Roger Freedman • Robert Geller • William Kaufmann III

Universe

Tenth Edition

Chapter 5

The Nature of Light

By reading this chapter, you will learn

- 5-1 How we measure the speed of light
- 5-2 How we know that light is an electromagnetic wave
- 5-3 How an object's temperature is related to the radiation it emits
- 5-4 The relationship between an object's temperature and the amount of energy it emits
- 5-5 ~~The evidence that light has both particle and wave aspects~~
- 5-6 How astronomers can detect an object's chemical composition by studying the light it emits
- 5-7 ~~The quantum rules that govern the structure of an atom~~
- 5-8 The relationship between atomic structure and the light emitted by objects
- 5-9 How an object's motion affects the light we receive from that object

Why light?

- With only a very few exceptions*, all the information about stars and galaxies reaches the Astronomers in the form of light

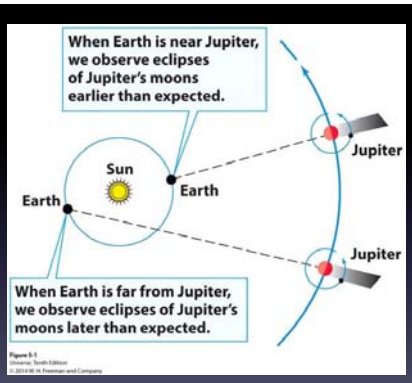
*gravity waves, neutrinos…

So what is light?

- Light is an *electromagnetic* wave
- It can also be thought of as a particle called a *photon: γ*
- This apparent contradiction is called the *particle/wave duality*
- The apparent contradiction is due to our inability to describe something that is neither entirely a wave nor a particle
- At times it's convenient to speak of light as a wave; at other times convenience begs for a particle

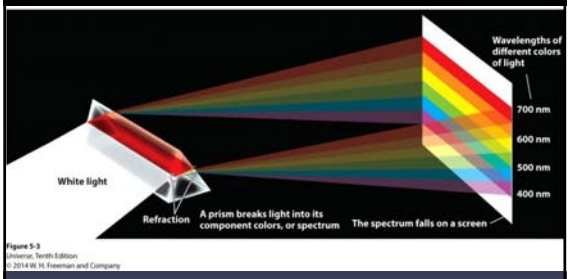
The Speed of Light

- The speed of light, denoted 'c', is a fixed speed
- We use *c* because the speed of a wave is constant in a particular medium
- The ultimate speed limit is 300,000 km/sec, about 186,000 miles a second~670 million miles an hour.
- Light can travel more slowly than this, for instance in glass or water, but never faster



Rømer's Evidence that Light Does Not Travel Instantaneously

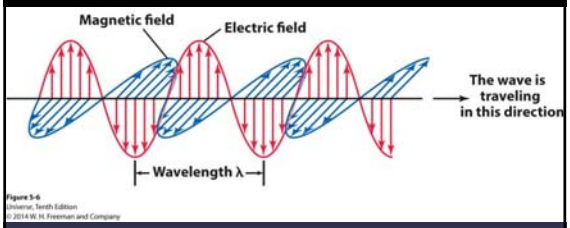
5-2: Light is electromagnetic radiation and is characterized by its wavelength



