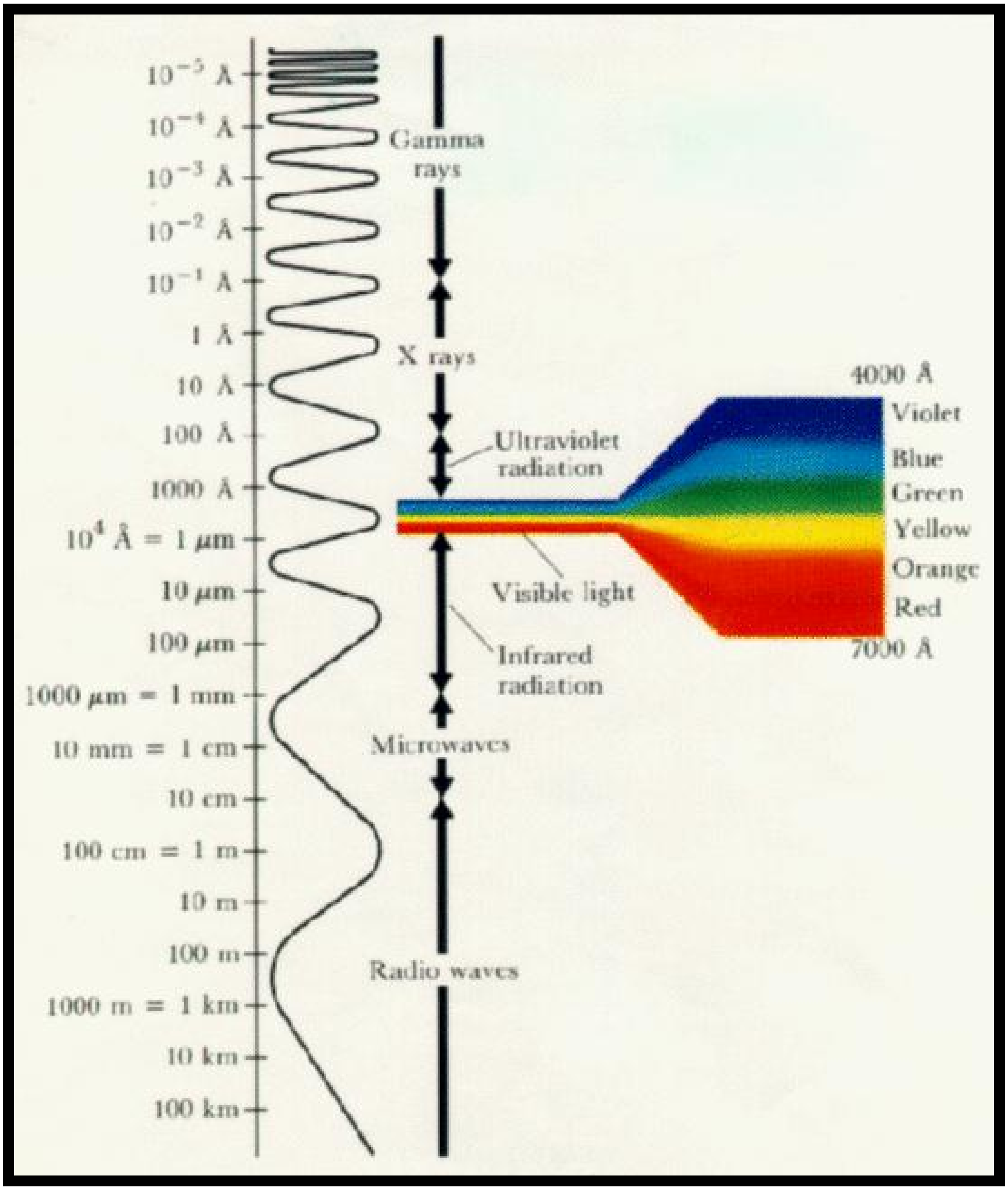
II. Electromagnetic Radiation Basics



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Introduction

One of the most beautiful experiences we can have is to gaze and wonder at the magnificent displays of nature. Everybody should at least see one sunrise and sunset per year. These moments of serene contemplative solitude remind us of what it is to be human, to wonder, and to imagine. The beautiful displays of light we see in sunrises, sunsets and auroras are no different than the radio waves being broadcast by your favorite FM radio station and received by your radio. In fact, you can even pick up radio waves from the Sun with your radio receiver. You just won't hear the latest rock n' roll song or top 40 music hits coming from the Sun. What you will hear sounds like static and comes primarily from radio waves generated by thermal processes from the Sun, more on that later.

