Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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BLACKBODY RADIATION RELATIONS

Good morning class and welcome to our continuing lectures on climate variability, climate dynamics and climate monitoring. In the previous class, we were looking at various ways to define radiation flux transport. We looked at two important quantities, one is called radiation intensity or radiance which can come in either spectral radiation intensity or spectral irradiance and total radiation intensity or radiance. Spectral radiation intensity looks at incident or outgoing radiation in a specific direction given by theta and phi angle for a unit solid angle around this direction for a unit area normal to this direction and for a specific wavelength. Whereas, total radiation intensity or radiance I is the integral of the spectral intensity over all wavelengths or frequency bands. We also looked at spectral flux density F or total flux density which are written as F plus lambda when if the flux is upwards towards the upper hemisphere or F minus lambda when the spectral flux is downwards towards the lower hemisphere and this is the integral over an entire hemispherical region of the entire radiation being emitted or moving upwards from a specific equatorial area per unit area of that plane.

And this is given by the integral over the azimuthal and the zenith angles over the entire upper hemisphere or the lower hemispheres. We also noted that for the special case of diffuse radiation, where the radiation intensity is not dependent on the direction from which the radiation is incident or towards which the radiation is being emitted. In that case, the flux density F and the intensity I are related by just the factor pi, whether it is the spectral case or the total case. Then we consider the idea that when radiation is passing through a medium, the medium may be a solid medium, a gaseous medium or a liquid medium, the radiation can have three possibilities.

It can get transmitted through that medium, it can get absorbed by that medium or it can get reflected by that medium. And what happens to the radiation and the fraction of each of these three phenomena depends on the wavelengths and the frequency bands of that radiation as well as on the type of medium through which that radiation is being transmitted. Today we will look at the special case of blackbody radiation where explicit relations of radiation intensity I and radiation flux density F can be derived. Blackbody radiation is a blackbody surface is a idealized surface that absorbs all radiation incident on it. So if you have a surface and radiation is incident on that surface, if it absorbs everything and reflects nothing back regardless of the wavelength or the frequency of that radiation, then that surface behaves like an idealized black body.

Because it does not reflect any radiation back, it necessarily means that all outward directed radiation from that surface is thermal emissions which is dependent on the surface temperature of the blackbody alone. It can be shown that among all possible objects a blackbody emits the maximum amount of thermal radiation for a given surface temperature and that all blackbodies emit an identical amount of thermal radiation if their surfaces are at the same temperature. So if you think of multiple surfaces, all of them are at the same temperature, say 500 degrees or 600 degrees, then we will see that if one of them is a blackbody, the total thermal emission from that surface is maximum compared to all other non-blackbody surfaces. Furthermore, all black body surfaces at a given temperature emit the same amount of energy through radiation and that the distribution of that radiation energy in each and every frequency band is identical. So, all black bodies behave identically at a given temperature with respect to thermal emissions.

And what is this? the function of blackbody radiation intensity. It is written as I nu, nu is frequency, so spectral radiation intensity for a blackbody at a given temperature. Here we shorthand it as B nu t, blackbody radiation intensity at a frequency nu for a given surface temperature t. And is given by this expression here. twice into h into nu cube by c square into 1 by e to the power h nu by Kb t minus 1 watt per meter square staradians hertz.

Here H is the Planck's constant. C is the velocity of light in meters per second. nu is the frequency in Hertz. Kb is the Boltzmann's constant in joules per Kelvin which is shown here. We can now integrate this over all frequency bands to get the total blackbody radiation intensity or the total radiance.

$$I_v|_{BB}(T) = B_v(T) = \frac{2hv^3}{c^2} \frac{1}{e^{hv/k_B T} - 1} \quad \frac{W}{m^2.sr.Hz}$$

$$k_B = 1.37 \times 10^{-23} \frac{J}{K} \text{ is the Boltzmann constant}$$

The total blackbody radiation intensity I for blackbody temperature, the lambda term has been eliminated, is the integral of the B nu t term over all frequency bands from 0 to infinity. And this gives us a very straightforward relation of sigma by pi t to the power 4 watt per meter squared stay radians. where sigma is the Stefan-Boltzmann's constant of 5.67 into 10 to the power minus 8 watt per meter square per Kelvin to the power 4. Now, since black bodies are diffuse emitters, hence the flux density F will be pi times the radiation intensity I, whether it is spectral or total.

