1 Lecture 6, 7, and 8: Light and Atoms

- Read chapter 3 in the textbook (don't be discouraged if you find the text excessively mathematical – we will take a more descriptive approach than the text – you will not be required to manipulate formulae!)
- Exercises: Do all "Review and Discussion" and all "Conceptual Self-Test"; Problem 4)

1.1 Light

- Preliminaries
  - everyone knows "what it is" (but might have difficulty defining it!)
  - almost all the information we receive from the Universe comes to us in the form of light (neutrinos the big exception)
  - light has a finite speed – first calculated by Danish astronomer Rømer in 1676 by timing the orbit of Jupiter's moon Io – he obtained $\sim 2 \times 10^8$m/s
  - present day value 2.99792458×10^8 m/s – in our course 3×10^8m/s
  - takes light about 1.3 seconds to reach the moon from the earth, 8 minutes to reach the earth from the sun and about 5 hours for light to reach Pluto from the sun
  - fundamental properties of light only completely understood in the 1950s (QED)!
- light – electromagnetic radiation
- radiation – energy transported away from a body through the vacuum, no physical contact with anything else required
- entire spectrum of electromagnetic radiation – visible light, only a small slice of the spectrum; other examples include radio and X-rays
- visible white light actually a mixture of the visible spectrum – R .O .Y .G .B .V – separated with a prism
- debate in the 17th and 18th century raged – Is light a particle or is light a wave?
- debate "settled" circa 1800 with Thomas Young's slit experiments – discovered that light could interfere, diffract – again an example of the scientific method, we must observe!
- A bit on waves
  - think of a pebble dropped into a pond
  - disturbance *radiated*, transported away from impact with water, energy in the mechanical motion of the water

- water does NOT move away from the impact – the water only moves up and down, no translational motion
- waves do NOT transport material along the direction in which the wave moves! (waves at the beach are NOT pure waves – they are an example of a *non-linear* system, called non-linear waves, that involves energy reflecting off the bottom of shore – very complicated motion)
- waves are characterized by their amplitude, wavelength, speed, period and frequency
- WAVE DIAGRAM
- amplitude – maximum departure from undisturbed state, measured in metres
- period = time it takes for the wave to repeat itself – measured in seconds
- frequency = 1/Period – number of crests per second, measured in Hertz (Hz)
- wavelength – distance needed for the wave to repeat itself (eg . distance between crests), measured in metres
- wave travels one wavelength in one period – wave velocity = wavelength/period
- remember, it is the disturbance that has a velocity, the material that the wave moves in just moves up and down!
- waves can interfere – two waves interact by adding their displacements from the undisturbed state
- if a crest from one wave lines up with the trough of another – they cancel – called destructive interference
- if a crest from one wave lines up with the crest of another – they add – called constructive interference
- can have everything in between – partial constructive, partial destructive
- Christiaan Huygens advanced the wave theory of light in the mid 1600s (also discovered Saturn's moon Titan, had a role in the invention of calculus and contributed to accurate time keeping)
- DVD/CD
- waves diffract – "blend" when they encounter an obstacle – interfere (Thomas Young's experiment)
- foundation of electromagnetic theory laid down by carfull observations by Michael Faraday in the first half of the 19th century and the theoretical work of James Clerk Maxwell in the middle of the 19th century – **Maxwell's equations**

• Maxwell's equations tell us that all light is electromagnetic radiation – long wavelengths (> 1 m) called radio waves, visible light, wavelength 400nm – 400nm ($1\text{nm} = 1 \times 10^{-9}\text{m}$), x-rays ($< 10$nm)

