Warming the Earth and the Atmosphere-II

GEOL 1350: Introduction To Meteorology

Overview

- Radiation
- Stefan-Boltzmann Law
- Wien’s Law
- Kirchhoff’s Law
- Earth’s Energy Balance

Radiation

- Energy transferred from the sun to the earth is called radiant energy, or radiation.
- Radiation travels in the form of electromagnetic waves that release energy when they are absorbed by an object.
- Electromagnetic waves do not require molecules to propagate.
- All objects with temperature above absolute zero emit radiation.

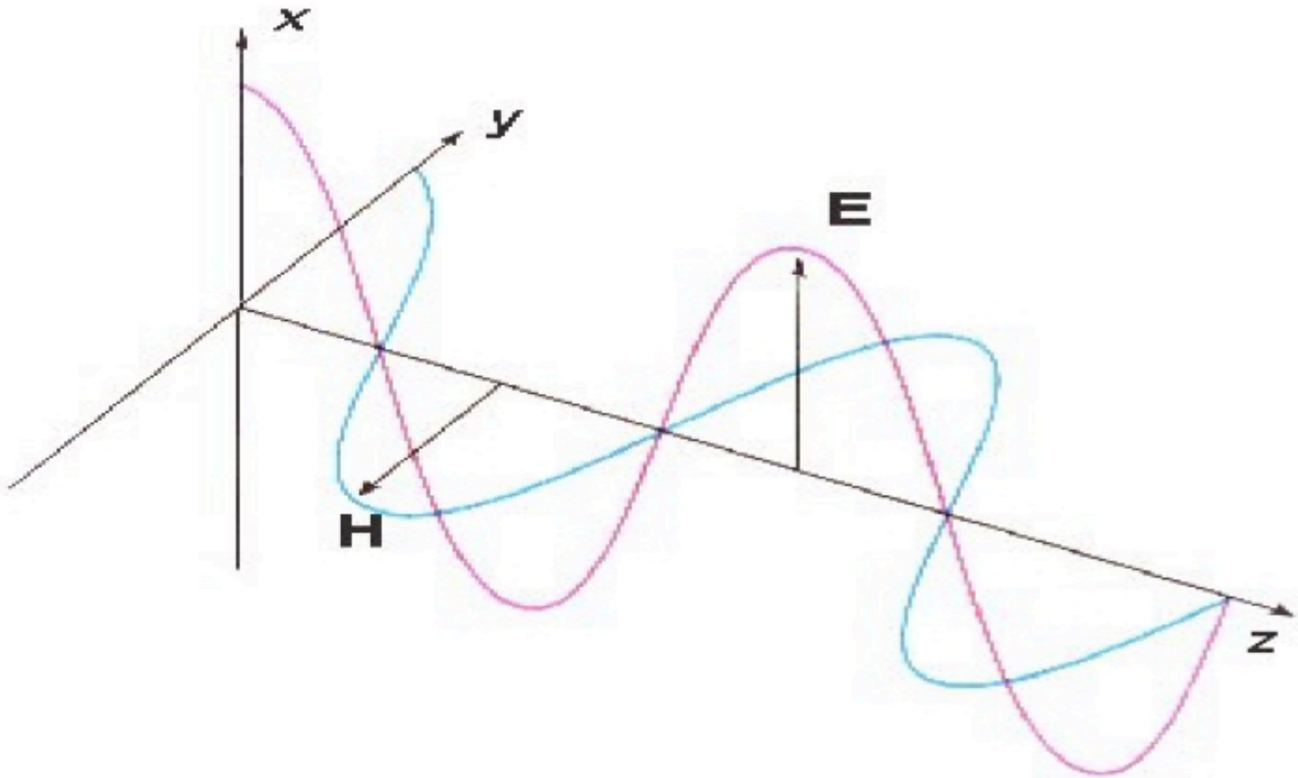
Electromagnetic Radiation

- **Electromagnetic radiation: A form of transmitted energy. Electromagnetic radiation is so-named because it has electric and magnetic fields oscillate in planes mutually perpendicular to each other and to the direction of propagation through the space.**

- **Electromagnetic radiation has dual nature: wave properties and particulate properties.**