$$I|_{BB}(T) = \int_0^\infty I_v|_{BB}(T)dv = \frac{\sigma}{\pi}T^4 \quad \frac{W}{m^2.sr} \qquad (74)\ where$$

$$\sigma = 5.67 \times 10^{-8}\ Wm^{-2}K^{-4} \quad Stefan - Boltzmann\ constant$$

So, the total irradiance or total radiation flux density whether it is the upward flux density or the downward flux density is given as flux density for black body at a given temperature which is shorthanded as just Bt is pi into R of I B Bt this term here which is sigma t to the power 4 watt per meter square. The black body radiation flux is sigma times t to the power 4 in watt per meter square and this is called the Stefan-Boltzmann's law of black body radiation.

$$F|_{BB}(T) = B(T) = \pi I|_{BB}(T) = \sigma T^4 \quad \frac{W}{m^2}$$

Similarly, the spectral radiation intensity v nu t if you multiply by pi, you will get the spectral flux density which is f nu v dt which is pi into that term in watt per meter square hertz. For any other surface, because the thermal emission will be lower than the black body thermal emission, we can use a factor emissivity epsilon to express the emissions of non-black body surfaces. we can write it in terms of the spectral emissivity E nu which goes in front of this term here.

$$F_v|_{BB}(T) = \pi I_v|_{BB}(T) \quad W/m^2Hz$$

So, I nu t for a given surface is epsilon nu the spectral emissivity into B nu t. So, this term here into the spectral emissivity gives the emissivity of a spectral radiation intensity of a non-blackbody.And when you are looking at the total radiation flux, then we write the total emissivity epsilon into this BT gives the total radiation flux of a non-blackbody surface.

$$I_v(T) = \varepsilon_v B_v(T)$$
$$F(T) = \varepsilon B(T)$$

Now, we can plot this BT term, sorry, not BT term, this F nu BBT term, the spectral radiation flux density term in watt per meter square hertz, this term here, in terms of the frequency. This we can do alternatively since frequency and wavelengths are inversely proportional, we can also write this in terms of the wavelength lambda.

So, if we do that, this is the F nu term in the y axis and this is the wavelength lambda in the x-axis and these are the F nu plots with the wavelength lambda for different blackbody surface temperatures and we immediately see two things. Firstly, the total radiation intensity is the integral of this over all wavelengths and this total area decreases very fast as the blackbody temperature decreases as we would expect because it is a T to the power 4 dependent. Secondly, the wavelength at which the emission peaks is going into higher and higher wavelengths or lower and lower frequencies as the blackbody temperature falls. In fact, for a given blackbody temperature the wavelength at which we are getting the maximum spectral radiation intensity or the maximum spectral flux density is given as is inversely proportional to the blackbody temperature and that is given by lambda at F nu max is B by T where B is 2.898 into 10 to the power minus 3 meter Kelvin.

$$\lambda_{max} = \frac{b}{T} \text{ where } b = 2.898 \times 10^{-3} \ m.K$$

So, this value gives you the wavelength at which a blackbody at a certain temperature T will emit the maximum amount of spectral flux density based radiation. Now, the sun can be considered to be almost a perfect blackbody with a surface temperature of about 6000 kelvins. So, if you look at the distribution radiation spectral flux density distribution for a black body with a surface temperature of 6000 kelvins and compared to that of sun, then they will be almost identical, which shows that sun can be well modeled as a black body with a surface temperature of 6000 kelvins. For earth, earth is not a perfect black body. We know this because earth has an albedo, it is certainly not absorbing all the solar radiation which is incident upon it.