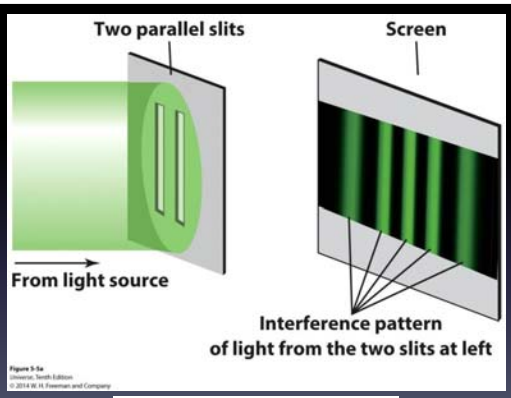
A Prism and a Spectrum

Frequency and Wavelength

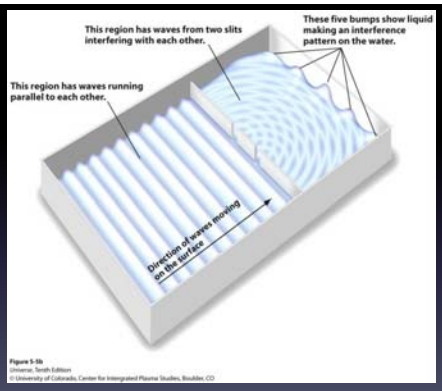
- Frequency *f* is how many waves occur each second, and wavelength λ is, obviously, the length of the wave
- Frequency is measured in Hz and wavelength is measured in meters
- The product of those two terms gives you the speed of the wave, c.



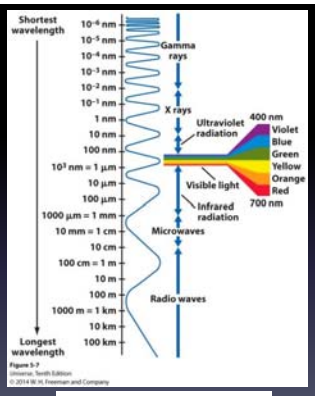
Electromagnetic Radiation



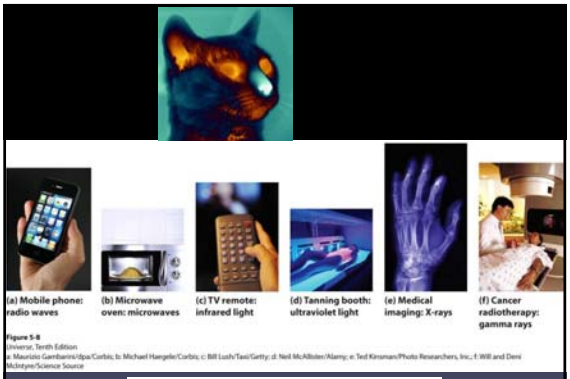
"Proof" that Light is a Wave: Interference



Wave Interference

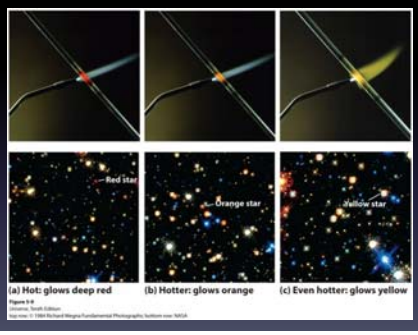


The Electromagnetic Spectrum



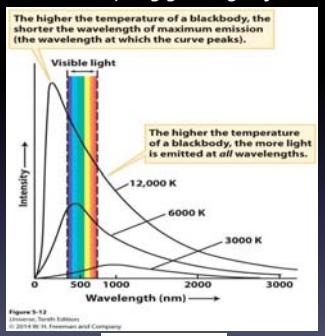
Uses of Nonvisible Electromagnetic Radiation

5-3: An opaque object emits electromagnetic radiation according to its temperature



Objects at Different Temperatures Have Different Colors and Brightness.

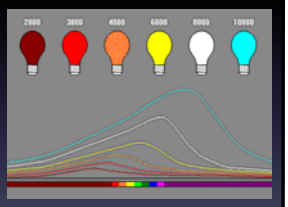
5-4: Wien's law and the Stefan-Boltzmann law are useful tools for analyzing glowing objects like stars

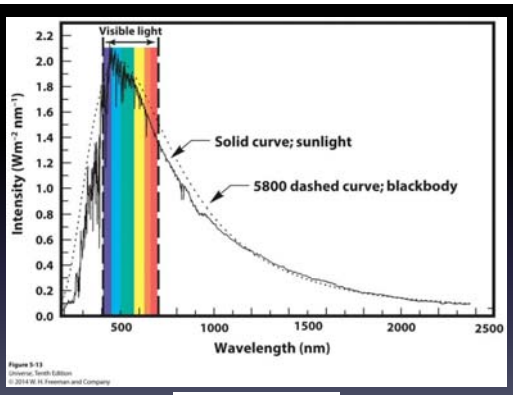


Blackbody Curves

Intrinsic Brightness: Blackbody Radiation

- Stars emit light because they are *hot!*
- Their color is determined by their temperature
- Consequently, their brightness is dependent on their temperature (among other things)



