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

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Lecture 24

DERIVATION OF ANALYSING THE ATMOSPHERE OF VENUS, RADIATION FLUXES

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. Today we will discuss another worked out example that will cover some of the ideas that we have discussed in this week. And this involves understanding the atmosphere and the temperature of Venus. As you may know Venus is a planet which is the third, the second planet from the Sun and is closer to the Sun than the Earth. In some ways it is very close to how the Earth is in its mass and composition. However, it has a runaway greenhouse gas problem which makes its atmosphere extremely hot and dense and its surface temperature significantly higher than that of Earth.

Today, we will discuss how to model the solar irradiance, the solar flux and to understand why the surface temperature of Venus is so high. So, let us look at some of the facts about Venus. So, analyzing the atmosphere of Venus. Okay, so now the distance from the Sun of Venus, so some major facts, Sun to Venus distance is equals to 108 million kilometers. So this is basically 108 into 10 to the power 9 meters. Let's call this distance as r. Radius of Venus, let's call this small r, is 6051.8 kilometers. which is 6051.8 into 10 to the power 3 liters. Now, the solar luminosity This is the total solar power, so that is the total energy per unit second that is being emitted by the sun at per second is given as 3.85 into 10 to the power 26 watts, okay.

Sun-Venus distance:

$$R = 108\,\text{million km} = 108 \times 10^{9}\,\text{m}$$

Radius of Venus:

$$r = 6051.8\,\text{km} = 6051.8 \times 10^{3}\,\text{m}$$

Solar luminosity:

$$L = 3.85 \times 10^{26}\,\text{Watts} = \dot{E}_S$$

So, this is the total radiant energy that the sun is emitting per unit second. So, here once again suppose this is Venus and this is Sun. So, Sun and Venus, this is the Sun to Venus distance r. So, the solar flux that is reaching the Venus is basically equal to the total solar luminosity divided by the surface of this sphere whose radius is this Sun to Venus distance. So, you can think of again the solar energy spreading outwards in an expanding spherical shell. And where this expanding spherical shell is equal to the distance between Sun and Venus, the solar flux per unit area at that point is what the Venus is getting. solar irradiance in watt per meter square of Venus that is watt the solar irradiance in that is watt per meter square that Venus is receiving is given by So, let us call this S0 of Venus equals to the solar luminosity, let us call this E s, E dot s.

The total solar luminosity is E dot s in watts by the radius, the surface area of this sphere whose radius is the distance between the sun and Venus, this is 4 pi r square, ok. So, we can solve this, you can just put the values of E dot s which is 3.85 into power 26 watts and 4 pi r square where r is 108.9 meters.

You can put these values and you will get the value as 2626 watt per meter square, ok.

$$S_0^{\nu} = \frac{\dot{E}_S}{4\pi R^2} \approx 2626\,\mathrm{W/m^2}$$

that the solar irradiance of earth, S0 of earth was given by 1360 watt per meter square. So you can see here that the solar energy per unit meter square that is reaching Venus is almost twice than that of Earth because Earth is further away from the Sun compared to Venus. S0 by V by S0 by E, this ratio, the irradiance ratio between Venus and earth is 2626 by 1360 equal to 1.93.

$$\frac{S_0^{\nu}}{S_0^{E}} = \frac{2626}{1360} = 1.93$$

So, the Venus is getting 1.93 times more energy per meter square compared to that of earth. Now if this is S0, if you remember Venus is like Earth, a spherical planet and so the projected area towards the Sun is the circular disc of radius small r and here this is a spherical surface of radius r. So the total energy E dot S v, the total energy that sun is sending to Venus is equals to S 0 into pi r square, where S 0 v is the previous value here, 2626 watt per meter square. And the surface flux, the solar flux per unit area of Venusian surface e sv is E dot s v by 4 pi r square because this is a sphere and its outer surface area is 4 pi r square. So, this is s 0 v into pi r square by 4 pi r square equals to S0 by 4.

$$e_{SV} = \frac{\dot{E}_{SV}}{4\pi r^2} = \frac{S_0^{\nu} \times \pi r^2}{4\pi r^2} = \frac{S_0}{4}$$

So, just like earth the solar flux per unit area at the top of the atmosphere is S0 by 4. So, for Venus e sv is equals to S0 by 4 equals to 2626 by 4. equals to 656.5 watt per meter square. So, in on earth it is around 360, on Venus it is around 656 watt per meter square.

$$e_{SV} = \frac{S_0}{4} = \frac{2626}{4} = 656.5\,\mathrm{W/m^2}$$

Now, we can then also find the black body temperature of Venus, black body temperature of Venus. So, sigma Te to the power 4 goes to S0 by 4 into 1 minus alpha.

