Climate Change Science
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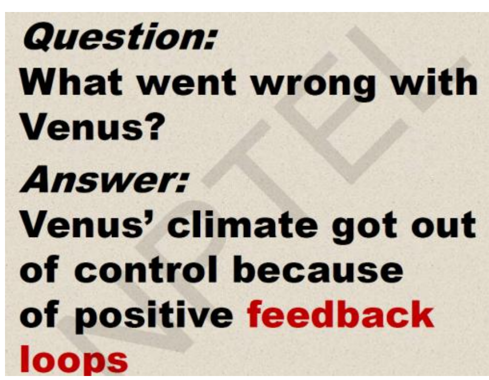
Lecture – 58
Venus energy balance

In the last lecture, we pointed out that the major greenhouse effect on Venus is caused by carbon dioxide. The next important entity is clouds because it is completely cloud-covered, and thirdly, a little amount of water vapor has a big effect. So, this is what makes Venus unique.

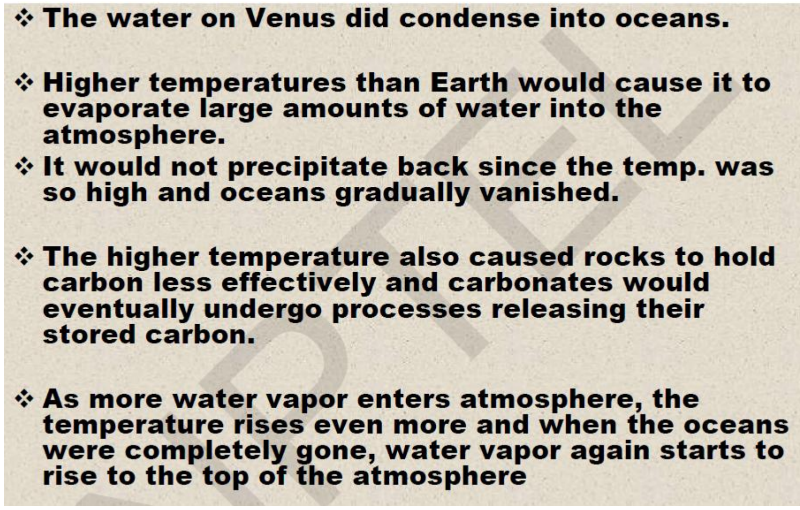
Table 1. The effect of the removal of infrared opacity sources on the surface temperature

Source Deleted	Change in Surface Temperature, K
CO_2	-420
Clouds	-140
H_2O	-70
OCS	-12
CO	-3
SO_2	-3
HCl	-2

The question is: what went wrong with Venus? Why did the Venus greenhouse effect become so strong? The answer is Venus' climate got out of control because of the runaway greenhouse effect, because there were a lot of positive feedback loops when Venus became hot. So, these feedback loops are similar to what we discussed for Earth, but much stronger and much more effective.

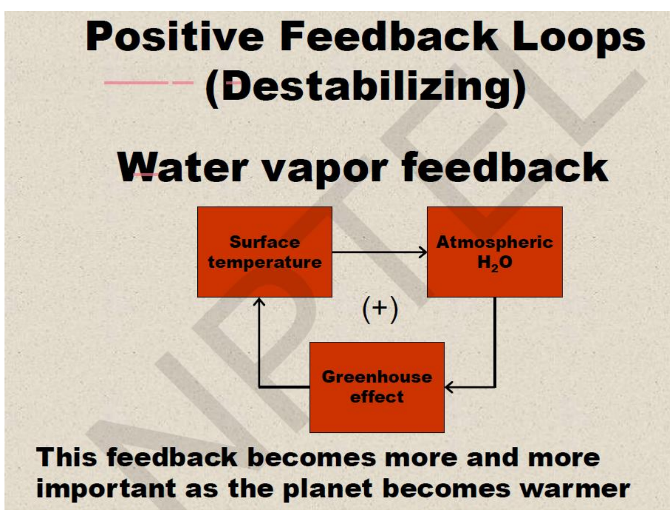


See, Venus had some ocean a long time back. There is no ocean now. Because it was closer to the Sun, it was hotter in the beginning, and the higher temperature caused the water on Venus to evaporate. Because the temperature was higher than on Earth, the water did not condense back. So, the ocean vanished.

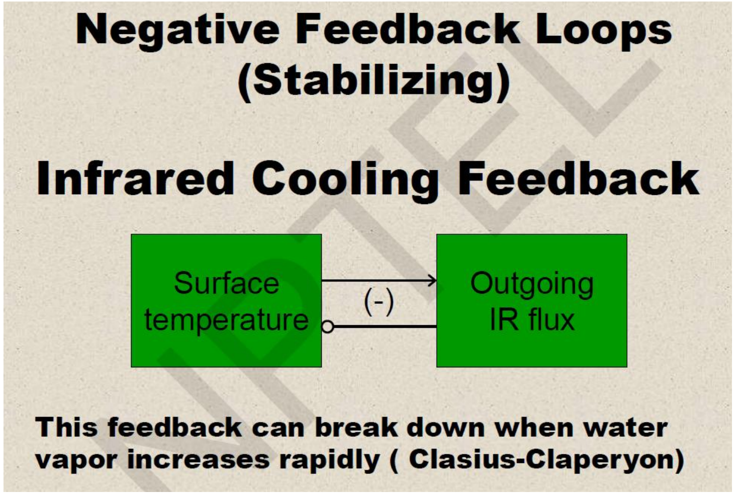


All the oceans on Venus just evaporated into the atmosphere. And once the temperature went above a certain value, then the rocks, which had a lot of carbon dioxide, also started having chemical reactions, which converted calcium carbonate into carbon dioxide and calcium oxide. So, as the temperature goes very high, all of you know from the Arrhenius equation that the reaction rate of a chemical reaction depends on temperature exponentially. So, as the temperature goes up, the reaction rate will go up exponentially. Earth is at a cool 15 ºC, but on Venus, as the temperature went up to 100–200 ºC, the reaction rate in Venus went up, and the rocks started chemical reactions which released carbon dioxide from the Venus surface into the atmosphere.

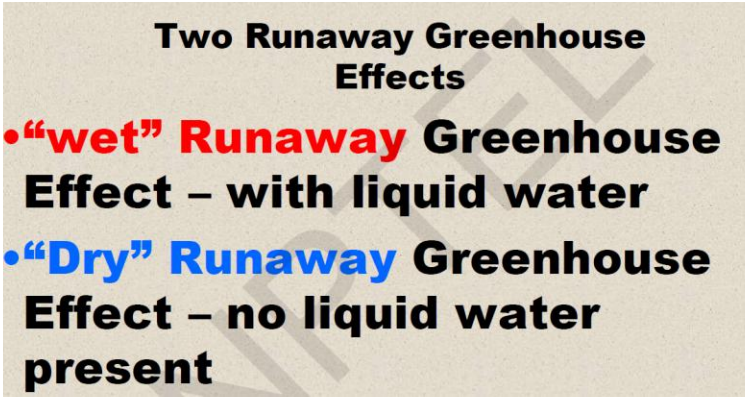
So, once all the water vapor evaporates, later on, the water vapor dissociates into hydrogen and oxygen, and hydrogen, being a light gas, will escape to space. So, this is the effect, the positive feedback loop, which caused the Venus temperature to rise so rapidly that the rocks started releasing carbon dioxide into the atmosphere. So, water triggered the runaway greenhouse effect on Venus.



This negative feedback effect is there; all of you know that as the temperature goes up, Earth loses more heat to space.