Wave Nature of Radiation

Radiation can be thought of as **a traveling wave.**

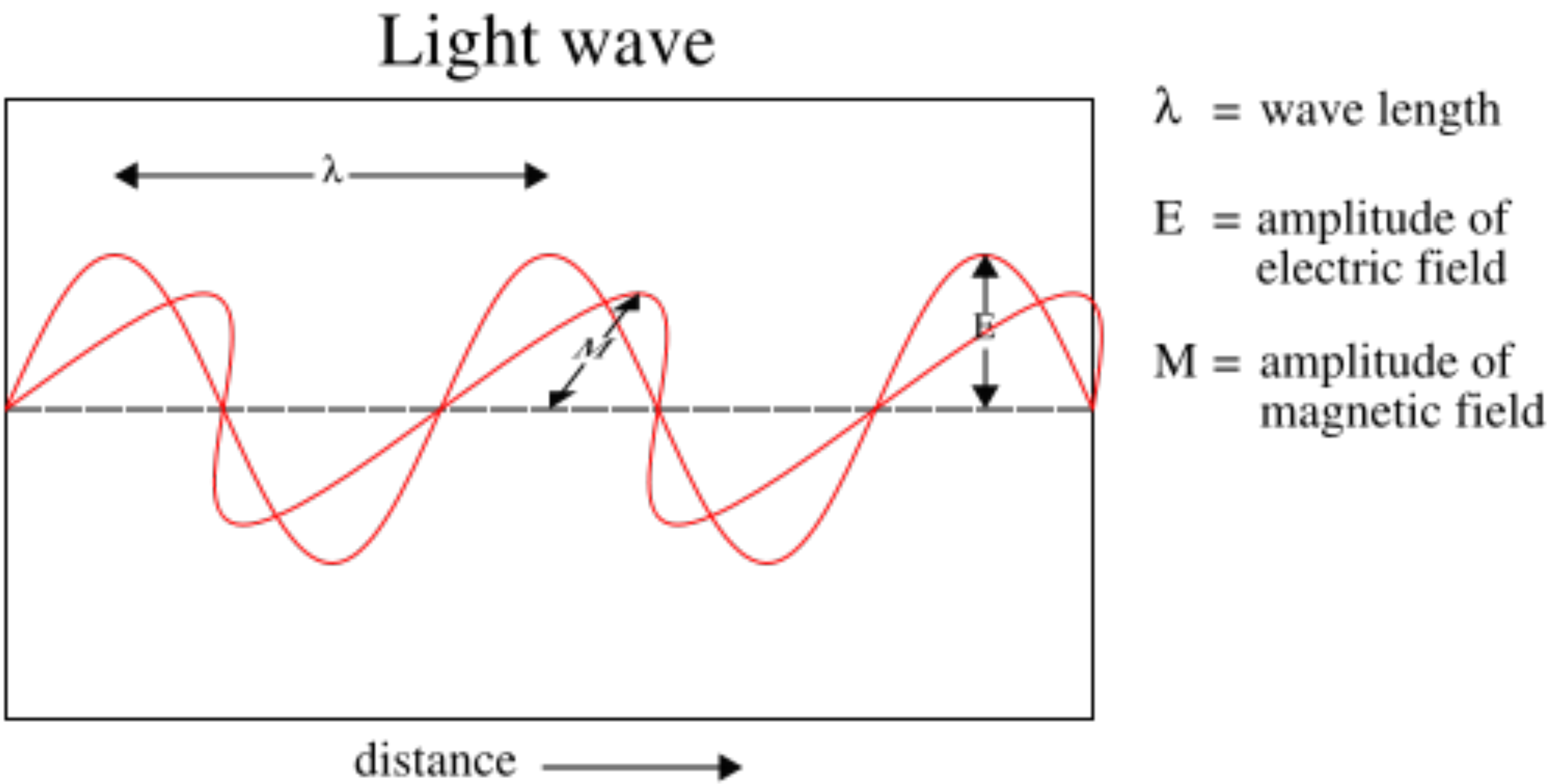


A schematic view of an electromagnetic wave propagating along the $\vec{z}$ axis.

The electric $\vec{E}$ and magnetic $\vec{H}$ fields oscillate in the x-y plane and perpendicular to the direction of propagation.

Wave Nature of Radiation

- Wave: Wavelength, Frequency, and Speed



Wave Nature of Radiation

- Wave: Wavelength, Frequency, and Speed
- Wavelength: Distance between two consecutive peaks (troughs).
- Frequency: Number of cycles per second that pass a given point in space.
- Speed: Speed of light in a vacuum

$$c = 3 \text{ x } 10^8 \text{ m/s}$$

Wavelength & Frequency Specification

- Relation between wavelength and frequency

- $\lambda\nu = c$

- λ is wavelength, ν is frequency, and c is speed of light.

- Since c is a constant, shorter (longer) wavelength corresponds to a high (low) frequency.