While we're at it, let's correct one of the most common misconceptions about radio waves. *Radio waves are not sound waves*. Radio waves are a type of light which is pure energy and is able to move through the vacuum of space. What radio stations do is to convert sound waves into radio waves which move through the air at roughly the speed of light. These waves reflect off of hills, are absorbed into the atmosphere, bounce off airplanes, reflect off of an ionized trail left behind from a meteor and then finally make it to your radio receiver where they are converted back into sound waves. At first, it seems like visible light and radio waves have nothing to do with each other but they are in fact the same thing. Both are electromagnetic waves. The only thing different about them is their frequency and wavelength. These things will become clearer as we move along so don't worry if some of these details have escaped you. Anything worthwhile takes time to understand and you need to take a few first steps before this all makes perfect sense. You might want to come back later and reread these first two paragraphs after you've gained a handle on the basics to see just how far you've come along.

1.1 Light

Light is just another word for electromagnetic wave.* There are some types of light that you cannot see like infrared and ultraviolet but that doesn't mean it isn't there. Radio waves are also light, just like visible light. X-rays and gamma rays are light also and so are the microwaves that heat your food. Some light is seen with the eye and some types of light are seen with an antenna.

Light travels at a speed of 186,282 miles per second or 299,792,458 meters per second**.** The speed of light appears to be a natural speed limit. All current theories of physics which have been spectacularly successful set the universal speed limit to the speed of light. There are theories of superluminal travel, of particles called tachyons (Greek for swift) that travel faster than light but these theories have internal contradictions like negative probabilities of being somewhere. Recently, scientists like Lee Smolin and Joao

Migueijo have come up with theories for faster than light travel. Whether their theories stand up to the test of time remains to be seem. For now, we live in a universe where everything travels at or slower than the speed of light.

The speed of light is a universal constant. For this reason it is convenient to name the speed of light by a symbol. The letter c represents the speed of light.

c = 2.997 * 10^8 meters per second.

Because the speed of light is so large, we resort to scientific notation to describe it. Scientific notation is basically a system where every number is described as a power of ten and you are allowed only one digit before the decimal point which has to be between one through nine. (See Appendix for more on scientific notation)

Light moves so quickly that it can travel from the Sun to the Earth in 8½ minutes. If you were to drive your car all day and all night at highway speed it would take you around 160 years to go from Earth to the Sun, assuming you don't burn to a crisp or crash into Mercury or Venus on the way.

Light is different from sound waves in several ways. Sound waves require a **medium** through which to travel. Sound can travel through solids, liquids and gases at varying speeds. Sound cannot travel through a vacuum. An interesting demonstration of this is to place an alarm clock inside a bell jar. You can still hear the clock ticking inside the bell jar if there is air inside the jar. Pump all of the air out of the bell jar and you can no longer hear the clock. (You might hear a little bit of sound but this sound is traveling through the solid bottom upon which the bell jar rests.) All the while you can see the clock just fine because light can travel in a vacuum. Light doesn't require a medium to travel through. For centuries, scientists were disturbed by this fact so they invented an imaginary medium for light to travel through called "ether". Owing to the extremely high speed of light this "ether" had to be incredibly rigid and be of lower density than anything discovered yet, two contradictory properties. The ether was essentially undetectable. The idea of the ether was finally dismissed when Albert Einstein's theory of Special Relativity published in 1905 permanently placed the ether in the drawer of junk science.

Light is a **transverse** wave. Shake a rope tied to a pole at one end and you a creating a transverse wave. The wave is traveling to the pole but the disturbance is traveling up and down or left and right, depending on how you are shaking it. An accurate picture of light is the following. Instead of shaking a rope you are shaking the very vacuum of space. The wave travels toward the pole. The disturbances going up and down are called **electric fields** and the disturbances going side to side are **magnetic fields**. Such a picture is 100% true. The direction that the electric field points toward is called the **polarization** of the light. This of course begs the question, how do you shake the very vacuum of space? The answer is extremely simple. Find a charged object, any electron will do, and shake it up and down. The electron will emit electromagnetic waves which are ripples on the very vacuum of space. An uncharged object like a piece of wood simply won't do.

