The Nature of Light

Chapter Five

Introduction To Modern Astronomy I

Introducing Astronomy
(chap. 1-6)

Planets and Moons
(chap. 7-17)

Ch1: Astronomy and the Universe
Ch2: Knowing the Heavens
Ch3: Eclipses and
the Motion of the Moon

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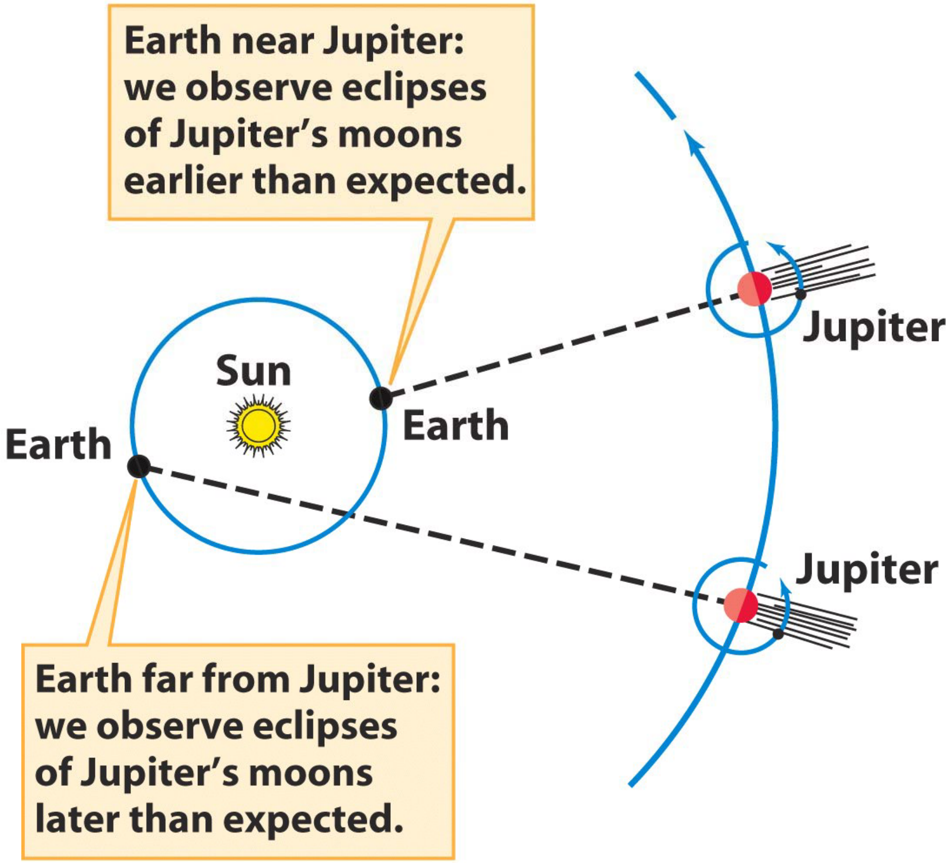
Guiding Questions

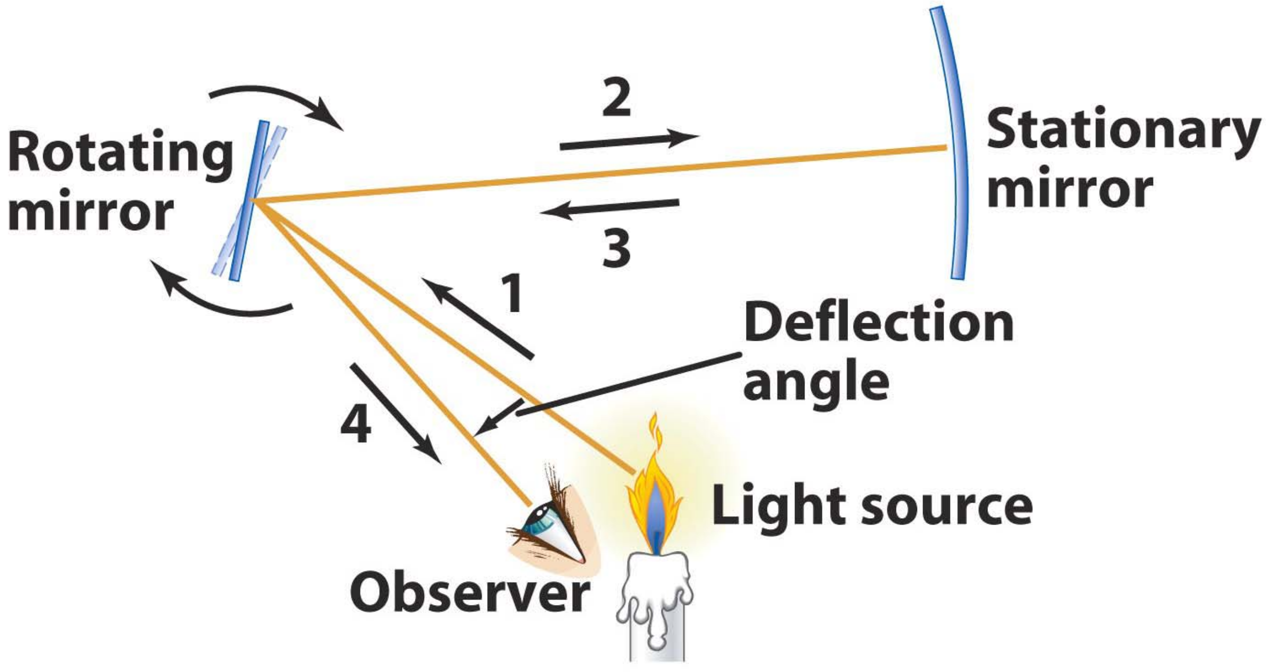
1. How fast does light travel? How can this speed be measured?
2. Why do we think light is a wave? What kind of wave is it?
3. How is the light from an ordinary light bulb different from the light emitted by a neon sign?
4. How can astronomers measure the temperatures of the Sun and stars?
5. What is a photon? How does an understanding of photons help explain why ultraviolet light causes sunburns?
6. How can astronomers tell what distant celestial objects are made of?
7. What are atoms made of?
8. How does the structure of atoms explain what kind of light those atoms can emit or absorb?
9. How can we tell if a star is approaching us or receding from us?

Speed of Light

- In 1676, Danish astronomer Olaus Rømer discovered that the exact time of eclipses of Jupiter's moons depended on the distance of Jupiter to Earth
- The variation is about 16.6 minutes
- This happens because it takes varying times for light to travel the varying distance between Earth and Jupiter



Speed of Light



- In 1850 Fizeau and Foucalt also experimented with light by bouncing it off a rotating mirror and measuring time
- The light returned to its source at a slightly different position because the mirror has moved during the time light was traveling
- The deflection angle depends on the speed of light and the dimensions of the apparatus.

Speed of Light

- The speed of light in the vacuum
  - C = 299,792.458 km/s, or
  - C = 3.00 X 10^5 km/s = 3.00 X 10^8 m/s
- It takes the light 500 seconds traveling 1 AU.

