IB Physics Topic B2 The Greenhouse Effect; SL & HL

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1 Gray Bodies and Emissivity

A gray body is one that emits less energy than a perfect black body, this is the case for most real-world objects. To encapsulate this reduction, the previously-mentioned Stefan-Boltzmann law is modified to include a factor ε which is the emissivity of the body.

- The emissivity of a body is a measure of how well it emits radiation compared to a black body.
- Formally, the emissivity is defined as the ratio of the energy radiated by a body to the energy radiated by a black body at the same temperature.

$$\varepsilon = \frac{\text{power emitted by the object}}{\text{power emitted by a black body at the same temperature}}$$

1. for an ideal black body, $\varepsilon = 1$
2. for a total reflector, $\varepsilon = 0$

The Stefan-Boltzmann law for gray bodies is given by

$$P = \varepsilon\sigma A T^4 \tag{1}$$

equivalently

$$I = \varepsilon\sigma T^4$$

where I is the intensity of radiation emitted by the body.

Note that, if one were to calculate the **net power** radiated by a body in a surrounding of temperature T_0, one would have to discount the power absorbed by the body from the surroundings, because while the body emits radiation, it also absorbs radiation from the surroundings. This may also be referred to as the net power exchanged between the body and its surroundings.

$$\Delta P = \varepsilon\sigma A\left(T^4 - T_0^4\right)$$

2 The Solar Constant

The solar constant is defined as

> the total intensity of solar radiation, across all wavelengths, that reaches a surface perpendicular to the line connecting the centers of the Earth and Sun at Earth's average distance from the Sun, taken at the top of the atmosphere

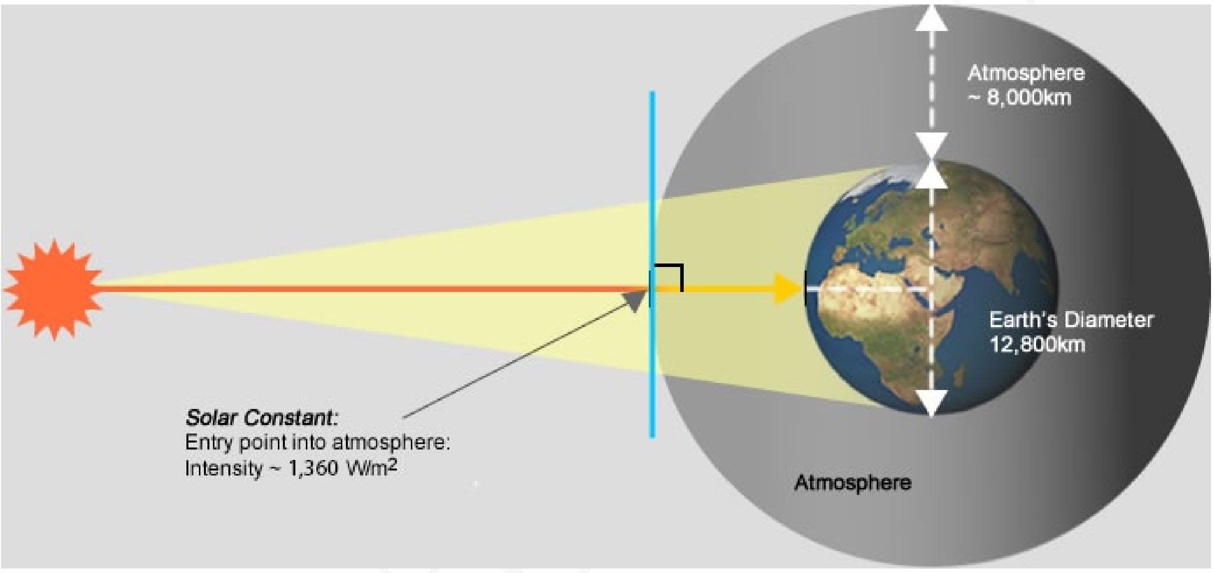

Figure 1: The Solar Constant

This constant has a value of about $1360\,\mathrm{W\,m^{-2}}$. However, this value varies periodically because

