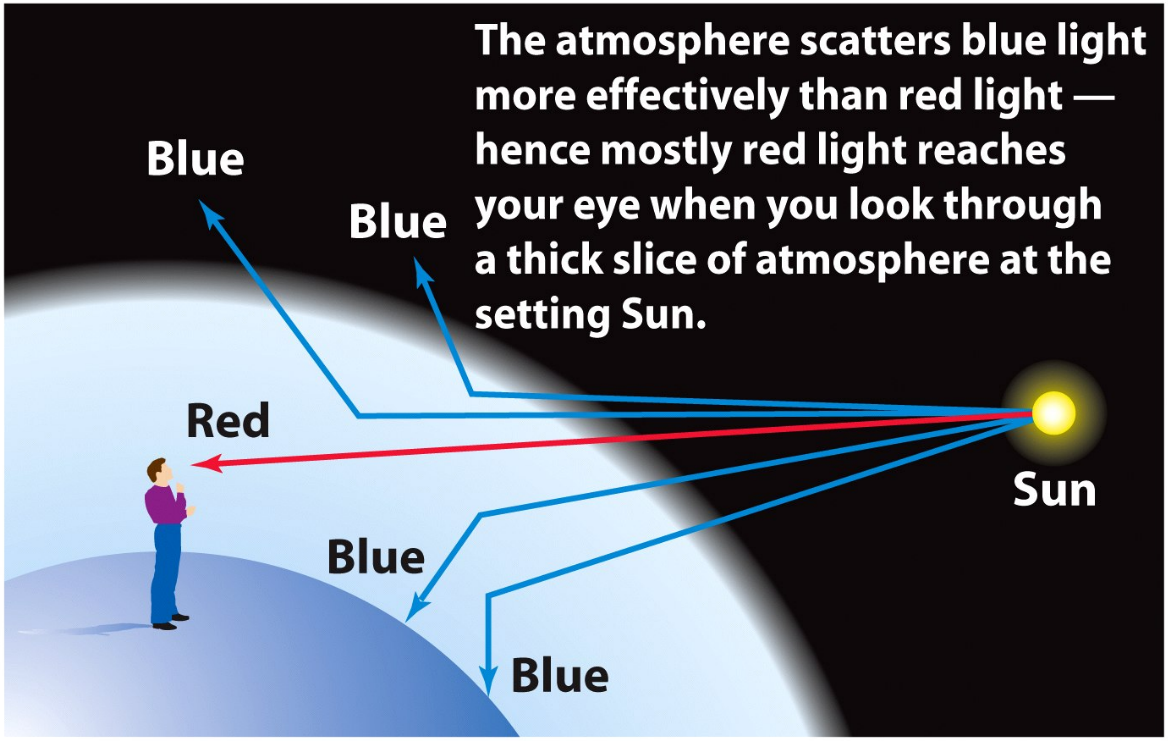
"White" Light

Molecules in Earth's Atmosphere
or
Dust Grains in Interstellar Space
or
Crystals in Tank

Transmitted Light

Scattered Light

Why is the Sunset Red?


The atmosphere scatters blue light more effectively than red light — hence mostly red light reaches your eye when you look through a thick slice of atmosphere at the setting Sun.

Why the setting Sun looks red

Box 5-4b
Universe, Eighth Edition

In the interstellar medium, scattering makes distant stars appear redder than they really are.

The Light Emitted by Opaque Sources

“ Blackbody Radiation”

Temperature is a measure of the average speed of the atoms in an object.

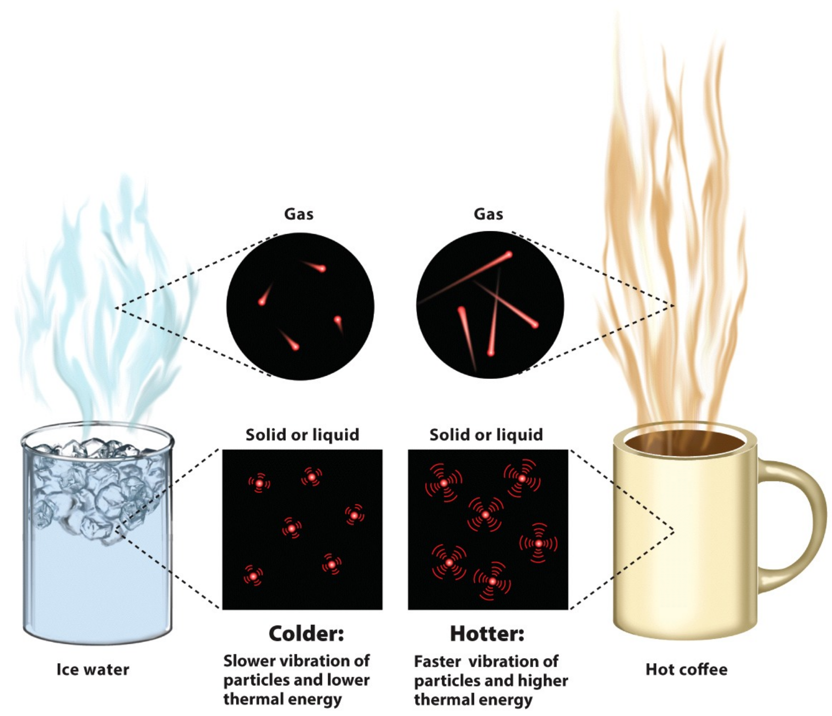
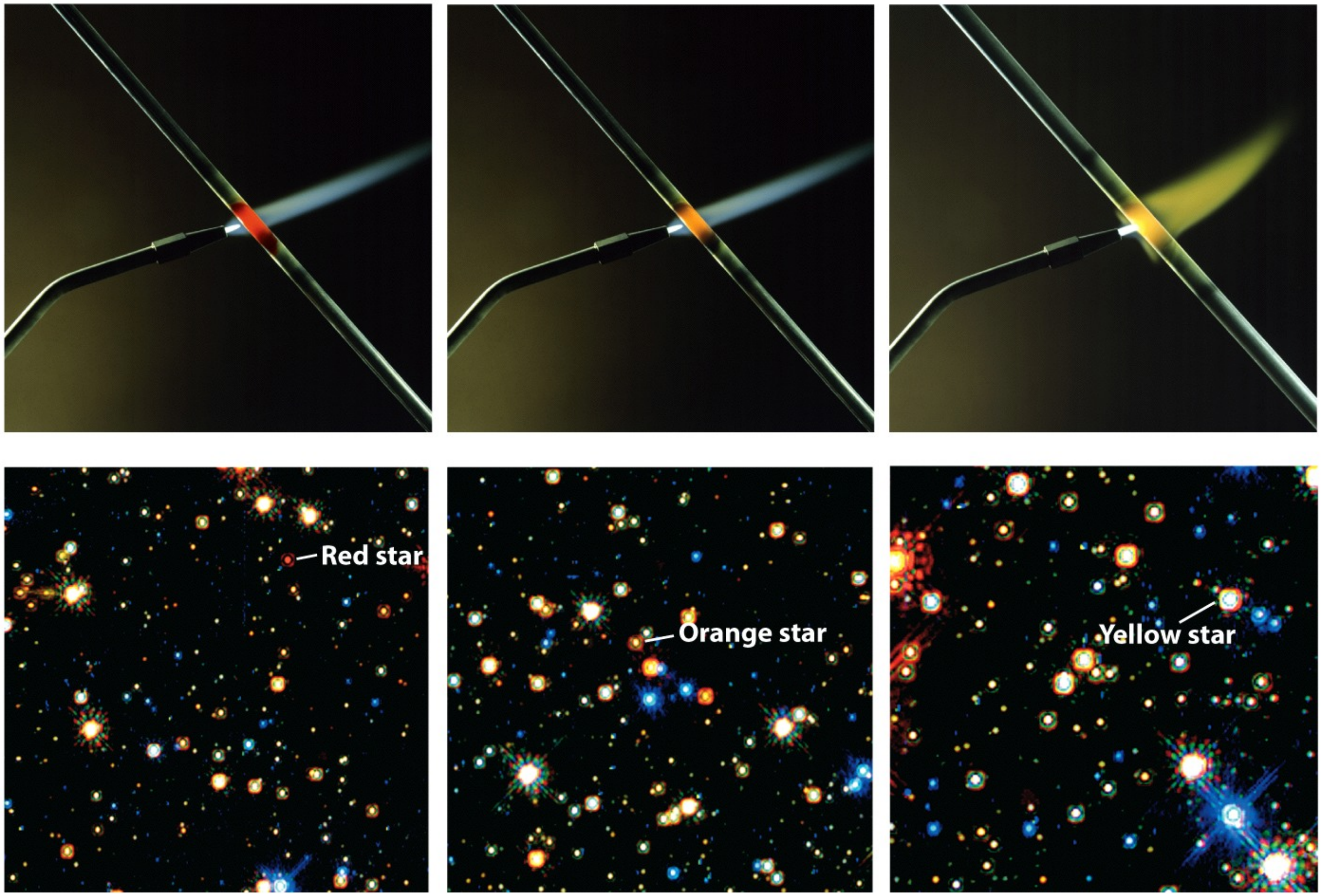


Figure 5-11
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

But photons travel at the speed of light, regardless of their energy.

What is meant then by the temperature of radiation?

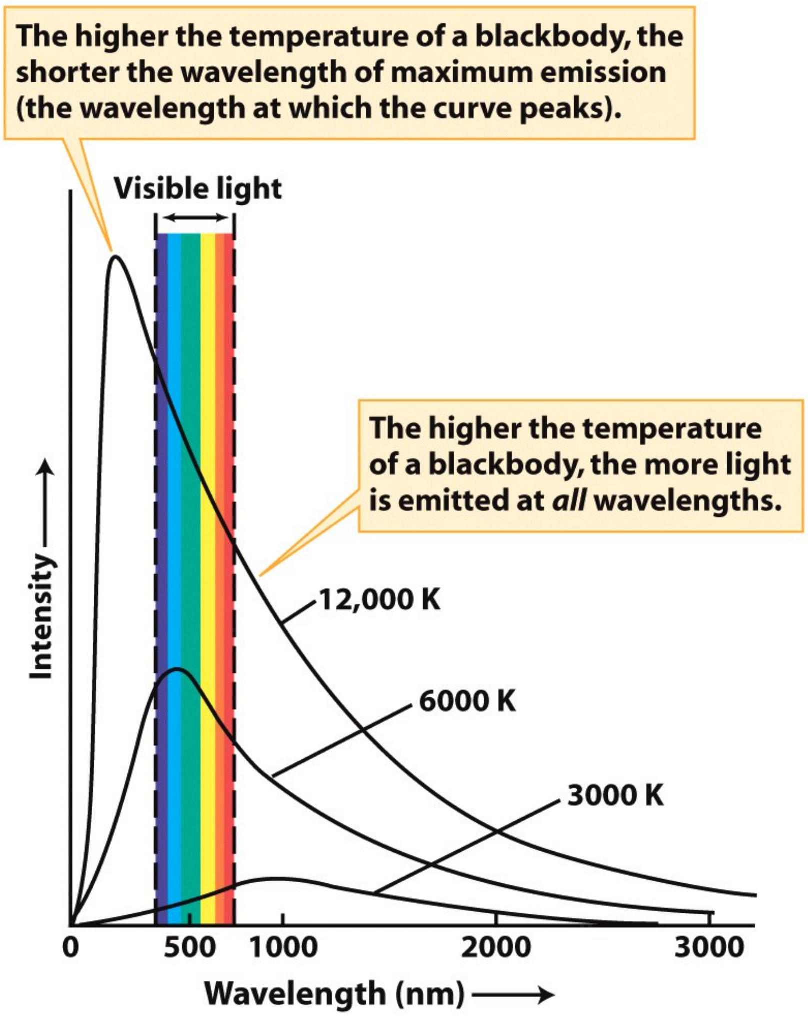
An opaque object emits electromagnetic radiation according to its temperature



(a) Hot: glows deep red (b) Hotter: glows orange (c) Even hotter: glows yellow

Figure 5-9
Universe, Tenth Edition
top row: © 1984 Richard Megna Fundamental Photographs; bottom row: NASA

The Hotter the Object the Bluer Its Light



The higher the temperature of a blackbody, the shorter the wavelength of maximum emission (the wavelength at which the curve peaks).

The higher the temperature of a blackbody, the more light is emitted at *all* wavelengths.

Figure 5-11
Universe, Eighth Edition
© 2008 W. H. Freeman and Company

Wien’s Law for a blackbody

$$\lambda_{max} = \frac{0.0029Km}{T}$$

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

T = temperature of the object (in Kelvins).

(The K and m above are units of Kelvins and meters).