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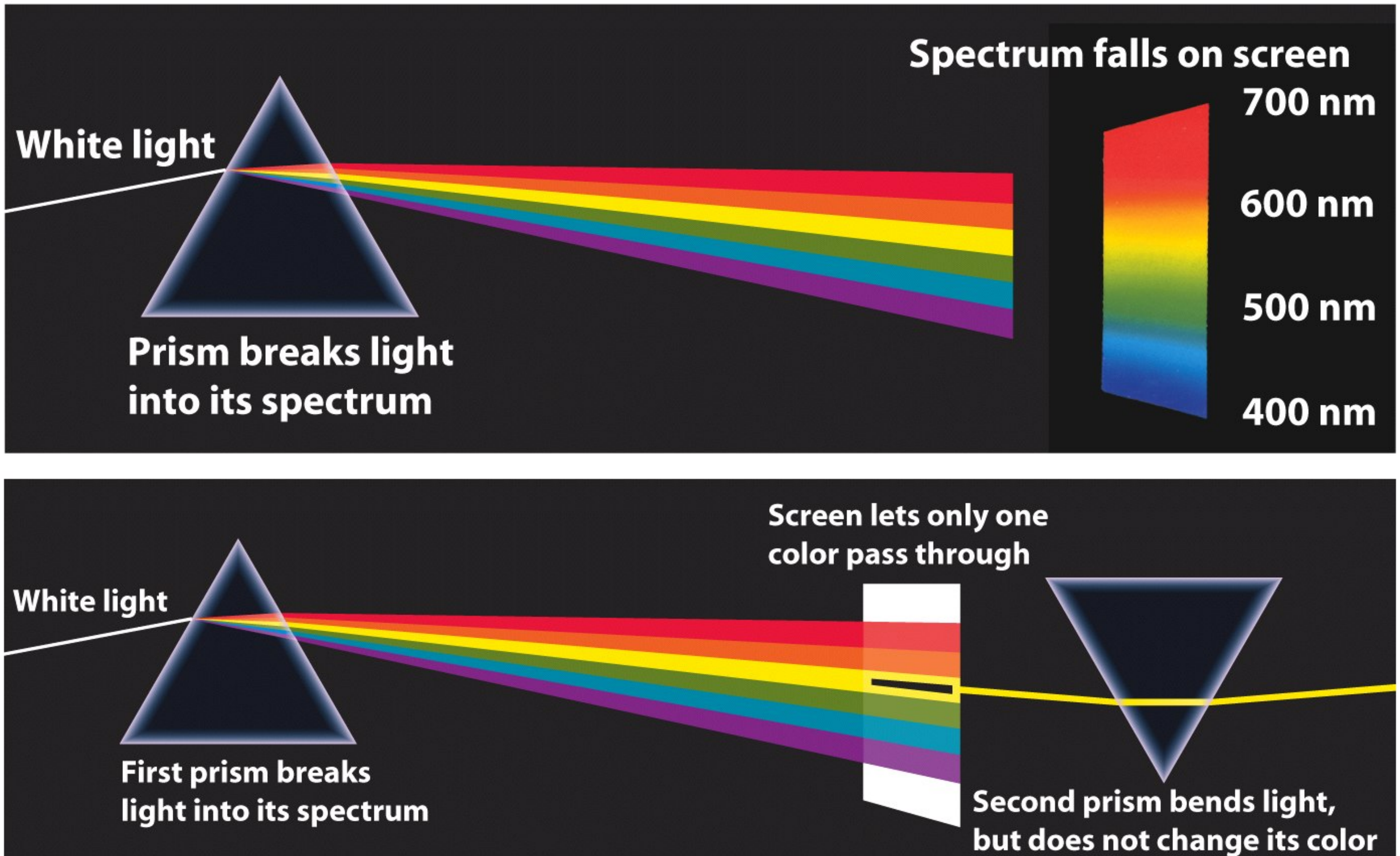
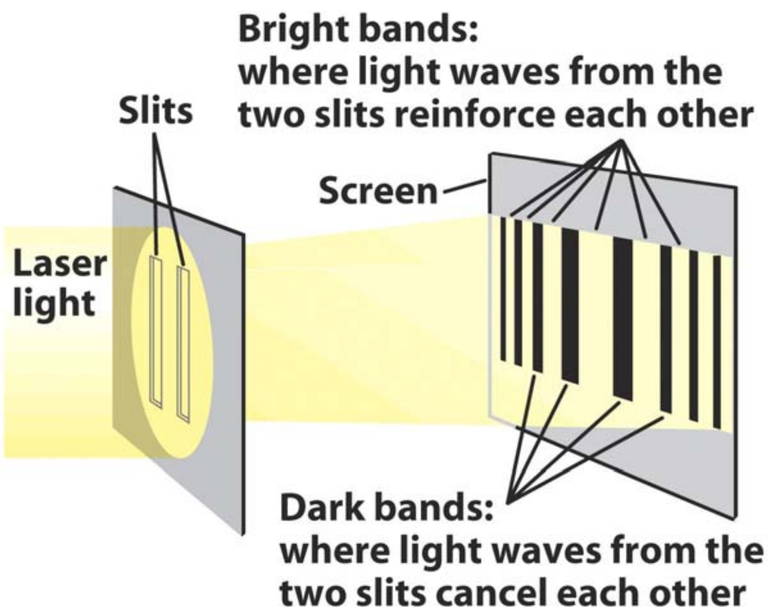
Light: spectrum and color

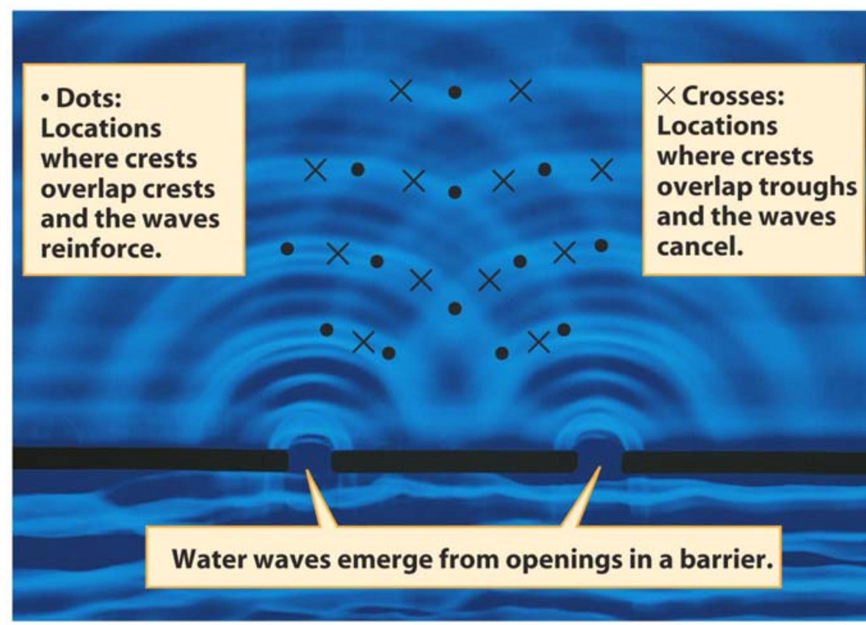
- Newton found that the white light from the Sun is composed of light of different color, or spectrum (1670).



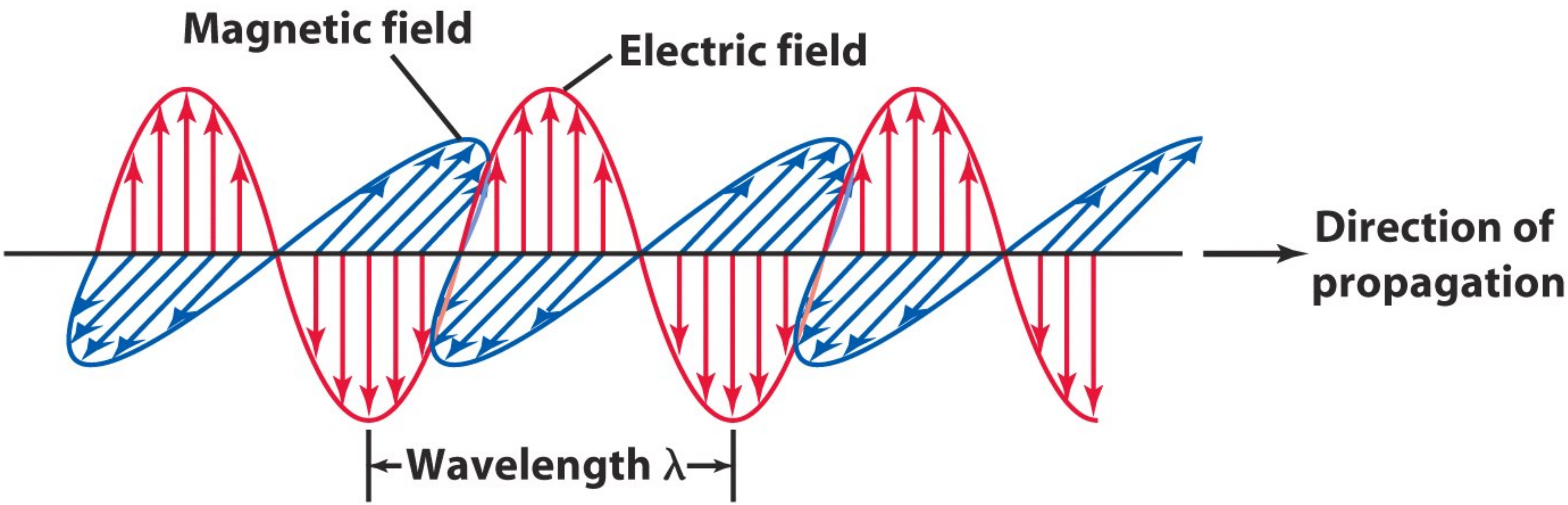
Light has wavelike property

- Young's Double-Slit Experiment indicated light behaved as a wave (1801)
- The alternating black and bright bands appearing on the screen is analogous to the water waves that pass through a barrier with two openings