1. Red light has a wavelength of 0.7 μm. Find its frequency. c = 3×10^8 m/s

Frequency $\nu = c/\lambda$

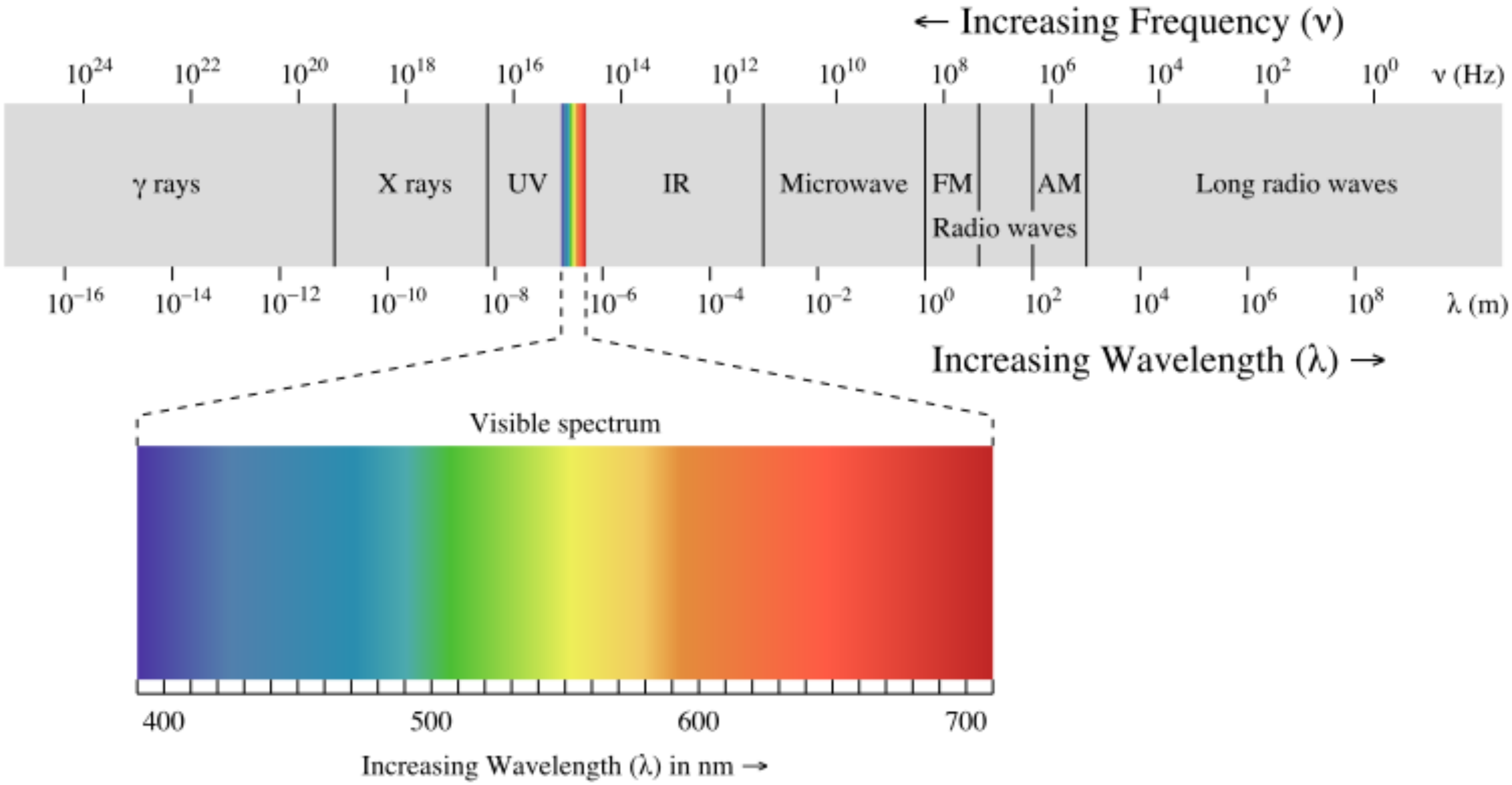
$= (3\times10^8 \text{ m/s})/(0.7\times10^{-6} \text{ m})$

$= 4.286\times10^{14}$ 1/s

$= 4.286\times10^{14}$ Hz

Spectrum of Electromagnetic Radiation

- Electromagnetic Spectrum



- Higher (Lower) frequencies have shorter (longer) wavelengths.