Hotter Objects Emit More Light

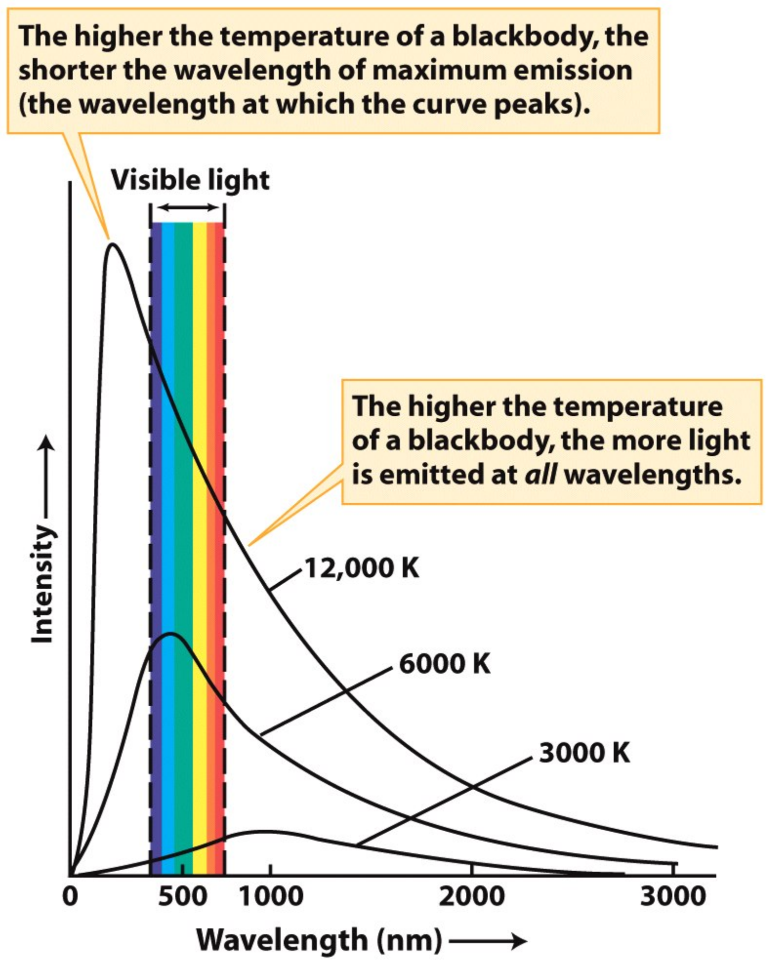


Figure 5-11
Universe, Eighth Edition

Intensity: [Energy emitted / time / area / unit wavelength / solid angle]

Flux: amount of energy passing through one square meter every second.

- Energy is usually measured in Joules (J).
- One joule per second is a Watt (W) – a measure of power.

Demo: Spectrum of an Incandescent Light Bulb

Passing electrical current through the wire in a lightbulb causes the wire to heat up. How will the light change as the current is increased?

A. The light will remain white but get brighter.
B. It will become brighter and bluer.
C. It will become fainter and bluer.
D. It will become brighter and redder.
E. It will become fainter and redder.

Demo: Spectrum of an Incandescent Light Bulb

Passing electrical current through the wire in a light bulb causes the wire to heat up. How will the light change as the current is increased?

A. The light will remain white but get brighter.
B. It will become brighter and bluer.
C. It will become fainter and bluer.
D. It will become brighter and redder.
E. It will become fainter and redder.

An Infrared Portrait

Human temperature in K = 273+37 = 310K

$$\lambda_{\max} = \frac{0.0029 Km}{310K} = 9.4 \times 10^{-6} m = 9400 nm$$

This is in the infrared!

Figure 5-10
Universe, Eighth Edition

In this image made with a camera sensitive to infrared radiation, the different colors represent regions of different temperature. Red areas (like the man's face) are the warmest and emit the most infrared light, while blue-green areas (including the man's hands and hair) are at the lowest temperatures and emit the least radiation.

Definition of a blackbody

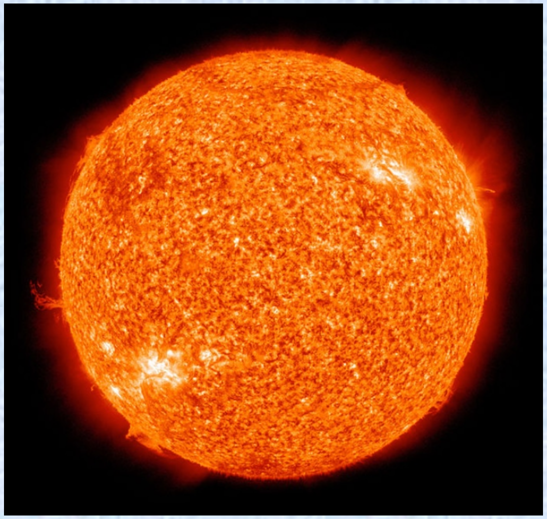
- A blackbody is an idealized object that absorbs all radiation falling on it. It does not reflect light, instead it re-emits light.

- The temperature of the radiation it emits is determined by the average speed of the atoms in the object.

- A blackbody does not have to look black! The Sun is nearly a blackbody.

- Most things in everyday life (people, furniture, etc.) are too cool to emit visible light, so you can't see them in the dark.

We know exactly how much radiation an opaque body emits.



The Stefan-Boltzmann Law gives the flux of a blackbody of a given temperature.

$$F = \sigma T^4$$

- T = Temperature in Kelvins
- The value of the Stefan-Boltzmann constant σ (a constant)= $5.67\times10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$.

Example: T(Sun) = 5800 K, so the flux from the
$(5.67\times10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4)}} \times (5800\ \mathrm{K})^4 = 6.42\times10^7$ W

The surface area of the Sun is $A = 4\pi R^2 = 4\pi$ (6.
The luminosity (or power) is **L = Flux × Area.**
$L = (6.42\times10^7\ \mathrm{W\ m^{-2}})(6.09\times10^{18}\ \mathrm{m^2}) = 3.9\times10$

Homework:
Find Flux from surface of Sirius:
$L = 25\ L_0$,
$R = 1.67\ R_0$.

Temperature, Energy Flux & Power Let's Check that You've Got It

In the movie *The Matrix* – people are used as batteries. If the average human's bodily surface area is 1.7 m^2, and has an average temperature of 37°C, how much energy per second (power) does a person radiate?

Answer. Treating a person as a blackbody, use the Stefan-Boltzmann law to determine the energy radiated per second per square meter, then multiply by the body's surface area to get the energy radiated per second.

Human temperature in K = 273+37 = 310K

$F = \sigma T^4 = (5.67\times10^{-8}\ W\ m^{-2}\ K^{-4})(310\ K)^4 = 524\ W\ m^{-2}$

Power or Energy Radiated per unit time: L = Area * F

$Power = 524\ W\ m^{-2}\ (1.7 m^2) = 891\ W$

About the power of a toaster!

Power Radiated by Stars (iclicker Question)

Why is a red giant much brighter than a red dwarf?

A. Red giants are hotter than red dwarfs.
B. The Stefan-Boltzmann Law tells us that the surface of a red giant emits more energy flux.
C. The Stefan-Boltzmann Law tells us that the surfaces of all red stars emit the same energy flux.
D. Red giants are bigger than red dwarfs, so they have more surface area.
E. Both C & D.

Power Radiated by Stars (iclicker Question)

Why is a red giant much brighter than a red dwarf?

A. Red giants are hotter than red dwarfs.
B. The Stefan-Boltzmann Law tells us that the surface of a red giant emits more energy flux.
C. The Stefan-Boltzmann Law tells us that the surfaces of all red stars emit the same energy flux.
D. Red giants are bigger than red dwarfs, so they have more surface area.
E. Both C & D.