• spectrum is a continuum – all wavelengths possible

- Maxwell's equations tells us that light is composed of a magnetic vibration and and electrical vibration perpendicular to each other
- DIAGRAM OF EM WAVE
- Maxwell's equations also tell us the speed of light in terms of other fundamental constants and tells us that all EM waves move at the same speed in the vacuum
- big puzzle – if waves are mechanical vibrations, what is the medium in which light travels (vibrates)? To what is the speed of light relative?
- confused scientists for over 40 years – luminiferous aether proposed
- Einstein provided the solution in 1905 – light does not require anything in which to travel (aether unnecessary) and all observers, regardless of their motion, measure the same speed for light
- Theory of Special Relativity – many predictions, NO discrepancy with any observation – cornerstone of modern physics
- electric charge, positive and negative – like charges repel, unlike charges attract
- electric field set up around a charged particle that tells other charged particles how to move
- when particles with electric charge are accelerated, they radiate electromagnetic waves – light is the results of vibrating sources of electric charge
- the relationship between electric and magnetic fields allows the "disturbance" of an electric (or magnetic) field to propagate through the vacuum – electromagnetic wave
- the speed of the "disturbance" – electromagnetic wave (light) – is the speed of light
- carefully study figure 3.9 of your textbook
  - electromagnetic spectrum from radio waves to gamma-rays covers a huge range of scales
  - materials have different optical properties at different wavelengths
  - Glass is transparent in the visible part of the spectrum, but is opaque in the ultraviolet
  - earth's atmosphere is transparent in part of the radio part of the spectrum and in and around the visible spectrum, but opaque in the high ultraviolet to gamma-rays (a good thing for us!) and mostly opaque in the infrared (greenhouse effect)
- light – wave – Doppler effect
- similar to listening to a whistling train approach – the pitch sounds higher than when the train leaves

- the sound waves are "squished" when the train approaches and "stretched" when the train departs
- same phenomena happens with light – as you approach a bright object the light becomes blue shifted, the wavelengths become shorter – when you depart, the light becomes red shifted, the wavelengths become longer
- BUT everyone still agrees on the speed of light!
- for light sources that are not moving close to the speed of light, we have:

$$\frac{f_{\text{true}}}{f_{\text{apparent}}} = 1 + \frac{v_r}{c}$$

1.2 Atoms and the quantum theory

- Thermal Radiation: more on light
  - temperature tells us if heat will flow from one body to the next – same temperature means no heat flow (thermodynamic equilibrium)
  - at the microscopic level temperature "measures" the random motion of the particles of what the material is made – the faster the particles move, the greater the temperature (kinetic theory of matter, again Einstein contributed to this in 1905!)
  - instead of using Celsius, use Kelvin, where 0°C is 273.15 K with gradation the same as Celsius, eg . water boils at 373.15 K (in reality the reference point is set by the triple point of water)
  - scientists prefer to use Kelvin over Celsius
  - !IT IS ERRONEOUS TO SAY THAT ABSOLUTE ZERO, OR 0 K, OCCURS WHEN ALL PARTICLE MOTION CEASES! (CAUTION: THE TEXTBOOK IS WRONG ON THIS POINT)
  - Recall that temperature is defined by whether or not heat will flow between two bodies – loosely, absolute zero is defined by a hypothetical thermodynamic process that would occur with zero heat transfer
  - all bodies with temperatures greater 0 K radiate electromagnetic radiation – blackbody radiation
  - all wavelengths emitted, but peaked near the frequency that characterizes the temperature
  - wavelength $\propto$ 1/Temperature (Wein's law)
  - see More Precisely 3-2
  - BLACKBODY RADIATION CURVE
  - scientists of the late 1800s puzzled by the resulting spectrum

  - theory at the time predicted that more and more radiation should be emitted at the gamma-ray end of the spectum (called the ultraviolet catastrophe
  - theory made predictions, contradicted observation – scientific method at work!
  - Max Planck found the solution – quantum mechanics
  - light behaves like a wave AND a particle – blackbody curve the result of the emission of discrete packets (quanta) of light – the photon
  - quantum mechanics predicts the blackbody curve
  - relationship between the temperature and the peak frequency
  - the element on your stove peaks in the infrared, but has a sizeable about on the emitted radiation in the red part of the visible spectrum – that's why you can see it
  - in astronomy, we can use this to calculate the temperature of stars!
  - the surface temperature of the sun is about 6000 K – peak frequency near yellow in the visible spectrum