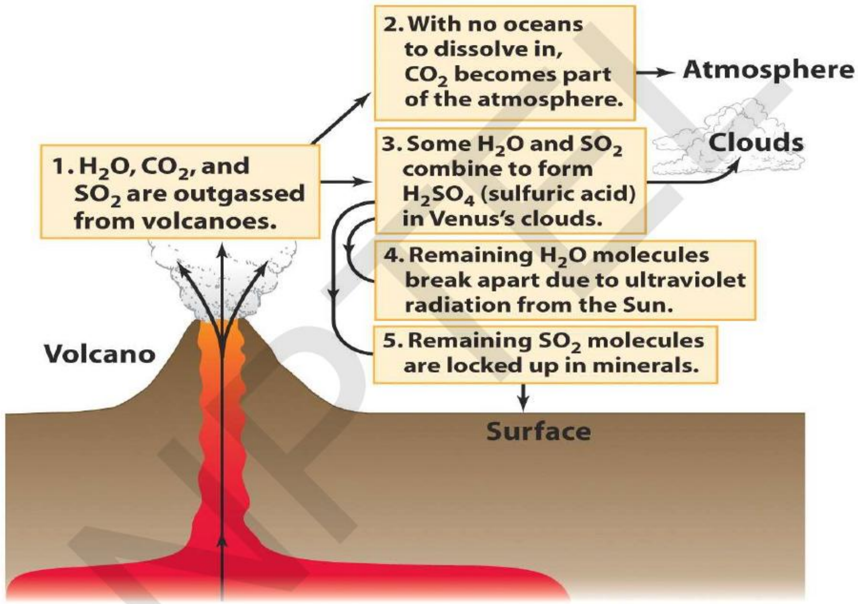
But if there is a lot of greenhouse gas in the atmosphere, this negative feedback will not be very effective. We will see how that will happen.



So, Venus had first a wet runaway effect, that is, water vapor evaporated from the ocean and increased the water vapor in the atmosphere, and increased the temperature more and more. Once water vapor escaped from Venus after dissociation, then the dry runaway greenhouse effect came, where carbon dioxide came out of the rocks into the atmosphere. So, this went on for a longer period. So, the temperature went further and further up until it reached 720º Kelvin.

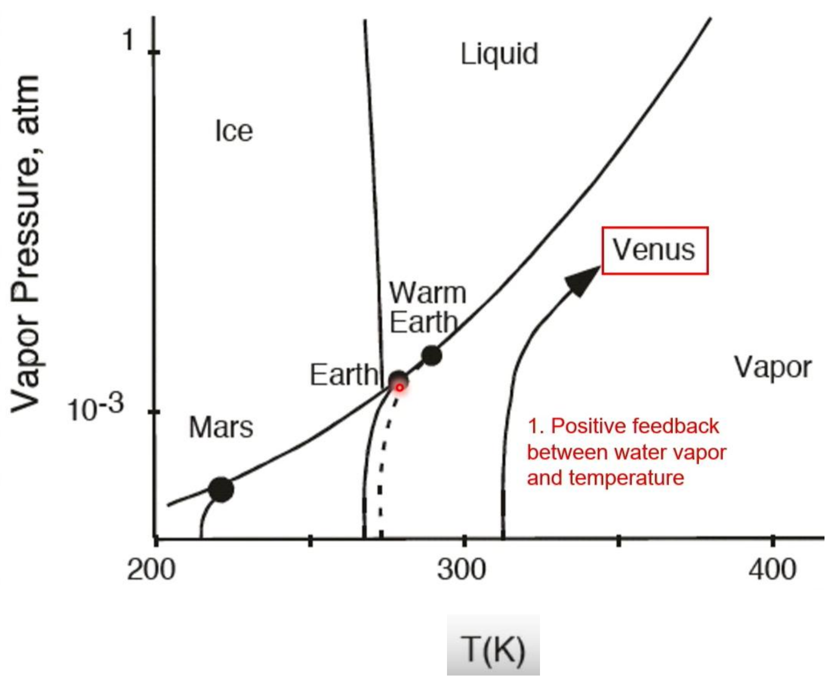
So, two runaway effects operated in Venus. One is wet in the beginning and dry later. This is assuming that Venus had an ocean. This is a hypothesis. We cannot yet prove that there was liquid water on Venus' surface. This is a hypothesis.

Venus also had volcanoes, which released carbon dioxide into the atmosphere. On Earth also, volcanoes release carbon dioxide, but this ultimately goes back into the surface of the Earth and beneath. Carbon dioxide is dissolved in rainfall, forms carbonic acid, which then reacts with calcium carbonate in the rocks and takes away the carbon dioxide into the ocean and ultimately into the rocks. So, in Earth's carbon cycle, the presence of water allows carbon dioxide to become carbonic acid and remove carbon dioxide from the atmosphere and put it into the ocean. Now, this could not happen on Venus when its temperature went up so high that water vapor completely escaped.