The Light from Stars, Galaxies, and Planets Shows Spectral Lines

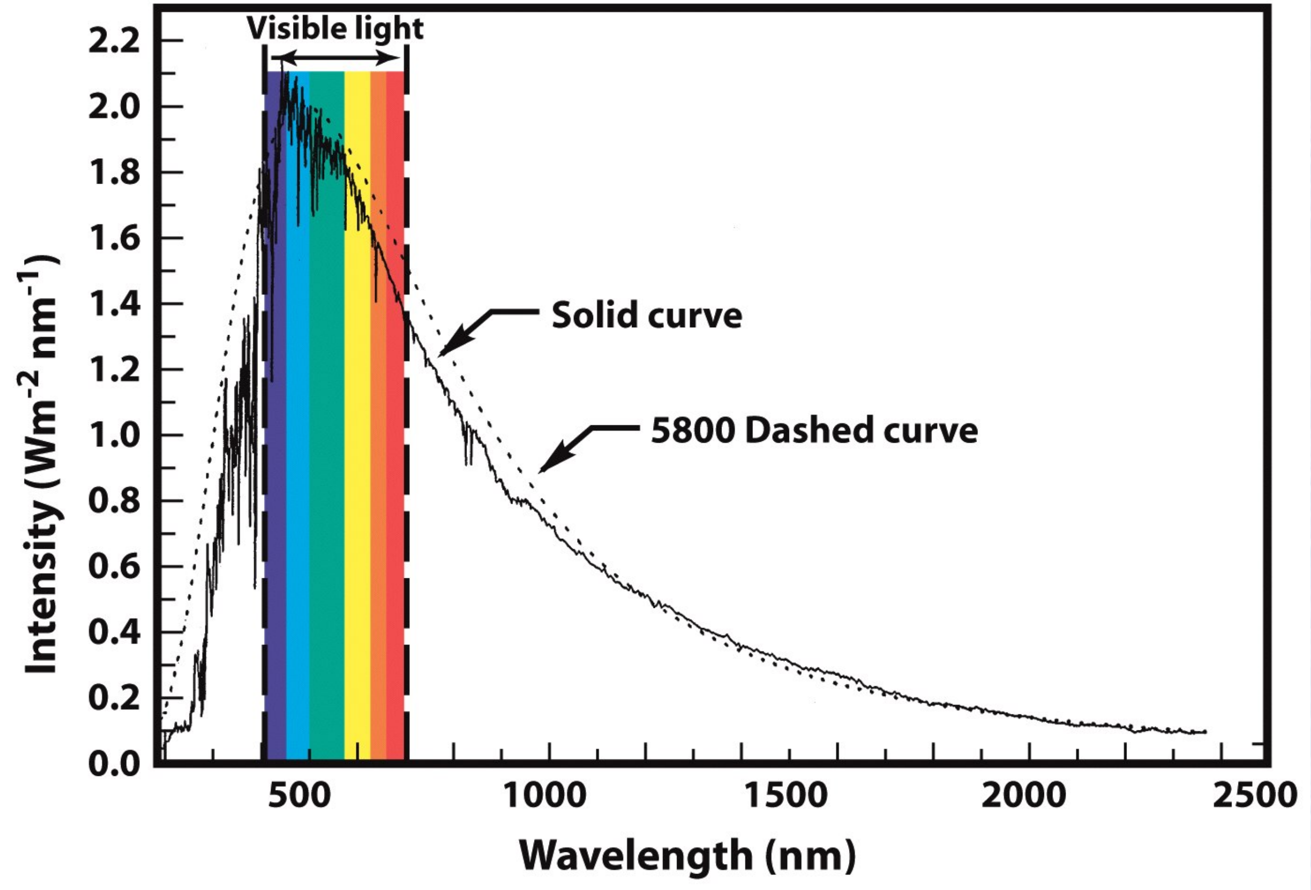


Figure 5-12
Universe, Eighth Edition

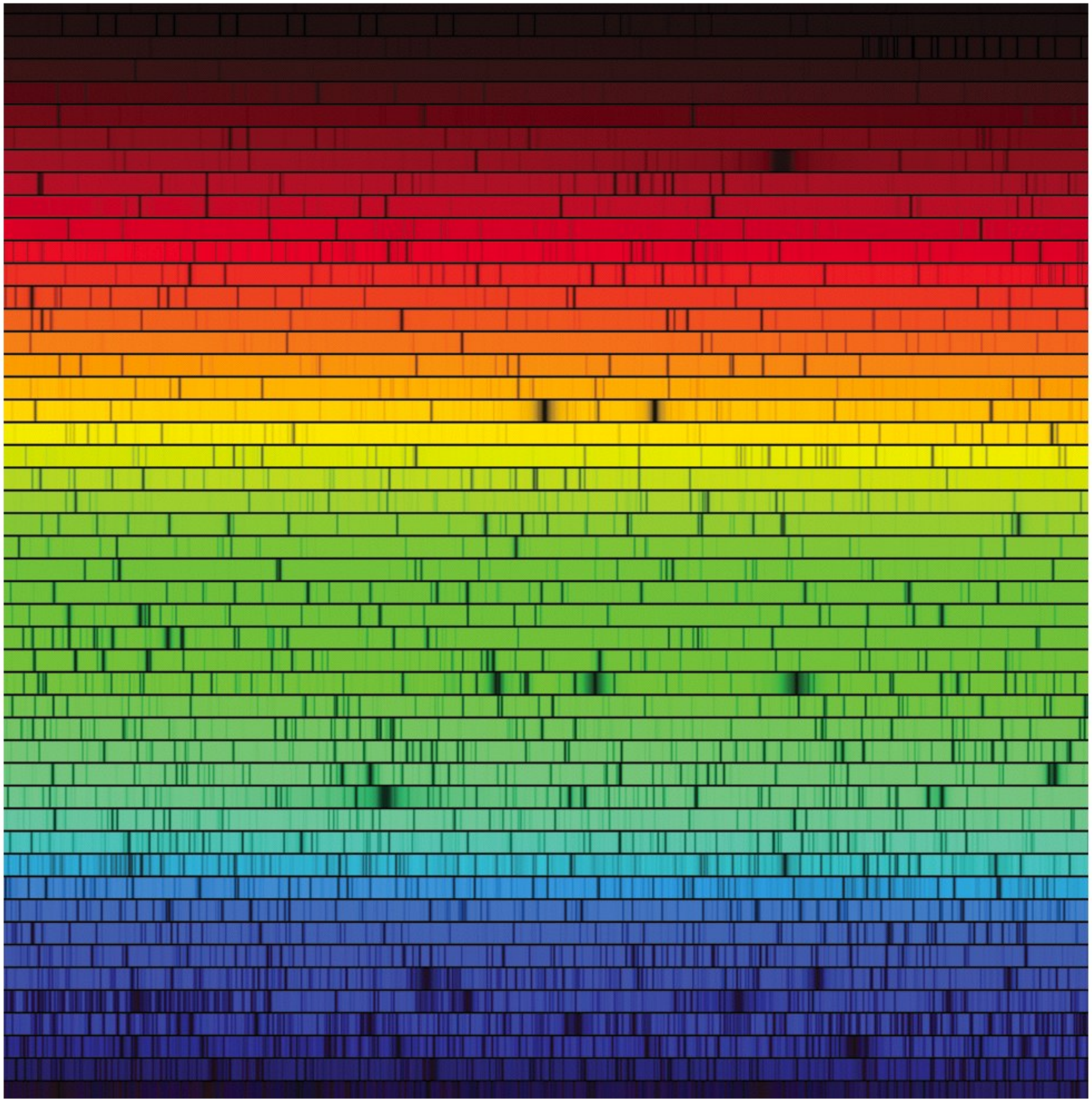
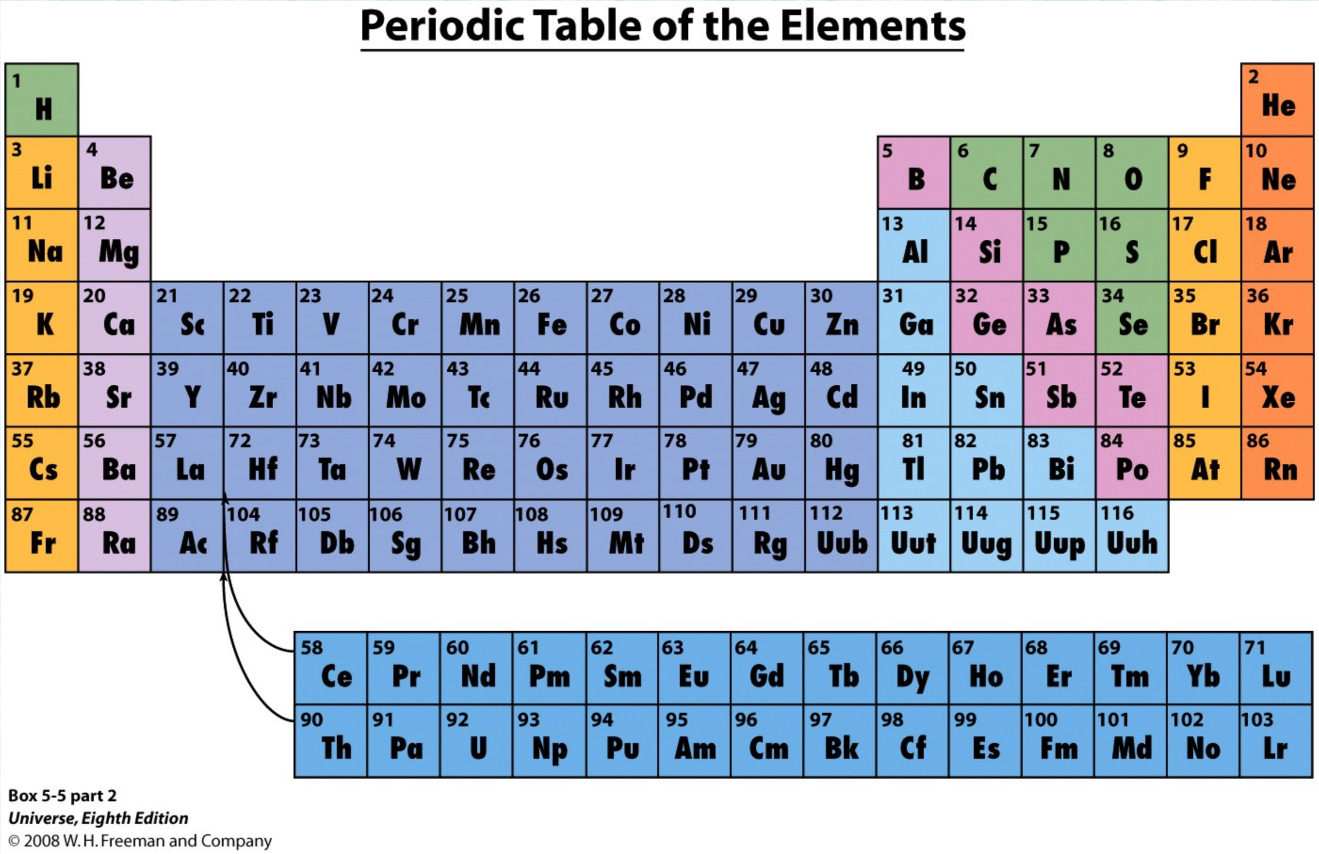


Figure 5-13
Universe, Eighth Edition

The Sun’s Spectrum

In 1814 Joseph von Fraunhofer magnified the solar spectrum seen through a prism, and found hundreds of dark lines.

Every Element Has a Unique Set of Spectral Lines



Periodic Table of the Elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uug	115 Uup	116 Uuh		
				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Box 5-5 part 2
Universe, Eighth Edition

Atomic number is the number of protons in an atom.

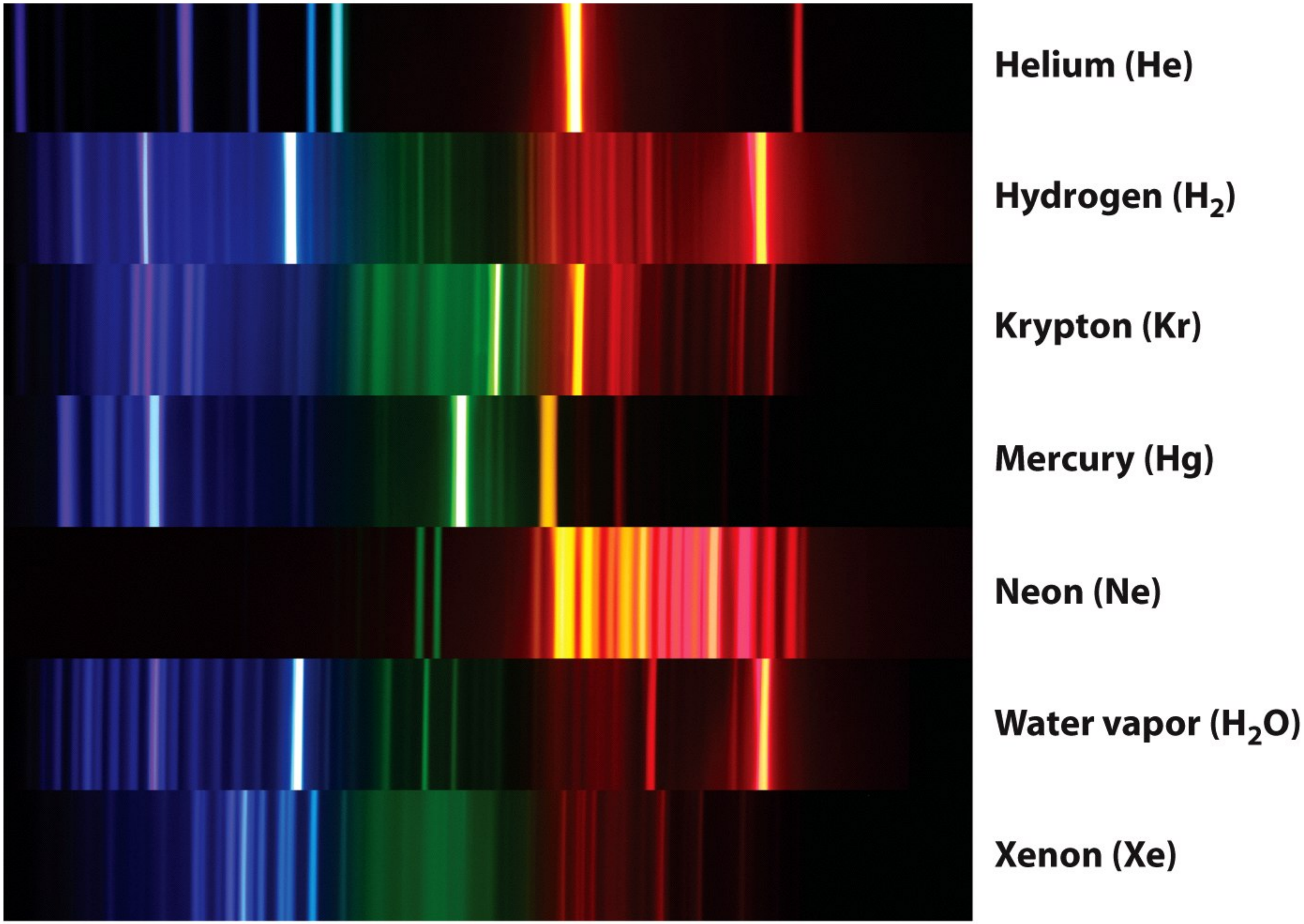
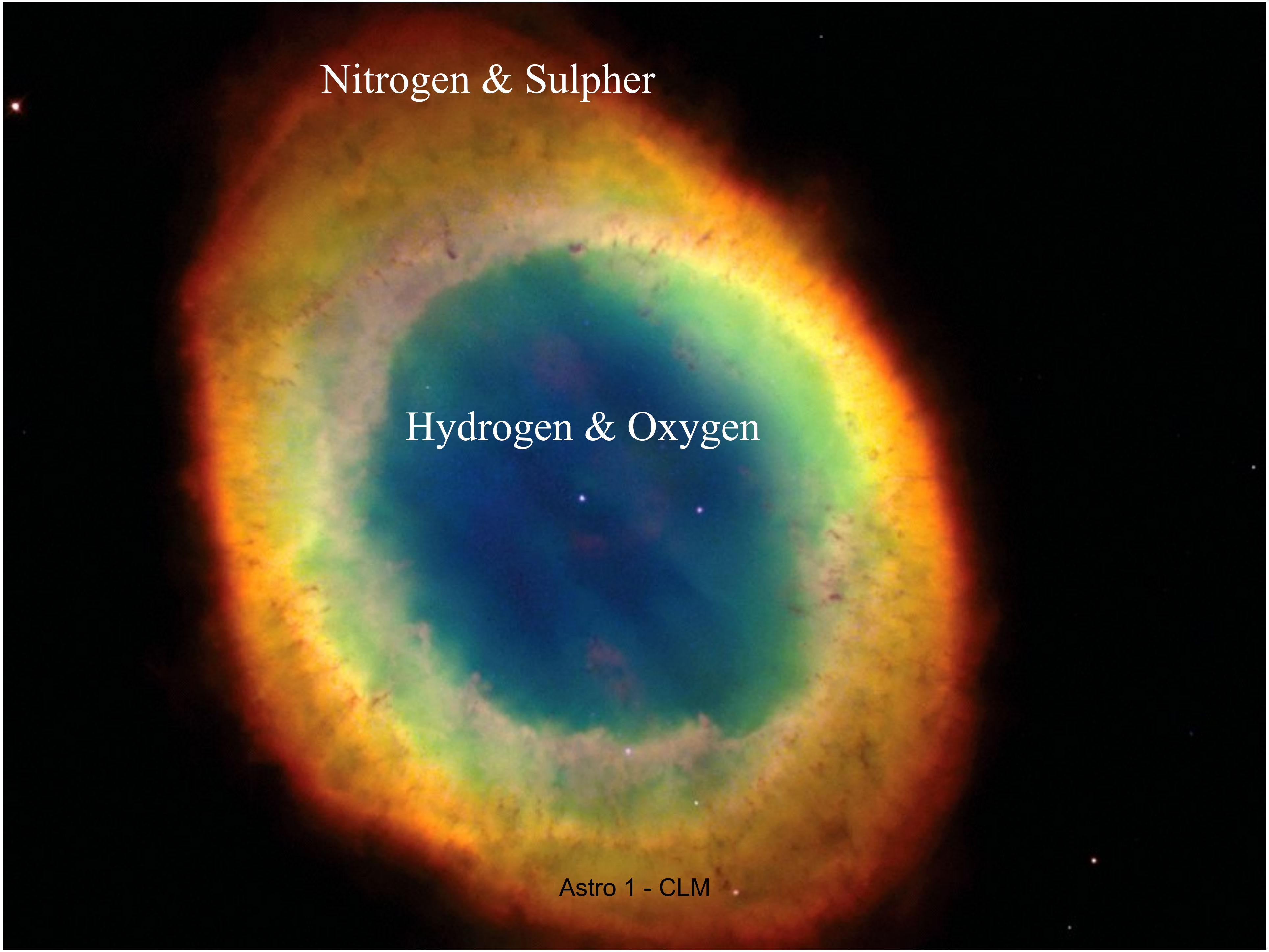
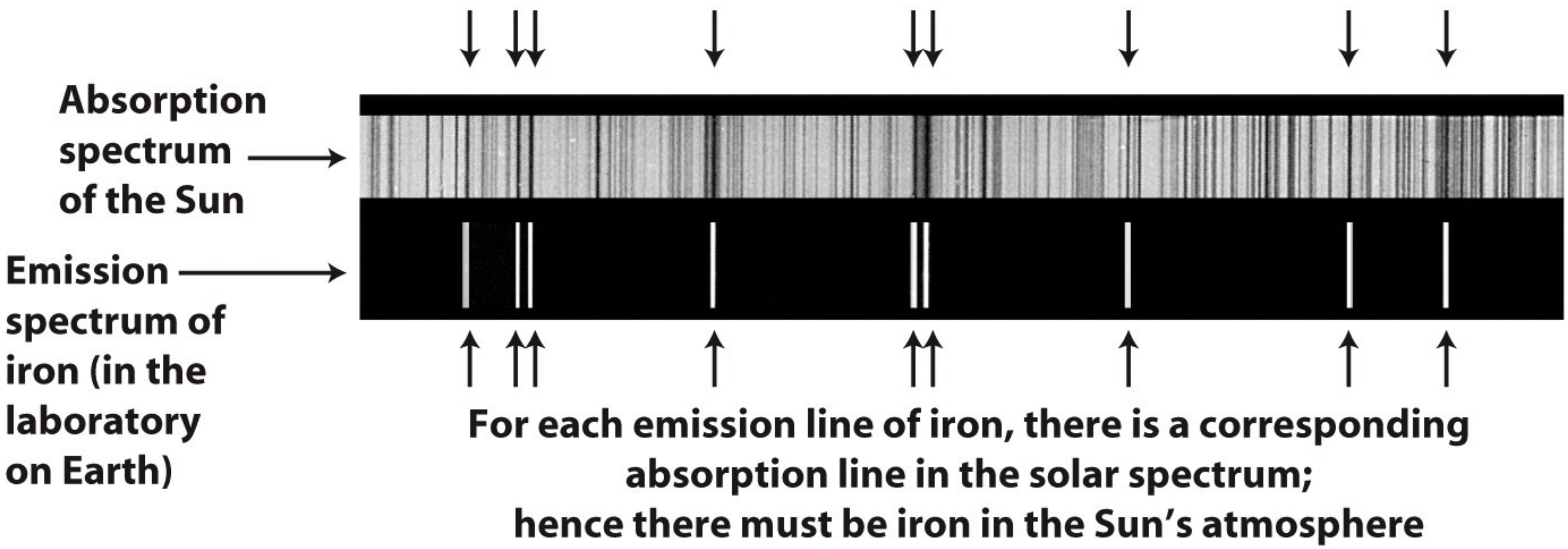


