Chapter 5

Nature of Light and matter

Astronomers study astronomical objects by observing how they emit and absorb LIGHT. Light requires no medium to be transmitted.

Dual nature of Light

(1) Wave

Varying electrical and magnetic fields, hence light is alternatively called **electromagnetic radiation**.

(2) Particle

Light particles are called **photons**.

Photons have no charge and no mass, but posses energy.

Use both pictures in explaining observed phenomena involving light.

Speed of Light (c)

C=2.9979 x 10^5 km/s (in a vacuum)

All observers, independent of their velocity relative to the source, measure the same speed of light.

Characterizing Light

Characterize light by its

(a) Wavelength (λ) or

(b) Frequency (ν) or

(c) Energy (E)

Equivalent to specifying the "color" of light. NB Color of an object depends on human perception --- energy distribution as a function of wavelength does not.

Wavelength (λ)

Spacing between crests. Spacing between repetitions.

Measured in nm (10^{-9} meters)

Frequency (ν)

Number of wave crests that pass an Observer in 1 second.

Measured in Hz (ie cycles per second)

Energy (E)

Each photon has a characteristic energy.

Relations

$$c = \lambda \nu$$

$$E = h c / \lambda = h \nu$$ (h= Planck's constant)

NB: Don't confuse energy of a photon with the total emitted energy by an object. Total emitted energy also depends on the total number of photons emitted.

Visible Radiation

Sometimes called optical radiation or simply light.

Moderate temperature (6000 degrees Kelvin) stars like the Sun emit a large fraction of their energy at visible wavelengths.

Visible light (a very small part of the electromagnetic spectrum) passes through the Earth's atmosphere.

The different types of visible light are:

Violet (shortest wavelength), Indigo, Blue

Green, Yellow, Orange, Red (longest wavelength).

ROY G. BIV.

Types of electromagnetic radiation (photons) in order of

decreasing energy,

decreasing frequency, and

increasing wavelength

Gamma Rays, X-rays, Ultraviolet, Visible, Infrared, Radio

Gamma (γ) Rays.

Greatest energies and shortest wavelengths.

Emitted by very energetic processes

Ozone in the Earth's atmosphere absorbs most γ-rays.

Best observed using space telescopes.

X-rays.

Emitted by very energetic processes.

Absorbed by the ozone in the Earth's atmosphere.

Ultraviolet (UV) Radiation.

Substantial amounts are emitted by:

energetic processes

hot stars

UV radiation is also mostly absorbed by the ozone in the Earth's atmosphere.

Visible Light

Infrared (IR) Radiation.

Substantial amounts are emitted by:

cool stars

dust

Extensive ground observations feasible in some bands.

Most wavelengths of IR radiation are absorbed by water vapor in the Earth's atmosphere.

Radio Waves.

Smallest energies

Longest wavelengths.

Substantial amounts are emitted by plasmas sometimes associated with magnetic fields.

Radio waves pass through the Earth's atmosphere.

Kelvin Temperature Scale

Kelvin temperature is a measure of agitation (random movement) of atoms and molecules.

The greater the agitation (i.e. the faster the atoms move) the greater the Kelvin temperature.

At T=0 Kelvin, atomic and molecular motion slows to a virtual halt, and the thermal energy content approaches zero.

$$T(\text{Kelvins}) = T(\text{Celsius}) + 273.15$$
$$F(\text{Fahrenheit}) = 1.8\ T(\text{Kelvin}) - 459.4$$

Example:

Water freezes at	273K	0°C
Water Boils	373K	100°C

Black Body

Perfect absorber and emitter of electromagnetic radiation.

Energy emitted by a Black Body is a function of temperature and wavelength *only*. Planck's Law gives the energy emitted by a black body as a function of wavelength and temperature T.

A Black Body emits a continuous spectrum

(Specific) Intensity of Light.

Amount of energy per unit time per unit area per unit steradian in a given direction.

Stellar Spectra

A star's continuous spectrum is generally shaped like that emitted by a Black Body.

A star is not a perfect Black Body.

A real stellar spectrum contains absorption (and/or emission) lines. These features allow us to deduce the chemical composition, temperature, density, and pressure of the star's atmosphere, and hence the size and mass of the star.

Wien's (Displacement) Law

As a black body (or star) gets hotter, more radiation is emitted at shorter wavelengths

(e.g., the color may shift from red to blue as it gets hotter).

The wavelength at which the energy emitted is a maximum is inversely proportional to temperature.

Mathematically

$$\lambda_{max}\ (\text{nm}) = 2.9 \times 10^6\ /\ T(\text{K})$$

Stefan-Boltzmann Law

If a black body (or star) gets even a little hotter more energy will come out of it **at all wavelengths**.

The TOTAL amount of energy emitted per second per m^2 (E) is proportional to temperature raised to the fourth power. i.e.

$$E = \sigma T^4 \quad \text{where } \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-2}$$

The functional dependance can be obtained by integrating Planck's Law over frequency.

To determine the total energy emitted by a body, we need to multiply the energy emitted by one square meter by the total surface area. This is just a statement that if we have 2 objects of the same temperature, the larger body will emit more radiation.

We can thus use the Stefan Boltzmann law to relate the Luminosity of a star to its RADIUS and its TEMPERATURE.

Luminosity = Number of square meters on the stars surface x Energy emitted by one square meter in one second.

implies

Luminosity = Star's surface Area x σT^4

or

$$L = 4\pi R^2 \sigma T^4$$

where R is the stars radius.

Spectroscopy

The splitting of UV, optical, and IR light into its component wavelengths or energies using prisms or diffraction gratings.

[Other devices are used to separate electromagnetic radiation into its component energies at other wavelengths.]