Light is Electromagnetic Radiation



- **The nature of light is electromagnetic radiation**
- In the 1860s, James Clerk **Maxwell** succeeded in describing all the basic properties of electricity and magnetism in four equations: the Maxwell equations of **electromagnetism.**
- Maxwell showed that electric and magnetic field should travel space in z/.z,

Light: Wavelength and Frequency

Frequency and wavelength of an electromagnetic wave

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

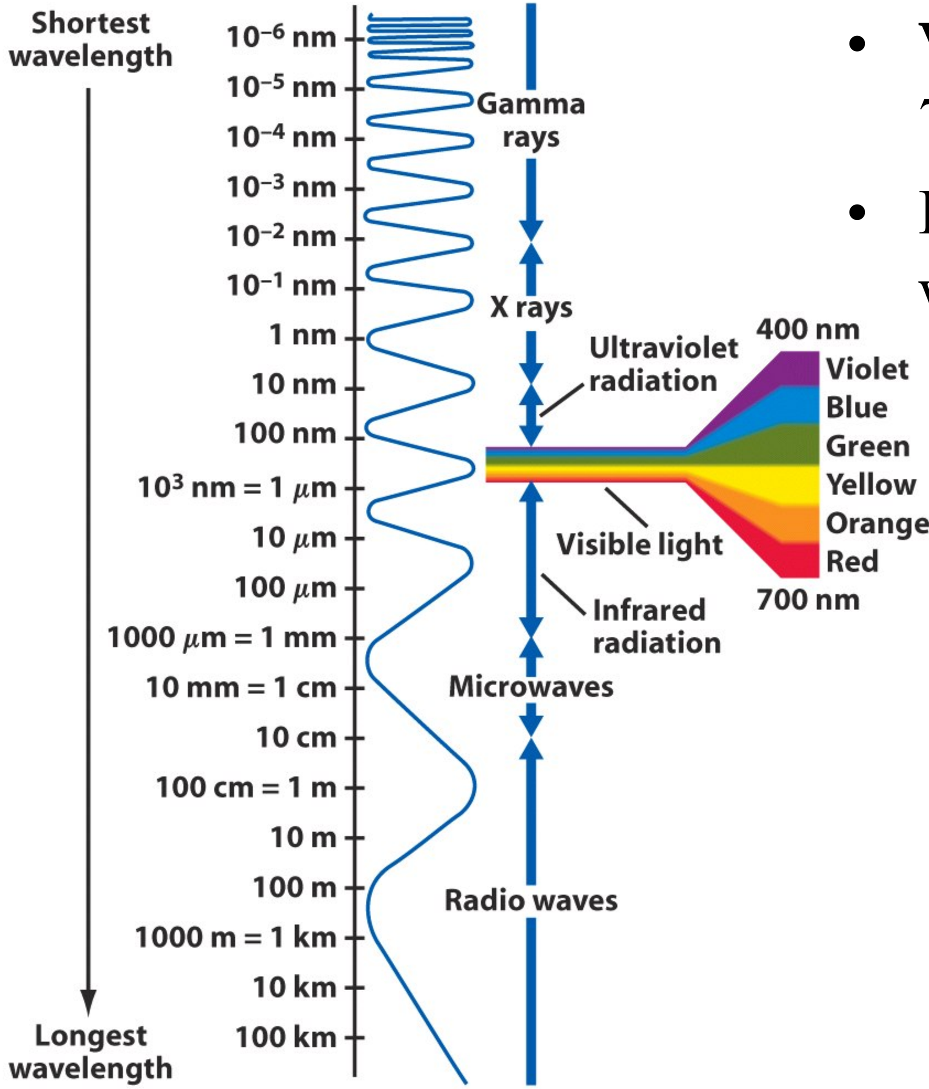
ν = frequency of an electromagnetic wave (in Hz)

c = speed of light = 3×10^8 m/s

λ = wavelength of the wave (in meters)

- Example
  - FM radio, e.g., 103.5 MHz (WTOP station) => $\lambda = 2.90$ m
  - Visible light, e.g., red 700 nm => $\nu = 4.29 \text{ X } 10^{14}$ Hz

Electromagnetic Spectrum

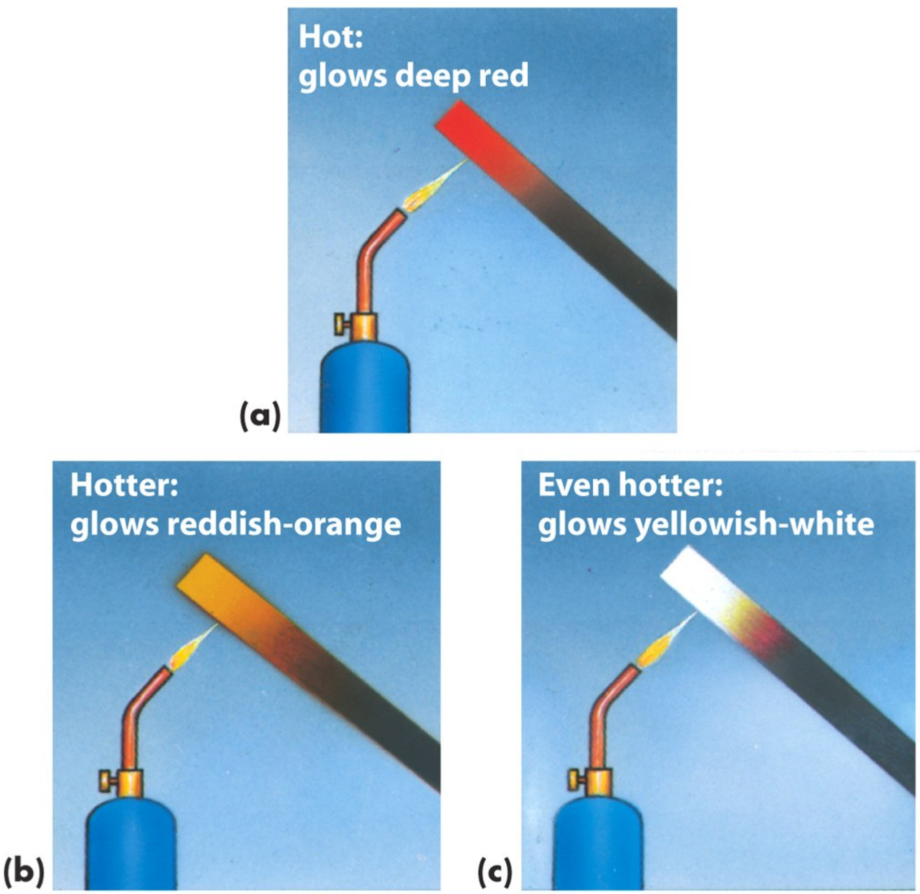


- **Visible light** falls in the 400 to 700 nm range
- In the order of decreasing wavelength
  - Radio waves: 1 m
  - Microwave: 1 mm
  - Infrared radiation: 1 μm
  - Visible light: 500 nm
  - Ultraviolet radiation: 100 nm
  - X-rays: 1 nm
  - Gamma rays: 10^{-3} nm

Radiation depending on Temperature

- A general rule:

  The higher an object's temperature, the more intensely the object emits electromagnetic radiation and the shorter the wavelength at which emits most strongly