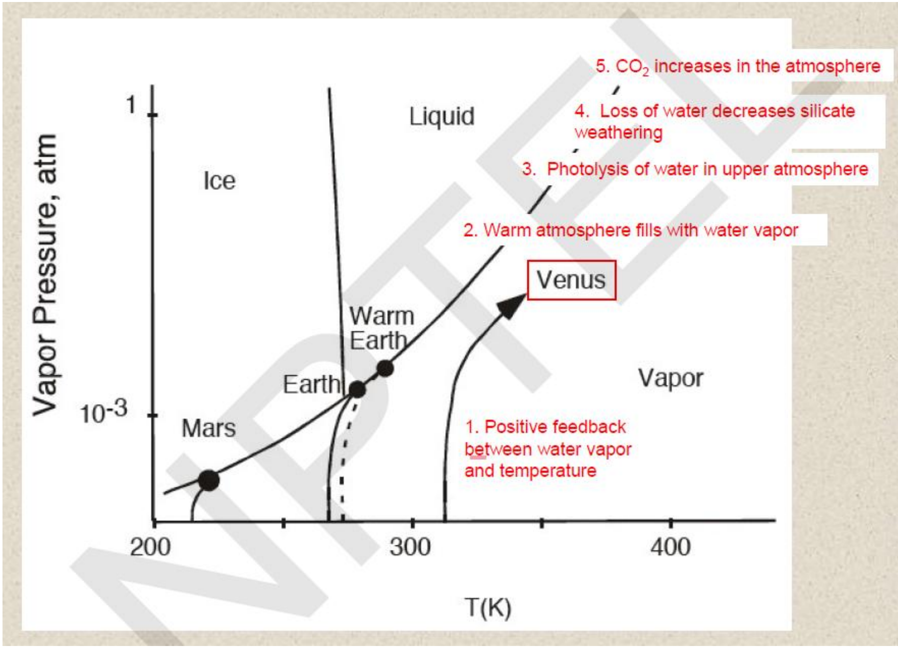


(b) Venus: H_2O, CO_2, and SO_2 are NOT recycled

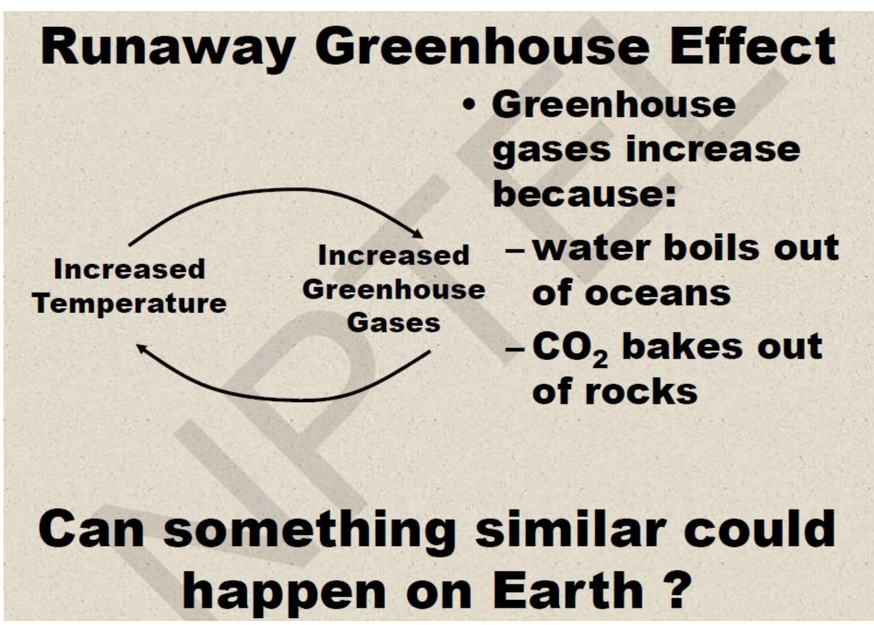
So, this is what astronomers think happened. Venus' temperature went up. On Earth, it went up and reached a point close to the triple point of water. Please look at the thermodynamics diagram of water vapor pressure versus temperature shown below. All of you know this from your thermodynamics background.



On Earth, the temperature was such that we were close to the triple point of water. Hence, on Earth, both ice, liquid water, and water vapor coexisted. So, we had the advantage of clouds, which could reflect the sunlight. We had the advantage of water vapor condensing and setting up a circulation in the Earth's atmosphere. All this is not there in Venus once the water vapor escaped.

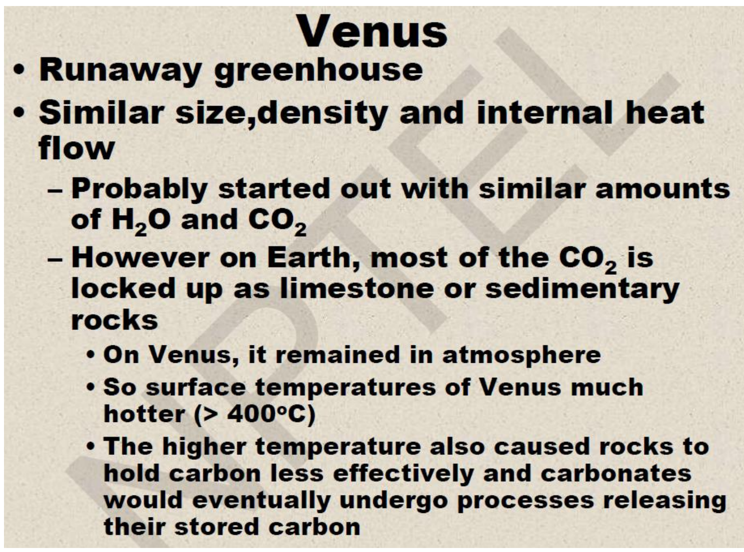


So, on Venus, this increase in temperature did not allow Venus to reach the liquid water phase. But it went another way, such that ultimately, there was photolysis of water, that is, dissociation of water into hydrogen and oxygen, which did not happen on Earth. So, water vapor decreased and carbon dioxide increased. So, on Venus, first, water vapor boils out. Then it causes a very high greenhouse effect in the atmosphere. After that, CO_2 bakes out of the rocks.



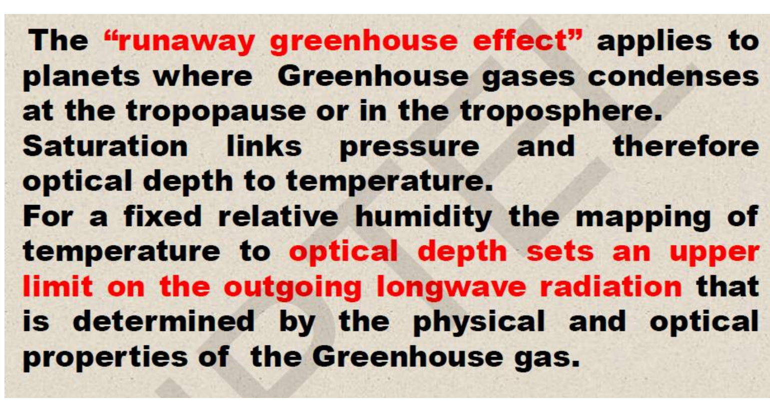
So, the question is: can something similar happen on Earth? The answer is: of course, it can happen—not immediately, but after a long time. Because if the temperature of the Earth keeps going up due to the release of carbon dioxide, then at some point, the water vapor will keep increasing like on Venus, and very soon, the temperature will become so high that rocks will start releasing carbon dioxide. That, of course, will not happen in the immediate future, but the potential exists if we continue to allow carbon dioxide to increase in the atmosphere.

So, now we understand that although Venus and Earth started with similar composition, similar diameter, and similar amount of carbon, on Venus, most of the carbon came into the atmosphere, and it increased the greenhouse effect. While on Earth, we were lucky that most of the carbon is stored safely as limestone in the sedimentary rocks of the Earth. It is locked up, but it can be released if the temperature goes up.

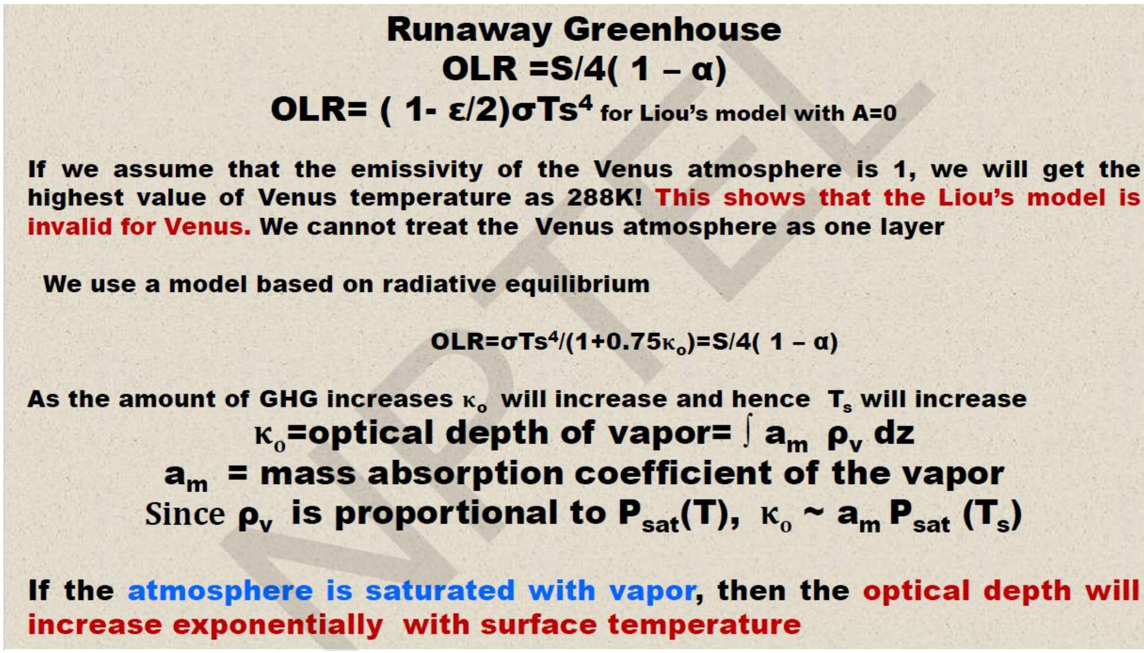


So, that is the message that we get from Venus—that Earth right now is at a much cooler temperature because most of the carbon dioxide on Earth is safely stored in the rocks and in the ocean, and only a small amount of carbon dioxide is in the atmosphere.