Figure 5-15
Universe, Eighth Edition


Nitrogen & Sulpher
Hydrogen & Oxygen

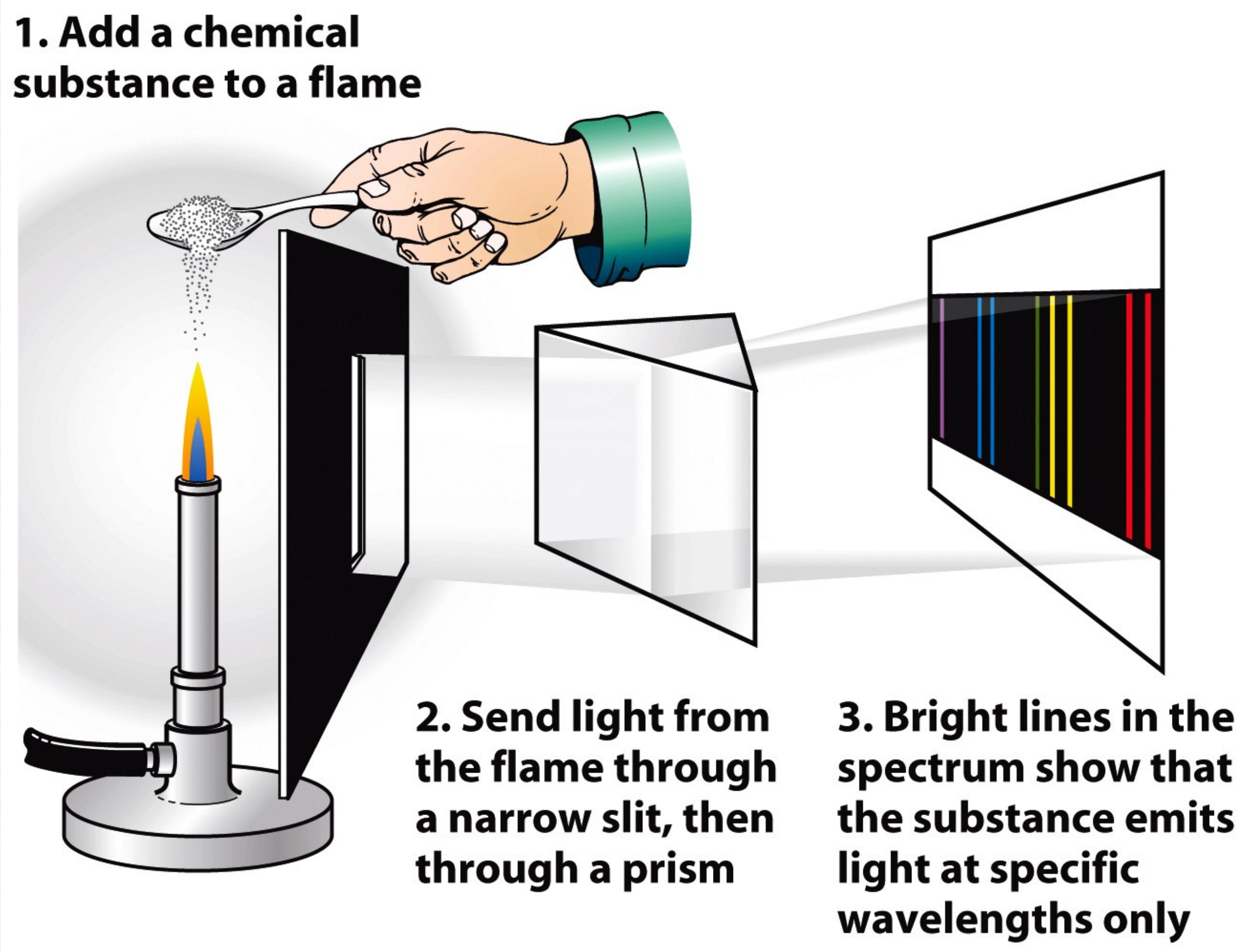
Spectroscopy Reveals the Chemical Composition of Celestial Objects



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

Demonstration



1. Add a chemical substance to a flame

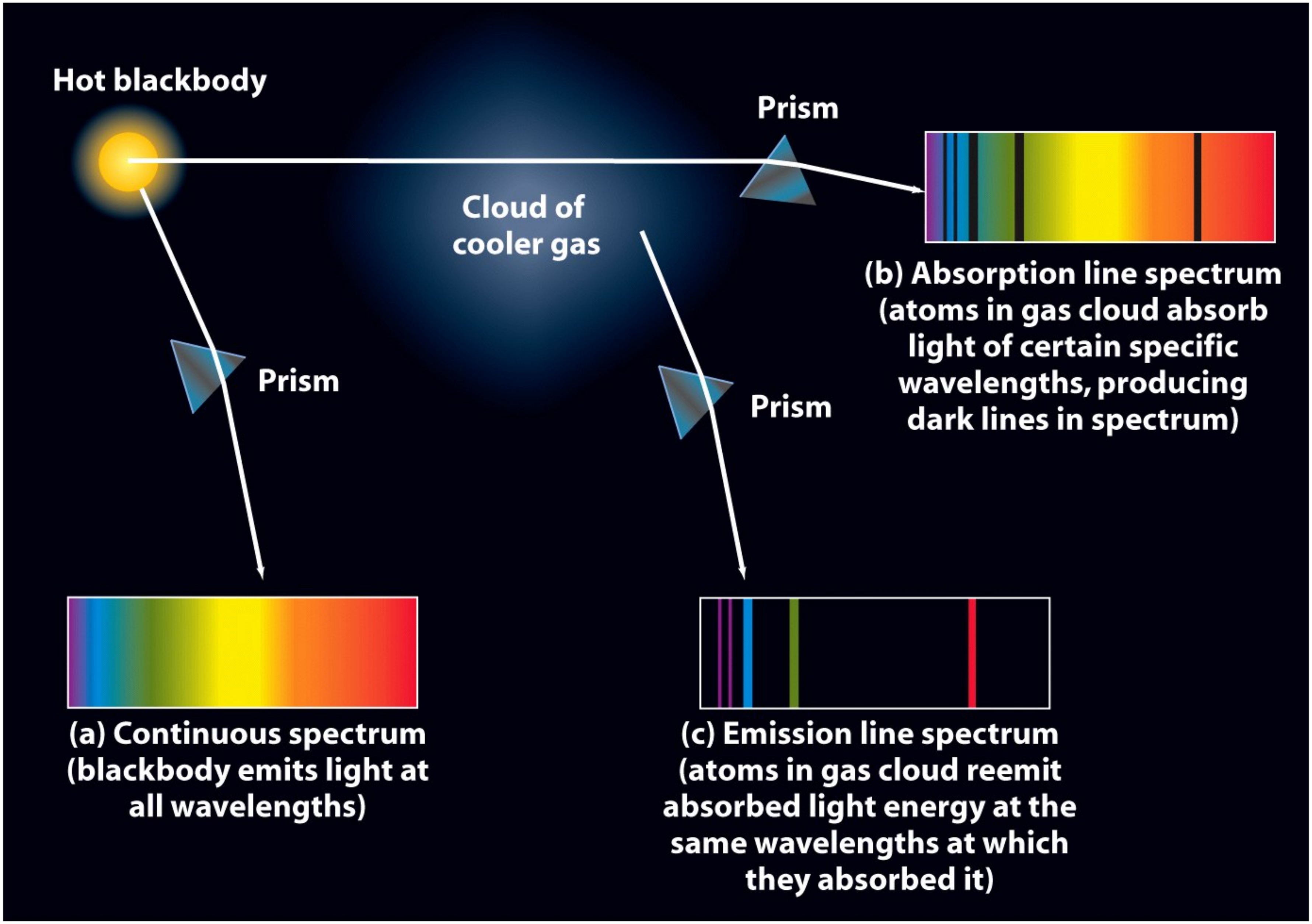
2. Send light from the flame through a narrow slit, then through a prism

3. Bright lines in the spectrum show that the substance emits light at specific wavelengths only

Figure 5-14
Universe, Eighth Edition

Kirchoff’s Laws

1. A hot, dense object such as a blackbody emits a **continuous spectrum** covering all wavelengths.
2. A hot, transparent gas produces a spectrum that contains bright (**emission**) lines.
3. A cool, transparent gas in front of a light source that itself has a continuous spectrum produces dark (**absorption**) lines in the continuous spectrum.