$$\sigma T_e^4 = \frac{S_0}{4}(1-\alpha)$$

Now, what is the albedo of Venus? If you see in the sky, Venus is the brightest planet in the solar system as seen from Earth. And this is not only because Venus is quite close to Earth, which is true, but also because it has a very high albedo value. Venus' atmosphere is highly reflective and has very high albedo, alpha v is around 0.7. So, 70 percent of the solar energy that is incident on Venus is being reflected by its atmosphere, whereas this value is much lower around 29 percent for that of Earth. So now, if you put alpha v as 0.7, the S0 by 4 value here and sigma is the Stephen Boltzmann's constant, this is 5.67 into 10 to the power minus 8 watt meter to the power minus 2 Kelvin to the power minus 2. If you put all of these values, The blackbody emission temperature of Venus is found to be 242.7 Kelvin which is approximately minus 30 degree.

$$\sigma = 5.67 \times 10^{-8}\,\mathrm{W/m^2\,K^4}$$

$$T_e = 242.7\,\mathrm{K} \approx -30^{\circ}\mathrm{C}$$

Now, the blackbody emission temperature of earth is much higher than this. It is around minus 18 degree. So, even though Venus is getting much higher solar flux. because it's closer to the Earth, because of its very high albedo, its emission temperature to space is much lower.

It's around minus 30 degrees because most of the solar energy is being reflected anyway. So thermal emission is much lower. However, because Venus's atmosphere is highly absorbing of greenhouse radiation, extremely thick, its surface temperature is very high. Venus's atmosphere is extremely thick and full of greenhouse gases like CO2 which is around 94% of the atmosphere. As a result, surface temperature of Venus S is 737 Kelvin, which is close to 450 degree centigrade, 450 to 470 degree centigrade.

So, venus's surface is at a much much higher temperature than that of its emission temperature. which means that we have to use the multiple atmosphere layer theory to explain the surface temperature of the Earth. We know that its atmosphere is very thick, full of greenhouse gases, it is perfectly absorbing of all surface emissions and because of its thickness, we have to assume that it has many many layers. So the Venus, if this is the surface, it has many many perfectly absorbing atmospheric layers. So, if this is n, n minus 1 going to 2, 2, 1 and this is the topmost layer which is at the emission temperature or that is being seen from space.

So, as we have done previously using this system where this is S0 by 4, 1 minus alpha and each of these at different layers Ta1, Ta2, Ta3. we have evaluated the expression that T s the surface temperature is n plus 1 to the power 1 by 4 T e. So, here T s to the power 4 is equals to n plus 1 T e to the power 4, implies N the number of atmospheric layers is Ts by Te to the power 4 minus 1. And how much is this? Ts is 737 kelvins, Te is 242.7 kelvins minus 1, which approximately gives you 80.

$$T_s = 737\,\mathrm{K}$$

$$T_s = (N+1)^{\frac{1}{4}} T_e$$

$$\Rightarrow T_s^4 = (N+1) T_e^4$$

$$\Rightarrow N = \left(\frac{T_s}{T_e}\right)^4 - 1 = \left(\frac{737}{242.7}\right)^4 - 1 \approx 84$$

Okay. So, We can model the Venetian atmosphere as composed of 84 isothermal perfectly absorbing layer of atmosphere. Starting from close to 737 kelvins on the ground and going up to 242 kelvins at the top. And this shows how thick the Venetian atmosphere really is to get its surface temperature such high value. And Venus is an example of a runaway, a planet where runaway greenhouse effect has caused such a thick atmosphere with very high surface temperatures, much, much larger than the emission temperature of the black. So this, with that brief discussion we will go to the, we will start introduction to the next topic where we will discuss this concept of radiation, radiation balance in much more detail to give us a more fine-grained understanding of the radiative models that control the energy budget of the earth.

So let us go there. So the next section that we will cover and which we will be covering very briefly today, it will be more detailed in the next class where we will start this, is a fine-grained understanding of the radiative transfers that is happening in the atmosphere. So, here we will begin with the understanding of what radiation is. Radiation is an electro, is basically a set of electromagnetic waves that is being emitted by different types of bodies which are at different temperatures. And the temperature of the body determines the intensity of the radiation as well as the distribution of that radiation in various wavelengths. The electromagnetic spectrum includes the visible light, the thermal radiation which is also called the infrared radiation, The ultraviolet radiation which is often well known for its cancer causing ability, X-rays which are used in medical devices, gamma rays which are highly energetic blasts that come from violent stellar explosion and also microwaves and radio waves.