So, the runaway greenhouse effect applies to planets where greenhouse gases condense at the tropopause or in the troposphere, and the saturation vapor pressure links pressure and temperature of the atmosphere.



For a fixed relative humidity, the mapping of temperature to optical depth sets an upper limit on the outgoing longwave radiation. That is determined by the physical and optical properties of the greenhouse gases. To explain this, let us go back to the energy balance equation, which we started the course with.



The outgoing longwave radiation (OLR) is balanced with the absorbed solar radiation S(1-α)/4. That is our balance, which we have used in many examples.

Now, if you use a simple Liou's model, which we discussed in great depth in the first few lectures in the course, and we neglect the absorption of solar radiation by the atmosphere (A=0) for convenience, then

$$OLR = (1 - \frac{\epsilon}{2})\sigma T_s^4$$

If we assume that emissivity (ϵ) of Venus is 1, which is reasonable because Venus contains a lot of carbon dioxide, so OLR will become $(0.5)\sigma T_s^4$. And the highest value we will get for Venus temperature, for the albedo of let us say almost 0, will be around 288 Kelvin. So, for albedo of 0.3, the temperature is 288 Kelvin. So, this shows that this simple model is not valid for Venus.

Why is it not valid? Venus' atmosphere is very thick today, 100 times thicker than the Earth's atmosphere. So, we cannot replace the entire atmosphere with one layer at one temperature, which is what we did for Earth and which was adequate for a simple model of the Earth's atmosphere. For Venus, we have to adopt a very different approach, where we would allow temperature to vary with height.

That makes the radiative transfer calculation very complicated, which we will not talk about in this course. But, if any of you are interested, there is an NPTEL course on thermal radiation heat transfer, in which I have given lectures, where we derive the equation for radiative equilibrium, where we allow the temperature of the atmosphere to change with height. So, if we do that, the OLR value for such an atmosphere in radiative equilibrium will be

$$OLR = \frac{\sigma T_s^4}{1 + 0.75K_0}$$

K_0 is the optical depth, the total optical depth of the entire atmosphere. That is nothing but the vertical integral of the mass absorption coefficient (a_m), which we discussed earlier in the course, multiplied by the density of the vapor (ρ_v) and the vertical level dz, and that you integrate from the surface to the top of the atmosphere.

$$K_0 = \int a_m \rho_v \, dz$$

Now, the mass absorption coefficient of the vapor in the atmosphere depends on the vapor pressure, which we assume is saturated. It is a saturated vapor pressure, which can be obtained from the Clausius-Clapeyron equation in thermodynamics. So, the optical depth, the total from surface to top of the atmosphere, is controlled by the mass absorption coefficient and the saturation vapor pressure of that greenhouse gas, which depends on temperature. So, we see that if the vapor in the atmosphere of Venus is saturated, then its amount will keep increasing with temperature, following the Clausius-Clapeyron equation. So, that is unavoidable, determined by the laws of thermodynamics.

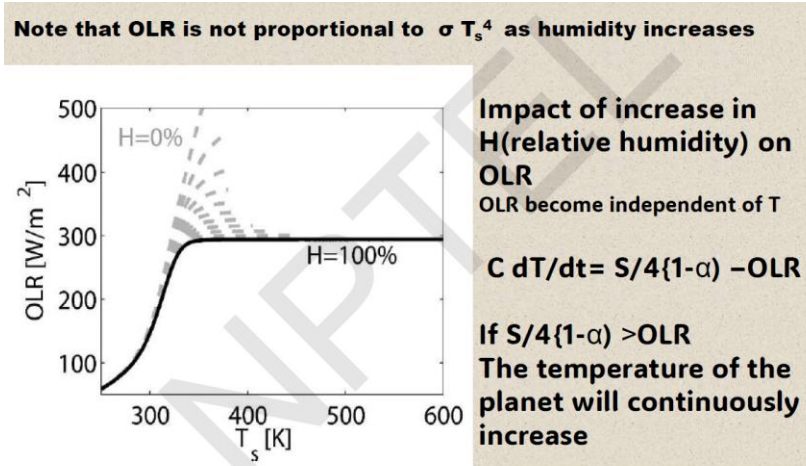
So, if the atmosphere of Venus is saturated with vapor, then the optical depth will increase exponentially with surface temperature, and that is what causes the runaway greenhouse. The runaway greenhouse effect is occurring because Venus, from the beginning, had either saturated water vapor or, after it evaporated, saturated carbon dioxide. So, initially it was a wet greenhouse effect, later on it was a dry greenhouse effect.

$$OLR = \frac{\sigma T_s^4}{1 + 0.75K_0} = S(1 - \alpha)/4$$

So, this is the key part, and this OLR equation is very important for you to understand that the right-hand side is controlled by the albedo (α) of Venus, which we can assume to be roughly constant because the cloud is always covering Venus.

So, as the temperature goes up, K_0 goes on increasing. So, OLR goes on decreasing. If OLR goes on decreasing, but the right-hand side remains constant, we see that there is an imbalance between the radiation emitted and the radiation absorbed. As the temperature goes up, the radiation emitted goes down, while the absorbed solar radiation does not change. So, this will force the temperature of the planet to go up. There is no alternative. That is what happened on Venus.

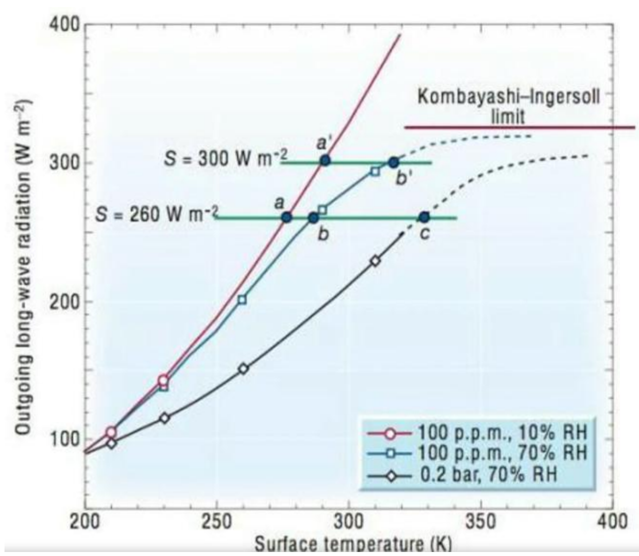
This can be shown graphically.



If there is no saturated vapor or no greenhouse gas in the atmosphere, OLR goes as σT_s^4. All of you know that, assuming the surface of Venus is black. But, suppose the vapor is saturated, the relative humidity is 100 percent. Then the OLR will not go on increasing. It will become completely flat because, as the temperature goes up and the water vapor increases, it traps more and more of the surface radiation. Very soon, the OLR is independent of temperature. So, that is the key point. There comes a point where OLR is independent of temperature, but the absorbed solar may not be dependent on temperature.

So, this quantity is higher than that quantity. So, the planet becomes unstable and it goes on a runaway greenhouse effect until some change in the absorbed solar radiation brings the right-hand side and left-hand side into balance. So, this is what you must understand. This is the nature of the greenhouse effect: that the planet's ability to emit radiation becomes less and less as the greenhouse gas goes up, while the absorbed solar radiation does not change much. So, this is what causes the runaway greenhouse effect.