Wavelength & Frequency Specification

- Most people in spectroscopy will use wavenumber instead of frequency.

- Wavenumber is defined as number of cycles in a given unit length.

- $\nu' = \nu/c = 1/\lambda$

Where ν is frequency, c is speed of light, and λ is wavelength.

Wavelength & Frequency Specification

- Wavelength Units:

  Angstrom (A); $1\ A = 1x10^{-10}\ m$

  Nanometer (nm); $1\ nm = 1x10^{-9}\ m$

  Micrometer (μm): $1\ \mu m = 1x10^{-6}\ m$

- Frequency Units: 1/s or hertz (Hz)

- Wavenumber Units: inverse length (cm^{-1})

Particulate Nature of Radiation

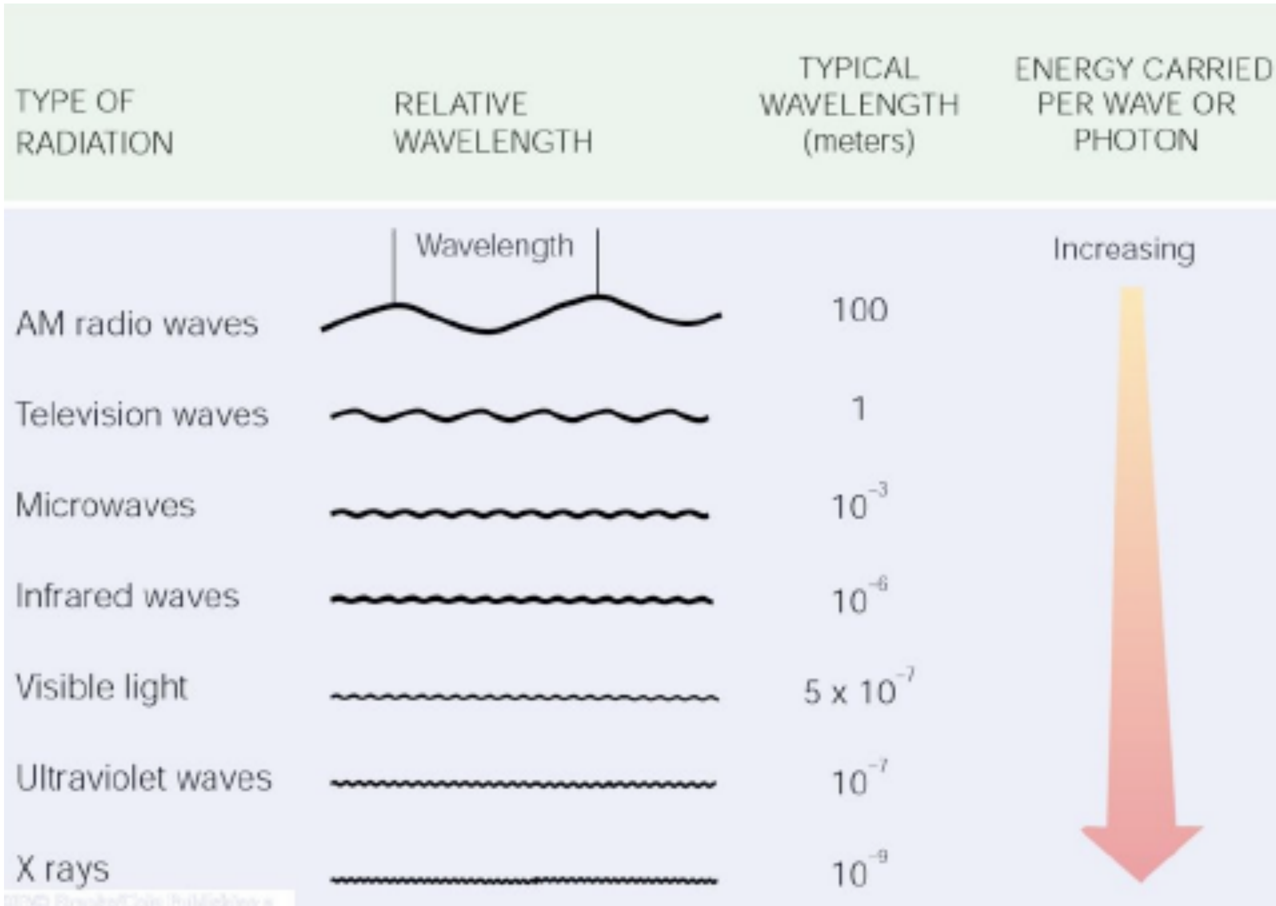
- We can think of radiation as **streams of particles**, or **photons**, that are discrete packets of energy.