- The output of the Sun varies by about $0.1\,\%$ over an 11-year cycle
- The Earth's orbit is slightly elliptical
- There are other longer periodic variations

S is calculated as

$$S = \frac{L}{4\pi d^2} = \varepsilon\sigma T^4$$

where L is the luminosity of the Sun, d is the distance from the Sun to the Earth. In other words, the solar constant for a particular planet d' away from the Sun, in terms of S, is given by

$$S' = S\left(\frac{d}{d'}\right)^2 \tag{2}$$

3 The Atmosphere

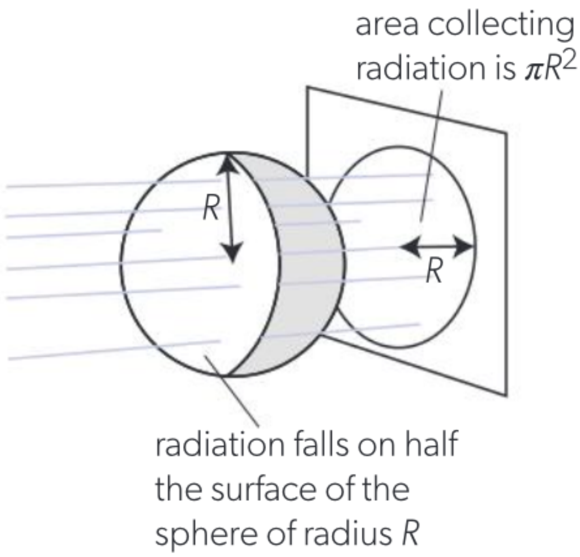

Figure 2: The Atmosphere

The radiation from the Sun that actually falls onto the Earth has an area of πR^2, where R is the radius of the Earth. The atmosphere then distributes this energy over the entire surface of the Earth, which has an area of $4\pi R^2$. Thus, **the average intensity** of solar radiation **on the entire surface** is $\frac{1}{4}S$.

In reality, this theoretical prediction is higher than the practical value of the intensity on the surface — the atmosphere also partially absorbs as well as reflects the radiation.

However, since the ground is not an idea black body, it will reflect off some of the incident radiation. The fraction of the total radiation reflected is called the **albedo**.

3.1 Albedo

The *albedo* of a surface is the **fraction of the total radiation incident on the surface that is reflected**. It is a ratio and hence a dimensionless quantity between 0 and 1. The albedo of the Earth is about 0.3, which means that about 30% of the radiation incident on the Earth is reflected back into space. Again, this value varies depending on the latitude, the surface, and the time of year. It is formally defined as

$$\alpha = \frac{\text{total reflected power}}{\text{total incident power}}$$

The "coefficient of absorption", on the other hand, is $1 - \alpha$; it shows the portion of the radiation that is absorbed by the surface. It is important to note that the intensity emitted = intensity absorbed.

4 The Greenhouse Effect

The Earth and the Moon have roughly the same distance from the Sun, but the Earth is warmer than the Moon. This is because the Earth has an atmosphere.

1. There are certain types of gases, e.g. CO_2, H_2O (water vapor), CH_4 (methane), and N_2O (nitrous oxide), that naturally occur in the atmosphere.

2. Others, such as Ozone, are partially natural and partially artificial; they contribute to the greenhouse effect too.

3. Collectively, they are the **greenhouse gases** — they are inert to photons at the frequency of visible light, but they interact with and absorb infrared radiation.

The origins of the greenhouse effect have two categories — artificial and natural. The natural greenhouse effect is due to the naturally occurring levels of certain gases; the artificial greenhouse effect is due to human activities that increase the levels of these gases — this is referred to as the **enhanced greenhouse effect**.

4.1 The Temperature Equilibrium

1. The atmosphere absorbs most of the infrared and ultraviolet radiation from the Sun, but allows most of the visible light to pass through. The surface then absorbs this visible light, increasing in temperature.