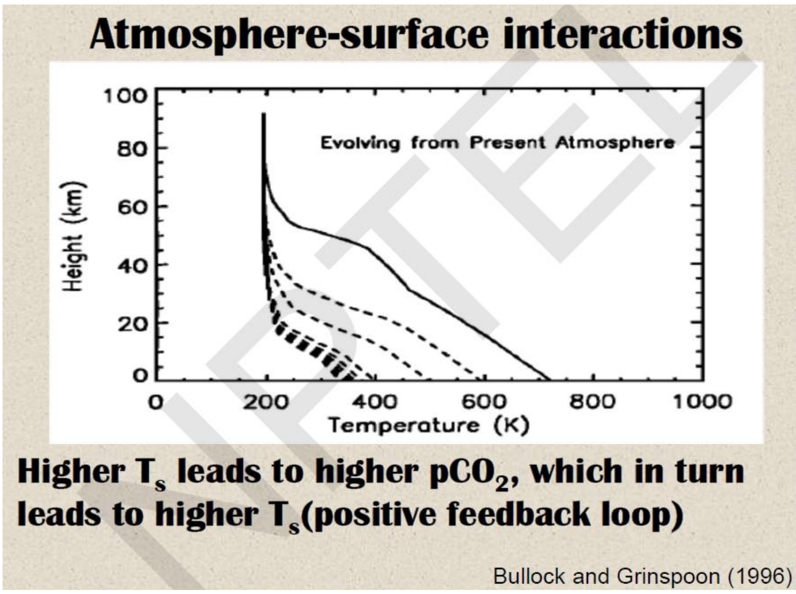
This is shown in another graph here, showing the outgoing longwave radiation in three cases.



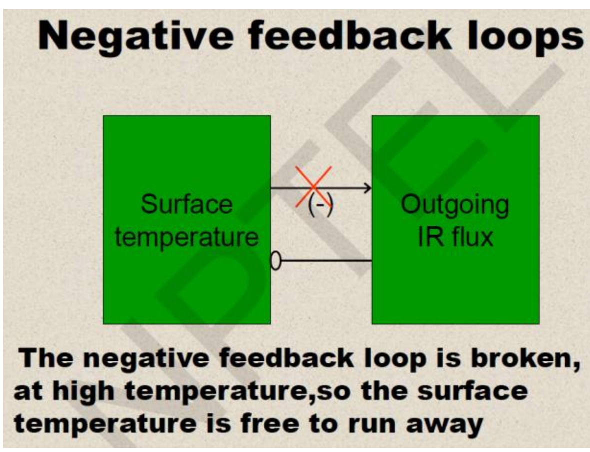
In one case, CO_2 is 100 ppm, the RH of water vapor is 10%, then there is no problem, but it keeps increasing. But if the CO_2 is 100 ppm and RH goes to 70%, then you can see that the OLR reaches an asymptote; it does not go beyond, in this case, 320 W/m^2. And if you increase the carbon dioxide concentration to 0.2 bar and the water vapor humidity is 70%, it is even less.

So, the key point is, depending on the properties of the greenhouse gas, which is saturated in the atmosphere, there is a limit called the Kombayashi-Ingersoll limit, which tells you what is the maximum amount of longwave radiation that the atmosphere can emit to space. So, if the absorbed solar is larger than that, then the atmospheric temperature will continue to increase until some balance is achieved.

Now, the graph shown below represents the simulation done by Bullock and Grinspoon, taking the Earth's atmosphere and increasing the amount of carbon dioxide.

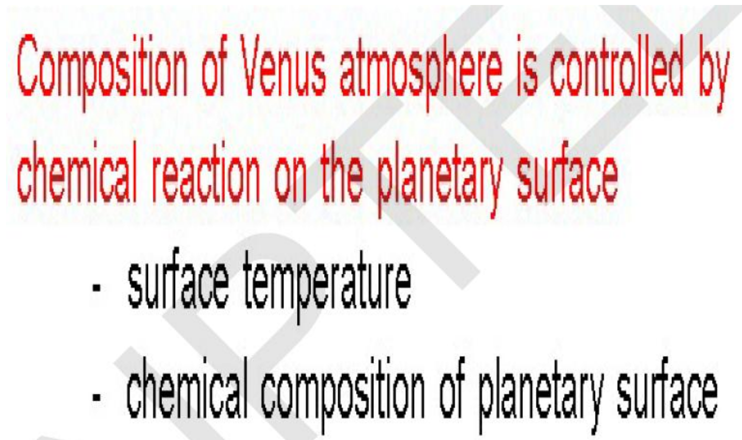


You can see that the temperature keeps going up, up to 700 Kelvin. As the temperature goes up, carbon dioxide goes up, and that is when the carbon in the rocks all comes out, and the temperature goes on increasing. So, this is possible on Earth also, provided the carbon dioxide comes out of the rocks.



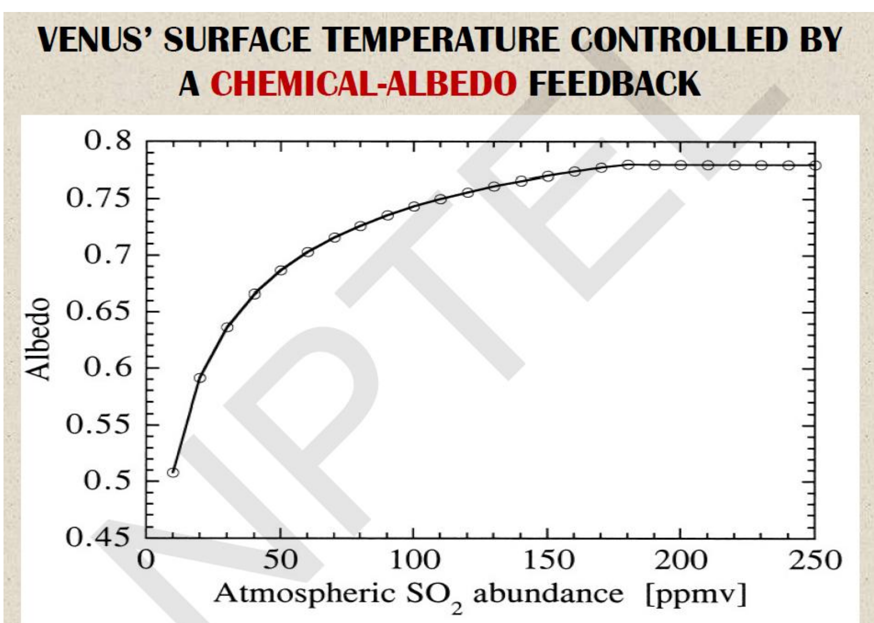
So, the key point is that if there is a sufficient amount of saturated vapor in the atmosphere, it will prevent the atmosphere from cooling to space. So, the negative feedback, which we call the Planck feedback, is not there. So, that is why the temperature keeps increasing.

Now, in contrast to the Earth, the composition of Venus' atmosphere is controlled by chemical reactions on the planet's surface. On Earth, the chemical reaction is not very rapid because the temperature of Earth is quite low, 288 Kelvin.