Particulate Nature of Radiation

- The energy of a photon is
- $E = h\nu$
- Where h = Planck's constant = $6.6261 \times 10^{-34} Js^{-1}$, ν = frequency (hz).

- Each photon's energy is related to the electromagnetic wave frequency (ν).

Radiation Characterized by Wavelength



Longer waves carry less energy than the shorter waves.

Basic laws for radiation

Stefan-Boltzman law: **The amount of energy per square meter per second that is emitted by an blackbody is related to the 4th power of its Kelvin temperature**

$$E = \sigma T^4$$

where E is in J s^{-1} m^{-2} or Watts m^{-2}

σ = 5.67 x 10^{-8} W m^{-2} K^{-4} ***Stefan-Boltzman constant***

As T increases, E increases by a power of 4. If T doubles, E increases by 16 times!

A warmer object emits much more radiation than a cooler object

The Sun's radiation

$$E_{sun} = 5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4} \ \times\ 5780^4\ K^4$$

$$= 6.328 \times 10^{7}\ W\ m^{-2}$$

The Earth's Radiation

$$E_{earth} = 5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4} \ \times\ 288^4\ K^4$$

$$= 390\ W\ m^{-2}$$

$$E_{sun}/E_{earth} = (T_{sun}/T_{earth})^4 = (6000/300)^4 = 1.6 \times 10^5$$

Wien's law:

Wavelength of peak radiation emitted by an object is inversely related to temperature

λ_{max} = 2897 / T ~ 3000/T

(λ_{max} is in μm and T is in Kelvin)

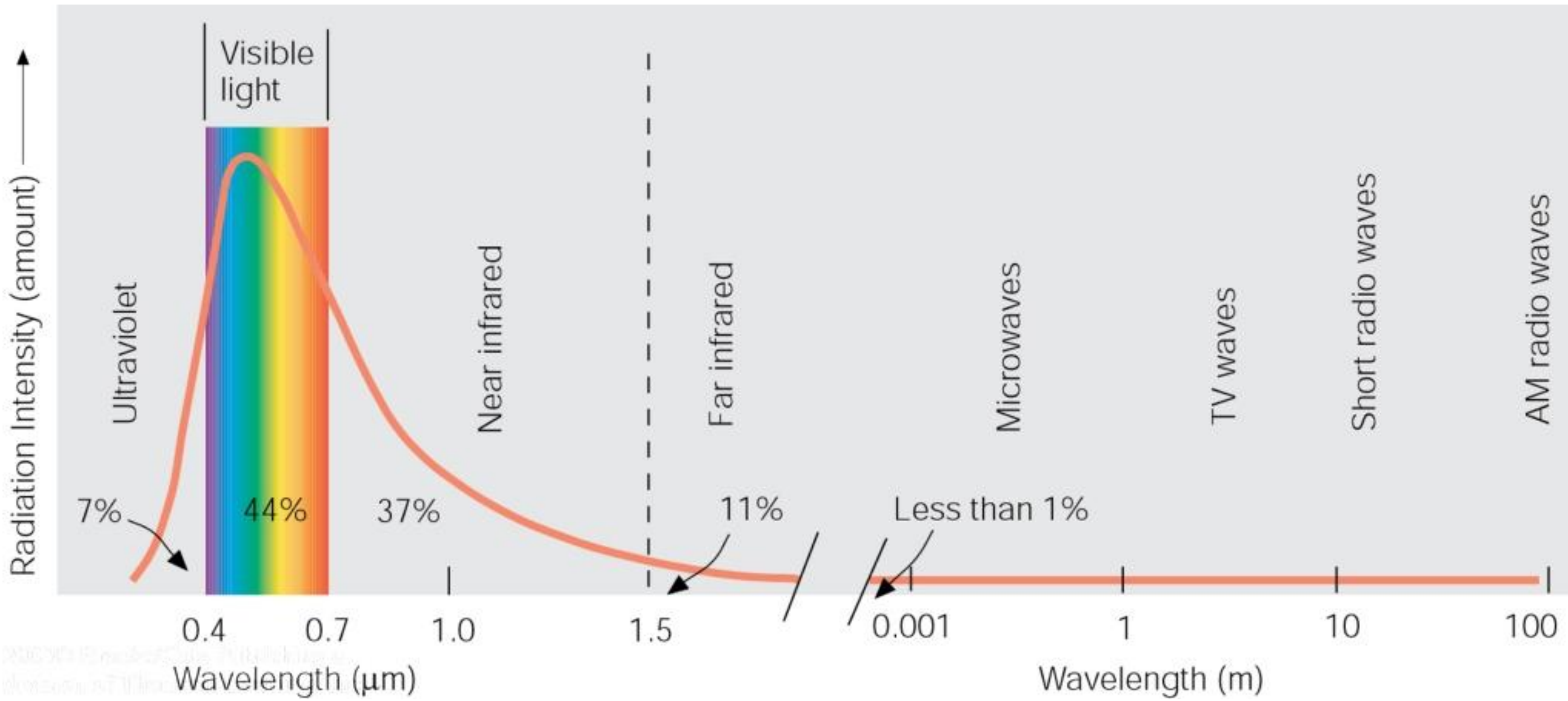
Solar radiation : $\lambda_{max\ sun}$ ~ 3000/6000 K ~ 0.5 μm,