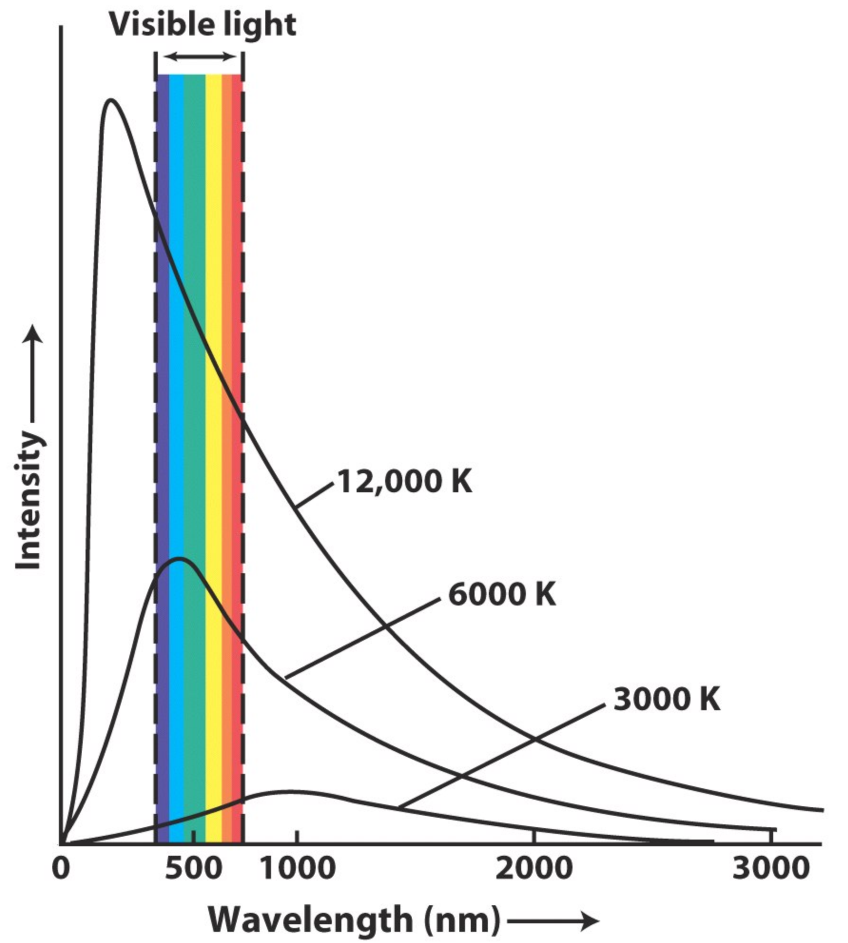


The example of heated iron bar. As the temperature increases

- The bar glows more brightly
- The color of the bar also changes

Blackbody Radiation

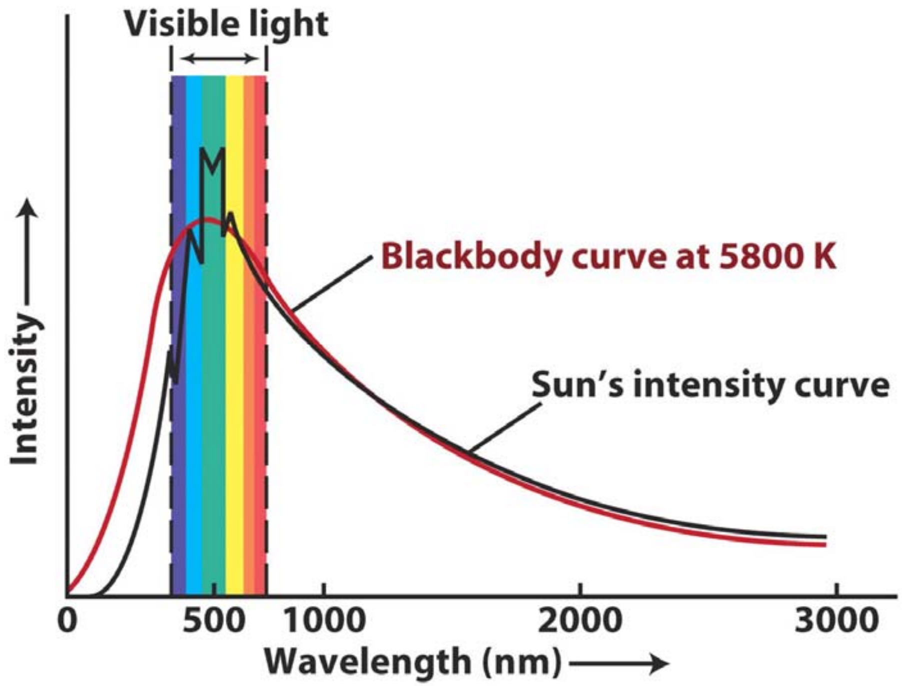
- A **blackbody** is a hypothetical object that is a perfect absorber of electromagnetic radiation at all wavelengths
  - **The radiation of a blackbody is entirely the result of its temperature**
  - A blackbody does not reflect any light at all
- **Blackbody curve**: the intensities of radiation emitted at various wavelengths by a blackbody at a given temperature
  - **The higher the temperature, the shorter the peak wavelength**
  - **The higher the temperature, the higher the intensity**



Blackbody curve

Blackbody Radiation

- Hot and dense objects act like a blackbody
- Stars, which are opaque gas ball, closely approximate the behavior of blackbodies
- The Sun's radiation is remarkably close to that from a blackbody at a temperature of 5800 K



The Sun as a Blackbody

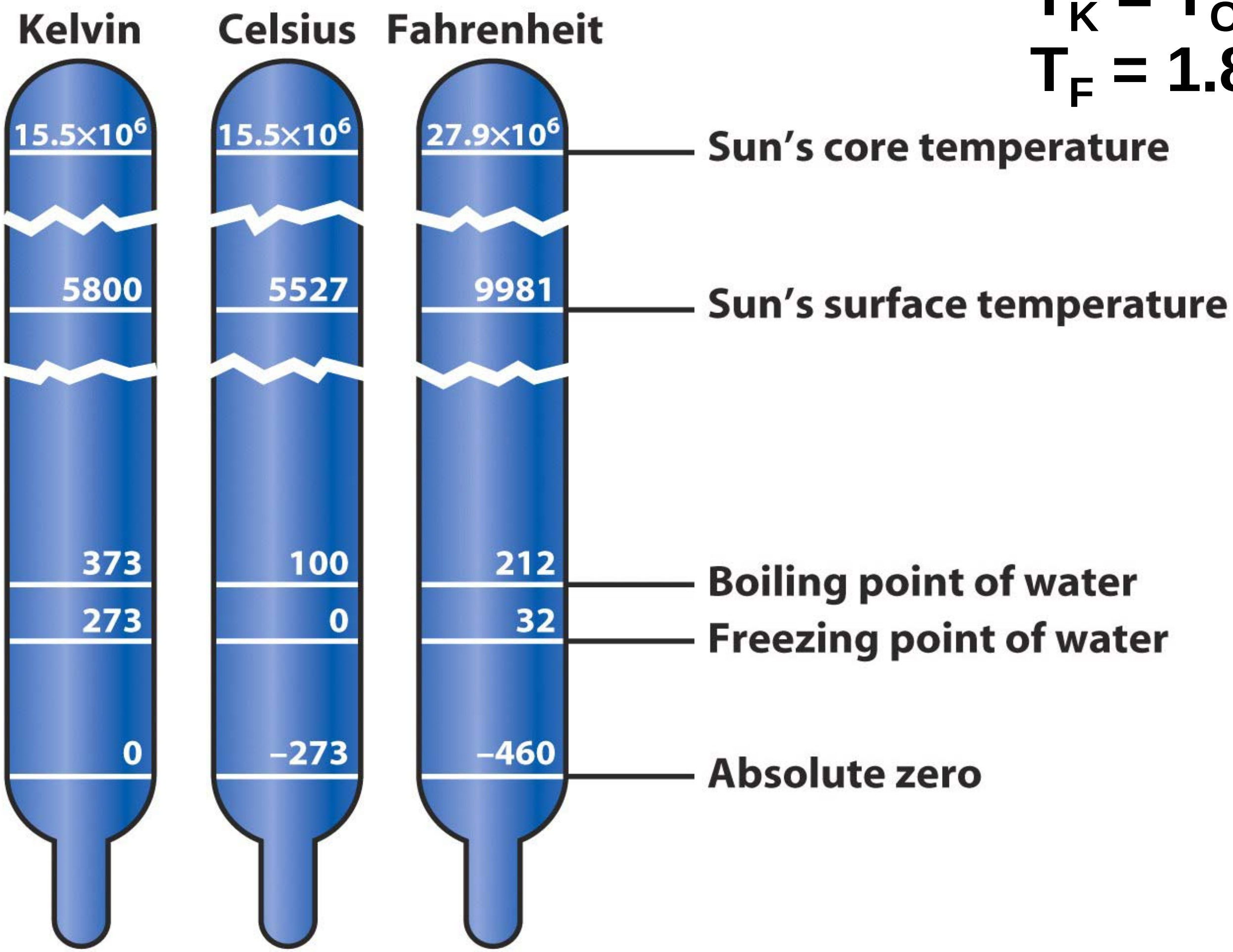
A human body at room temperature emits most strongly at infrared light

(Box 5-1, P97) Three Temperature Scales

Temperature in unit of Kelvin is often used in physics

$$T_K = T_C + 273$$

$$T_F = 1.8 (T_C+32)$$



Blackbody Radiation: Wien's Law

- **Wien's law states that the dominant wavelength at which a blackbody emits electromagnetic radiation is inversely proportional to the Kelvin temperature of the object**

