Lecture notes, September 5.

The Sun emits energy in the form of electromagnetic radiation [Fig. 1]. The energy travels outward from the Sun in straight lines. As solar radiation travels through space, a part of it is intercepted by the surrounding planets. The Earth is not the only planet that receives solar radiation. Each planet of the solar system receives its own part, and the amount of received energy depends on the planet location. The Earth intercepts only about one-half of one-billionth of the Sun's total energy output.

The Sun emits so-called **shortwave radiation**. The wavelength range is 0.3–3mkm. The total spectrum includes near ultraviolet, visible, near infrared and shortwave infrared light. The spectrum of visible light is 0.4-0.7mkm. The shorter the wavelength of light, the more energy it contains.

It takes about 8 minutes for sun energy to reach the atmosphere of the Earth and a part of it is reflected back to the outer space. The proportion of the incident light which is reflected back is called **planet albedo**. Let designate it as α.

As the output of energy from the sun is nearly constant, the amount of solar energy incident on a small area of the top of the atmosphere can be calculated. This amount is called **solar constant**. The strict definition is that the solar constant is the amount of solar energy incident in 1s on a $1m^2$ area along the direction of propagation (units J/sm^2). Let designate it as L and L = $1370W/m^2$. Pay attention that exactly this amount is incident over the regions of the equator.

How to calculate approximately the total amount of solar energy received by the Earth? The Earth intercepts parallel rays of the Sun in an area equal to the disk of Earth radius [Fig. 2]. The area of the disk is πR^2, R=6400km. Recall that the solar constant is the amount of energy incident on a unit area. The total amount of solar energy intercepted by the Earth is $L\pi R^2$. The total amount of solar energy entering the atmosphere is $(1-\alpha)\ L\pi R^2$.

Let consider what processes are going on the Earth. For the time being let forget about the atmosphere and make an assumption that this amount of energy is incident directly on the Earth surface. The Earth absorbs that energy and reemits it in the form of **longwave radiation**. The range of the spectrum is 3-30mkm, and it includes middle infrared and thermal infrared bands. Absorbing the shortwave radiation and emitting the longwave, the Earth saves heat inside. How to calculate the total amount of emitted longwave radiation?

Stefan-Boltzmann radiation law is useful here. This law is applicable to perfect black bodies. **Black body** is an object that absorbs and emits radiation uniformly and with 100% efficiency. The Stefan-Boltzmann radiation law states that the energy emitted by the black body is directly proportional to the fourth degree of its temperature: $E=\sigma T^4$. $[E]=W/m^2$, $[T]=K$ (absolute temperature, K=C+273), $\sigma = 5.67x10^{-8} W/m^2/K^4$. As the distribution of outgoing longwave radiation is quite even, the Earth can be considered a black body. The total amount of radiation emitted by the Earth is $\sigma T^4 4\pi R^2$.

In case of no atmosphere, how to write the equation for the global radiation balance? It is

$(1-\alpha)\ L\pi R^2=\sigma T^4 4\pi R^2$. This is an explanation for the second and third equations in the lab.

Let put the atmosphere back. Most of the atmosphere consists of nitrogen (78%) and oxygen (21%), other gases account for the remaining 1%. Nitrogen is a neutral substance. It does not enter easily into chemical reactions. Oxygen is highly active chemically. Water vapor (can vary highly in concentration), carbon dioxide (0.035%), methane, and nitrous oxide (N_2O) are called **greenhouse gases**. These gases (mainly water vapor and carbon dioxide) have the ability to absorb longwave radiation emitted by the Earth and reemit it from much colder levels to the outer space. They are able to store heat in the atmosphere and keep the Earth warm. It looks like the Earth is surrounded by a thermal blanket. This phenomenon is called the **greenhouse effect**. What is negative is the enhanced greenhouse effect. As $T_{atm} > T_{earth}$, it leads to the increase in the Earth temperature. The more the concentration of greenhouse gases, the higher the temperature of the atmosphere. Let try to find the relationships between the Earth and atmosphere temperatures using an **"atmosphere layer model"**.