Earth radiation: $\lambda_{max\ earth}$ ~ 3000/300 K ~ 10 μm,

Solar radiation is shortwave radiation

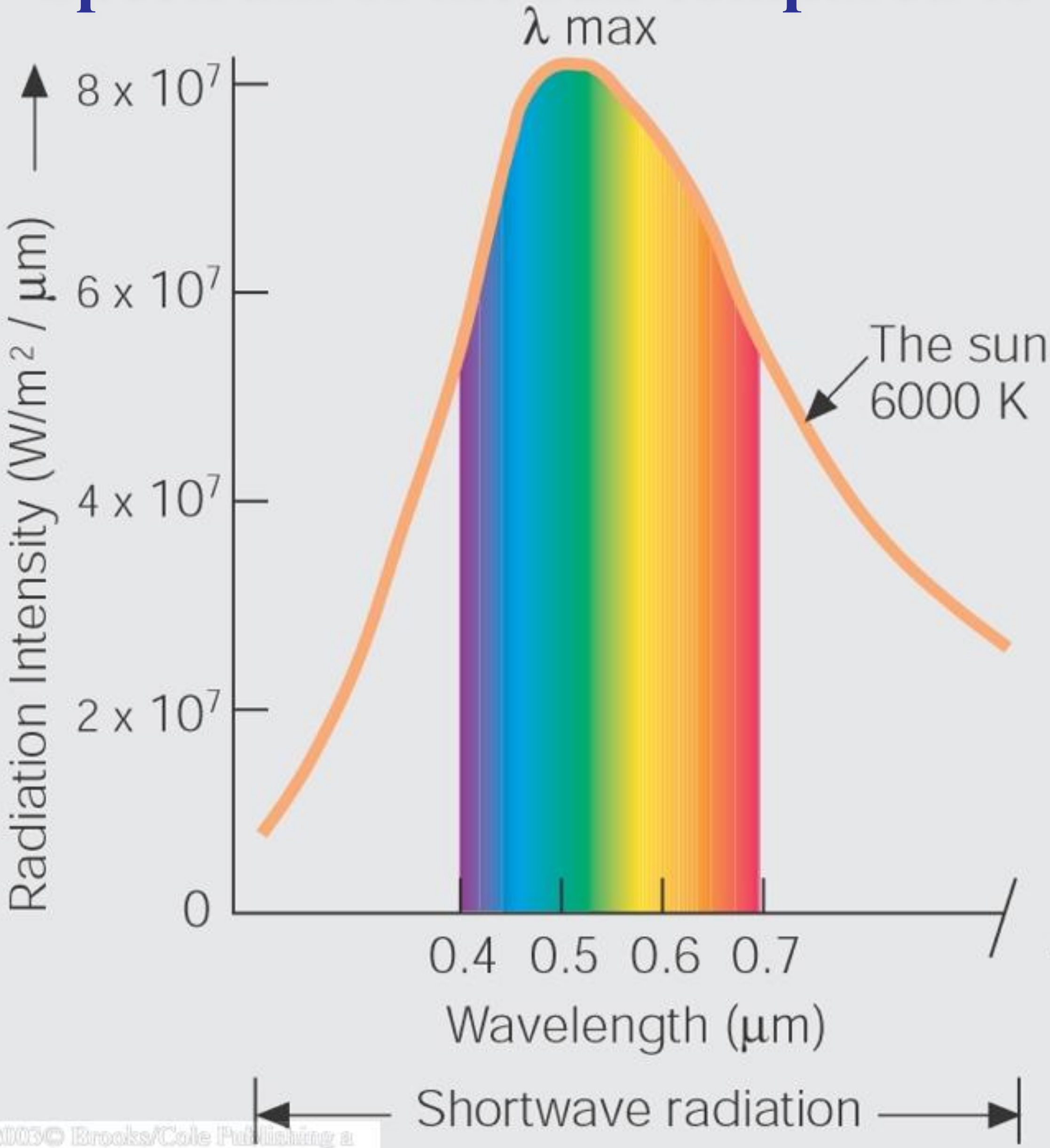
Earth radiation is longwave radiation

Electromagnetic Spectrum of the Solar Radiation

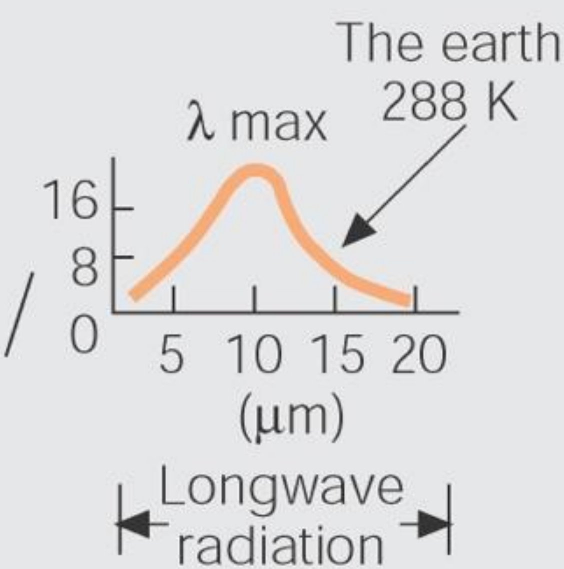


Solar radiation has peak intensities in the shorter wavelengths, dominant in the region we know as visible, but extends at low intensity into longwave regions.