(b) Absorption line spectrum (atoms in gas cloud absorb light of certain specific wavelengths, producing dark lines in spectrum)

(a) Continuous spectrum (blackbody emits light at all wavelengths)

(c) Emission line spectrum (atoms in gas cloud reemit absorbed light energy at the same wavelengths at which they absorbed it)

Figure 5-16
Universe, Eighth Edition

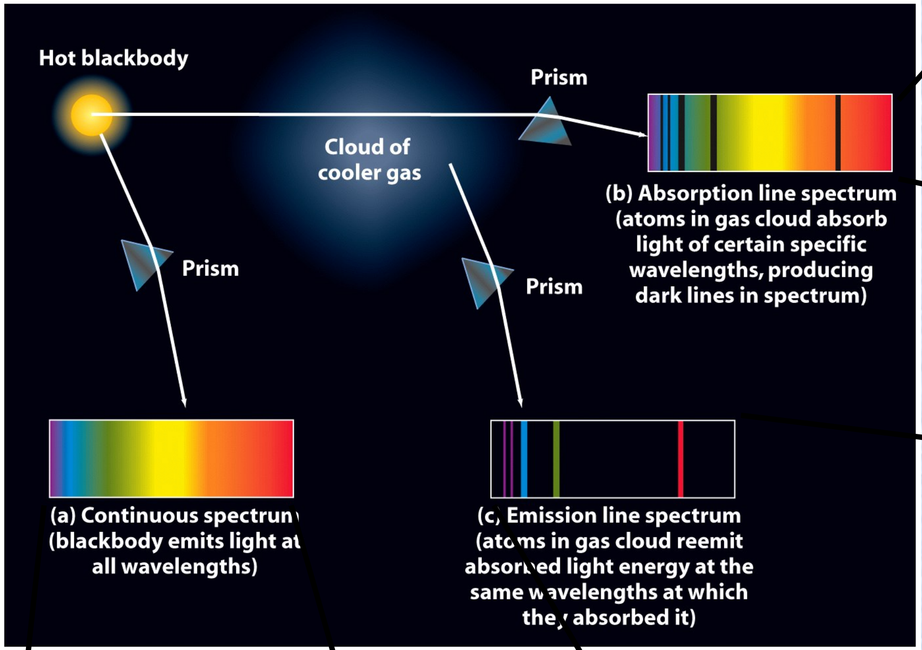
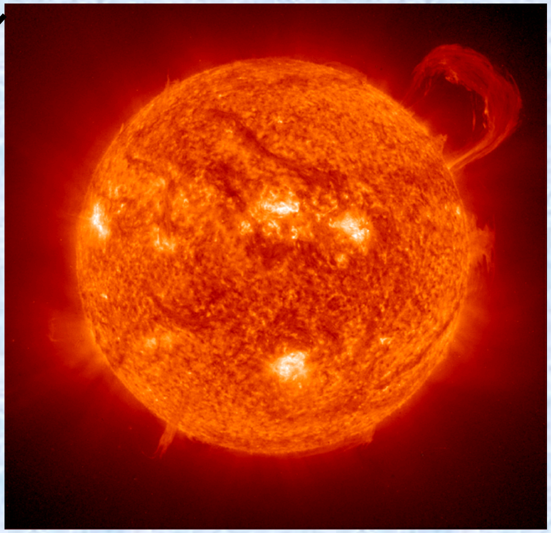
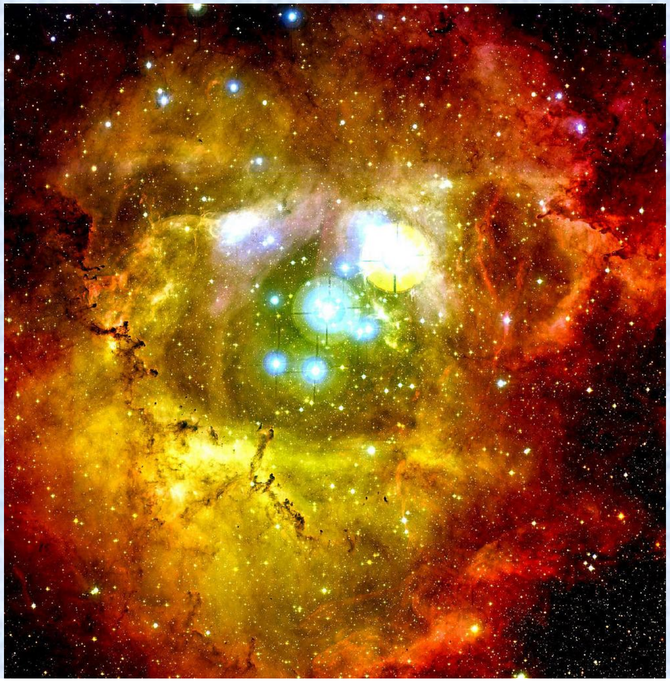


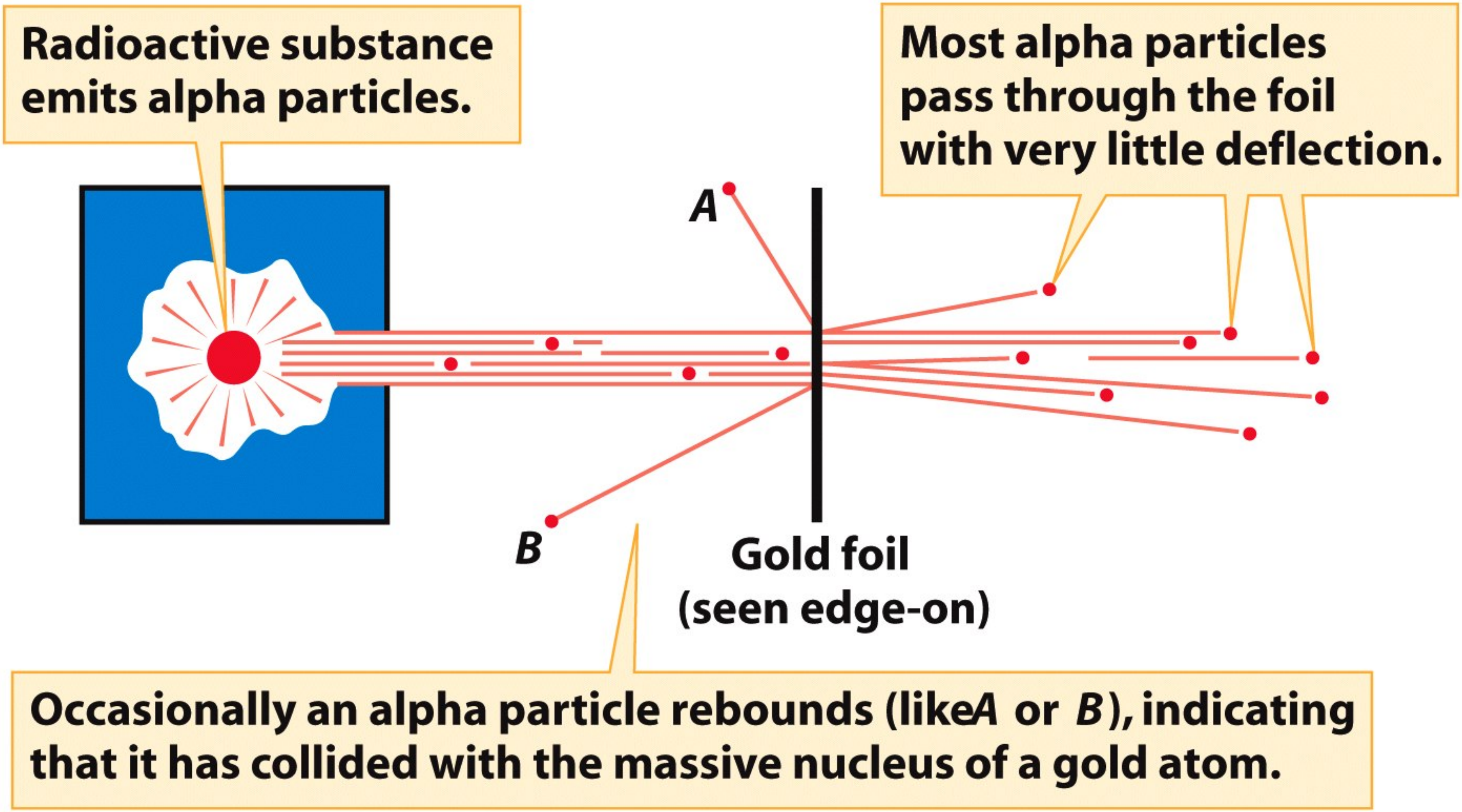
Figure 5-16
Universe, Eighth Edition
© 2008 W. H. Freeman and Company





What causes spectral lines?

The structure of atoms



Radioactive substance emits alpha particles.

Most alpha particles pass through the foil with very little deflection.

Occasionally an alpha particle rebounds (like *A* or *B*), indicating that it has collided with the massive nucleus of a gold atom.

Figure 5-19
Universe, Eighth Edition

Rutherford’ s Experiment

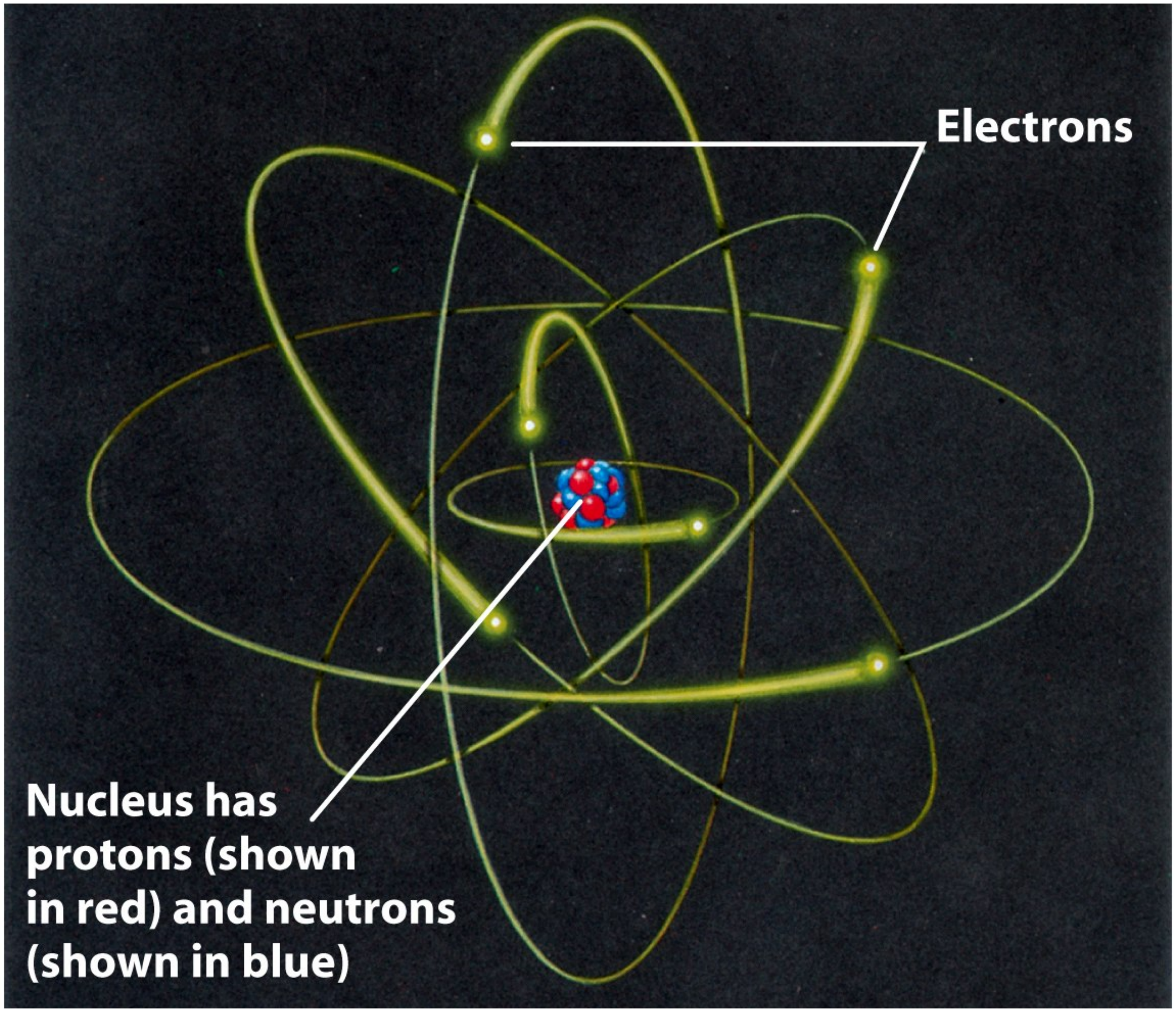


Figure 5-20
Universe, Eighth Edition

Rutherford's model of the atom.

Today we know this is not exactly correct – electrons do not orbit the nucleus, but the basic idea is right -- protons and neutrons exist in the nucleus, and electrons are outside of it.