Consider the processes that occur when sun light is incident at the top of the atmosphere. As stated previously, a part of it is reflected back to the outer space. Another part is absorbed by the atmosphere and the rest is incident on the Earth surface. **(1)** The first assumption is that solar energy comes through the atmospheric layer unchanged, i.e., the amount of energy, incident on the Earth is $(1-\alpha)\ L\pi R^2$. In reality, a part of incident shortwave radiation is reflected back and goes through the atmosphere to the outer space. **(2)** The second assumption: all incident shortwave radiation is absorbed by the Earth. The Earth reemits it in the form of longwave radiation. Let designate it as IR_e. A small part of this radiation goes through the atmosphere to the outer space. It goes through atmospheric windows [Fig. 3]. This part includes the range of wavelengths, which are not absorbed by the atmosphere (4-6, 8-14, 17-21 mkm). **(3)** The third assumption: all longwave radiation from the Earth is absorbed by the atmosphere (greenhouse gases) and then reemitted equally upward and downward. The total amount reemitted by the atmosphere is IR_a, amounts reemitted up and down are $IR_{a,up}$ and $IR_{a,down}$. The following statements are true:

$IR_a= IR_{a,up}+ IR_{a,down}$, $IR_{a,up}= IR_{a,down}= IR_a/2$.

Radiation balance: the amount of radiation incident on the top of the atmosphere = the amount of radiation leaving the atmosphere. Mathematically,

$(1-\alpha)\, L\pi R^2= IR_{a,up}$.

According to the Stefan-Boltzmann law, $IR_{a,up}=\sigma(T_a)^4 4\pi R^2$. Here the Earth radius can be used, because the main part (97%) of the atmosphere is contained within the first 30 km above the Earth surface. The total height of the atmospheric layer is about 10000 km.

According to the third statement, $IR_e= IR_a$, i.e.

$\sigma(T_e)^4 4\pi R^2=\sigma(T_a)^4 2\pi R^2$.

Therefore, the following relationship for the Earth and atmosphere temperatures is true:

$T_e=2^{1/4}T_a$.

This is a mathematical explanation for the greenhouse effect.

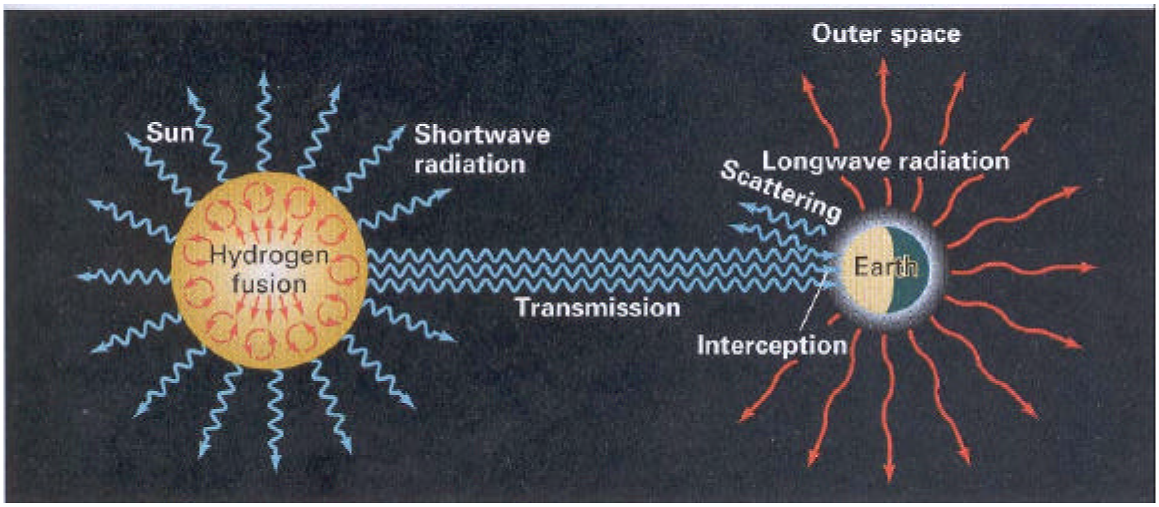
Outer space
Sun
Shortwave radiation
Longwave radiation
Scattering
Hydrogen fusion
Earth
Transmission
Interception

Fig. 1.

