## Electromagnetic Radiation

Energy that comes to us from the sun is transported in the form of waves known as electromagnetic energy. This combines electricity and magnetism such that setting up an electric current creates a magnetic field, and conversely, a magnetic field will set up an electric current. Electromagnetic waves, as with all waves, have properties of frequency, wavelength, and propagation speed, which can be combined to form the relationship

$c = \lambda \bullet f$ or **propagation speed = wavelength x frequency.**

(The property amplitude is not important in our discussion of EM radiation. Acoustic waves have amplitude, which relate to power or volume.)

In the case of EM radiation, the propagation speed (c) is a constant equal to the speed of light in a vacuum or approximately 3x108 m/s. The speed of light, according to Einstein, is the maximum speed attainable of anything except space. To understand the speed at which light travels, imagine traveling 186,000 miles in one second! The relationship listed above translates to mean that frequency is inversely proportional to wavelength. Each frequency, therefore, relates directly to one and only one wavelength. The following chart gives the typical wavelengths and corresponding frequencies of important spectra of radiation.

**The Electromagnetic Spectrum**

| | |
|---|---|
| X-ray | ~ .01 μm |
| Ultraviolet | ~ .1 μm |
| Infrared | ~ 10 μm |
| Visible | from .39 μm to .76 μm |
| Microwave | ~ 100 μm |
| Radio wave | >10 mm |

The visible spectrum is relatively small with the darkest red at the long end of the scale to the darkest violet at the short. There are (as commonly accepted) seven colors of the rainbow: red, orange, yellow, green, blue, indigo, and violet forming the acronym "ROY G. BIV". A typical wavelength for blue light is .47 microns and for red is .64 microns. (Remember these numbers for future use!)

## The Sun

As we have said repeatedly, the sun is the ultimate source of our weather. Taking that statement one step further, we will find that it is the unequal heating of the earth that creates pressure imbalances, and thus creates winds. But since it is the sun that is so important, we must first understand the nature of the sun and the energy it gives us.

*Distance*

- The sun is 93,000,000 miles away from the earth.
- It takes light over eight minutes to travel that distance.
- A car traveling 60 mph, 24 hours a day would reach the surface of the sun in 200 years, assuming it doesn't vaporize!

*Radius*

- The radius (the distance from the center to the surface) of the sun is 870,000 miles or 1.4 million km!
- This compares to the earth's radius of 6400 km.

*Energy*

- The sun is composed of helium (He) and hydrogen ($H_2$).
- Acting like a nuclear reactor, hydrogen fuses into helium, a process known as fusion.
- $4 \times 10^6$ tons of mass is being converted to energy every second. Remember $E=mc^2$?
- At that rate we only have 100 billion years left ($10^{11}$).
- Most of our energy comes from a shell of gas 500 km thick surrounding the sun known as the photosphere.

*Mass*

- Relative to the earth, the sun is 329,390 times more massive.

*Temperature*

- The temperature of the sun is 5780˚K.
- This compares to the temperature of the earth which is 15˚C or 288˚K. In other words, the sun is 20 times hotter than the earth.

## Blackbody Radiation

**Blackbody** - a hypothetical body consisting of a sufficient number of molecules absorbing and emitting electromagnetic radiation in all parts of the electromagnetic spectrum so that:

a) all incident radiation is completely absorbed; and

b) in all wavelengths bands and in all directions (**isotropically**), maximum possible emission is realized.

Although a blackbody does not really exist, we will consider the planets and stars (including the earth and the sun) as blackbodies. Even though by definition, they are not perfect blackbodies, for the sake of understanding and simplicity we can apply the characteristics of blackbodies to them.

According to the above definition, a blackbody will emit radiation in all parts of the EM spectrum, but by intuition, we know that one will not radiate in all wavelengths equally. So the first thing we would like to know about blackbody radiation is in what wavelengths is radiation primarily emitted. Secondly, we know that all blackbodies do not radiate energy at the same rate, certainly shown by the sun's power compared to that of the earth. Therefore, it would be beneficial to know something about the rate of blackbody emission. Fortunately for us, we can answer both questions knowing only one characteristic of an object -- temperature.

**Wien's Displacement Law**

$$\lambda_{\max} = \frac{2897}{T(^\circ K)} \mu m$$

Wien's displacement law says that the wavelength of the maximum emitted radiation is inversely proportional to the absolute temperature (˚K). If we plug in the temperatures of the earth and the sun, we will see that lambda max is 10μm and .49μm, respectively. Whereas the earth emits mostly infrared radiation, the sun emits mostly visible light. In fact, 43% is visible, 37% is near infrared and only 7% is ultraviolet. Wien's law allows us to determine temperatures of other stars depending on its color. Something that glows blue hot is much warmer that one that glows red hot!