Spectrum of the sun compared to that of the earth



The hot sun radiates at shorter wavelengths that carry more energy, and the fraction absorbed by the cooler earth is then re-radiated at longer wavelengths, as predicted by Wein's law.



Wien’s law

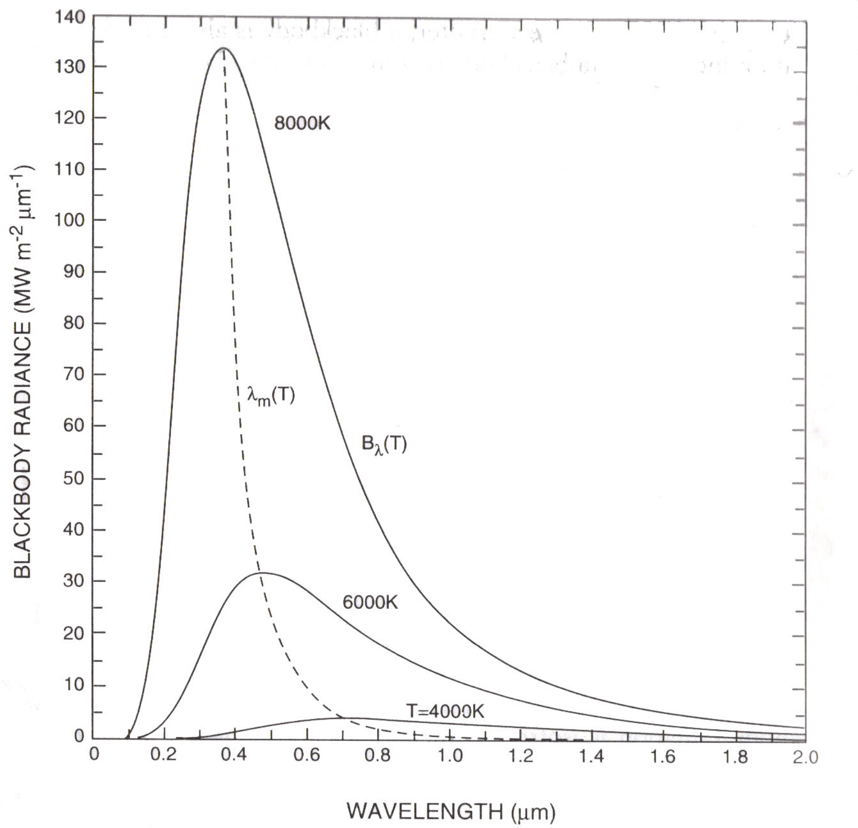


Figure 8.7 Spectra of emitted intensity $B_\lambda(T)$ for blackbodies at several temperatures, with wavelength of maximum emission $\lambda_m(T)$ indicated.