The Bohr Model of the Atom

Niels Bohr
1885-1962

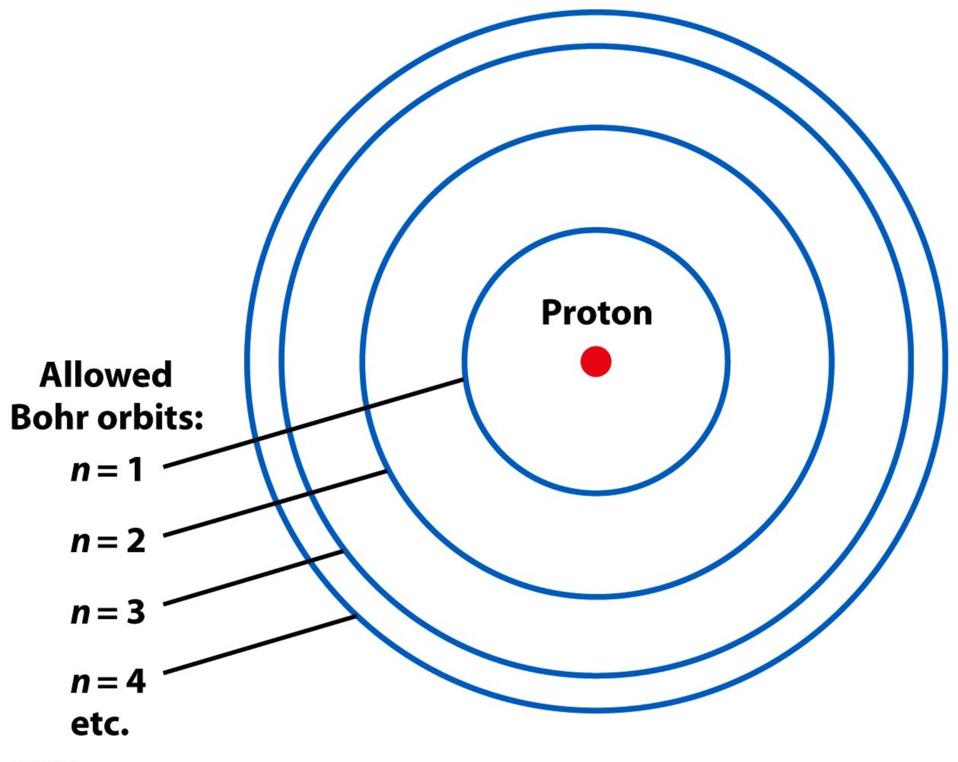
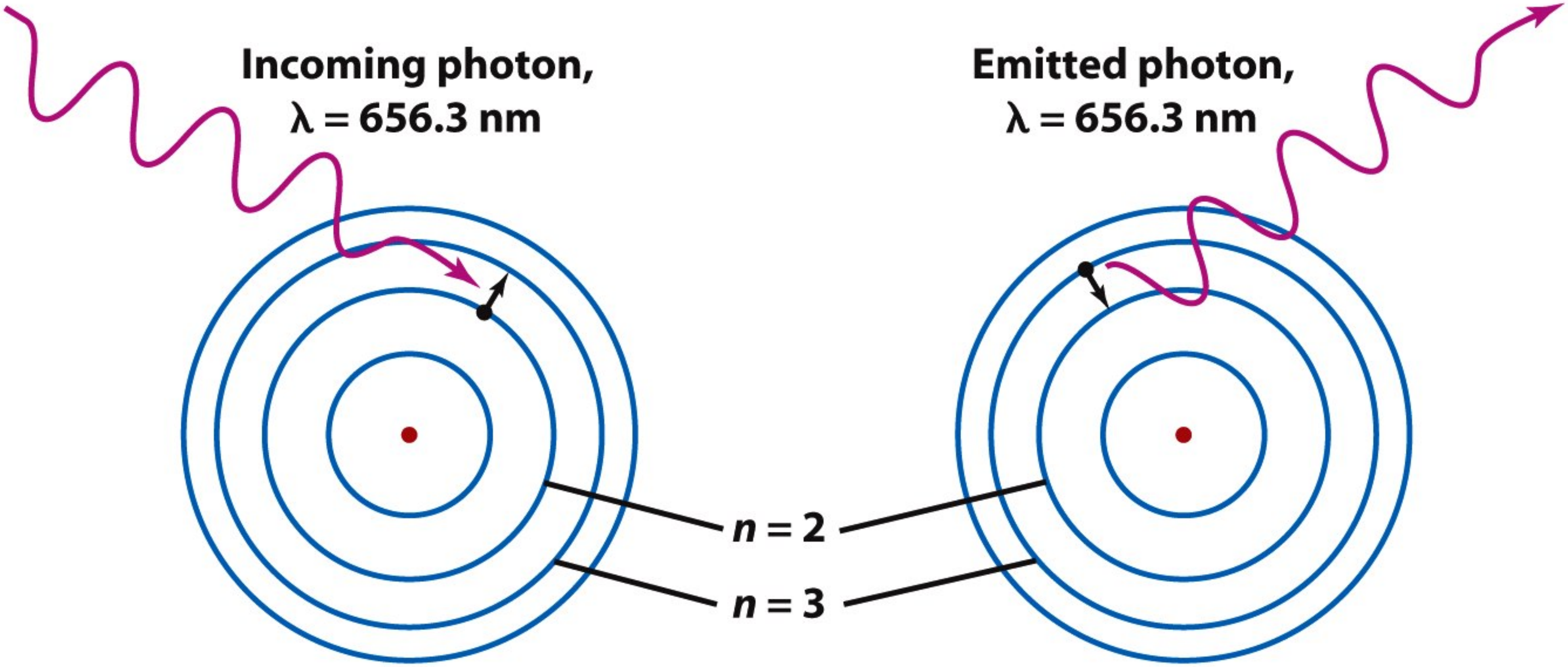


Figure 5-22
Universe, Eighth Edition

Was a postdoc with Rutherford. In 1912, to explain discrete nature of spectral lines, hypothesized that electron orbits are quantized (quantum mechanics!).

Spectral Lines & Quantum Nature of Atoms



(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

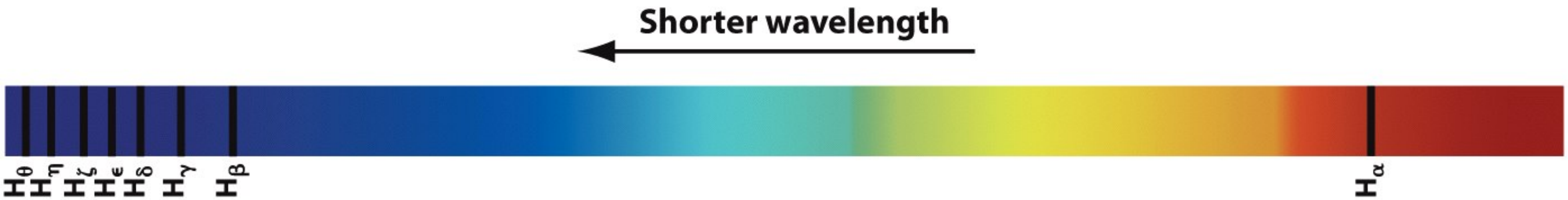


Figure 5-21
Universe, Eighth Edition

In 1885 Swiss schoolteacher Johann Jakob Balmer, by trial and error, created a formula that can predict where lines of hydrogen fall in the spectrum of a star.

We still call these Balmer lines.

$$\frac{1}{\lambda} = R\left(\frac{1}{4} - \frac{1}{n^2}\right)$$

R = Rydberg constant = 1.097×10^{7} m^{-1}
n = any integer greater than 2

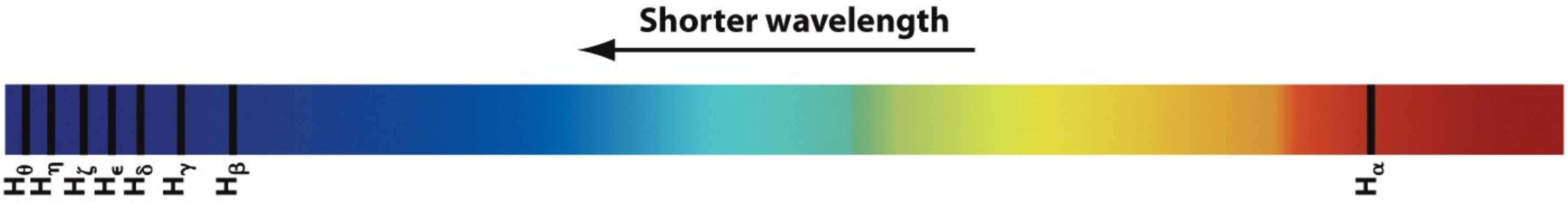


Figure 5-21
Universe, Eighth Edition

$$\frac{1}{\lambda} = R\left(\frac{1}{4} - \frac{1}{n^2}\right)$$

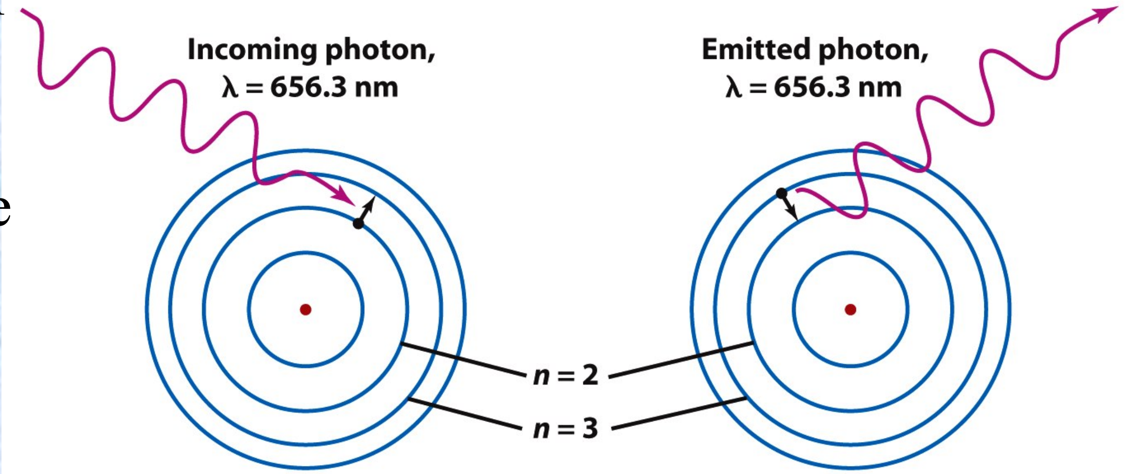
The Balmer series and fomula.

R = Rydberg constant = 1.097×10^{7} m^{-1}

Bohr figured out the physical explanation for Balmer's formula – the spectra from stars depends on the structure of atoms!

$$\frac{1}{\lambda} = R\left(\frac{1}{N^2} - \frac{1}{n^2}\right)$$

N = lower orbital
n = higher orbital



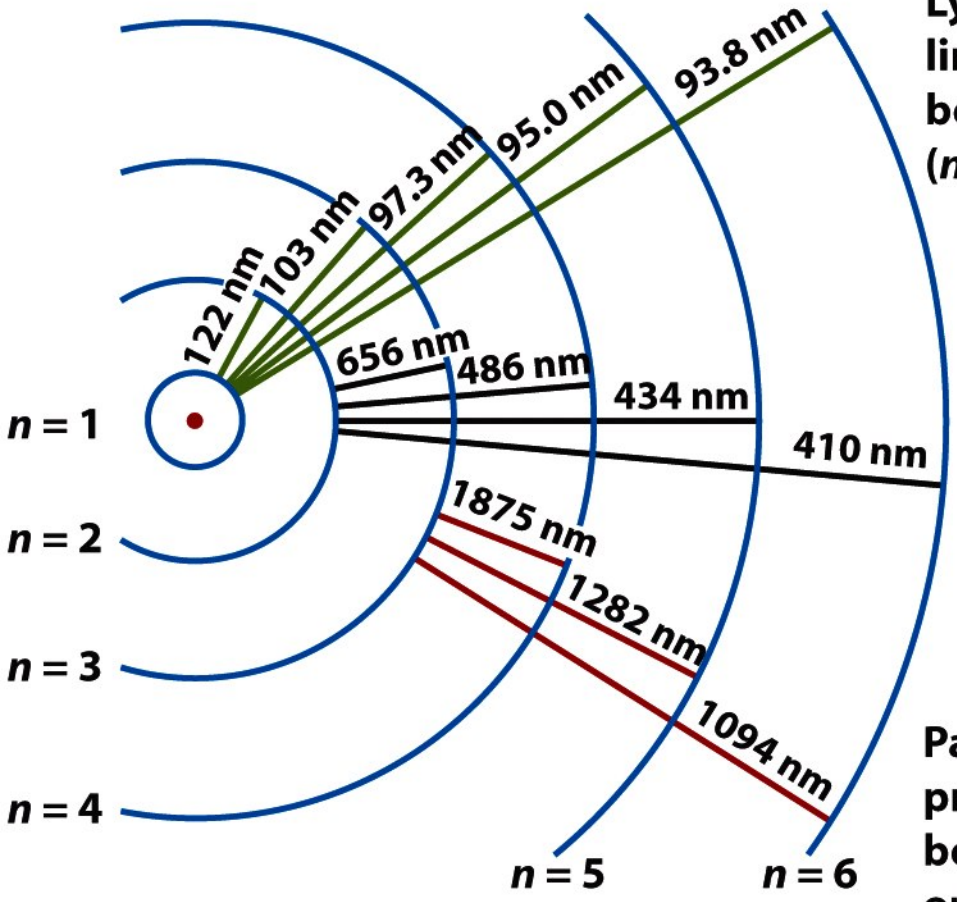
(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up to the $n = 3$ orbit

(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

Electron Transitions in the Hydrogen Atom

The same wavelength occurs whether a photon is emitted or absorbed.