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

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

T = temperature of the object (in kelvins)

For example

- The Sun, λ_{max} = 500 nm → T = 5800 K
- Human body at 37 degrees Celcius, or 310 Kelvin → λ_{max} = 9.35 μm = 9350 nm

Blackbody radiation: Stefan-Boltzmann Law

- **The Stefan-Boltzmann law states that a blackbody radiates electromagnetic waves with a total energy flux *F* directly proportional to the fourth power of the Kelvin temperature *T* of the object:**

$$F = \sigma T^4$$

- F = energy flux, in joules per square meter of surface per second
- σ = Stefan-Boltzmann constant = 5.67 X 10^{-8} W m^{-2} K^{-4}
- T = object's temperature, in kelvins

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Dual properties of Light:
(1) waves and (2) particles

- Light is an electromagnetic radiation wave, e.g, Young's double slit experiment
- Light is also a particle-like packet of energy - **photon**
  - **Light particle is called photon**
  - The energy of phone is related to the wavelength of light
- **Light has a dual personality; it behaves as a stream of particle like photons, but each photon has wavelike properties**

Dual properties of Light: Planck's Law

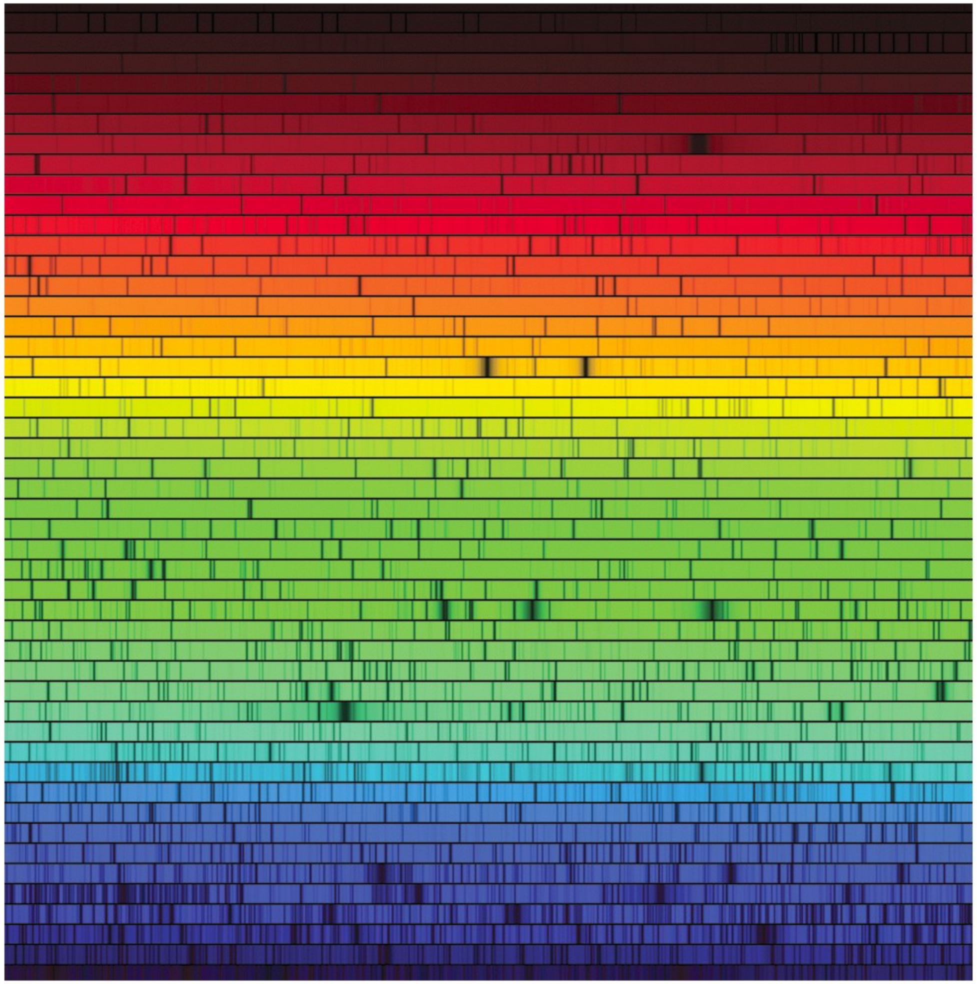
- Planck's law relates the energy of a photon to its wavelength or frequency
  - E = energy of a photon
  - h = Planck's constant
    = 6.625×10^{-34} J s
  - c = speed of light
  - λ= wavelength of light

$$E = \frac{hc}{\lambda}$$

- **Energy of photon is inversely proportional to the wavelength of light**
- Example: 633-nm red-light photon
  - $E = 3.14 \times 10^{-19}$ J
  - or E = 1.96 eV
  - eV: electron volt, a small energy unit = 1.602×10^{-19} J

Spectral Lines

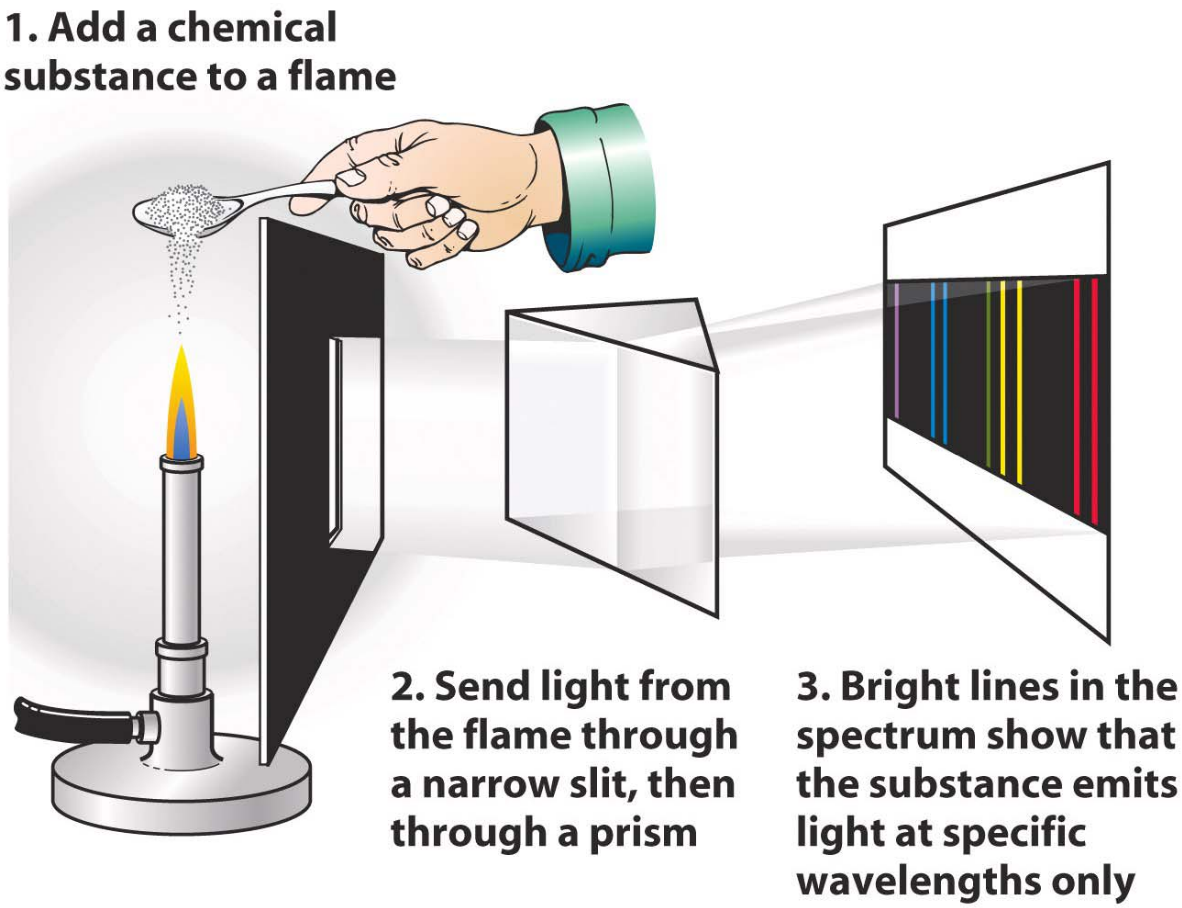
- The Sun’s spectrum: in addition to the rainbow-colored continuous spectrum, it contains hundreds of fine dark lines, called **spectral lines** (**Fraunhofer**, 1814)