2. Since the Earth is above 0 K, it **re-radiates** back at the atmosphere, at a much lower frequency (longer wavelength) than the radiation it absorbed from the Sun.

3. Just as when the radiation came from the Sun, the atmosphere absorbs parts of the radiation from Earth in the infrared part of the spectrum, and re-radiates it arbitrarily in all directions.

4. Some are returned to the surface of the Earth, which increases the temperature of the Earth. This means that a portion of the energy is trapped.

The whole system is in an **equilibrium**, where

$$\text{incident energy from the Sun} = \text{energy radiated back into the space} \tag{3}$$

The “Earth” refers to the entirety of the Earth-atmosphere system. The *enhanced greenhouse effect* causes an increase in the level of energy retained in the system, which then requires an increase in the energy emission of the Earth to **maintain the equilibrium**. Per the *Stefan-Boltzmann law*, this means that the Earth must **increase in temperature** until reaching a new and higher equilibrium point.

4.2 Energy Absorption

This subsection explores why greenhouse gases absorb energy. Both ultraviolet and infrared can be absorbed, but in different ways:

1. Ultraviolet radiation has **high energy** and can **break molecular bonds** in gases.
   (a) For example, when oxygen molecules absorb UV light, they break into individual oxygen atoms, leading to the **formation of ozone** (O_3).
   (b) This process is a reaction in the upper atmosphere that protects us from harmful UV radiation by absorbing it.
2. Infrared radiation has lower energy compared to UV, so it can't break chemical bonds. Instead, it interacts with the **vibrational modes of greenhouse gas** molecules like carbon dioxide.
   (a) Each gas molecule has specific vibrational modes that are like the natural frequency of the molecule.
   (b) **Resonance** occurs when the frequency of incoming IR radiation matches the natural frequency of the vibrational modes in the molecule. This causes the molecule to absorb energy and vibrate more intensely.

4.3 Modeling Climate Balance

4.3.1 Naive Model

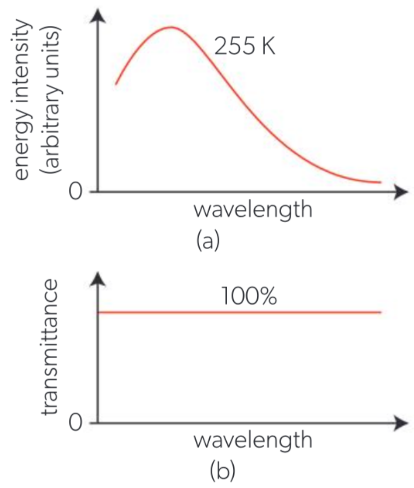

Figure 3: Naive Model

The initial naive model uses the assumption that the atmosphere does not absorb any radiation emitted by the Earth.

1. We start by assuming that the Earth behaves like a black body and that it emits radiation with an intensity of $238\,\mathrm{W\,m^{-2}}$.

2. The Earth emits radiation at a temperature of 255 K in this case.

3. The transmittance (the extent of transparency) is $100\,\%$ for all wavelengths, so the Earth's radiation completely passes through the atmosphere.

4.3.2 Revised Model

In reality, the atmosphere absorb the infrared and ultraviolet parts of the spectrum.

1. The absorbed area is shown by the regions where the transmittance is 0 %.
2. Ultraviolet is **below** 300 nm, and infrared is **above** 700 nm. The left-out region in the middle of the two is the visible light spectrum.
3. The atmosphere absorbs but then re-radiates it back to the Earth, **decreasing the level of energy going back into the space**.
4. This **breaks the equilibrium**; as the incoming energy is now greater, the Earth must increase in temperature to maintain the equilibrium.