Microwaves you have seen microwave devices and radio waves are used in radio technologies on earth. And the difference between all of these is that what is the wavelength or the frequency of the radiation. So for example radio waves are waves whose wavelength. So what is a wavelength? Wavelength is the crest to crest or trough to trough distance. of the, of a certain wave. The distance between two successive crests or two successive troughs is the wavelength of a certain wave. So, for radio waves that distance can be more than a kilometer. So, the magnitude is 10 to the power 3 meters or at the range of kilometers. For microwaves or microwave devices that you are seeing in your kitchen table, These values are much smaller of around 10 to the power minus 2 meters that is around 1 centimeter. So radio waves typical wavelengths are 1 kilometer, microwaves typical wavelengths are 1 centimeter. If you go further to where we are emitting thermal radiation or infrared radiation, the wavelength decreases to 10 to the power minus 5 meters. basically 0.01 millimeters. So much much smaller than what can be seen by naked eye. The visible wavelength spans a very narrow band of 0.5 into 10 to the power minus 6 meters. So around 0.5 micrometers is the typical wavelength of visible spectrum. Beyond that you have the even shorter wavelength ultraviolet spectrum which is 10 to the power minus 8 meters. So, now as we go towards ultraviolet is going below micrometers to 10 to the power minus 8 meters, then x rays another 100 times smaller to 10 to the power minus 10 meters and then gamma rays of 10 to the power minus 12 meters. And you can see in this visual imagery how the wavelength size is decreasing and typical sizes of other entities that can be comparable to the wavelength sizes in discussion. So between radio and microwave, we are looking at sizes of buildings, people and ants. Infrared is kind of the point of a pin, so less than one millimeter. Then when you go to the visible spectra, the size of bacteria is kind of 1 micrometer. So that is the size of a bacteria. When you are looking at ultraviolet rays, 10 to the power minus 8 radiation, the size of typical molecules, CO_2, organic molecules, et cetera, is the ultraviolet range. The X-ray, the size is typical to the size of an atom. So 10 to the power minus 10 meters is also called 1 angstrom, which is typical size of atoms. Then gamma rays, again 100 times smaller is typical size of an atomic nuclei. When you look at the relationship between wavelength and frequency, they are inversely proportional.

So, frequency is the speed of light divided by the wavelength. Its unit is second inverse or hertz. Speed of light is 3 into 10 to the power 8 meters per second. So, what you have to do is just get the wavelength. put it in the denominator, speed of light 3 to the power 8 and you will get the frequency of that wave.

What does frequency gives? It gives you the second inverse and what it tells is how many waves will travel in one second in a given location. So how many successive crests or successive troughs will be travelling over a period of one second through a certain point through which the wave is propagating. So that is the frequency, how many times the wave will move through, how many crests will move through that location in a given second. And as wavelengths become shorter, the frequency becomes higher because for all electromagnetic waves in vacuum, the velocity is constant. And the velocity of the wave of all electromagnetic waves in vacuum is the velocity of light C, which is three into 10 to the power eight meters per second.

So basically, velocity of the wave is wavelength into its frequency. And since velocity is constant, for in a certain media for electromagnetic waves. So, for vacuum it is 3 into 10 to the power 8 meters per second, 10 to the power 8 meters per second. So, frequency is inversely proportional to wave length and that means that your wavelength decreases the frequency will increase and vice versa so long wave waves like radio waves microwaves have frequency values of 10 to the power 4 or 10 to the power 8

Hertz so 10,000 crests will pass per second for a radio wave 10 to the power 8 So like 100 million, something like that.

Waves will pass when it comes to a microwave. For infrared, it's 10 to the power 12, the frequency. For visible spectrum, it's around 10 to the power 15, somewhat more. So maybe 5 into 10 to the power 15, like that. For ultraviolet, it's 10 to the power 16, the frequency in hertz.

X-rays, it's 10 to the power 18. And for gamma rays, it's 10 to the power 20. The second point here is energy of a wave is related to its frequency values. So, there is a entire quantum mechanical relationship here. So, every wave energy is discrete and it is based on the energy of the photon that comprise the wave. So, from quantum theory we can say that every electromagnetic wave has discretized energy packets and the energy packets are called photons.

and wave is composed energetically at least as a collection of this energy packets called photon and the energy of these individual photons is related to its frequency as E nu equals to h into nu. h is a constant called the Planck constant which is 6.6 into 10 to the power minus 34 joule second. So, clearly energy of photons is quite small, especially for low frequency waves.

So, this is 10 to the power minus 34. For example, here somewhere it is for microwave and infrared it is 10 to the power 8. So, energy of a photon of a microwave or an infrared wave is around 10 to the power minus 24 joules only. Whereas for a gamma ray the energy can be 10 to the power minus 14 joules because here you are getting 10 to the power 20 hertz as frequency. So the energy of the photon increases with its frequency but every individual photon has a very small amount of energy.

So that's the idea of the electromagnetic spectrum. What is a wave? What is its wavelength? What is its frequency? And we divide the spectrum into multiple types of waves based on its wavelength or frequency values. Radio waves are the lowest in terms of frequency and largest in terms of wavelengths. Gamma rays are the highest in terms of frequency and lowest in terms of wavelengths. photon energy is proportional to that of the frequency. So, gamma rays are made of highly energetic photons, radio waves are made up of much lower energy photons, ok.

So, we will stop here today. This is just an introduction. We will continue with this discussion and see how to further understanding of how radiation is emitted and absorbed in different types of medium. Thank you for listening and see you in the next class.