All light is created this way, a charged object changes it's state of motion and creates electromagnetic waves in the process. How do we detect electromagnetic waves? Easy! An electron shakes thereby emitting light waves. The light waves travel through the vacuum of space. These waves cause the electrons inside your antenna to shake up and down too creating a tiny voltage. Bingo, you have detected an electromagnetic wave! Our eyes do essentially the same thing but through chemical processes involving visible light.

Contrary to what you have thought, radio waves are not complex, they are simple. Suppose you are standing at the shore of a perfectly still body of water. There are two buoys on both sides of the shore. Everyone knows that if you push one buoy up and down it will make waves. These waves spread out and travel across the lake. Eventually the waves reach the other buoy and cause it to move up and down. The lake is the vacuum, the waves are light (electromagnetic waves) and the buoys are electrons.

1.1 Summary and Key Concepts

- Visible, ultraviolet and infrared light, radio waves, microwaves, x-rays, gamma rays are all the same thing, electromagnetic waves.

- The speed of light is 2.997 * 10^8 meters/second.

- Light can travel in a vacuum whereas sound cannot.

- Light is a transverse wave with the electric and magnetic field of light moving at right angles to the direction of the wave.

- Light is intimately related to electricity and magnetism. Light is produced by altering the state of motion of a charged object. Shake an electron and it will make light waves that can shake other distant charged objects.

*** Jargon Alert** – "Electromagnetic wave" has seven syllables, "light" has only one syllable. Scientists just say "light" when they mean "electromagnetic wave" to avoid annoying their colleagues. Since light waves are the same thing as electromagnetic waves, no harm is done. It's the same thing as choosing whether to say "dog", "canine", or "mans best friend". Take your pick. You can also say "radiation" to mean "light".

1.1 Questions and Investigations

1. How many miles can light travel in one day? One month? One year?

2. Light from the edge of the observable universe takes 13.7 billions years to reach Earth. Bizarre objects like quasars at the edge of the observable universe emit lots of radio waves which we can detect. How far away are these objects?

3. Can you infer what a light-year is? Check out if your hunch is right looking in a dictionary or science book. Write down an explanation of what a light-year is for someone who doesn't know. How would you explain it to them?

4. Why does the Sun shine? Where does the light come from? We know light comes from charged particles being shaken or changing their states of motion but what is shaking the particles in the Sun?

5. The most abundant state of matter in the universe is plasma. What's plasma? Could plasma also be a source of electromagnetic waves?

6. Whatever in the universe isn't plasma is either radiation or atoms. Atoms are made up of protons, neutrons and electrons. The net charge of a proton is +1.6 *10^-19 Coulombs. The charge of an electron is -1.6 *10^-19 Coulombs. The net charge of a neutron is zero but if we shake a neutron it still emits electromagnetic waves! What is going on here? (Hint: Look up quarks.)

1.2 Wave Basics

There are two basic types of waves longitudinal and transverse. And now for a little terminology which will all become clear if you apply yourself and practice.

Sound is a perfect example of a longitudinal wave. When you speak, little regions of air vibrate back and forth while the sound wave is traveling forward at around 343 m/s. **Compressions** are regions where the air molecules are closest together in these little regions of air vibrating back and forth. **Rarefactions** are the regions of least air molecule density. The distance between successive compressions is the **wavelength**. The degree to which the air is compressed or stretched can be assigned an **amplitude**, which is a measurement of loudness or of the energy being carried by the sound wave. The time necessary for a fixed region of air to complete a full cycle of compression to rarefaction and back to compression is called its **period** and is usually measured in seconds. The number of cycles per second is called the **frequency** of the sound wave and is usually measured in **Hertz** (Hz). A longitudinal wave is so named because the disturbance that the wave produces is in the same direction that the wave travels.