- Atoms: spectroscopy and quantum mechanics
  - one of the most remarkable things about the Universe – matter is made up of atoms
  - periodic table of elements – atom of a given element (and the same isotope) is EXACTLY the same as any other
  - atoms have a nucleus made of protons and neutrons , and orbital electrons
  - neutron and proton have roughly the same mass, the electron is about 2000 times less massive
  - tempting to think of the atom as a miniature solar system with the nucleus as the sun and the electrons like planets – but doesn't work!
  - recall that moving in a circle means acceleration and accelerated electric charge means electromagnetic radiation – the "solar system" model predicts that the electrons would radiate all their potentail energy away and spiral into the nucleus – all matter would collapse
  - solution took about 20 year (1905-1925) to develop – quantum mechanics
  - quantum mechanics based on the uncertainty principle – we can't know the speed and position of a particle simultaneously to arbitrary precision
  - quantum mechanics tells us that nature is inherently random, the best we can do is calculate the probability of certain outcomes
  - electron exists as a "probability" cloud around the nucleus
  - "probability" cloud related to wave behaviour of the electron – interference with a three dimensional standing wave!

- the "most probable" postion appears as its orbit
- making a transition between orbitals (different types of standing waves) requires a specific amount of energy – transitions are quantized
- a beam of light contains photons with different energies
- if a beam of light is passed through a gas of atoms, some of the photons with the exact energy (frequency) required to make an orbital transition is absorbed by the electron and the electron jumps to the new orbital – this removes some of the photons at that frequency, so we end up seeing a dark bar (missing frequency) when we examine the light at the other side
- each type of atom has its own unique set of absorption lines
- a hot gas of atoms emits light as well – electrons jump down to a lower orbital and emit a photon at the transition energy (frequency) – the light appears as a series of bright bars corresponding to the emission of the photons
- each type of atom has its own emission lines
- emission lines and absorption lines are in the same place – same energy levels involved
- this phenomena was notices as early as the 1850s (before quantum mechanics) and formulated as Kirchhoff's laws – explained by quantum mechanics
- DIAGRAM OF SPECTRAL LINES
- complicated systems, such as molecules (contain many atoms) exhibit the same emission/absorption line feature (but harder to analyze):
  * electron transitions within molecules – ultraviolet lines
  * vibrational changes – infrared lines
  * rotational changes – radio emission
- can obtain the emission/absorption spectrum for atoms through laboratory experiments (theoretical calculation matches observations very well)
- emission/absorption lines important to astronomy – we can tell of what stars are made by examining light coming from the star – just look at the emission/absorption lines in the star light and compare to the known spectrum of elements in the periodic table!
- can do the same with dust in space – nebulas, interstellar dust, etc.
- process called spectral-line analysis
- can do more than just find out of what stars are made – can also find out how fast they are moving radially from us – use the Doppler effect
- Doppler effect stretches, compresses wavelengths and so moves the spectral lines, can tell how fast objects are moving away or toward us
- strength of spectral lines tells us the temperature of stellar surfaces/atmospheres – the hotter the gas, the more electrons are in excited states or ionized

- the random motion of the atoms (or molecules) in a gas causes line broadening through the Doppler effect (thermal broadening – can use this information to help determine the temperature of the gas
- broadening can also occur from a rotating source – usually not possible to resolve both sides of the source, Doppler effect from both sides super-imposed
- DIAGRAM OF ROTATING SOURCE
- other line broadening mechanisms do not depend on the Doppler effect – magnetic fields can broaden lines, atomic collisions
- starlight, with the right equipment, yields a tremendous about of information about the source, including of what it is made, how fast it is moving toward or away from us, how hot it is, how strong magnetic fields around the source are, how fast it is rotating, etc.