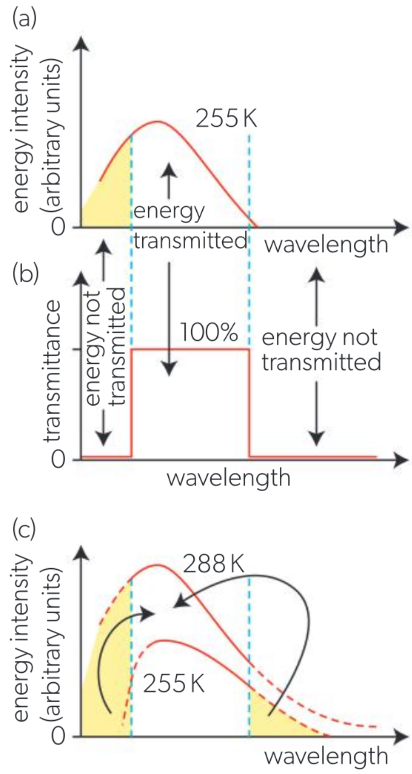

Figure 4: Corrected Model

It must be noted that, for each of UV and IR, there also exist specific wavelengths within themselves that are absorbed by different gases. For example, for infrared, the transmittance graph is as follows

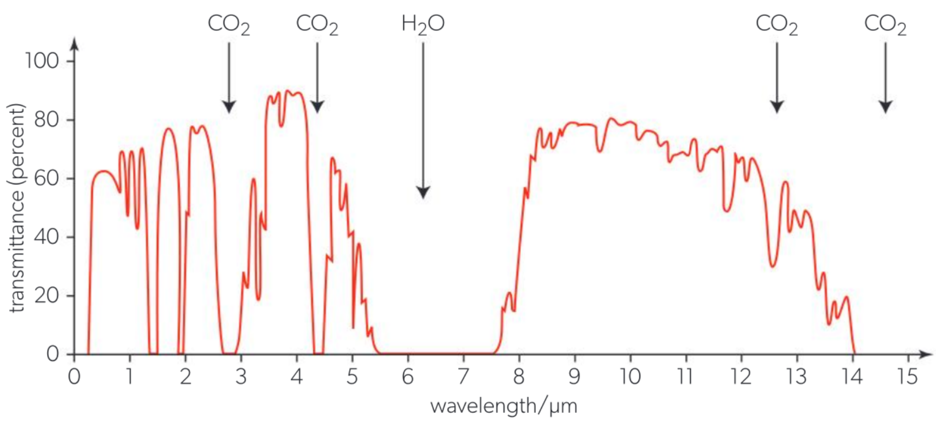

Figure 5: Infrared Transmittance

5 Earth Energy Balance

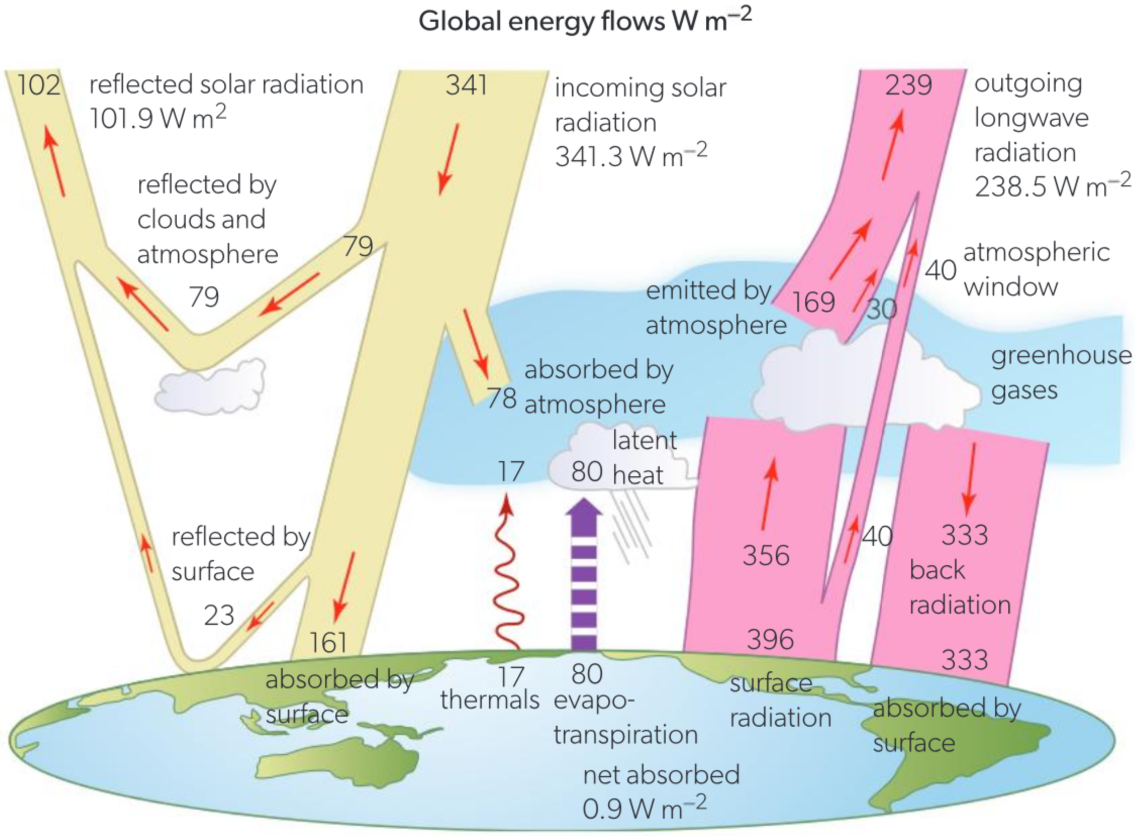

Figure 6: Earth Energy Balance

The above graph provides a simplified visualization of the energy balance system. The numbers do not matter.

5.1 Global Warming

Studies have shown that the global warming is mostly a result of **the burning of fossil fuels**, which releases carbon dioxide into the atmosphere. Since the industrial revolution, the concentration of CO_2 has increased from about 280 ppm to 410 ppm.

