General Astronomy (29:61)
Fall 2012
Lecture 15 Notes, October 3, 2012

1 Light...the Sidereal Messenger

In this chapter we discuss light, or more generally *Electromagnetic Radiation*. In most of astronomy, light from astronomical object is all the information we have. We can't go there. If we want to learn about these objects, we have to become very good at the physics of electromagnetic radiation.

Read the introductory paragraph to this chapter. It is very good.

What is light, or electromagnetic radiation? It is a wave of electric and magnetic fields. It is a *transverse wave*, meaning that the thing that is "waving" is perpendicular to the direction of propagation.
⟶ demos, diagrams in online plots and diagrams.

In an electromagnetic wave, the direction of propagation, and the flux of energy flow is given by

$$\vec{S} = \vec{E} \times \vec{H} \tag{1}$$

(see online diagrams)

1.1 Wavelength and Frequency

Like all waves, electromagnetic waves have a wavelength, which we denote by the Greek letter λ. A wave also has a frequency, which is how many times per second a crest passes over us. For frequency we generally use the Greek letter ν (some less elitist textbooks use plain old f).

The wavelength and frequency are related via a very important equation,

$$\nu = \frac{c}{\lambda} \tag{2}$$

Here c is the speed of light in vacuum. It is one of the most important fundamental physical constants. It has the value $c = 2.9979 \times 10^8$ m/sec.

Our present day understanding of electromagnetic radiation comes from the year 1865, when the physics super-star James Clerk Maxwell showed that the existence of transverse waves emerged from 4 equation describing electric and magnetic fields (Maxwell's Equations)

1.2 Light in Quantum Mechanics

About 100 years ago there was a major revolution in physics, when it was found that the laws of physics that existed up to then could not explain phenomena that occurred on the scale of atoms. It was found on the basis of experiment, and only later explained on the basis of equations, that on very small scales matter can act like a wave.

At the same time, it was found that under certain circumstances, electromagnetic waves acted like particle, having a well-defined energy and momentum. These wave packets that act like particles are called *photons* (again, read introduction to Chapter 5.

Although hard and fast rules are difficult to come by, it is probably right to say that electromagnetic waves show particle aspects when they contain a lot of energy, and when they are absorbed and emitted by atoms or molecules. EM waves act more like "classical" waves when they have relatively low frequencies and are generated by things like antennas.

1.3 The energy of a photon

A photon has an energy which is uniquely determined by its frequency. This is given by one of the most famous equations in physics,

$$E = h\nu \tag{3}$$

where h is our next fundamental constant of physics, *Planck's Constant* $h = 6.6261 \times 10^{-34}$. Planck's constant is extremely important because it says how important quantum mechanical phenomena are.

The equation as given above will give a photo energy in Joules, if the wave frequency in Hertz (cycles/sec) is specified. However, atoms are little things, and for them a Joule is a lot of energy. It is convenient to specify a "atom-sized unit" of energy called the *electron volt*, with shorthand notation of eV. 1 eV $= 1.602 \times 10^{-19}$ Joules.

The book makes the interesting observation that the photons that interact with our eye, and produce the sensation of light, have energies between 1.8 and 3.1 eV.

2 The Electromagnetic Spectrum

One of the amazing things about electromagnetic radiation is the bewildering variety of phenomena that are EM waves with different wavelengths. It is amazing that the radio waves one detects with an FM radio, the x-rays used in dental exams, and the ultraviolet radiation that causes sunburn are all electromagnetic waves. Only the wavelength (frequency) changes. Look at Table 1 of Chapter 5 for the numbers on this (also see accompanying online plots and diagrams).

One of the intriguing aspects of astronomy is that we can study the universe across the electromagnetic spectrum. We speak of radio astronomy, visual wavelength astronomy, infrared astronomy, ultraviolet astronomy, x-ray astronomy, and gamma ray astronomy. Observing at different wavelengths gives us different clues about the objects. In some cases, you can only see a certain type of astronomical object in one wavelength range (e.g. pulsars at radio wavelengths).

3 The Interaction of Radiation and Matter

In astronomy, we are interested in the interaction of light with matter. For the most part, we will mean photons interacting with atoms and molecules. We are interested in how matter produces light, and how light is absorbed by matter. To understand what is happening, we need to know something about the structure of atoms and molecules.

3.1 The Hydrogen Atom

Hydrogen is an extremely important element in astronomy. You learned in HS chemistry that it is the simplest element, with a nucleus of one proton (sometimes the nucleus also has a neutron) and one electron orbiting the nucleus.

It is important in astronomy because the universe likes hydrogen. It doesn't contribute a lot of mass to the Earth; the most conspicuous presence of hydrogen is in water in the oceans. However, the most massive planets, Jupiter and Saturn, are primarily hydrogen by mass. The Sun is even more so. 75 % of the mass of the Sun is in the form of hydrogen, and 24 % of the remainder is helium, the 2nd simplest element.

Think of the hydrogen atom. There is an electrostatic force between them, and a corresponding potential energy $U(r)$, where r is the distance between the proton and electron. There is also kinetic energy K , as the electron and proton move about the center of mass (since the proton is so much more massive than the electron, this kinetic energy is mainly that of the electron).

The total energy of the hydrogen atom, E, is just the sum of these two,

$$E = K + U \tag{4}$$

This sort of sounds like the Earth and Sun in the solar system. However, there is a *huge difference*. In the solar system, the energy of a planet (or comet, or asteroid) can take on any value. In the case of a hydrogen atom, the energy is *quantized*; it can take on only certain values. The realization that this was the case was the big push towards the development of quantum mechanics.

The derivation of this is given on pages 112 and 113, leading to equations 5.10 and 5.12. This result is called the *Bohr Atom*, after the physicist Niels Bohr who (presumably) first derived it. Many physicists don't think it should be taught at any level because it is not right.

The crucial ingredients of the derivation are as follows.

1. The potential energy between the proton and electron is given by

   $$U(r) = -\frac{e^2}{4\pi\epsilon_0 r} \tag{5}$$

   where $\epsilon_0 = 8.8542 \times 10^{-12}$ is the *permittivity of free space.* The kinetic energy is given by

   $$K = \frac{1}{2}mv^2 \tag{6}$$

2. We assume the orbits are circular, so $\vec{v}$ is perpendicular to $\vec{r}$
3. We substitute the expression for the angular momentum into the expression for the kinetic energy
4. Require that the total energy is a minimum for the specified angular momentum (this is a condition for circular orbits
5. Invoke Planck's discovery, that the angular momentum is quantized, $L = n\frac{h}{2\pi}$

The result of this exercise is we find two things.

First, the orbital radii must be quantized, or take on only discrete values, as given by Equation 5.8

$$r_n = \frac{4\pi\epsilon_0\hbar^2 n^2}{e^2 m} \tag{7}$$

Second, the energy is also quantized, with the following expression

$$E_n = -\left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{m}{2\hbar^2 n^2} \tag{8}$$

Next time, we'll explore the consequences of these results.