Lecture #6: Radiation and Spectra I

Making Measurements of the Solar System:
- The Nature of Light.
- Properties of Electromagnetic Radiation.
- Spectroscopy.

The Main Point
Measuring the light from objects in the Solar System (and beyond) provides most of our information on their fundamental properties.

The Nature of Light
- Light provides information on distant objects that are too far away to routinely visit (or visit at all!)
- Light is a form of electromagnetic radiation:
  - Radiating "disturbances" in electric & magnetic fields.
  - Disturbances generated by motions of charged particles.
  - Electricity, magnetism, and light are all related.
- Much of what we know of planets, moons, asteroids, comets, and the Sun comes from decoding their light!

Light as a Wave
James Clerk Maxwell
(1831-1879)

- Discovered the relationship between electricity and magnetism.
- Developed theory of the wave nature of light:
  - One of the most famous and fundamental set of equations in physics!
  - Oscillating fields are generated by subatomic motions.
  - The fields propagate into space like waves on a pond.
  - These waves propagate at the speed of light: \( c = 3 \times 10^8 \text{ m/sec} \).
  - Physicists have shown that \( c \) is the Universal Speed Limit!
Wave Properties of Light

- Light travels just fine through a vacuum.
- A fundamental parameter of light is its wavelength ($\lambda$).
- Closely related parameter: frequency ($f$).
- $f = \frac{c}{\lambda}$.
- One wave cycle per second = 1 Hertz (1 Hz).

Interactions of waves and particles

Concept: Tossing a pebble into a pond generates waves. As waves travel past the leaf (an analogy for light interacting with a charged particle), it bobs up and down at the same frequency as the wave, but doesn’t move across the pond. The wave carries energy away from a point but does not carry matter. A particle is a thing and a wave is a pattern revealed by its interaction with particles.

Quantum Mechanics

- In some experiments, light acts as a particle rather than a wave ("wave-particle duality of light"). A photon is a particle of light.
- An entire subfield of physics devoted to reconciling the wave and particle nature of light.
- A photon is a little packet of energy.
- The energy is carried in discrete quanta (pieces):
  - Energy is quantized, like coins or rungs on a ladder.
- The energy of a photon is proportional to its frequency:
  - $E = hf$.
  - $h \approx$ Planck’s Constant (6.626x10^{-34} J•s; Appendix A).
  - Alternately, $E = h c / \lambda$.

- Longer wavelength: Less energy.
- Shorter wavelength: More energy.

Propagation of Light

- Important difference between the actual brightness of an object, and its apparent brightness as measured in the sky.
- The apparent brightness of a source decreases as the square of the distance from it: $F_{\text{apparent}} = F_{\text{actual}} / r^2$.
- $F_1 = B$,
- $F_2 = B / 4$,
- $F_3 = B / 9$, ...

- Provides a rough way to estimate distances!
Visible Light

- The light we see is only one small piece of the vast range of electromagnetic radiation.

The Electromagnetic Spectrum

- Radio Waves: Lowest energy, longest wavelengths (few mm to many km).
- Infrared Radiation: Wavelengths of a few microns (µm) to a few mm ("heat").
- Visible Light: Wavelengths of about 400 to 700 nm (human eye response).
- Ultraviolet Light: Wavelengths from ~ 20 to 400 nm, higher energy than visible.
- X-Rays: Wavelengths from about 0.01 to 20 nm.
- Gamma Rays: Highest energy, shortest wavelengths (< 0.01 nm).

Some wavelengths reach the Earth's surface, others do not (with implications for astronomy & biology!)
Radiation and Temperature

- Electromagnetic radiation is emitted from an object in a predictable way that depends primarily on its temperature.
- Imagine an idealized object that does not reflect or scatter any radiation, but absorbs all the energy that falls on it:
  - Such an object is called a blackbody.
- Two laws of physics govern the behavior of a blackbody:
  - Stefan-Boltzmann law: Total energy emitted per unit time per unit area is proportional to the fourth power of its temperature:
    \[ E = \sigma T^4 \] (\( \sigma \) = Stefan-Boltzmann constant, Appendix A).
  - Wien’s law: The wavelength of the maximum energy emitted by a blackbody is inversely proportional to its temperature:
    \[ \lambda_{\text{max}} = \frac{2,900,000}{T}, \] where \( \lambda_{\text{max}} \) is in nm (10^-9 m) & T is in Kelvin.

Spectroscopy

- The dispersion of light and measurement of its intensity at different wavelengths is called spectroscopy:
  - Single measurement: spectrum.
  - Multiple measurements: spectra.
- Light can be dispersed using devices such as prisms which refract light, or gratings which diffract (interfere) light.
  - A rainbow is an example in nature of refraction of light by water droplets acting like tiny prisms.
- Spectroscopy is a form of remote sensing and provides a "fingerprinting tool" for determining the composition of astronomical objects without having to go there.
Summary

- Light is a form of electromagnetic radiation.
  - Sometimes acts like a wave.
  - Sometimes acts like a particle.
- Light is classified by its wavelength or energy.
  - (High E) Gamma rays, X-rays, UV, VIS, IR, Radio (Low E).
  - Higher energy = shorter wavelength \((E = h c / \lambda)\).
- Objects emit radiation in proportion to the fourth power of their temperature \((E = \sigma T^4)\).
- Spectroscopy is an important exploration tool.

Next Lecture...

- Radiation and Spectra II.
  - Models of Atomic Structure.
  - Absorption of Radiation.
  - Doppler Shift.
- Applications in Planetary Science.
- Reading:
  - Chapter 5.