Gas	Pre-1750 concentration / ppb	Recent concentration / ppb	% increase since 1750
carbon dioxide	280 000	410 000	46
methane	700	1900	170
nitrous oxide	270	330	20

Figure 7: Global Warming

Analysis of Antarctic ice cores has shown that the concentration of CO_2 has never been this high in the last 800,000 years.

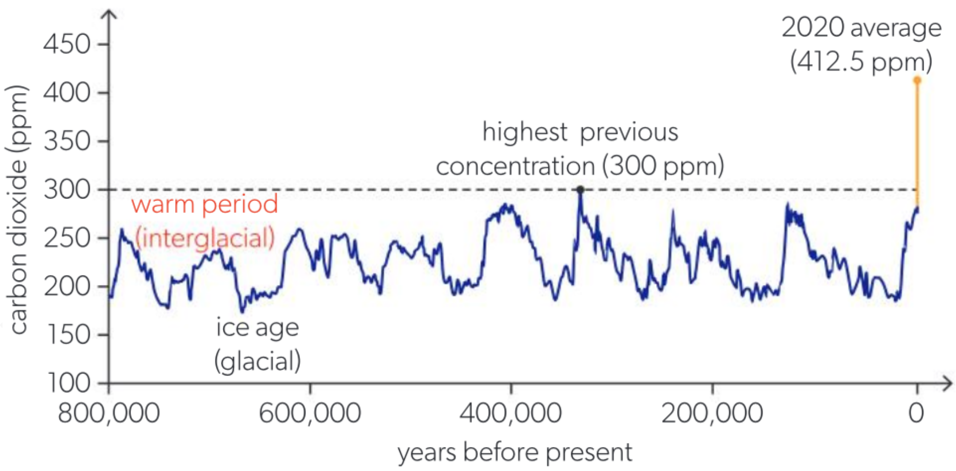

Figure 8: Ice Core Analysis

5.1.1 Consequences that Further The Warming

Global warming leads to a series of consequences that themselves will further the warming:

- The melting of ice caps and glaciers will **decrease the Earth's albedo**, which will increase the amount of radiation absorbed by the Earth.
- Higher seawater temperatures will reduce the solubility of CO_2 in the water, which will increase the concentration of CO_2 in the atmosphere.