Lyman series (ultraviolet) of spectral lines: produced by electron transitions between the *n* = 1 orbit and higher orbits (*n* = 2, 3, 4, …)

Balmer series (visible and ultraviolet) of spectral lines: produced by electron transitions between the *n* = 2 orbit and higher orbits (*n* = 3, 4, 5, …)

Paschen series (infared) of spectral lines: produced by electron transitions between the *n* = 3 orbit and higher orbits (*n* = 4, 5, 6, …)

Figure 5-24
Universe, Eighth Edition

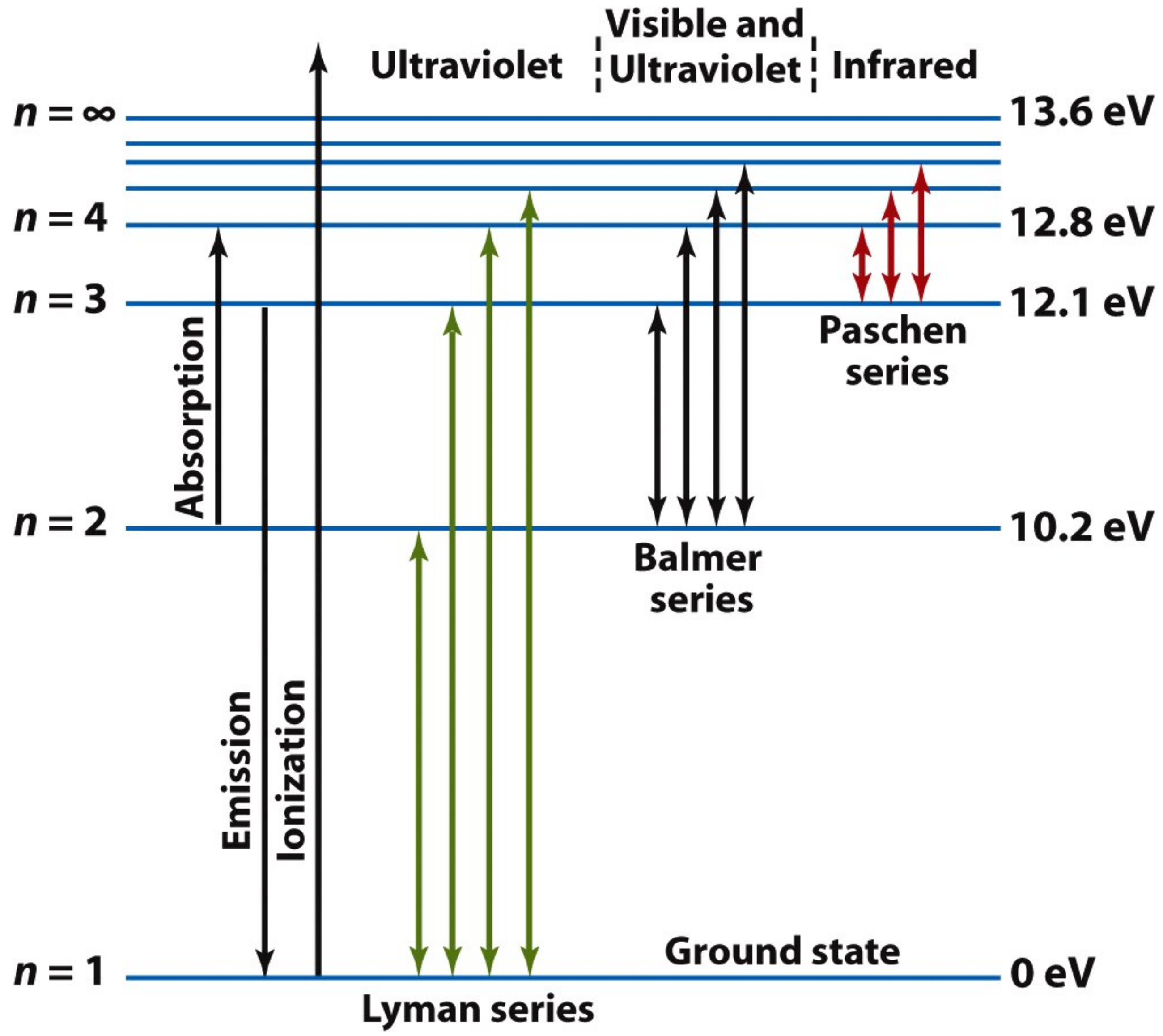


Figure 5-25
Universe, Eighth Edition

Summary

- Light is electromagnetic radiation.
  - Wave-like properties: diffraction, etc.
  - Particle-like properties: $E = h\nu = hc/\lambda$
  - Blue light scatters more strongly than red light (in atmosphere).
- **An opaque object emits light according to its temperature.**
  - **Wien's law: λ_{max} (in meters) = (0.0029 K·m)/T.**
  - The **Stefan-Boltzmann law**: $F = \sigma T^4$.
- Atomic structure causes spectral lines.
- **Kirchoff's Laws**
  - A hot body produces a continuous spectrum
  - A hot transparent gas produces emission lines
  - Cool transparent gas in front of a hot body produces absorption lines

Homework #3 – Due 10/18/19

- On your own: answer all the review questions in chapter 5
- To TAs: answer questions,
  - 5.34 – emission from Pele, an active volcano on Io(Note that Io's surface temperature is -150^o C and not 2150^o C)
  - 5.37 – Emission lines from hydrogen atoms, Paschen-delta
  - 5.43 – Is Megrez approaching or moving away from us?
  - *5.44 – How fast must you drive to Doppler shift a 'red' traffic light into a 'green' light?*

Why did the moon turn orange-red during the lunar eclipse? (iclicker Question)

A. The moon emits orange-red light because of its temperature.
B. Red light was scattered towards the moon by the earth's atmosphere.
C. The earth emits red light, and we saw that light reflecting off the moon.
D. The light emitted by the moon was red because of the moon's Doppler shift.
E. Sunlight passing through earth's atmosphere was illuminating the moon. The blue light had been removed by scattering.

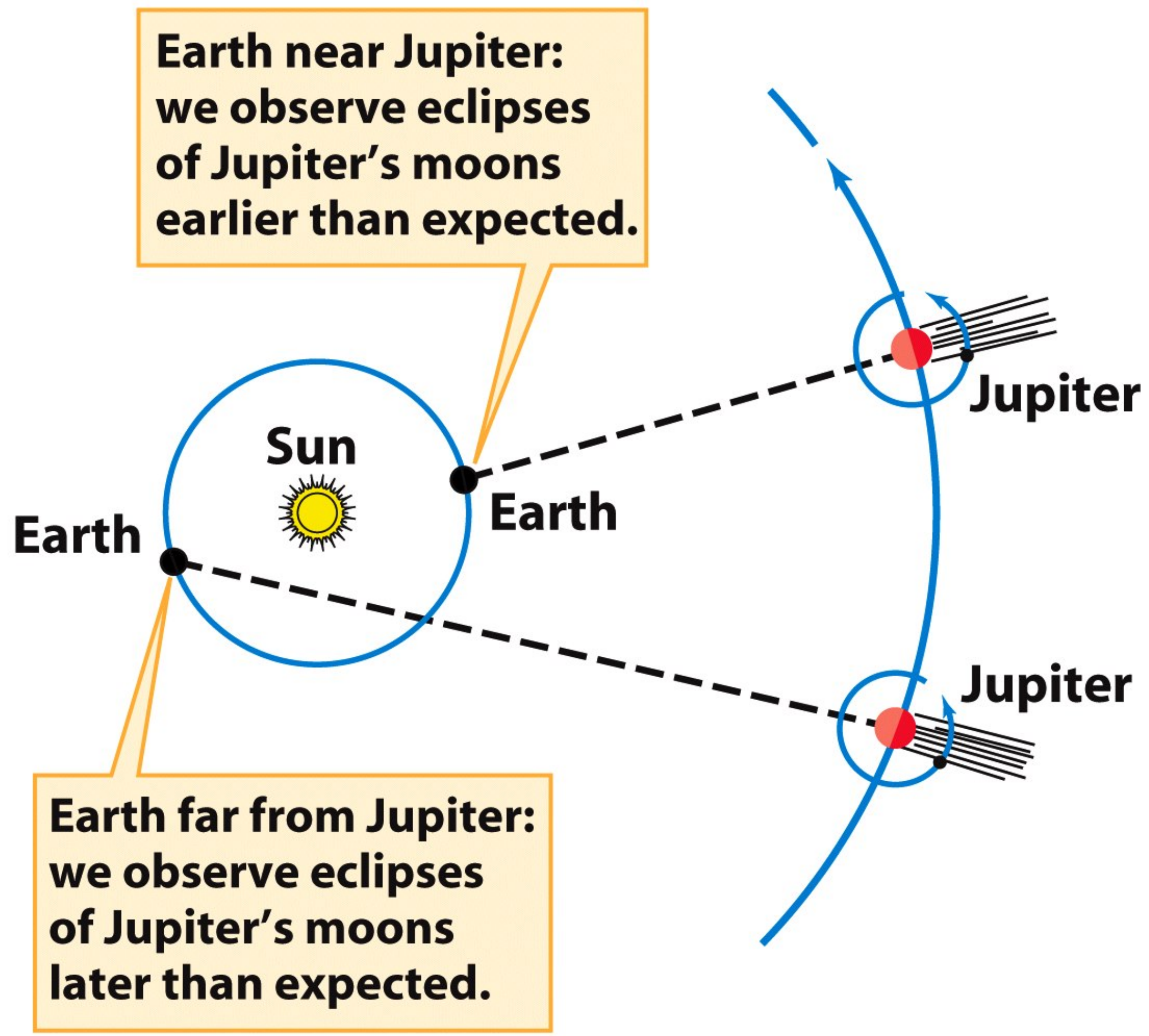


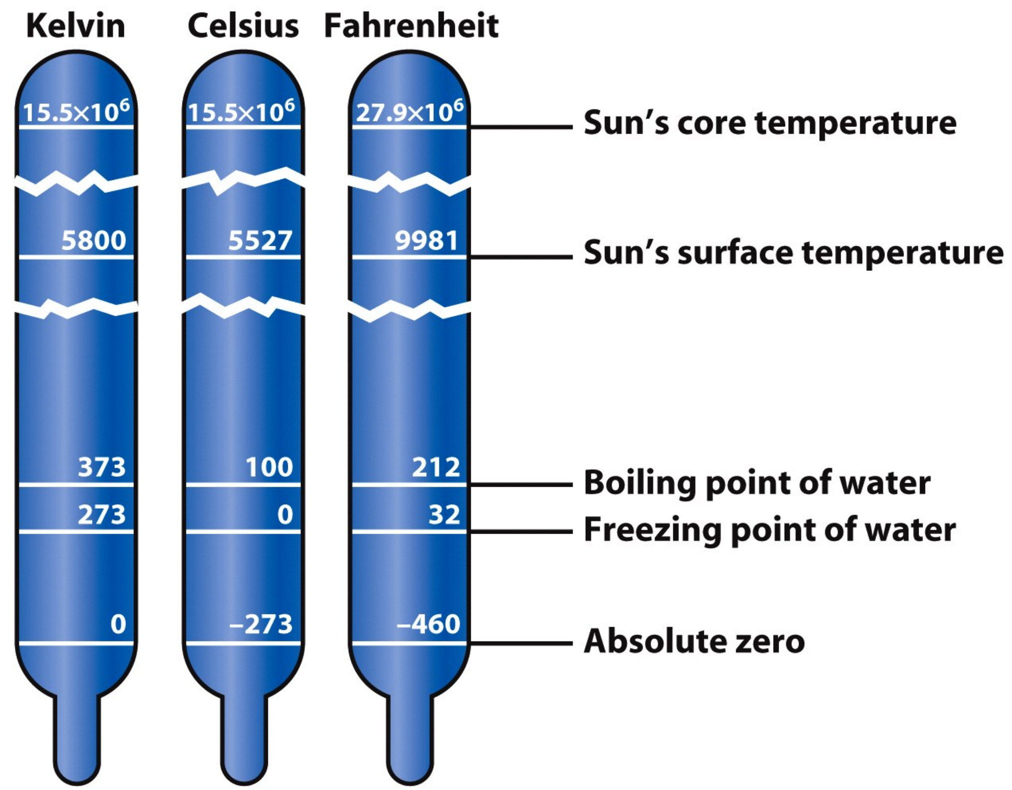
Figure 5-1
Universe, Eighth Edition

Is the speed of light finite? Galileo tried, but couldn’t measure it.