STUDY HINT: The internet, as with all things in life, can either be good or bad, useful or a waste of time. For seeing a longitudinal wave or sound wave in action, the internet is extremely useful. Java applets are little programs that run in your web browser. These Java applets have been very good for writing short programs that simulate physical phenomena. Go to your favorite search engine and enter "Java physics applets longitudinal sound wave" or something similar. It isn't difficult to find a Java applet for just about any physical phenomena you might wish to see. They are very interesting and entertainingly informative. They can be a resource to help you understand some of the trickier aspects of science and can help make the difference between "kinda-sorta understanding" to solid knowledge and an "easy A".

Shaking a rope tied to a fence is a perfect example of a **transverse** wave. The waves are all traveling toward the fence and the little disturbances (bumps) on the individual segments of rope are moving up and down. Transverse means to lay crossing at a 90˚ angle. The rope itself moves **transversely** to the direction to wave is traveling. The peak of a transverse wave is called the **crest**. The bottom of a transverse wave is called the **trough**. The height of the wave crests is called the **amplitude** of the wave. The point of zero amplitude midway between crests and troughs is called a **node**. Crests and troughs can be referred to as **anti-nodes**. The distance between successive crests is the **wavelength** of the transverse wave. The time lapse between successive crests is the **period**. The number of crests (or complete wavelengths) that go by a fixed point in one second is called the **frequency** of the wave.

Wavelength is given the symbol λ (pronounced "lambda") which is the Greek letter representing the "l" sound. Think of the "l" sound in λ as "length", as in wavelength. Period is given the symbol τ (pronounced "tau", rhymes with "cow") which is the Greek letter representing the "t" sound. Think of the "t" sound in τ as "time", as in time for one complete wavelength to transit a fixed point. Is this all Greek to you? It is to me!

Frequency and period are **reciprocals** of one another. Think about it for a moment. Suppose you are standing on the shore and you count 5 waves going by in one second. The frequency of these waves is 5 Hertz ($f = 5$ Hz). The period, or time it takes for one of these waves to go by, is 1/5 second. Five and 1/5 are reciprocals of one another. Aha! Now you get it!! You genius you!!

Whoa that was hard but as you will see it's not so hard if you get to play a little bit of ***SLINKY*** **!!!**

Diversion 1.2

- You'll need a … Slinky toy
- Flat table surface at least 6' by 3'.
- Two people one at each end of the slinky.

1. Have one person produce a longitudinal wave while the other end of the slinky is held still. Observe the compression traveling through the slinky. A single compression is called a **pulse** wave.

2. The same person will now produce several longitudinal waves, one after another continuously. Observe the areas of compression and rarefaction. If the slinky is

shaken at just the right frequency the compressions and rarefactions will stay in the same place. This is called a **standing wave**.

3. Note that the slinky segments are moving back and forth around what is essentially the same place although the wave is moving forward in one direction. Watch any part of the slinky and compare it to the motion of the wave to see that this is so.

4. Now both people will produce longitudinal waves. Note that the waves pass effortlessly through one another. The sound waves you make in conversation do this all the time.

5. One person will now produce a single transverse pulse wave. (A single pulse will do.) The wave goes forward but the slinky goes side to side.

6. This one is tricky but really cool to watch! One person will produce a single transverse pulse one way and the other person will produce a single pulse wave going the other direction. When the waves meet they cancel. This is called **destructive interference** and is a property of all waves. Even sound waves can cancel each other. After the two waves meet, they continue on as if they had never met.

7. As you might have suspected if waves can cancel each other out by destructive interference, they can also undergo **constructive interference.** Create two pulses that meet each other head on and observe the addition.

8. Shake the slinky at just the right frequency to create **transverse standing waves**. Can you do it?

9. Send a single transverse pulse to the end of the slinky. Notice that some of the energy in the wave is **reflected** back. The rest of the energy was absorbed by your partner at the other end of the table. When the pulse is reflected back is it pointing in the same direction as before or reversed? Try this with a longitudinal pulse.

10. Most mechanical waves, like water waves, are combinations of transverse and longitudinal waves. Experiment with a few combinations on the slinky.

Now give someone else a try!