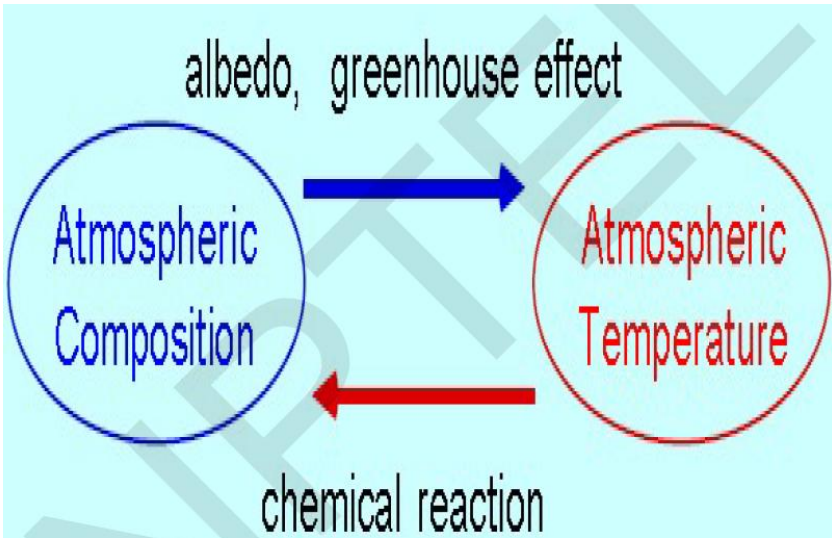
While the Venus temperature is high. The chemical reaction is very rapid on Venus. So, the surface temperature depends upon how much of the gas escapes from the rocks into the atmosphere. So, composition is controlled by chemical reaction and the surface temperature of Venus. On Earth, it is much smaller because of the lower temperature.

Here is an example: how the albedo of Venus, which contains sulphuric acid, haze particles, and clouds, increases with amount of sulphur dioxide in Venus.



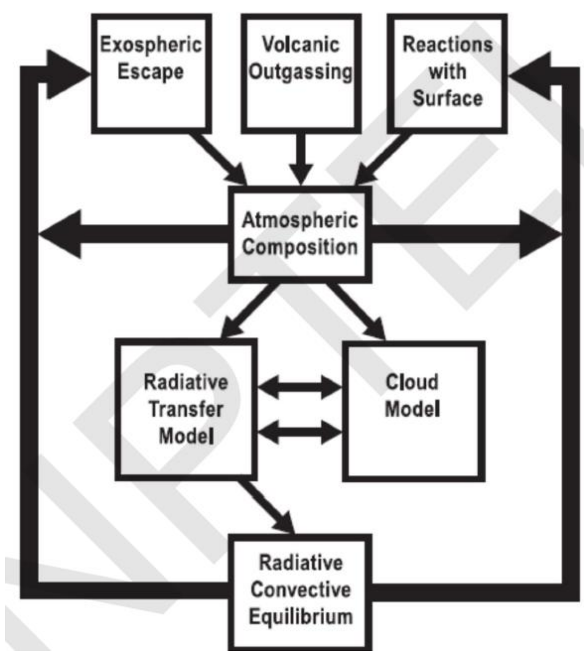
You can see that as sulphur dioxide increases, more clouds form, and more aerosols are present. So, there is chemical albedo feedback. On Earth, we have ice-albedo feedback; on Venus, we have chemical albedo feedback.

So, in Venus, because of its high temperature, the atmospheric composition controls the temperature of Venus, and the temperature of Venus controls the composition.



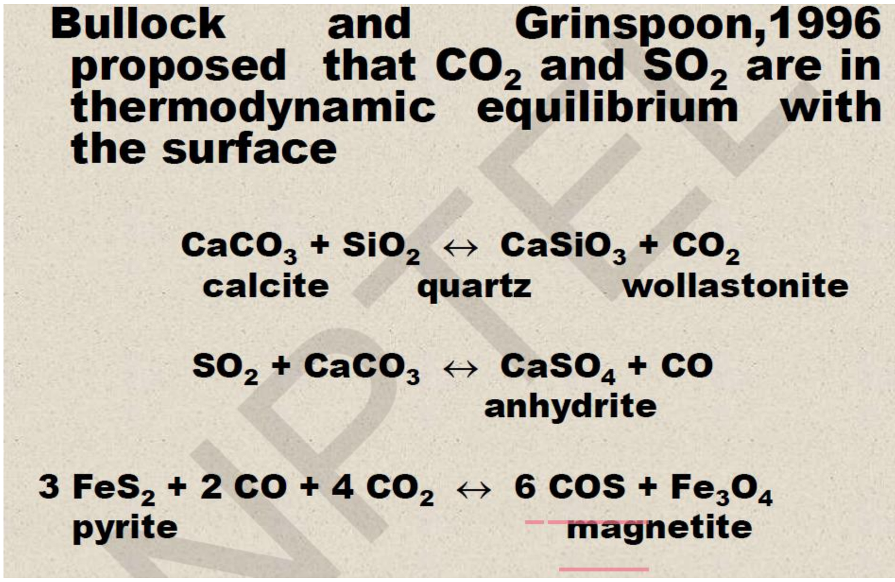
So, this is an interacting system. As the temperature goes up, the atmospheric chemical composition changes, SO_2 and CO_2 change, and as they change, they change the atmospheric temperature. So, here you are talking about both albedo change due to sulphur dioxide and greenhouse effect change due to carbon dioxide.

In Venus, the energy balance is more complicated.

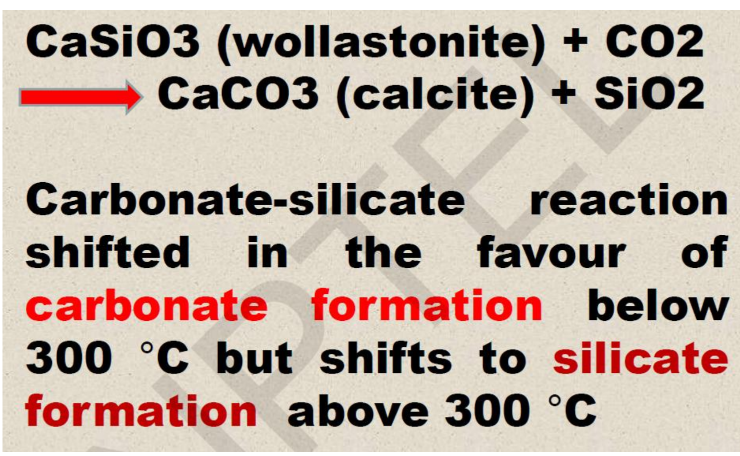


There is volcanic outgassing like on Earth, there is surface reaction, chemical reaction going on which changes the composition of the Venus atmosphere, and that affects the radiative heat transfer in Venus, and there are clouds in Venus which trap radiation. So, all these are controlling the radiative-convective equilibrium in the Venus atmosphere.

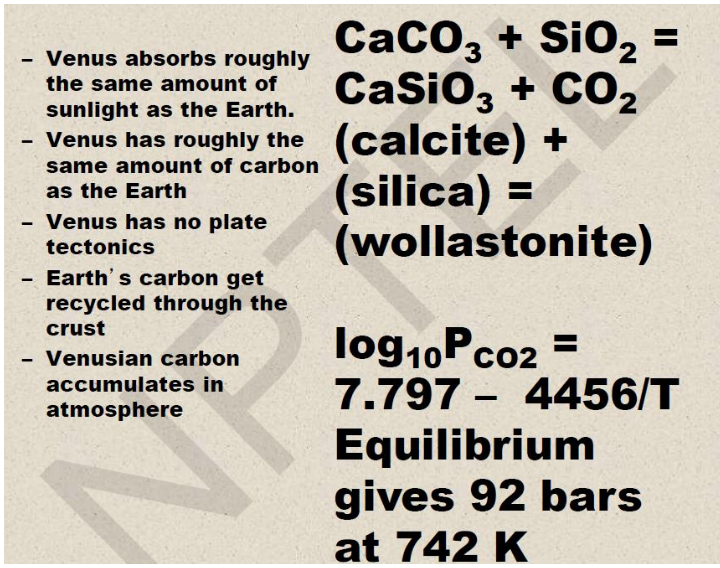
Now, Bullock and Grinspoon talk about the kinds of reactions that go on in the Venus surface.