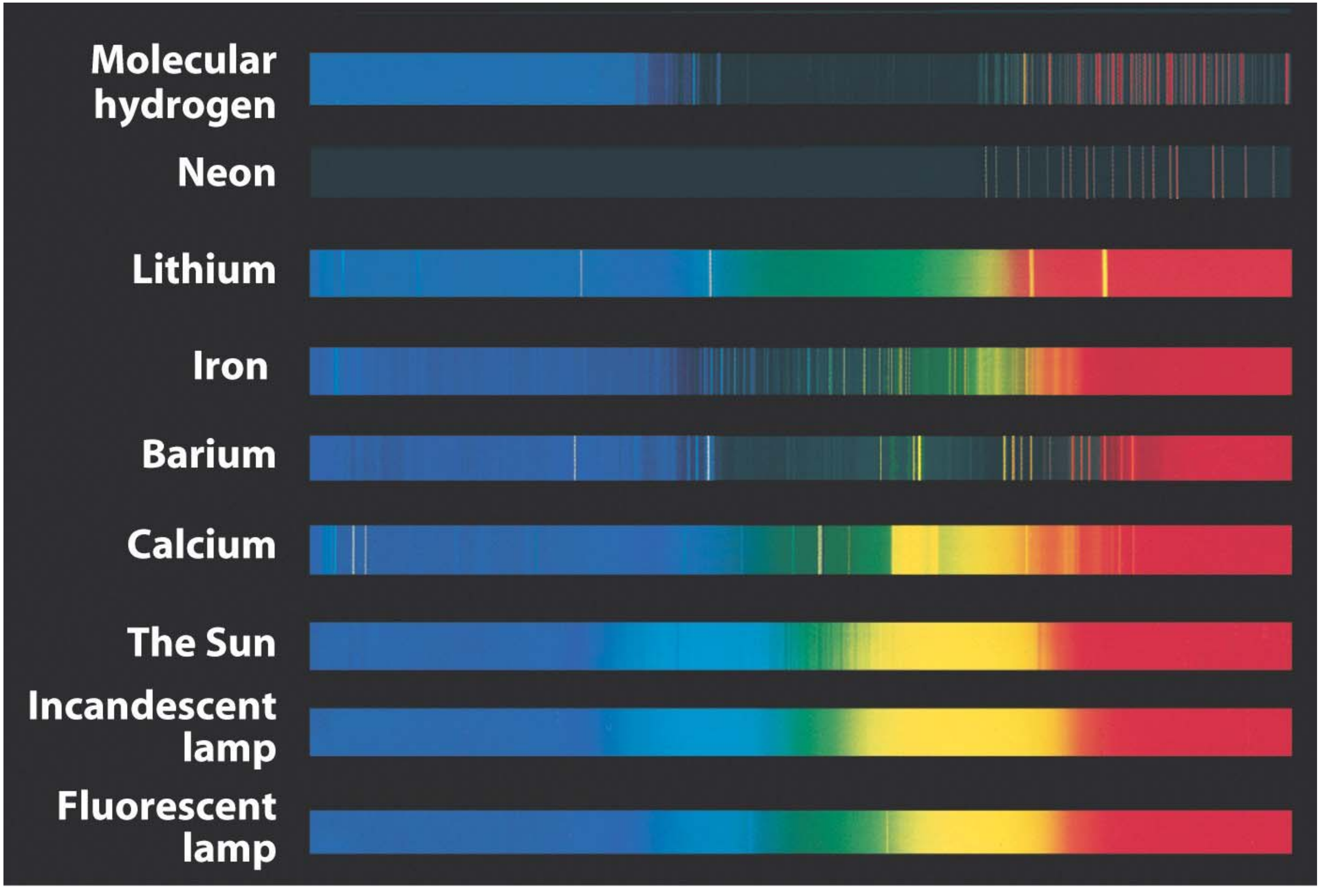
  - A perfect blackbody would produce a smooth, continuous spectrum with no dark lines

Spectral Lines

- Bright spectrum lines can be seen when a chemical substance is heated and valoprized (Kirchhoff, ~1850)

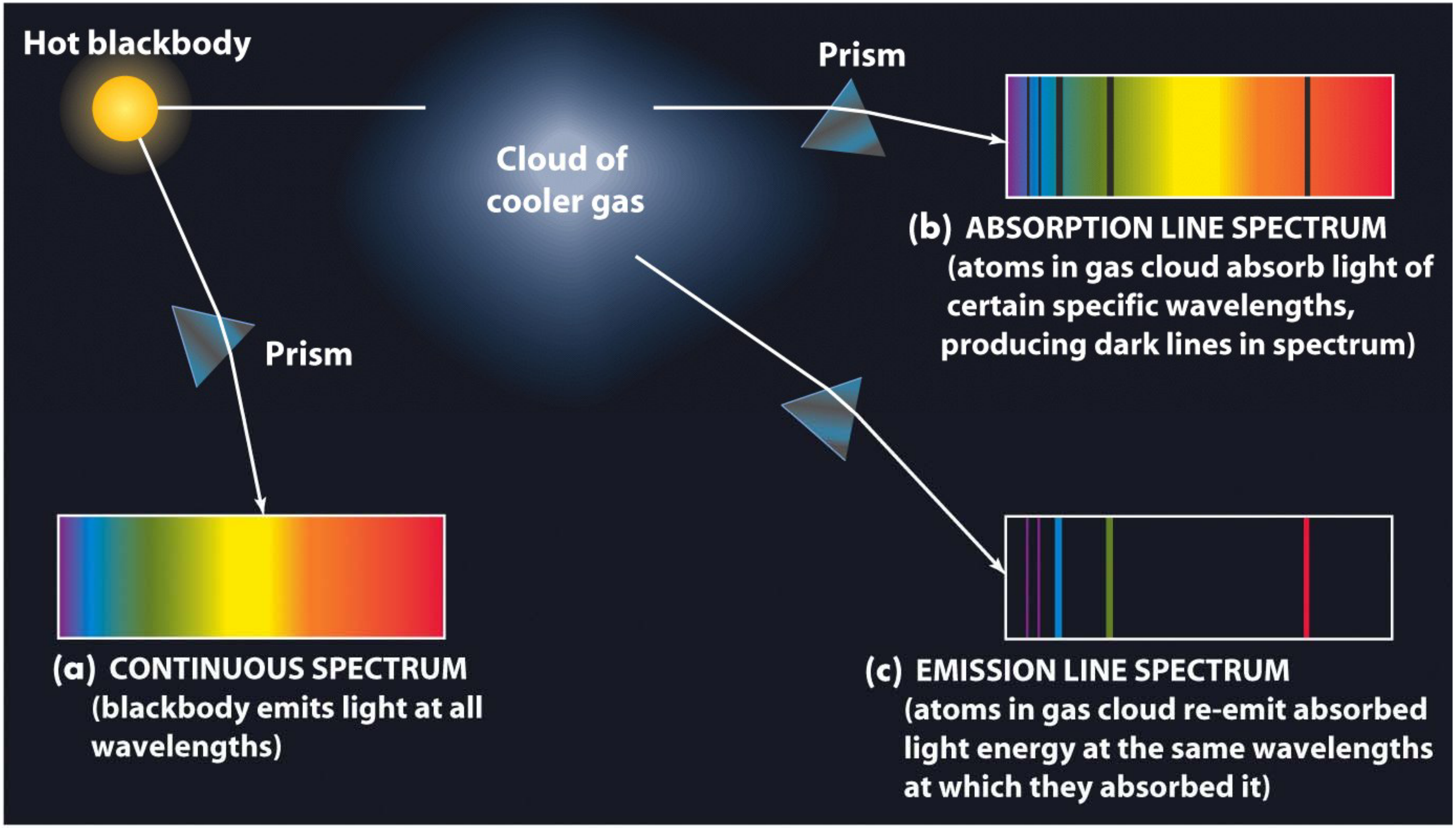


Each chemical element has its own unique set of spectral lines.