However, the earth's temperature is quite low. So, its blackbody emission temperature to space is around 255 kelvins. And if you see the thermal emission profile of earth, the spectral flux density of earth then we see that flux density distribution is very close to the distribution of a black body whose surface temperature is 255 Kelvin. So, in the emission range that matters, which is the infrared range where earth is emitting most of its energy through thermal emissions, earth does behave almost like a perfect black body. So, earth can also be considered to be a black body at 255 Kelvin in the infrared emission range where it primarily emits its thermal radiation.

So then using these we can then plot the distribution of flux density with wavelength and this is what is shown here for both Sun and for Earth. Here the total the spectral flux density has been divided by the total flux density that is being emitted over the entire wavelength band. So, this is basically a gives us the fraction of the total energy that is coming from at a given wavelength and this is done because sun's total emission energy is much larger than earth's emission energy because sun is at 6000 kelvins and earth is at 255 kelvins. So here it gives the fractional contribution to the total energy being emitted at any wavelength band for either the Sun or for Earth.

This is 0 to 1. If we do that, then we see that Sun is primarily emitting from the UV range of around 0.2 micrometers to the near infrared band of around 4 micrometers. 4 to 5, 4 micrometers. Whereas earth is primarily emitting in the far infrared band from 5 micrometers to around 100 micrometers. So, earth's emission frequencies and sun's emission frequencies are quite separate from each other and earth's emission kind of achieves its maxima at around 15 micrometers which is in the far infrared region whereas sun's emission achieves a maxima around at around 0.5 to 0.6 micrometers which is within the visible yellow green range of the spectra. Sun's rays are coming through the atmosphere where Earth's emissions are going through the atmosphere back into space. So the atmospheric gases are interacting with electromagnetic waves over the solar frequency band which is called the short wave region as well as the terrestrial frequency band which is known as the long wave region. So we need to next look at how the atmospheric gases behave in the presence of these frequency bands. Will they transmit them or will they absorb them? What these things depend upon? So now here we look at why atmospheric gases absorb certain wavelengths and does not absorb certain other wavelengths.

The idea is this, atmosphere is a composition of multiple gases primarily nitrogen and oxygen but it also contains other trace gases like water vapor, like carbon dioxide, like ozone, like nitrous oxide etc. These gases have different molecular structures. All of these molecules are multi-atomic molecules. So, these have, so if you ignore argon which is a single atomic inert gas and does not play any role in any absorption or emission phenomena, all the other gases present in the atmosphere are multi-atomic molecules. They can be diatomic, triatomic and in case of methane, it can be, it has five atoms present.

Okay. Now, the arrangement of these molecules are also quite different from each other. Nitrogen, oxygen and ozone are homoatomic molecules. This means these molecules are made up of a single atomic type. Nitrogen made of nitrogen atoms only, oxygen and ozone made up of oxygen atoms only. Whereas the rest like CO, CO2, H2O and CH4 are made up of at least two different types of atoms and hence are called heteroatomic molecules.

The other thing is some of the molecular structures are linear like nitrogen, oxygen and CO as well as CO2 and N2O. These are all linear structures, a single line. Water vapor and ozone are planar molecules. They are not linear, but all the atoms are in a single two-dimensional plane, wedge-shaped plane. Whereas methane is a three-dimensional molecule with one wedge like this and the other wedge going like this.

So it's a three-dimensional molecule with a central wedge somewhere in between. So it is not in a single plane. So the atomic structure can be linear, planar or three-dimensional. Furthermore, the molecules can or cannot have dipole moments. Dipole moments means there is an asymmetric charge distribution within the molecule.

For example, Nitrogen and ozone are perfectly symmetric homoatomic molecules and hence do not have any asymmetric charge distribution at all. Carbon monoxide have a positively charged end at carbon and a negatively charged end at oxygen. So it acts as a plus minus charge distribution and hence has an asymmetric charge distribution which makes so that the molecule has a dipole moment. Carbon dioxide is symmetric about the carbon atom and hence does not have a dipole moment. Nitrous oxide have a positive side and a negative side N and O, so it has a dipole moment.