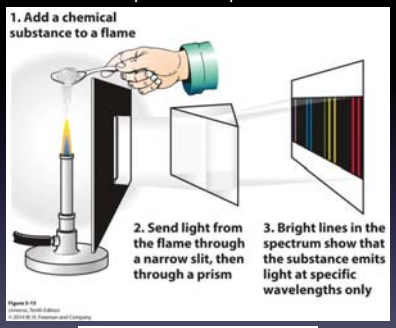


The Sun as a Blackbody

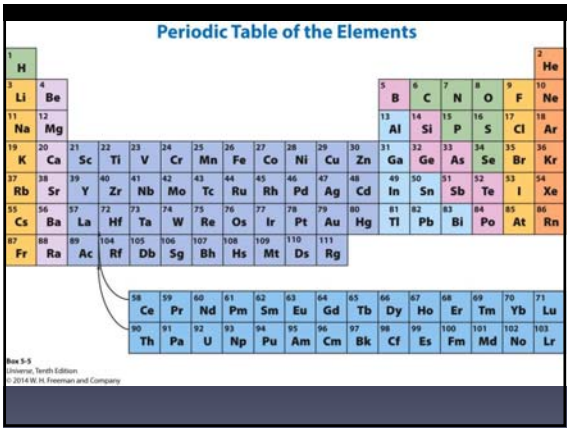
The black spaces are the squiggles seen in the Sun's blackbody curve *(explanation forthcoming)*

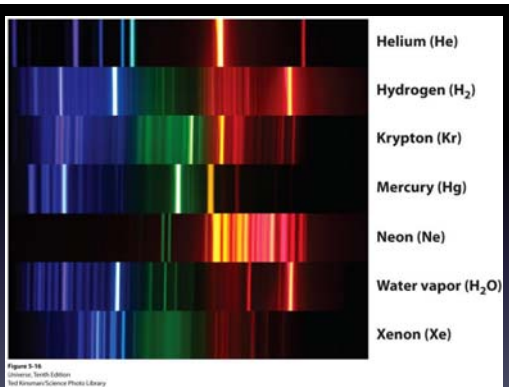
The Sun's Spectrum

5-6: Each chemical element produces its own unique set of spectral lines

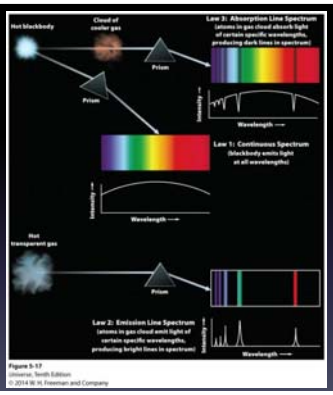


The Kirchhoff-Bunsen Experiment

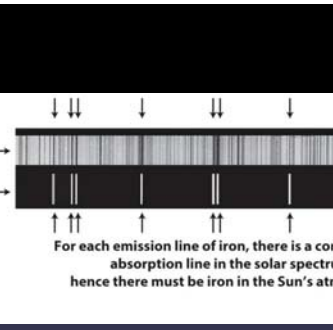




Various Spectra



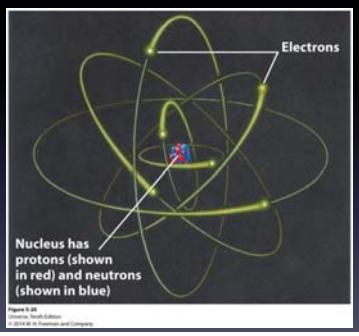
Kirchhoff's Laws for Continuous, Absorption Line and Emission Line Spectra



Iron in the Sun

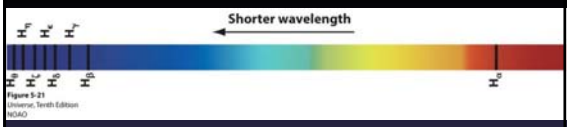
Analyzing the Composition of a Distant Nebula