**Stefan-Boltzmann's Law**

$$E^* = \sigma \cdot T^4$$

Stefan-Boltzmann's law states that the rate that a body emits radiation (per unit area) is directly proportional to the body's absolute temperature to the fourth power. With this fact we can determine that the sun radiates 160,000 times more energy than the earth. In fact we receive only 1/2 billion of the sun's total energy. This is enough however to light New York City street lights for 2 days by collecting light for twelve hours on one football field!

## Variability of Incoming Radiation

- The earth is tilted 23½˚ off the perpendicular to the plane of the ecliptic.
- **Latitude** lines, or **parallels**, divide the earth from east to west.
- **Longitude** lines, or **meridians**, divide the earth from north to south.
- We assume that the rays of the sun are all parallel, known as parallel beam radiation.
- **Insolation** is the amount of radiation received at surface.
- **Equinox**: **eq**ual day, **eq**ual night; sun over the **eq**uator.

- **Solstice**: the sun is furthest from the equator. 23½˚ N is the **Tropic of Cancer**; 23½˚ S is the **Tropic of Capricorn**.
- The path of the earth's orbit around the sun is elliptical.
- Its nearest point in January is 91 million miles away and is called the **perihelion** (near sun). Its farthest point in July is 96 million miles and called the **aphelion**.
- During the aphelion the earth travels the slowest, while during the perihelion, the earth travels fastest.
- The amount of insolation varies with season and latitude.
- Averaged, the northern and southern hemispheres receive the same amount of insolation each year as proved by Alexander von Humboldt, despite the variations in earth-sun distance.
- There is about a one-month lag between the longest day and the warmest day (or shortest and coldest days). This is caused by the temperature responding to the balance of incoming vs. out-going radiation. The spring season is retarded because of the energy needed to first melt the snow and ice.
- The basic cause of the weather is that the poles are cold and the equator is warm (due to angle of incidence) and the atmosphere attempts to find a balance. The earth is differentially heated by the sun because the earth is a sphere.

## Radiation and the Atmosphere

When solar radiation enters the earth-atmosphere system, three things can happen to it. First it can be reflected (also known as back-scattered); second, it can be absorbed; and third, it can be scattered.

### Absorption

The absorptivity of the atmosphere varies from wavelength to wavelength. Certain wavelengths are readily absorbed while others transverse the atmosphere with relatively little change. It is the individual air molecules that absorb the radiation.

Ultraviolet is absorbed very effectively by atmospheric oxygen and ozone among others. Less than 2% of the incoming ultraviolet energy penetrates the whole atmosphere.

The two most important absorbers of infrared radiation are water vapor and carbon dioxide. These are the primary gasses in the phenomenon known as the Greenhouse Effect.

On the other extreme, visible light is not significantly affected by absorption, therefore it is known as an **atmospheric window**. An atmospheric window is a part of the electromagnetic spectrum that is not absorbed.

One other note of importance is to realize that the atmosphere can absorb radiation as it comes from the sun and as it leaves the earth. Remember that the majority of incoming radiation is in the visible spectrum while outgoing radiation is primarily infrared.

### Reflection

In the atmosphere, dust and clouds are the two most important reflectors of radiation. Even though clouds are poor absorbers, depending on their size and drop-size distribution, they can reflect up to 70% of the incoming radiation. In fact, on a global average, clouds reflect 20% of the incoming radiation. This means that clouds represent 2/3 of the earth's **albedo**. Albedo is the percentage of radiation reflected. The earth's albedo is 30.

In addition to dust and clouds, the earth's surface can also reflect radiation. Snow, ice and light colored objects have high albedos while forests, blacktop and dark colored objects have low albedos. Water generally has a very low albedo if the sun is near its zenith (directly overhead), but will reflect almost all radiation if the sun is at low angles to the water.

**Scattering**

As light enters the atmosphere, it will encounter particulate matter such as dust, and other aerosols, cloud droplets, and other objects that will alter the course of the incoming radiation. Loosely defined, scattering is the changing of direction of radiation. In this sense, reflection is just scattering in the reverse direction. In addition to the objects that scatter listed above, air molecules cause radiation to scatter as well. In fact, it is the presence of the air that causes the sky to be blue.

In order to describe scattering, we must first develop a relationship between the wavelength of the radiation in question and the size of the particle that will be the scatterer.

We will define a size parameter, $\alpha = \mathbf{2\pi r/\lambda}$, where $2\pi r$ is the cross-sectional circumference of the scatterer.

**Case 1** $\alpha > 50$ This would mean that the scatterer is much larger than the wavelength of the radiation. Remembering that most of the incoming radiation is on the order between .01 μm and 15 μm, this would be the case for radiation striking dust and more importantly, cloud droplets. This type of scattering is called **geometric optics**. With geometric optics, it is assumed that the scattering object is so large that it is seen as a plane and that it will "reflect" in a way that the angle of incidence is equal to the angle of refraction. Thus, to say that clouds are good reflectors is really to say that clouds backscatter effectively. (One can imagine that we are so small compared to the earth, the earth seems flat.)