Wave Velocity

If your car travels 100 miles in two hours, your average speed over that interval is 50 miles per hour. The velocity of a wave is calculated exactly the same way as for ordinary objects except that it's disguised in the language we use to describe waves. The usual formula for velocity (speed) is as follows.

$$\text{velocity} = \text{distance} / \text{time}$$

Now let's talk waves. Instead of distance we like to think about wavelength. Instead of time we like to consider the period, the time it takes for one wavelength to go by. We can just substitute distance for wavelength and period for time.

$$v = \lambda / \tau$$

Since period τ and frequency f are reciprocals of one another we can just write the following.

$$v = f * \lambda$$

This last formula, $v = f * \lambda$, is the one most often used for wave velocity although the former is equally valid. In order for the units to come out correctly e.g. m/s, you need to convert Hz into 1/s so you get m/s instead of m * Hz.

The Electromagnetic Spectrum

All electromagnetic waves are transverse waves that can travel at the speed of light in a vacuum. If you want to listen to 101 FM and you're tuned to 102 FM, you are tuned to the wrong frequency. Our eyes are tuned to receive the wavelength of visible light and microwave radio receivers are designed to detect microwave wavelengths. All of the various parts of the electromagnetic spectrum are just light at different frequencies. Nature makes no distinction between radio waves, visible light, and gamma-rays but we do. Here's a short table of wavelengths and frequencies of the electromagnetic spectrum.

Table 1.2 *

Part of EM Spectrum	Wavelength (m)	Frequency (Hz)
Radio waves	0.3 - 3000	
Microwaves	0.3 – 0.0003	
Infrared light	3e-4 to 4e-7	
Visible light	4e-7 to 7e-7	
Ultraviolet light	4e-7 to 3e-9	

X-rays	3e-9 to 3e-11	
Gamma rays	3e-11 to 3e-13	

* 4e-7 means 4 * 10^-7 (four times ten raised to the minus seventh power)

You might have noticed that the column for frequency was left empty. Your job is to fill in the missing data. Since the speed of light is c, we want to use $c = f * \lambda$ instead of the formula $v = f * \lambda$ because electromagnetic waves always travel at the speed of light. This is an interesting fact because light is confined to one speed. Light is unable to travel slower in a vacuum. It can travel slower however through a piece of glass for instance. Between the molecules in the glass light is traveling at velocity c. When the light bumps into a glass molecule, a small lapse of time occurs before the light is re-emitted. This causes the light to appear to travel slower than c inside the glass. In fact, light never travels slower than c, but light can make a few pit stops on the way to its destination.

Polarization

Take a rope, tie it to a pole. Let the rope pass between the vertical gaps of a picket fence so that it is free to move up and down. Shake the rope vertically and transverse waves pass through the vertical gap in the fence unimpeded. Shake the rope side to side and all but a few waves will get through. This simple picture illustrates the concept of **polarization** in it entirety. You can **polarize** the waves on a rope so that they all point in the same direction. Similarly, light has its own polarization. The polarization is given by the direction of the electric field. When light comes in too many polarizations the result is glare, bright light with no clear image. When light is highly polarized you can see much more clearly and the colors stand out in bold relief. You might have experienced this phenomenon when a cloud passed over the Sun in just the right manner. Everything becomes so nice and colorful. Look at the surface of a lake or stream. Streaks of light due to glare at the surface prevent you from seeing all the way to the bottom. If that light were polarized you could see much further into the water.

1.2 Questions and Reflections

1. Recently scientists have been able to slow the speed of light to 38 mph. How is this possible? Read about it at http://www.rowland.org/atomcool/light.html

2. Unlike other waves, the speed of light must remain constant in a vacuum, unable to travel faster or slower. What effect does increasing the frequency have on wavelength? What effect does shortening wavelength have on the frequency?

3. The names for the various parts of the electromagnetic spectrum are chosen for mankind's convenience, not because nature makes any distinction between them.

To nature, all the different parts of the electromagnetic spectrum are just electromagnetic waves of different frequencies. What are some specific motivations for naming radio waves, microwaves, infrared, visible, ultraviolet, x-rays and gamma rays as they are? Everyone can share results and complete all parts of the spectrum with their historical motivations for their names.

4. What are some examples of light interfering constructively and destructively? Find an easy example you could show the class with a little help from your teacher.