In 1676 Olaus Rømer noticed that the measurements of the eclipses of Jupiter’s moons were systematically off, depending on how distant Earth was from Jupiter. From this he deduced the speed of light (in terms of AU).

Spectra are the “fingerprints” of atoms and molecules.

Temperature Units



Box 5-1
Universe, Eighth Edition
© 2008 W. H. Freeman and Company

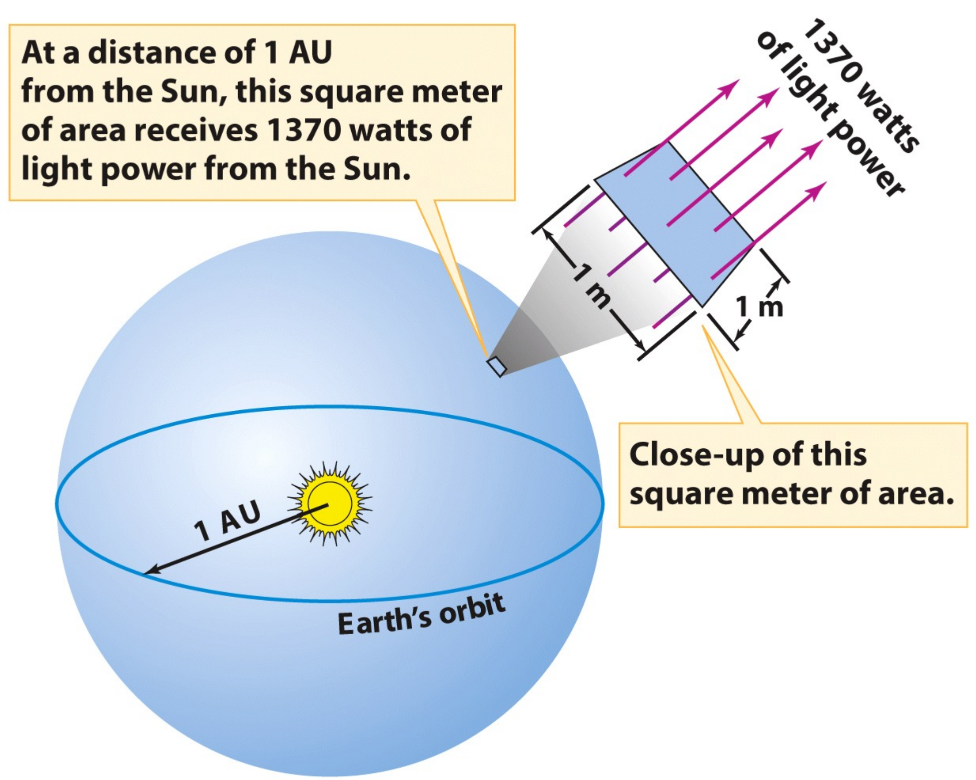
$$T_C = \frac{5}{9}\left(T_F - 32\right)$$

$$T_F = \frac{9}{5}\left(T_C + 32\right)$$

$$T_K = T_C + 273$$

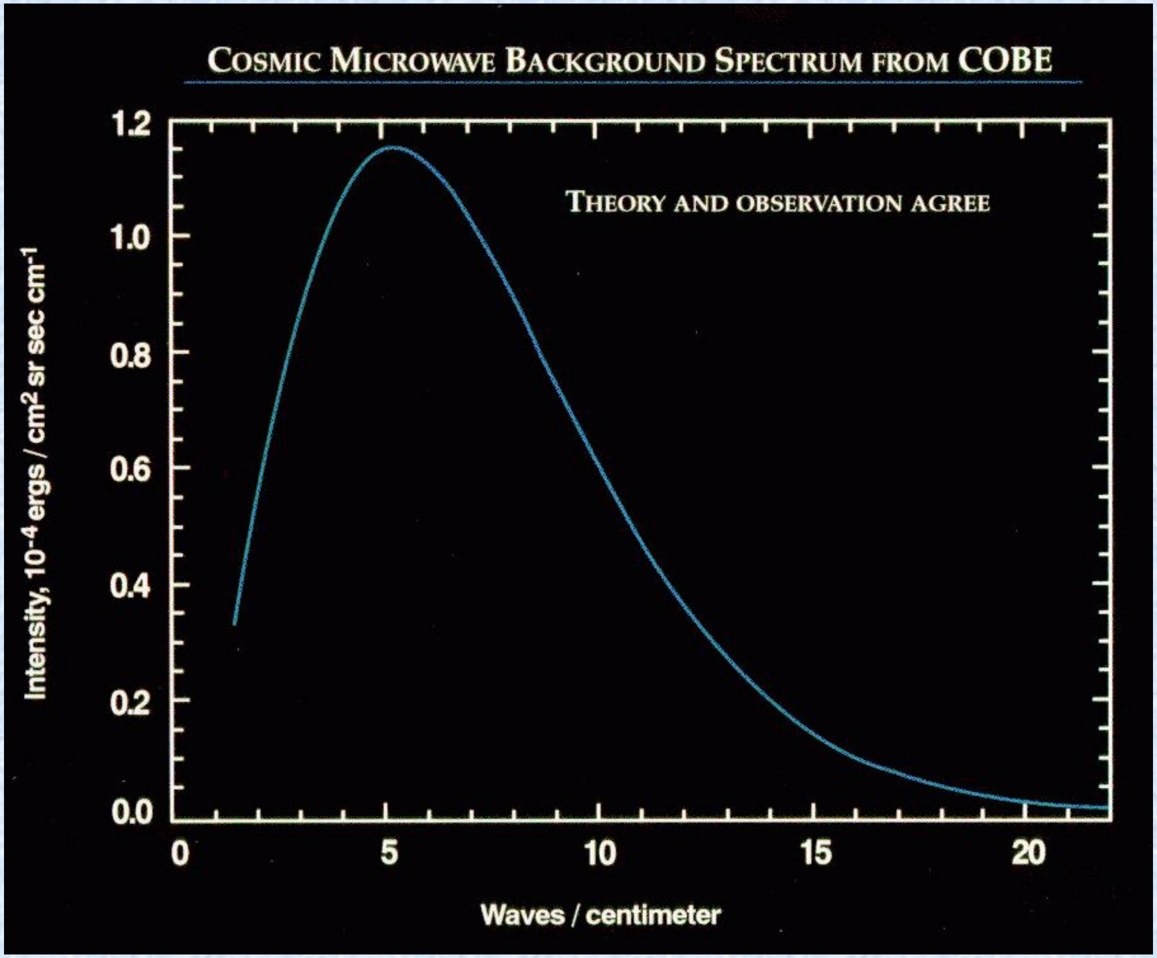
Astronomers use the Kelvin temperature scale. The "degrees" are the same as the Celsius system, only with 273 added, and they aren't called degrees (just K). The are no negative numbers – "absolute" zero is the coldest possible temperature.

Inverse Square Law



Box 5-2
Universe, Tenth Edition

Cosmic Microwave Background. The CMB is a "perfect" Blackbody



COBE FIRAS 1989; T=2.725 K

Seeing in the Dark (iclicker Question)

- Suppose you want to build a camera that can see people in the dark. Approximately what wavelength does your camera need to be able to image?

A. X-Rays
B. Ultraviolet Light
C. Optical Light
D. Infrared Light
E. Radio signals

Demo: Doppler Shift of Sound Waves (iclicker Question)

A speaker is whirled around on a rope.
The sound from the speaker will do the following.

A. Rise to higher frequency as the speaker moves towards the listener. Fall to lower frequency as the speaker moves away from the listener.
B. Fall to lower frequency as the speaker moves towards the listener. Rise to higher frequency as the speaker moves away from the listener.
C. Get louder as the speaker approaches the listener and get softer as the speaker moves away.
D. Get louder as the speaker moves away and get softer as the speaker moves towards the listener.
E. Both A & C

The Wavelength of Light is Affected by the Relative Motion between the Source and the Observer

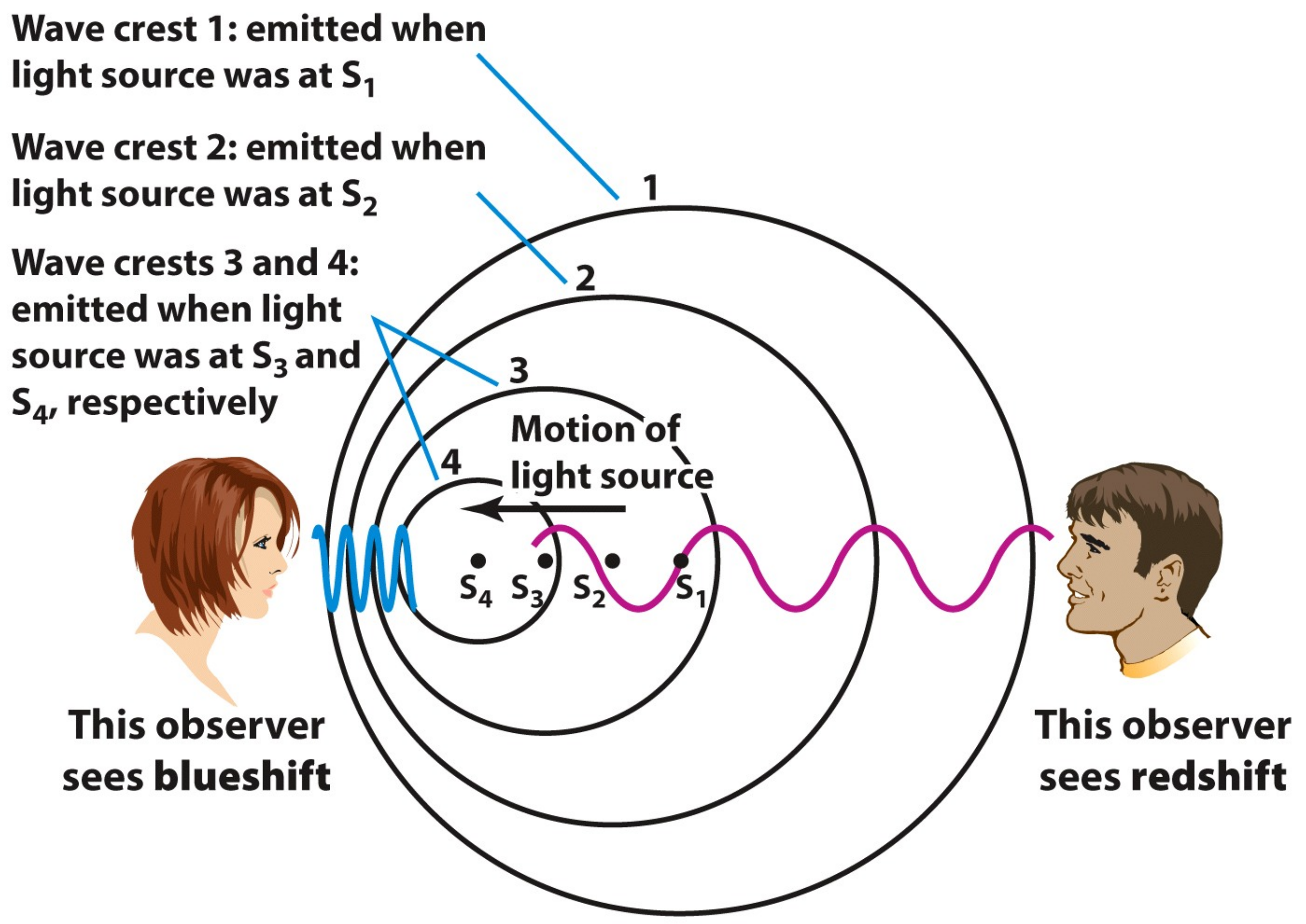


Figure 5-26
Universe, Tenth Edition
© 2014 W. H. Freeman and Company

Doppler Shift Equation

$$\Delta\lambda / \lambda = v / c$$

$\Delta\lambda$ = wavelength shift

λ = wavelength if source not moving

v = speed of the source along the line of sight

c = speed of light = 3e5 km/s

Spectral Lines (iclicker Question)

Professor Martin used a spectrograph on the Keck telescope to observe a distant galaxy. She detected an absorption line from sodium atoms. The wavelength she measured was 0.22 nm bluer than the laboratory wavelength of 589.0 nm. What should she conclude?

A. There are cool clouds between the observer and the galaxy.
B. There gas between the galaxy and the observer is hotter than the galaxy.
C. The gas clouds are moving away from the galaxy towards the observer.
D. The gas clouds are falling into the galaxy.
E. Both A and C

Icliker Question: Structure of Atoms

- Most of the mass of ordinary matter resides in the

  - A) electrons and nuclei, shared equally
  - B) nuclei of atoms
  - C) electrons around the nuclei of atoms
  - D) energy stored within the atom in electromagnetic forces
  - E) Atoms have no mass.