6 Exam Questions

6.1 Re-radiating Infrared

The average temperature of ocean surface water is 289 K. Oceans behave as black bodies.

(a) Show that the intensity radiated by the oceans is about 400 $\mathrm{W\,m^{-2}}$

$$\varepsilon = 1$$

$$I = \varepsilon\sigma T^4 = 1 \times \sigma \times 289^4 \approx 400\mathrm{W\,m^{-2}}$$

(b) Explain why some of this radiation is returned to the oceans from the atmosphere. [3]

- Most of the emitted radiation is in the infrared part of the spectrum, this is because
$$\lambda = \frac{b}{T} = \frac{2.9 \times 10^{-3}}{289} \approx 10 \times 10^{-6}\mathrm{m} = 10\mathrm{\mu m}$$
- This radiation is absorbed by greenhouse gases in the atmosphere such as CO2 or methane.
- The gas then re-emits/re-radiates this radiation ...
- ... partly back towards oceans and partly into other arbitrary directions.

6.2 M19 SL Paper 2 TZ1 Q6

The Moon has no atmosphere and orbits the Earth. The diagram shows the Moon with rays of light from the Sun that are incident at 90° to the axis of rotation of the Moon.

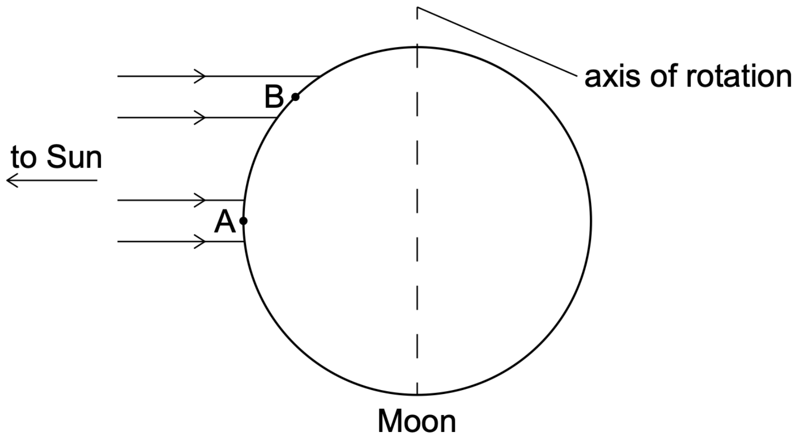

Figure 9: Moon

(a) (i) A black body is on the Moon's surface at point A. Show that the maximum temperature that this body can reach is 400 K. Assume that the Earth and the Moon are the same distance from the Sun. [2]

$$T^4 = \frac{S}{\varepsilon\sigma} = \frac{1360}{1 \times 5.67 \times 10^{-8}}$$

$$T \approx 400\text{K}$$

(ii) Another black body is on the Moon's surface at point B. Outline, without calculation, why the maximum temperature of the black body at point B is less than at point A.

Answer:

i. Energy/Power/Intensity lower at B, since it is further away from the Sun.

ii. Since $T^4 \propto I$, the temperature at B will be lower.

(b) The albedo of the Earth's atmosphere is 0.28. Outline why the maximum temperature of a black body on the Earth when the Sun is overhead is less than that at point A on the Moon.

- Because a portion of the radiation from the Sun is reflected back into space by the atmosphere; this portion is about 28%.

(c) The Moon orbits the Earth in a circular path. Outline why

(i) a force acts on the Moon.

- There is an attractive gravitational force between the planet and the Moon.

(ii) this force does no work on the Moon.

- The force and the velocity are at 90° to each other and there is no change in GPE of the moon.

6.3 Radiation Processes in the Atmosphere

What is the average intensity radiated by the atmosphere towards the surface?