Kirchhoff's Laws on Spectrum

- Three different spectrum: continuous spectrum, emission-line spectrum, and absorption line spectrum

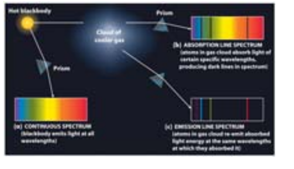


Kirchhoff’s Laws on Spectrum

- Law 1- Continuous spectrum: a hot opaque body, such as a perfect blackbody, produce a continuous spectrum – a complete rainbow of colors without any spectral line

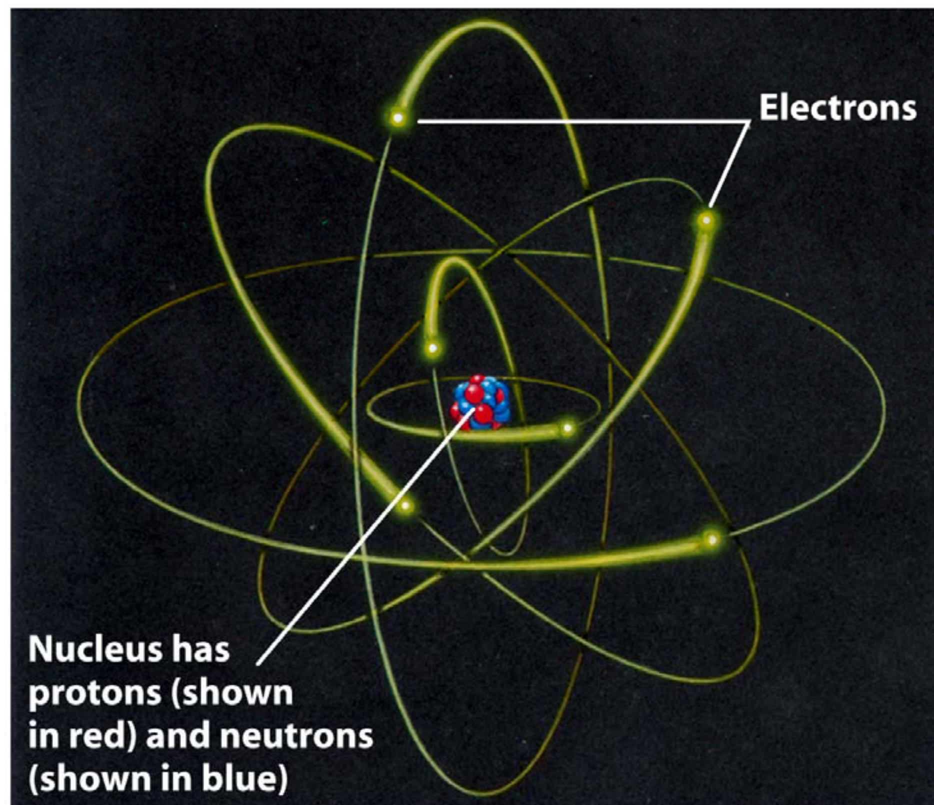
- Law 2 – emission line spectrum: a hot, transparent gas produces an emission line spectrum – a series of bright spectral lines against a dark background

- Law 3 – absorption line spectrum: a relatively cool, transparent gas in front of a source of a continuous spectrum produces an absorption line spectrum – a series of dark spectral lines amongst the colors of the continuous spectrum. **Further, the dark lines of a particular gas occur at exactly the same wavelength as the bright lines of that same gas.**



Structure of Atom

- An **atom** consists of a small, dense **nucleus** at the center, surrounded by **electrons** which orbit the nucleus.
- The **nucleus** contains more than 99% of the mass of an atom, but concentrates in an extremely small volume
- A nucleus contains two types of particles: **protons and neutrons**
- A proton has a positive electric change, equal and opposite to that of an electron.
- A neutron, about the same mass of a proton, has no electric charge.
- An atom has no net electric charge



(Box 5-5, P108) Periodic Table

Periodic Table of the Elements

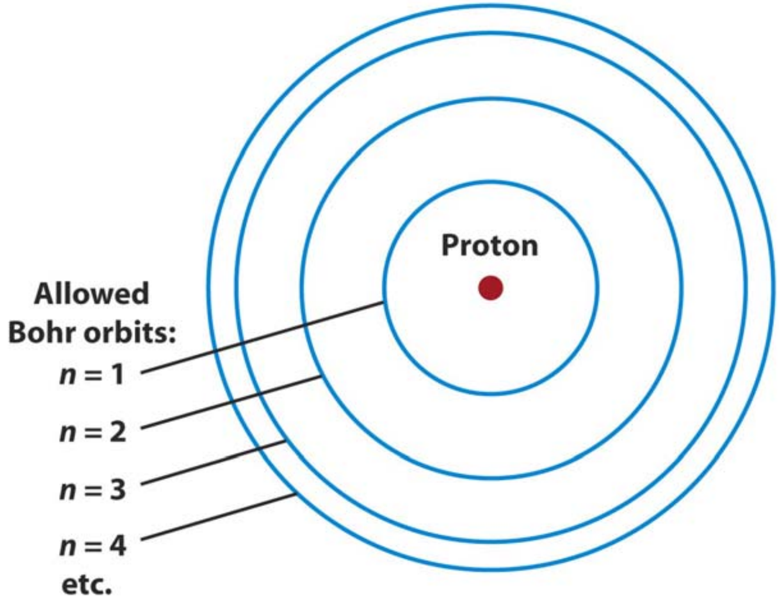
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	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	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111	112	113	114	115	116	117	118

57 La	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
89 Ac	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

- The number of protons in an atom’s nucleus is the **atomic number** for that particular element
- The same element may have different numbers of neutrons in its nucleus, which are called **isotopes**

Bohr’s Model of Atom

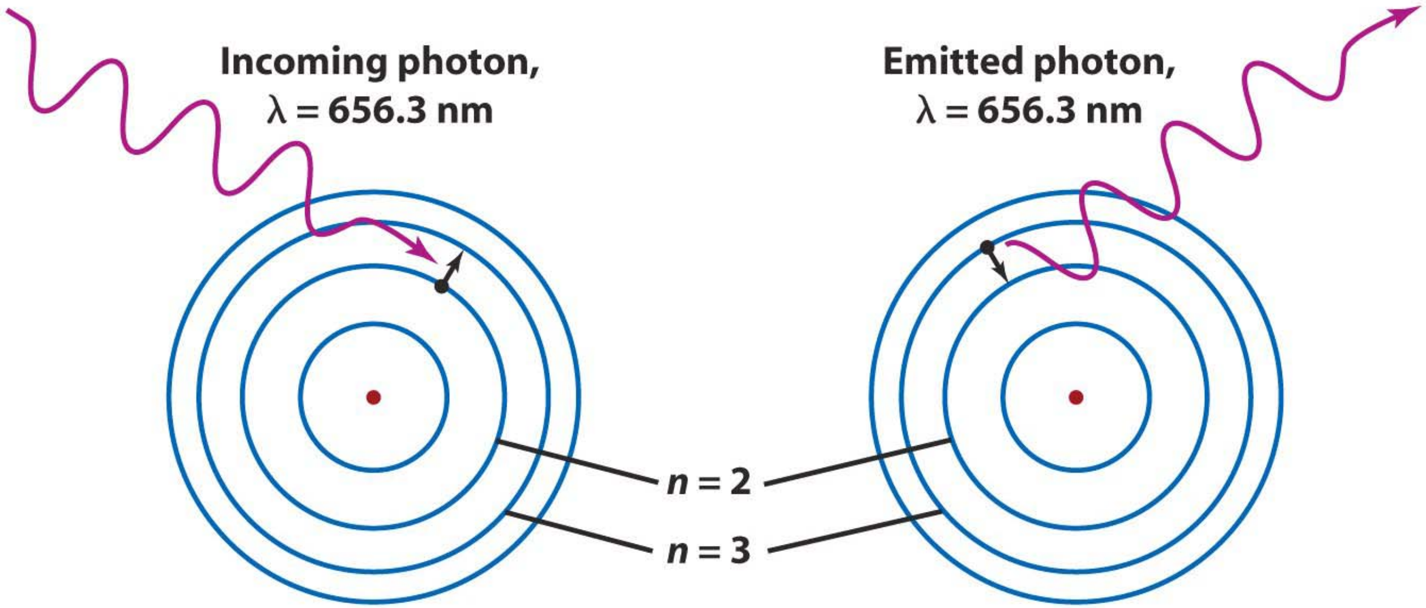
- **Electrons occupy only certain orbits or energy levels**
- **When an electron jumps from one orbit to another, it emits or absorbs a photon of appropriate energy.**
- **The energy of the photon equals the difference in energy between the two orbits.**