One is calcium carbonate reacting with silicon dioxide that produces calcium silicate and carbon dioxide. There is also a reaction between sulphur dioxide and calcium carbonate, which produces calcium sulphate and carbon monoxide. So, these reactions are going on, along with also pyrite and magnetite. All these reactions are going on. All of them depend on temperature. As the temperature goes up, all these reactions go much more rapidly and they release more carbon dioxide.



So, this particular reaction (shown in the picture above) they have discussed the carbonate-silicate reaction, creates calcium carbonate when the temperature is below 300ºC. But if the temperature goes above 300 ºC, the reaction goes the other way around, and it releases carbon dioxide. So, all of you know the reaction can go both ways, a chemical reaction, which way it goes depends on the temperature. At low temperature, the reaction goes in the forward direction. At high temperatures, the same reaction goes in the backward direction. Once the Venus temperature reaches above 300 ºC due to the water vapor greenhouse effect, this reaction will take over and release more carbon dioxide. So, that is the point you have to remember about Venus. It started with the water vapor as a main source of the wet greenhouse, and then it went on to the dry greenhouse, which is given by the above reaction.

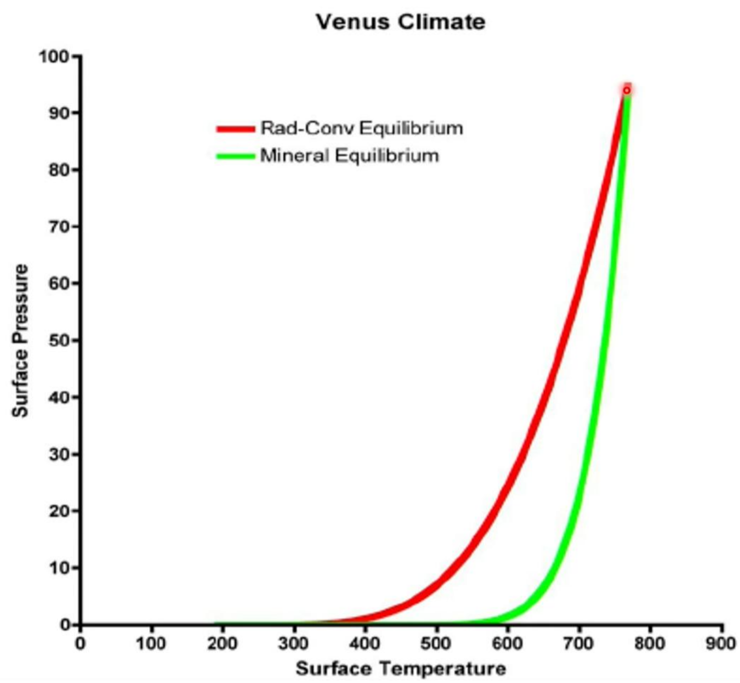


Now, you can calculate the reaction rate of releasing carbon dioxide and what its partial pressure will be.

$$log_{10}(Pco_2) = 7.797 - \frac{4456}{T}$$

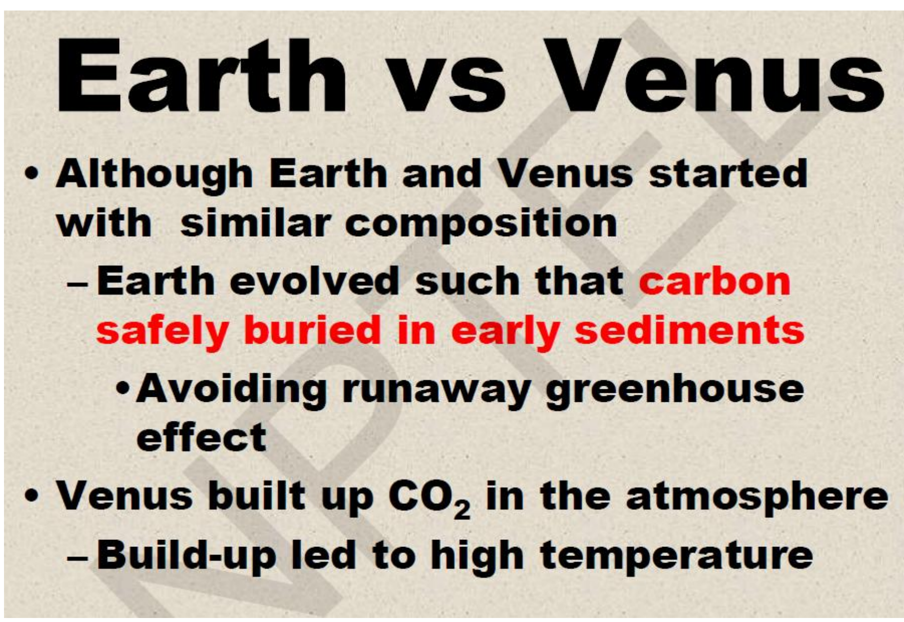
This is the relationship between carbon dioxide and temperature on Venus due to a chemical reaction. This is governed by the Arrhenius chemical reaction equation. This is similar to the Clausius-Clapeyron equation for water vapor, but this is occurring at a higher temperature. So, this particular equation says that at 92 bar surface pressure at a temperature of 742 K, we reach a chemical equilibrium.

It is a very interesting result. Because the observed pressure in Venus is around 92 bar and the observed temperature is around 720 K, this is the equilibrium condition according to the Arrhenius equation. So, this can be shown graphically in a very nice way (please look at the graph shown below). In Venus, the final temperature and final pressure reached are governed by chemical equilibrium and radiative-convective equilibrium.



And these two meet at 720 Kelvin. So, the present temperature of Venus is 720 Kelvin because at that temperature, the radiative-convective equilibrium and the mineral equilibrium due to chemical reactions that release carbon dioxide reach a condition where the temperature and pressure ensure that chemical reactions are in steady state and the energy balance is in steady state. Both must be in steady state to have the final steady state Venus pressure and temperature.

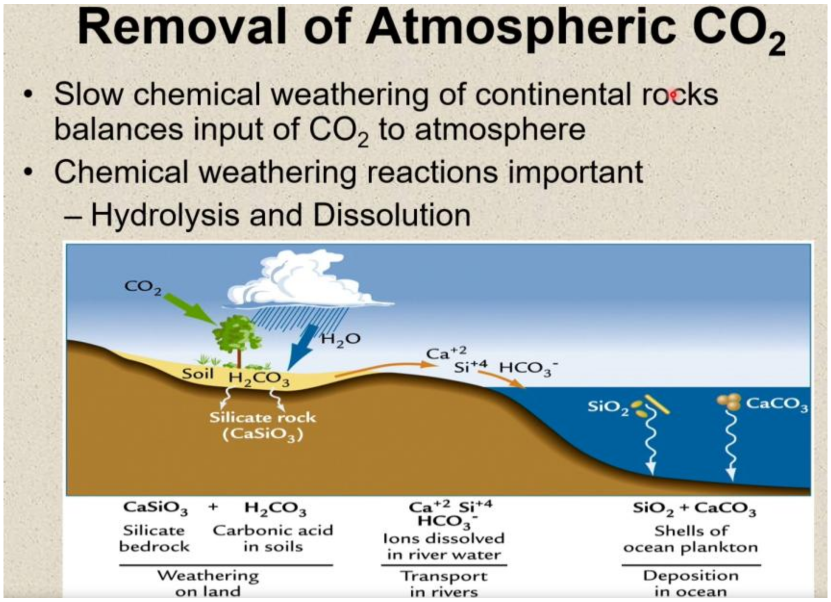
So, this is an important point you have to remember, that the present Venus temperature of 720 K and pressure of 100 bar is because of the combination of chemical equilibrium and radiative-convective equilibrium.