**Case 2** $\alpha \approx 1$ When light intercepts an object whose size is on the order of its own wavelength, the scattering process becomes very involved. This is part of the regime known as **Mie scattering**.

The physics become too involved for discussion on the introductory level.

**Case 3** $\alpha << 1$ In this case, the type of scattering is named **Rayleigh scattering** and is actually a specialized case of Mie scattering. Rayleigh scattering is important when discussing how air molecules scatter light. It was shown by Rayleigh that light will scatter according to the relation

$$Q_S = \text{constant} \cdot \alpha^4$$

which says that the scattering efficiency of light is directly proportional to $\alpha$ to the fourth power. Unfortunately, $\alpha$ depends on two variables. This problem is easily solved if we consider the variations in the size of the air molecules to be slight. We can then assume that the circumference of the air molecule does not vary, or rather that it is a constant. Therefore,

$$Q_S = \text{constant} / \lambda^4$$

saying that the scattering efficiency is inversely proportional to the wavelength to the fourth power. This in turn means that the smaller the wavelength of radiation, the more the scattering that will occur.

**Why the Sky Is Blue**

I first want to compare the scattering of blue light to that of red light. This means that I am looking for a ratio of

$Q_S$(blue)/$Q_S$(red).

Recalling that a typical wavelength of blue light is .47μm and for red it is .69μm, we can solve the above equation to find the answer of 3.5.This translates to mean that blue light scatters 3.5 times more efficiently than red light, which is the principle reason that the sky is blue. However, keeping in mind that the shorter the wavelength the better it will scatter, why isn't the sky violet?  The answer is three-fold. First of all, there is more blue than violet in sunlight; second, our eyes are more sensitive to blue than to violet; and third and most important is the fact that all of the colors scatter somewhat. What we see is actually a combination of all the colors blended together, in varying amounts, known as "sky blue". It is that color which is directed toward our eyes after being scattered several times by the molecules of air.

**Why the Sun Is Red at Sunset.**

At sunset, the sun's rays are penetrating a thicker slice of the atmosphere allowing more time for the rest of the colors to scatter "out" of the sun. Red light scatters the least and consequently, it is the only color that remains to make the sun visible.

**Radiation Budget**

The radiation imbalance is solved by considering two other methods of heat transfer: conduction and convection.

**Conduction** is the transfer of heat from a warm object to a cooler object through contact, or the "touching" of the substances through which **sensible** heat is transferred.

**Convection** is the transfer of heat within a fluid by fluid motions. Frequently, convection refers to vertical motion, which relates to the hydrologic cycle where latent heat is transferred in effect from the surface to the atmosphere.

***A Word On Latent Heat's Role In The Earth's Energy Budget****...*

We want to understand how the energy budget of the earth is balanced by the presence of water, or more specifically, how the hydrologic cycle is necessary to the maintenance of the earth's energy balance.

We know that radiation is the primary mechanism for transferring energy between the atmosphere and the earth.  Conduction plays a small role since conduction only operates effectively in a very thin layer of air near the earth called the molecular boundary layer. The air moves (or convects) and transfers the heat throughout the rest of the troposphere. However, since the heat is already in the air, there is no further transfer form ground to air.

The result is excess heat in the earth itself.  Fortunately, this build-up of energy does not go into raising the temperature.  Instead, it goes to evaporating water.  As water evaporates, what was once liquid and part of the earth, is now gaseous and part of the atmosphere.  Through convective motions (in this case, convection refers to vertical motions) air rises, and cools adiabatically.  As air cools, the air will eventually reach saturation where further cooling will result in condensation of the water.  Just as heat is needed to evaporate water, that heat is released to the atmosphere when water vapor condenses.  This heat is known as latent heat since it was hidden within the water molecules.  If clouds have enough vertical development, rain forms and the rain is brought to the surface by the earth's gravitational attraction.  This final step is important since it brings the water back to the surface of the earth.

**The General Circulation**

The **Global Hadley Cell** is a simple model that does not take into account the earth's rotation. It has air rising at the equator and sinking at the poles.

The **3-cell** model has air rising at the equator and at 60˚ and sinking air at 30˚ and 90˚ (poles). It contains the **Polar Cell**, the **Ferrell Cell** and the **Tropical Hadley Cell**.

**Convergence** is coming together. **Divergence** is going apart.

**Subsidence** is sinking air.

The winds are deflected by the **Coriolis force**. The Coriolis force deflects moving objects to the right in the NH and to the left in the SH.

Polar winds are the **polar easterlies**.

Mid-latitude winds are the **prevailing westerlies**.

Tropical winds are easterly in the NH (SH) they are called the **Northeast (Southeast) trade winds**.

The **ITCZ** or **inter-tropical convergence zone** is an area dominated by surface lows and thunderstorm development.

These "**hot towers**" pump latent heat high into the troposphere where that heat is transferred poleward.