Bohr’s Model of Hydrogen

Bohr's Model of Atom

- **Absorption** is produced when electron absorbs incoming photon and **jumps from a lower orbit to a higher orbit**
- **Emission** is produced when electron **jumps from a higher orbit to a lower orbit** and emits a photon of the same energy

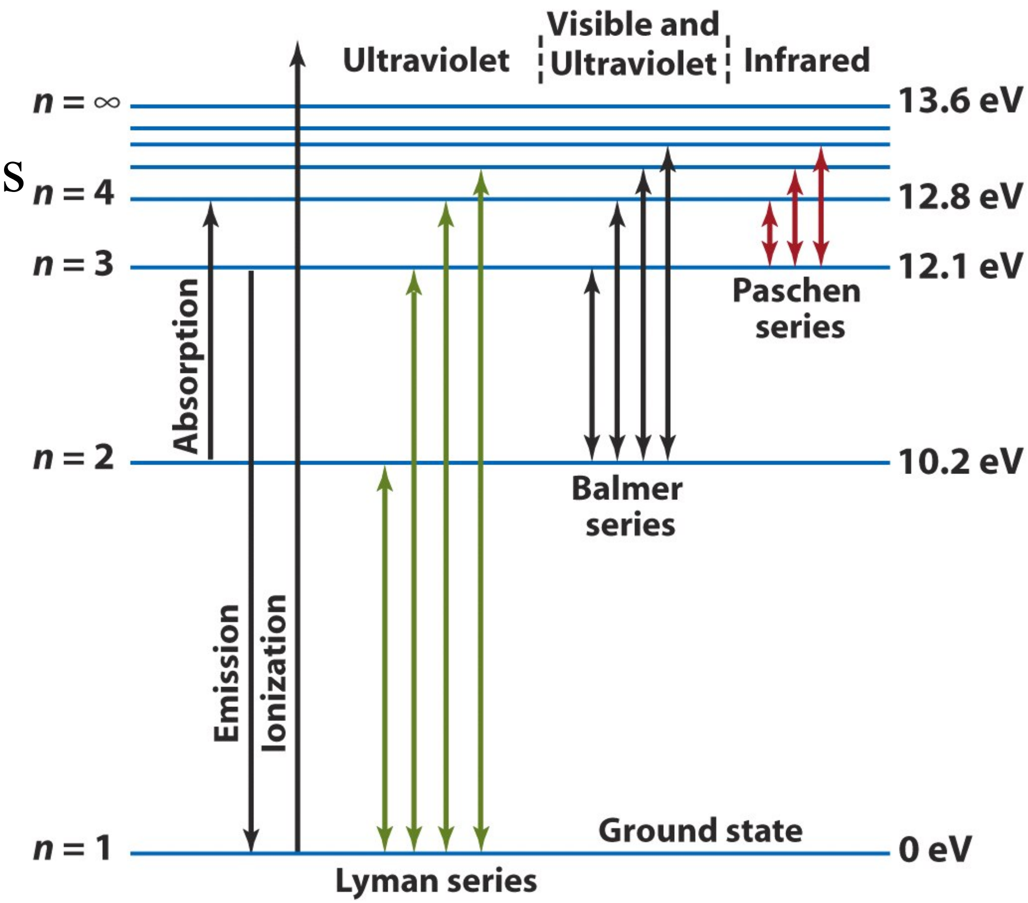


(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the *n* = 2 orbit up to the *n* = 3 orbit

(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

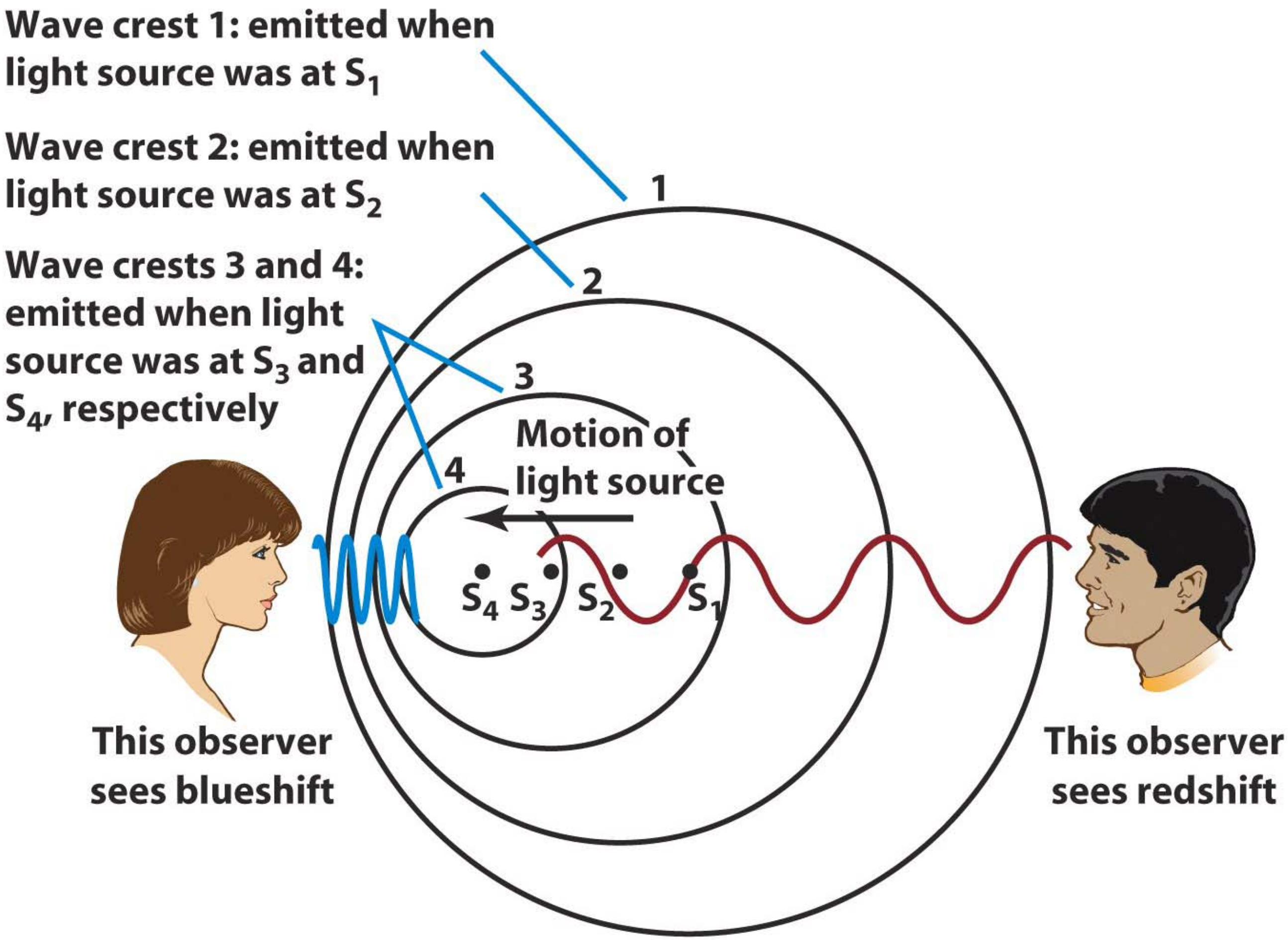
Bohr's Atomic Model for Hydrogen

- The strongest hydrogen spectral line from the Sun, Hα line at 656 nm, is caused by electron-transition between n=3 orbit and n=1orbit
- **Lyman series lines**: between n=1 orbit and higher orbits (n=2, n=3, n=4,…)
- **Balmer series lines**: between n-2 orbit and higher orbits (n=3, 4, 5,…)



Doppler Effect

- **Doppler effect: the wavelength of light is affected by motion between the light source and an observer**



Doppler Effect

- **Red Shift**: The object is moving away from the observer, the line is shifted toward the longer wavelength
- **Blue Shift**: The object is moving towards the observer, the line is shifted toward the shorter wavelength

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

$\Delta\lambda$ = wavelength shift

λ_o = wavelength if source is not moving

v = velocity of source

c = speed of light

- Questions: what if the object's motion perpendicular to our line of sight?

Final Notes on Chap. 5

- There are 9 sections. All section are covered

- There are 6 boxes. Only box 5-1(three temperature scale) and box 5-5 (periodic table) are covered.

- **Ch.5 Section 5-1: Sep. 25, 2006, Lect.4**
- **Ch.5 Section 5-2 ---- 5-4: Oct. 02, 2006, Lect.5**
- **Ch.5 Section 5.5 --- 5-9: Oct. 10, 2006, Lect. 6**