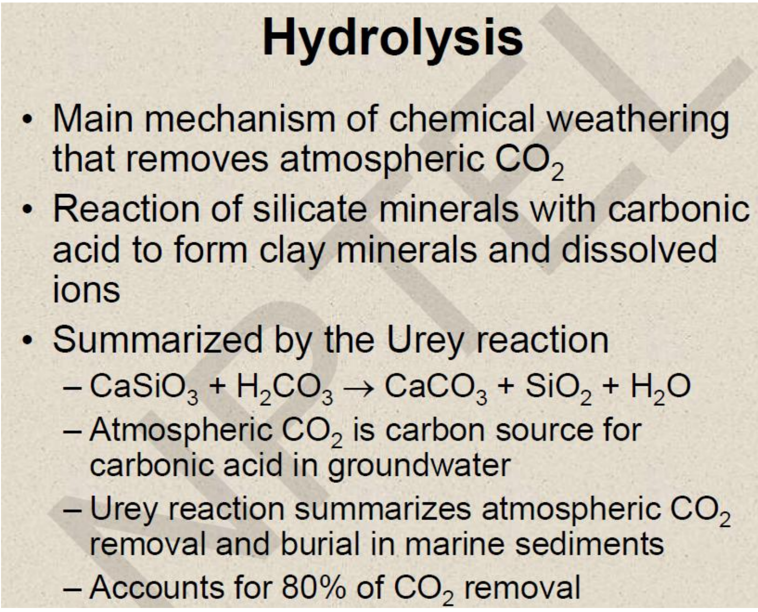
Now, the conclusion is: Earth and Venus started in a similar way and Earth's carbon is safely buried in sediments and in ocean, avoiding runaway greenhouse effect. In Venus, CO_2 built up in the atmosphere and it reached very high temperature.

So, if you want to prevent runaway greenhouse on Earth, you need to make sure we do not go on burning fossil fuels forever. If you did that, then there is a possibility of a runaway greenhouse effect on Earth also—not in the next 100 years, but over a long period.

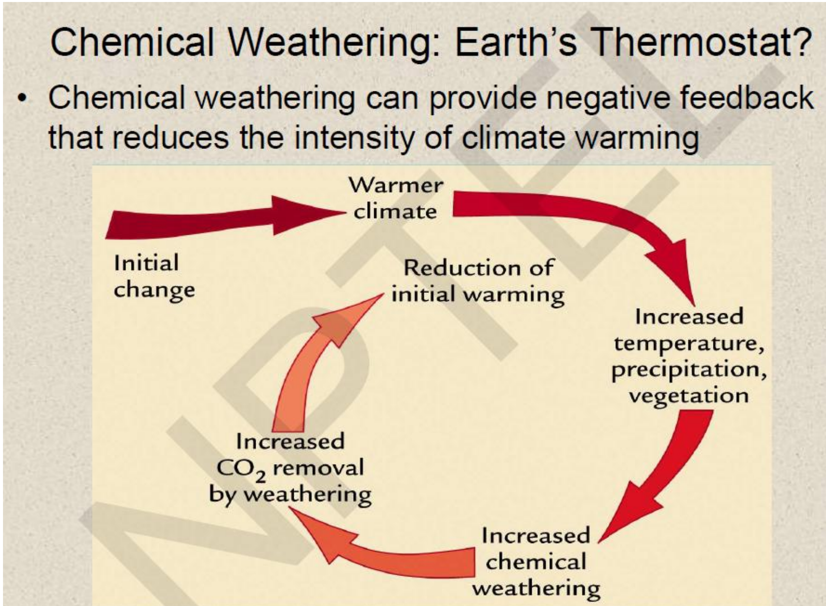
So, Earth is continuously removing carbon dioxide due to the CO_2 cycle on Earth through vegetation and other natural processes. That is not happening on Venus because Venus has no ocean now.



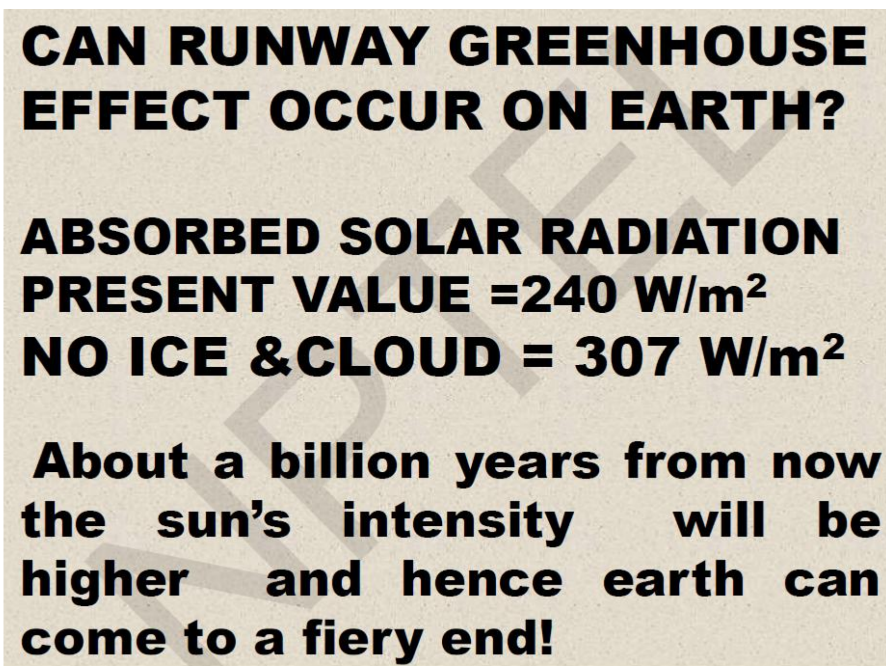
This hydrolysis is what controls CO_2 on Earth.



Chemical weathering will occur on Earth only at much higher temperature.



So, on Earth, a runaway greenhouse effect can occur if there is no ice and clouds. If you go on allowing the temperature to go up, all the ice melts, and the clouds all move away, then that can happen. One more way is: the Sun's intensity is continuously increasing as a star. If it reaches very high values a billion years from now, then Earth will also have a runaway greenhouse.



So, global warming could lead Earth to a very hot future.

So, we end by saying that there is no likelihood that Earth will actually come to resemble Venus, but Venus serves both as a warning that major environmental effects can flow from seemingly small causes and as a test bed for the models we develop on Earth. This is a comment made by Hunten a long time back, more than 30 years ago.

There is no likelihood that the Earth will actually come to resemble Venus, but Venus serves both as a warning that major environmental effects can flow from seemingly small causes, and as a test bed, for our predictive models of the Earth".
D.Hunten,, Adv Space Research 1992

It tells you that we may not reach the condition of Venus, but Venus is a warning that such a thing could happen if we are somewhat careless. So, I end this lecture on that note, and our last lecture will be a wrap-up on what we have learnt in this course. Thank you.