5-7: An atom consists of a small, dense nucleus surrounded by electrons

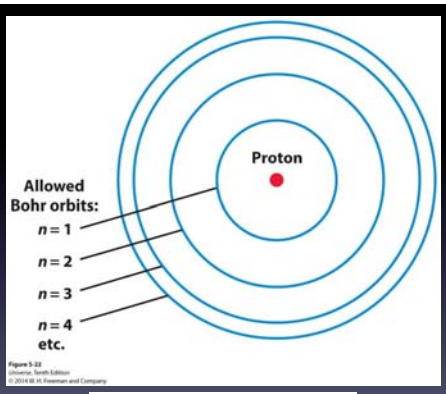


Rutherford's Model of the Atom (*he didn't know about neutrons at the time*)

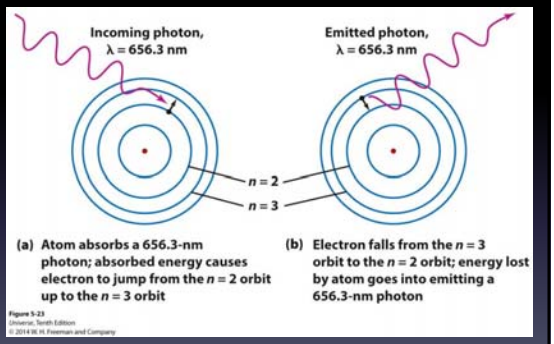
5-8: Spectral lines are produced when an electron jumps from one energy level to another



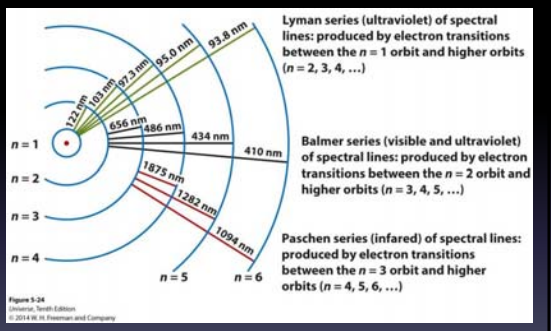
Balmer Lines in the Spectrum of a Star



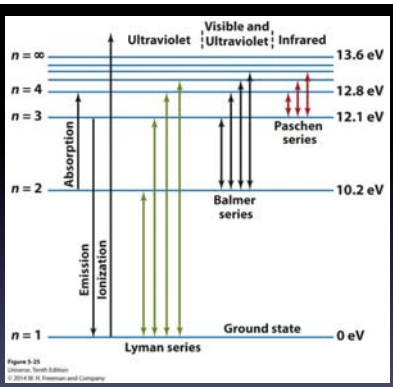
The Bohr Model of the Hydrogen Atom



The Absorption and Emission of a H_α Photon

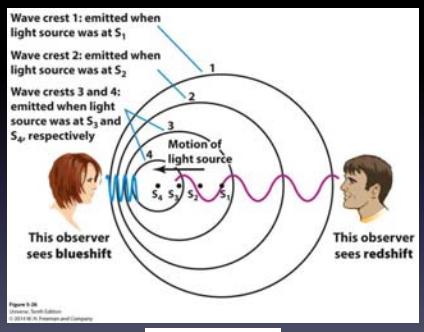


Electron Transitions in the Hydrogen Atom



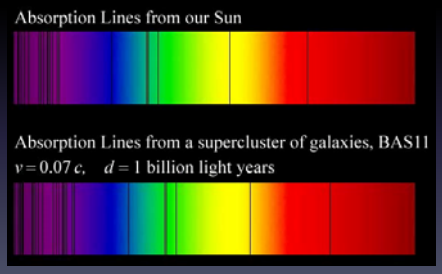
Energy-Level Diagram of Hydrogen

5-9: The wavelength of a spectral line is affected by the relative motion between the source and the observer