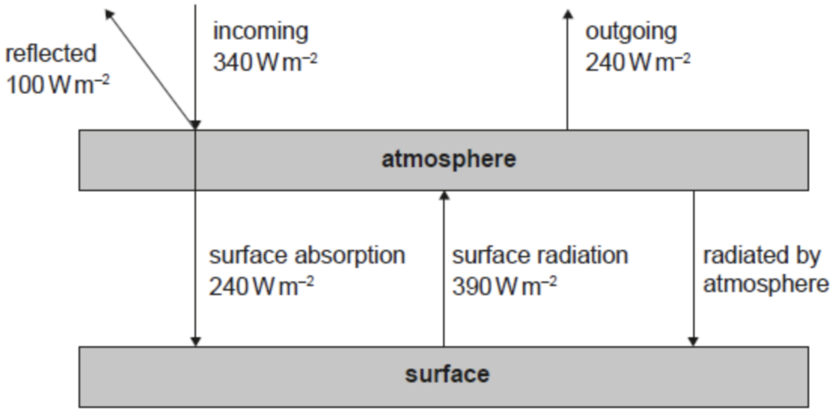

Figure 10: Radiation Processes in the Atmosphere

- We must first identify the quantity we are interested in determining — this is the right-most unlabeled arrow.
- It is important to realize that the intensity emitted by the surface must equal the intensity absorbed by the surface. This is the most crucial step in any question of this kind.
- The total emitted intensity is 390 $\mathrm{W\,m^{-2}}$, and the total absorbed intensity is 240 + our desired quantity.
- Baby maths – the answer is 150.

6.4 Titan and the Sun

Titan is a moon of Saturn. The Titan-Sun distance is 9.3 times greater than the Earth-Sun distance.

(a) Show that the intensity of the solar radiation at the location of Titan is 16 W m^{-2}.

- We invoke the equation Equation (2) with $\dfrac{d}{d'} = \dfrac{1}{9.3}$ to obtain

$$S' = 1360 \times \left(\frac{1}{9.3}\right)^2 = 15.72... \approx 16\mathrm{W\,m^{-2}}$$

(b) Titan has an atmosphere of nitrogen. The albedo of the atmosphere is 0.22. The surface of Titan may be assumed to be a black body. Explain why the **average** intensity of solar radiation **absorbed** by the whole surface of Titan is 3.1W m^{-2}.

- An albedo of 0.22 means that 22% of the radiation is reflected back into space and only 0.78 enter the atmosphere. Also, because the area of contact with radiation is πR^2 and the total surface area is $4\pi R^2$, the average intensity across the whole Moon is $\dfrac{1}{4}$ of the previously calculated value.

$$0.78 \times 16 \times \frac{1}{4} = 3.12 \approx 3.1\mathrm{W\,m^{-2}}$$

(c) Show that the equilibrium surface temperature of Titan is about 90K.

$$T = \sqrt[4]{\frac{S}{\varepsilon\sigma}} = \sqrt[4]{\frac{3.1}{1 \times 5.67 \times 10^{-8}}} = 85.98... \approx 90\mathrm{K}$$

6.5 Emissivity Ratio Question

Two surfaces X and Y emit radiation of the same surface intensity. X emits a radiation of peak wavelength twice that of Y.
What is $\frac{\text{emissivity of X}}{\text{emissivity of Y}}$?

- We use Wien's Law

$$\lambda \propto \frac{1}{T}$$

  to deduce that the temperature of X is half that of Y.

- We then use the Stefan-Boltzmann law for intensity

$$I = \varepsilon\sigma T^4 \implies \varepsilon \propto \frac{1}{T^4}$$

  joined with the previous proportionality to obtain

$$\varepsilon \propto \frac{1}{T^4} \propto \lambda^4$$

- Hence, a factor multiplied to the wavelength is raised to the power of 4 when applied to the emissivity. Hence the answer is 16.

Somebody stop global warming...