Similarly, water vapor also has a dipole moment with a positively sided H atoms on this side of the wedge and the negative oxygen atom on the other side of the wedge. So again the dipole moment distribution is different for different types of molecules. So all of these aspects linear, planar, three-dimensional, homoatomic, heteroatomic whether it does or does not have a dipole moment is important in understanding how these atoms behave in the presence of electromagnetic waves. The primary idea here that we will say is very simply, an atom will absorb the photons corresponding to the electromagnetic wave of a certain frequency. If the photons frequency, remember each electromagnetic wave has a frequency nu, which means it is made up of packets of photonic energies E equals to h nu, correct? These photons can only be absorbed by the gases if the frequency of that photon is related to the frequency of a certain degree of freedom associated with the movement of that molecule.

What do we mean by that? Let us consider the simple case of a dipole moment. Consider the simple CO molecule. Suppose this CO molecule is able to rotate about the center line which is separating the C and O atoms. So it is rotating like this. then its positive and the negative charges are interchanging positions after half a rotation.

Correct? So, the plus is going this side, minus is going this side over every half rotation. So, what you have is a shifting of the positive and the negative sides of this molecule as the CO atom rotates about its axis of symmetry. the shifting of positive and negative charge basically is associated with a fluctuation in the magnetic field. And fluctuation in the magnetic field gives rise to an electromagnetic vibrational frequency.

Correct. The rate at which the positive and the negative side switches sides, the positive and the negative charges switch sides, that will have a certain frequency. How many times per second do they switch sides? That frequency is the frequency of an electromagnetic excitation caused by the rotation of this dipole moment. And if the electromagnetic wave incident on this carbon monoxide molecule has the same frequency as the rotational excitation frequency of this dipole moment, then that photon will get absorbed and the carbon atom will start to rotate at that specific frequency value. This is how the rotational mode of dipole fluctuation gets activated through the absorption of photons from an electromagnetic wave. If the frequencies do not match, if the rotational speed at which CO atom will rotate is different from the frequency nu of the electromagnetic wave, then the dipole fluctuation will not get activated and the photon will not get absorbed.

So, the photons frequency must match the rotational frequency of this dipolar molecule. Similarly, for other dipoles also, electromagnetic waves, if they are able to activate the rotational vibrational, rotational modes of movement for these molecules, then and only then will the photons get absorbed, otherwise not. Similarly, again we consider say for example, the CO2 molecule. Now the bonds between them are not rigid bars.

They are like steep springs. So the O and C are attached by a spring mass system. You can think of this as a spring mass system. C and OR is also like a spring mass system. So these molecules, these atoms can kind of vibrate about their bonds. And so there will be a set of natural vibrational frequencies associated with every interatomic bond for these molecules.

This vibrational frequency is the natural frequency for vibration of these bonds. How the C and O atoms move apart and come back. How many times? That is the vibrational frequency of that CO bond or OO bond or OH bond for water vapor. And if again the electromagnetic wave has frequencies corresponding to any of the vibrational frequency modes of these atoms, then and only then will these atoms absorb these photons and activate that vibrational frequency mode. So basically the photonic energy is getting absorbed and converted into rotational energy of the atom or vibrational energy of the atom if the frequencies align themselves.

Otherwise they will not be absorbed. That is why only certain wavelengths of light or electromagnetic wave is getting absorbed by certain atmospheric gases. whereas other wavelengths are not being absorbed. Because each of these molecules will have different rotational frequencies and different vibrational frequencies depending on the type of molecule they are and the stiffness of these bonds. And based on that there will be certain preferred frequencies at which they will selectively absorb the electromagnetic radiation and that is the foundation why the atmosphere absorbs certain radiation bands and does not absorb other radiation bands. So, this overall idea is explained here, you can go over this.

Basically, Absorption for the vibrational modes will happen if the frequency of vibration is equal to the frequency of the electromagnetic wave. Similarly, the dipolar rotational modes will be activated when the corresponding frequency is matching with the frequency of the electromagnetic waves, ok. So then we can then, so we will stop here today. We will next, in the next class take up the question of what are the bands which the different gases actually absorb and why and then combine all of them to see which are the bands in which the atmosphere is transparent to radiation and which are the frequency bands in which the atmosphere is strongly absorbing of radiation. So thank you for listening and see you in the next class.