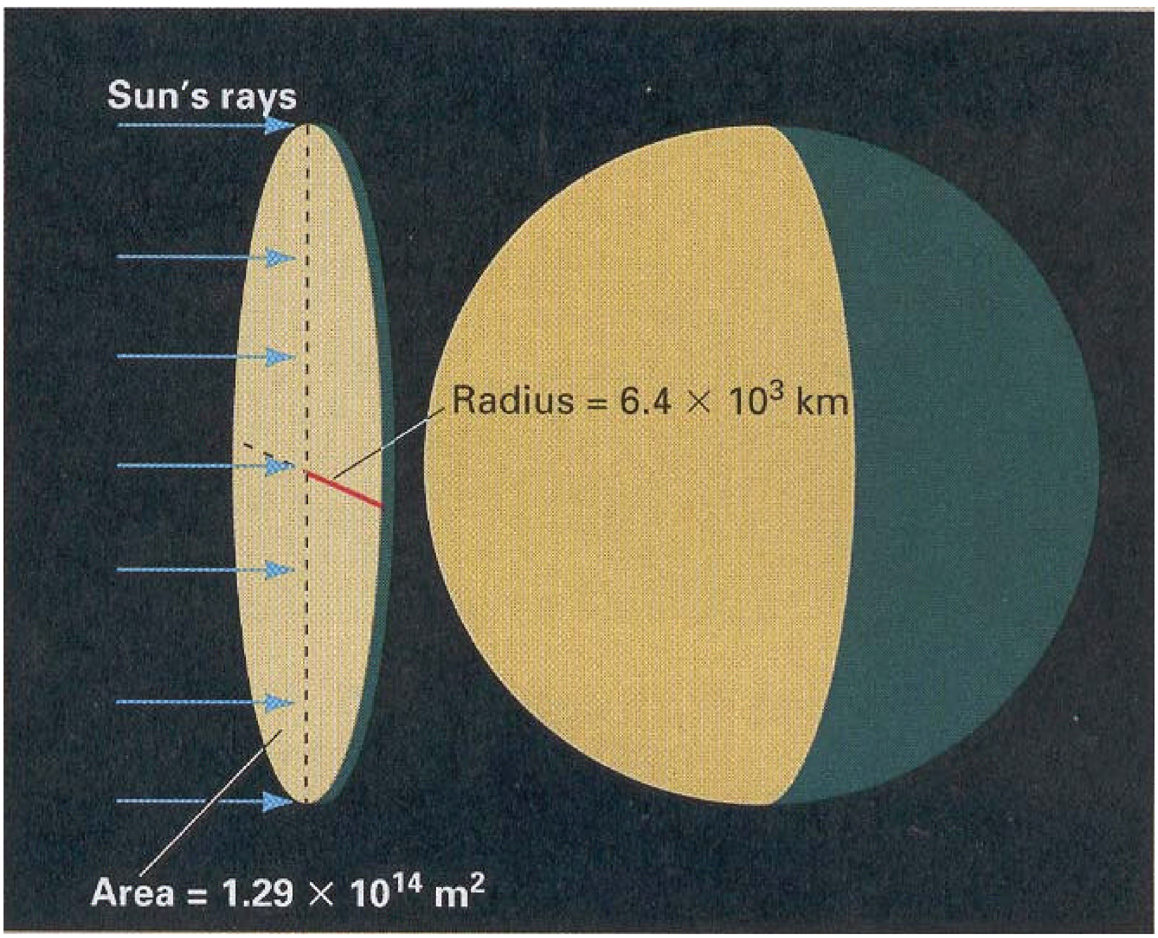
Sun's rays
Radius = 6.4 × 10³ km
Area = 1.29 × 10¹⁴ m²

Fig. 2.

Much of the Earth surface radiation is absorbed by the atmosphere (the primary absorbers are H_2O and CO_2), but a small part of it goes through the atmosphere unchanged and leaves the planet through **atmospheric windows**.

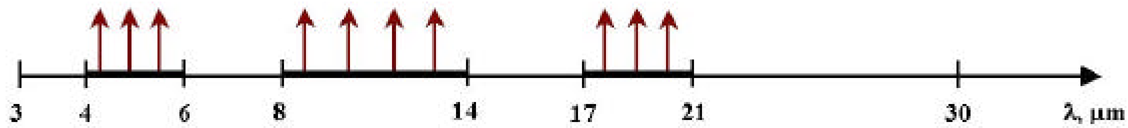

Fig. 3.