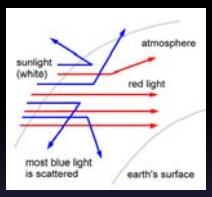
The Doppler Effect

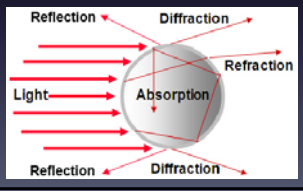
Red Shift

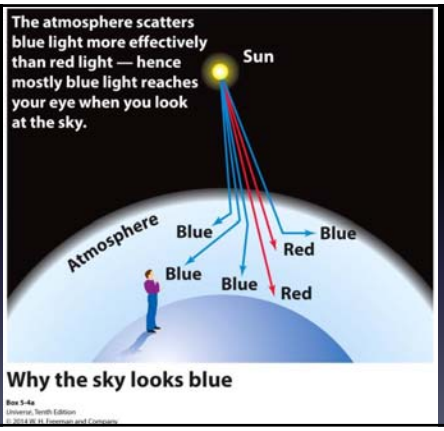


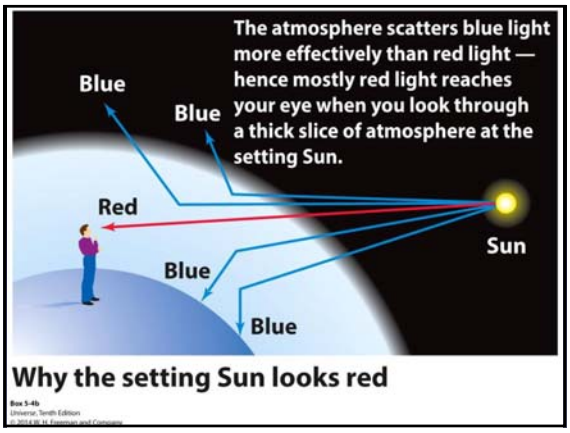
Scattering

- Why the sky is blue
  - Windblown dust
  - Ice crystals in clouds
  - Smog









Key Ideas

- **The Nature of Light:** Light is electromagnetic radiation. It has wavelike properties described by its wavelength λ and frequency ν, and travels through empty space at the constant speed $c = 3.0 \times 10^8$ m/s = 3.0×10^5 km/s.
- **Thermal energy:** The thermal energy of a material comes from the kinetic energy of its microscopic particles (atoms and molecules). The hotter a material, the faster its particles move, and the greater its thermal energy.
- **Blackbody Radiation:** A blackbody is a hypothetical object that is a perfect absorber of electromagnetic radiation at all wavelengths. Stars closely approximate the behavior of blackbodies, as do other hot, dense objects.

Key Ideas

- The intensities of radiation emitted at various wavelengths by a blackbody at a given temperature are shown by a blackbody curve.
- **Wien's law** states that the dominant wavelength (and overall color) at which a blackbody emits electromagnetic radiation is inversely proportional to the Kelvin temperature of the object.
- **Photons:** Light is made of particles called photons. Each photon has a wavelength equal to the wavelength of the light that the photons make up.

Key Ideas

- **Kirchhoff's Laws:** Kirchhoff's three laws of spectral analysis describe conditions under which different kinds of spectra are produced.
- A hot, dense object such as a blackbody emits a **continuous spectrum** covering all wavelengths.
- A hot, transparent gas produces a spectrum that contains bright (**emission**) lines.
- A cool, transparent gas in front of a light source that itself has a continuous spectrum produces dark (**absorption**) lines in the continuous spectrum.

Key Ideas

- **Atomic Structure:** An atom has a small dense nucleus composed of protons and neutrons. The nucleus is surrounded by electrons that occupy only certain orbits or energy levels.
- When an electron jumps from one energy level to another, it emits or absorbs a photon of appropriate energy (and hence of a specific wavelength).
- The **spectral lines** of a particular element correspond to various electron orbital transitions between energy levels in the atom. Each atom has a unique "spectral fingerprint".

Key Ideas

- **The Doppler Shift:** The Doppler shift enables us to determine the line-of-sight (radial) velocity of a light source from the displacement of its spectral lines.
- The spectral lines of an approaching light source are shifted toward short wavelengths (a **blueshift**); the spectral lines of a receding light source are shifted toward long wavelengths (a **redshift**).
- The size of a wavelength shift is proportional to the radial velocity of the light source relative to the observer.