5. Create a poster which labels the parts of a transverse and longitudinal wave and also compares and contrasts sounds waves with light waves.

6. To which color of the visible spectrum is the eye most sensitive? You'll need to do some investigating. Can you imagine a reason for this? Share it.

7. We know that the speed of light is always a constant c = 2.997*10^8 m/s. But, light can appear to move slower because of microscopic collisions resulting in the absorption and emission of light which accounts for lost transit time. What is the speed of light in some materials compared to others? Investigate.

8. If you are feeling ambitious and in need of deep answers to deep questions, what is **refraction** and what is **index of refraction** and how does it relate to the speed of light?

9. What are some advantages to polarizing light when taking pictures with a camera? How is this done?

1.3 Photons and Planck's Relation

Light is an electromagnetic wave but looked at another way it also behaves like a particle. This is known as the **wave-particle duality of light** and is central to modern physics particularly the science of **quantum mechanics**. Tiny packets of light that act as particles are called **photons**. Albert Einstein postulated their existence and won the Nobel Prize in Physics for his explanation of the photo electric effect. Today, a very sensitive photometer can detect individual photons but demonstrating the existence of photons in the past had been problematic, only indirect tests confirming the existence of photons were possible.

Turn on a stove and in a few minutes it will glow red hot. You can actually see the heat from the stove because it is hot enough to glow in the visible part of the spectrum. Allow the stove to cool off and it still glows as before except your eyes can't see it. The glowing light from a cool stove is in the infrared part of the spectrum which is too low of a frequency for our eyes to see. Infrared is extremely useful for night vision because everything glows with its own heat.

In 1899, Max Planck was investigating the power at which an object glows in relation to the frequency of light it emitted. In the course of his study he made an idealization, that the object under study was a perfect absorber and internal reflector, a **black body**. His investigations of black body radiation were motivated by a glaring contradiction between experiment and theory known as the ultraviolet catastrophe. At higher frequencies, black bodies are observed to emit less power for a given temperature. Everybody's theory up to that point was predicting the wrong result. Their theories were saying that at a given temperature the power keeps getting higher with higher frequency, an incorrect result. This puzzled the scientists of the day. The answer to their problem was so simple, even a non-scientist could understand it but it was an answer so simple that even Professor Planck himself was not prepared to accept it.

$$E = h * f$$

$$h = 6.026 * 10\text{^-}34 \text{ Joules} * \text{seconds}$$

That's the answer. The energy of a photon or **excitation** of the electromagnetic field is a function of the frequency times Planck constant h. The constant h was calculated to fit the experiment. It is one of the universal constants of physics along with the speed of light, the charge of an electron, and Newton's gravitational constant.

Increase the energy of individual photons and you increase their frequency. Examine a super nova using a radio telescope and you find lots of high frequency x-rays, remnants of a high-energy event. Light from thermal processes has correspondingly lower energy and lower frequencies. It is important to keep in mind that it is not the total energy that corresponds to frequency but rather the energy of the individual photons themselves. You can have a tremendous amount of energy with a large accumulation of lower energy photons. Total energy doesn't matter. Individual photon energy does.

Total Energy = h * f * number of photons

The above, simplified formula assumes that every photon oscillates at the same frequency. This is not the case in reality. The total energy of a beam of light from a source contains photons of many different frequencies, every frequency contributing a certain amount of energy and having its own number of photons.

An excellent web resource for observing the black body spectrum derived from Plank's Radiation Distribution Law can be found at http://www.mi.infm.it/manini/dida/BlackBody.html.

Questions

1. If you rub your feet on a shag carpet you can accumulate enough charge to produce a visible spark. A hot stove emits visible light and so must have the same energy as the spark. What's wrong with this thinking?

2. How much energy does an individual photon from your favorite FM radio station contain?

3. What frequency would a single photon require in order to raise the temperature of 1 gram of water by 1 Celsius degree?

4. Describe qualitatively the emission spectra for a black body radiator that obeys Plank's Radiation Law. What happens at the lowest and highest frequencies? Is the curve symmetrical like a bell curve or lop-sided? What are the Raleigh-Jeans Radiation Law and Wien's Radiation Law and how do they relate to Planck's Radiation Law? Use all resources available to you.