Types of Spectra

Continuous Spectrum

Intensity changes smoothly with wavelength (color)

Source: Incandescent light bulb

Nail heated by blowtorch

Emission line Spectrum

Light emitted at only a few particular wavelengths

Source: Hot tenuous gas

An emission line occurs at a particular wavelength when the intensity of electromagnetic radiation at that wavelength is greater than at neighboring wavelengths.

Absorption line Spectrum

A continuous spectrum upon which dark bands (or lines) are seen.

Source: Observing a continuum source through a cooler intervening gas.

An absorption line occurs at a particular wavelength when the intensity of electromagnetic radiation at that wavelength is less than at neighboring wavelengths.

Spectral Line Formation:

Spectral lines arise from changes in the amounts of energy present in the atoms, ions, or molecules that cause them.

The allowed energy states of an atom, ion, or molecule are **discrete** (i.e., separate and distinct); they are **quantized.**

When atoms, ions, or molecules change from one discrete energy level to another by the absorption or emission of a photon, a spectral line is formed.

If a photon is **emitted**, an **emission** line is produced.

If a photon is **absorbed,** an **absorption** line is produced in the illuminating continuum.

An element, when heated in gaseous form, displays a characteristic set of emission lines.

THIS SET IS UNIQUE.

If a continuous spectrum, coming from another source of higher Temperature, is observed through the gas then a set of absorption lines is observed at the same wavelength as the emission line spectrum.

Atoms, Ions, Molecules:

All have a unique spectral signature.

Atoms

Fundamental building block of matter.

Composed of neutrons, protons and electrons.

The neutrons and protons reside in the nucleus around which the electrons orbit.

The orbits of the electrons are quantized. Only certain discrete orbits are allowed.

Equal numbers of electrons and protons.

Approximately. same number of neutrons as protons.

Definitions:

CHARGE:

Fundamental concept in electromagnetic theory.

Particles of like charge behave in a similar manner.

ELECTRON:

A particle with rest mass and negative (-) charge.

PROTON:

A particle with rest mass and positive (+) charge. The rest mass of a proton is almost 2000 times the rest mass of an electron.

NEUTRON:

A particle with rest mass slightly larger than a proton but no charge. When an electron and proton are pushed together, you have a neutron.

ELEMENT

Number of protons determines the chemical element and hence its properties.

e.g. Hydrogen has 1 proton, Carbon has 6 protons

Oxygen has 8 protons.

ISOTOPES

Atoms with the same number of protons but a different number of neutrons. Behave almost identically in chemical reactions.

eg Hydrogen (1 proton, 0 neutrons) ^{1}H

Deuterium (1 proton, 1 neutron) ^{2}H

The Hydrogen Spectrum:

Neutral hydrogen atom

One proton in its nucleus, and an orbiting electron.

Continuous Absorption

If the neutral hydrogen atom absorbs enough energy, the electron will be knocked out of the hydrogen atom and we will have an ionized hydrogen atom (which is simply a proton) and a free electron.

The neutral hydrogen atom has to absorb a very energetic UV photon ($\lambda < 912$Angstroms) for this to happen.

The absorption is continuous for $\lambda < 912$Angstroms.

Spectral Lines

There are specific wavelengths (narrow band) of less energetic photons that the neutral hydrogen atom can also absorb.

Absorption of these energies causes the electron to move to a higher (`more excited') energy state.

A free electron has a natural tendency to recombine with the proton and return to its lowest energy state (i.e. the ground state).

An electron in an excited energy state also has a natural tendency to return to its ground state.

The absorption and emission caused by electron transitions between energy states in the hydrogen atom are termed the Lyman Series, the Balmer Series, the Paschen Series, the Brackett Series, etc.

Lyman Series

Transitions between ground and excited states

Balmer Series

Transitions between 1st excited state and higher excited states.

Paschen Series

Transitions between 2nd excited state and higher excited states. etc.

Excited States and Ions

An atom is *neutral* (has no charge) when it has an equal number of protons and electrons. The Roman symbol I is used to denote a neutral atom.

eg. He I

When ALL electrons are in their lowest energy state, an atom (or ion) is said to be in the ***ground state***. When we add energy to the atom an electron can be excited to a higher energy level -- atom (or ion) is in an ***excited state.*** If sufficient energy is added, the electron can escape the atom completely --- the atom is said to be ***ionized*** (it is an ion).

He II - a Helium atom with ONE electron removed.

He III - a Helium atom with TWO electrons removed.

Atoms can be ionized by collisions (e.g. with electrons) or by absorbing radiation of sufficient energy.

The Doppler Effect

Change in wavelength that results when a source of waves and the observer are moving *relative to each other.*

When a wave is emitted by an object moving ***toward you***, the wavelength is seen to ***decrease***.

Similarly, when a wave is emitted by an object ***moving away*** from you, the wavelength is seen to ***increase***.

This is the Doppler Effect.

Because the change in wavelength can be used to measure the speed at which an object is moving toward or away from us, the Doppler Effect is one of the most important tools used to understand the Universe.

With electromagnetic radiation, the amount of the shift in wavelength depends on how fast an object is moving compared to the speed of light. Something moving 3,000 km/s will produce a 1% shift in wavelength since the speed of light is 100 times greater.

The Doppler Effect and Sound Waves

In our everyday experience we often hear the Doppler Effect involving sound waves.

NB Sound waves are very different from electromagnetic radiation. Sound waves require a medium in which to propagate.

We hear as a result of sound waves (rapid changes in atmospheric pressure), but we can't hear a radio wave.

Radio waves are detected using antennas; they are interpreted and converted to sound waves using a receiver, amplifier, and speaker.

The Doppler effect in sound depends on both the velocity of the source and and the velocity of the observer, since the medium (air) provides an absolute reference frame.