- **Hotter the object the shorter the wavelengths of the maximum intensity emitted.**

Selective Absorbers **– Objects that selectively absorb and emit radiation**

Krichhoff's Law: **good absorbers are good emitters at a particular wavelength**

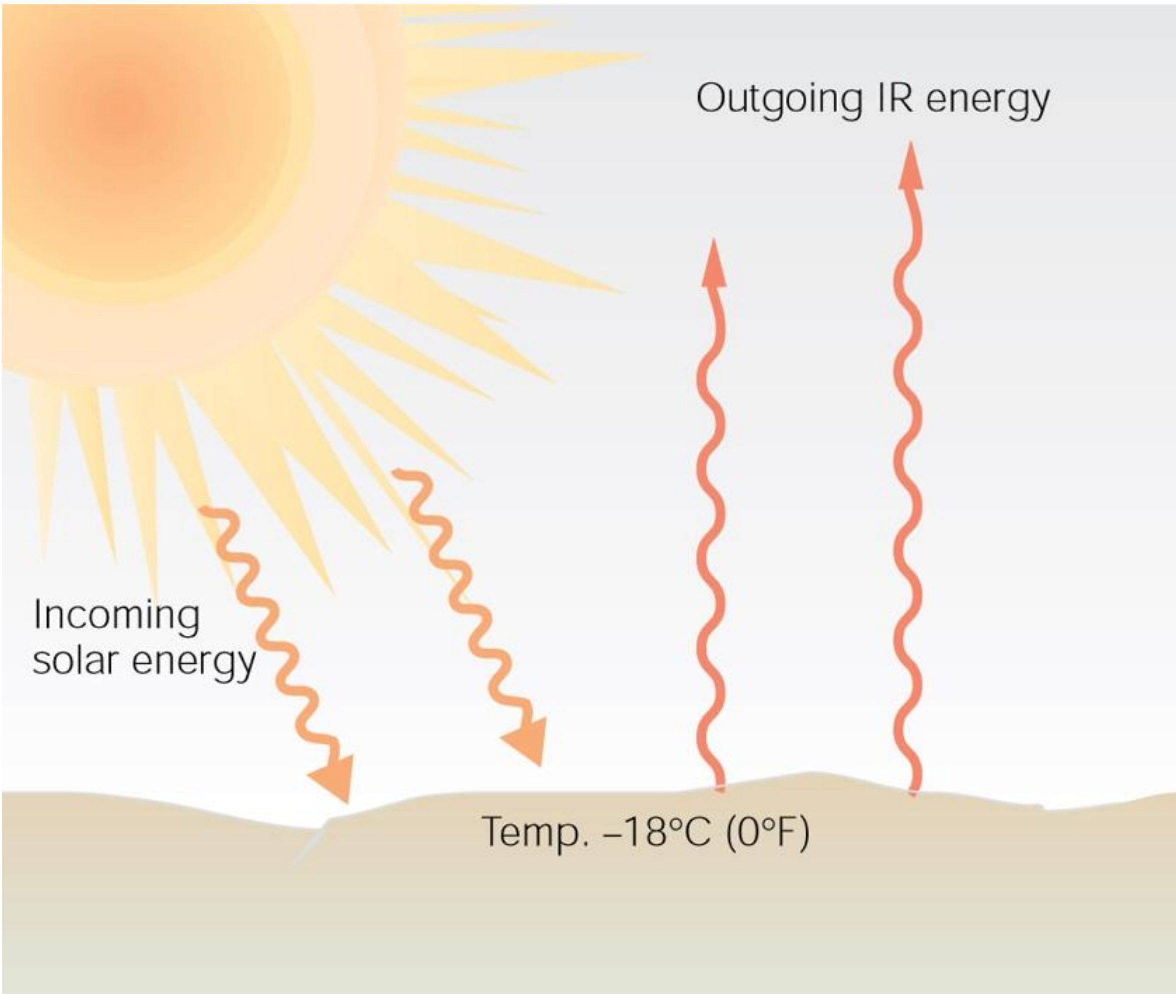
All gases in earth's atmosphere are selective absorbers

1. **The atmospheric gases are transparent to visible radiation**

2. **Water vapor and carbon dioxide are strong absorbers (also emitters) of infrared radiation. These gases are also known as greenhouse gases which helps to keep the lower atmosphere warm**

3. **Ozone and molecular oxygen are good absorbers of ultraviolet radiation – keeping us from getting burned**

If the earth always radiates energy, why doesn't it cool?



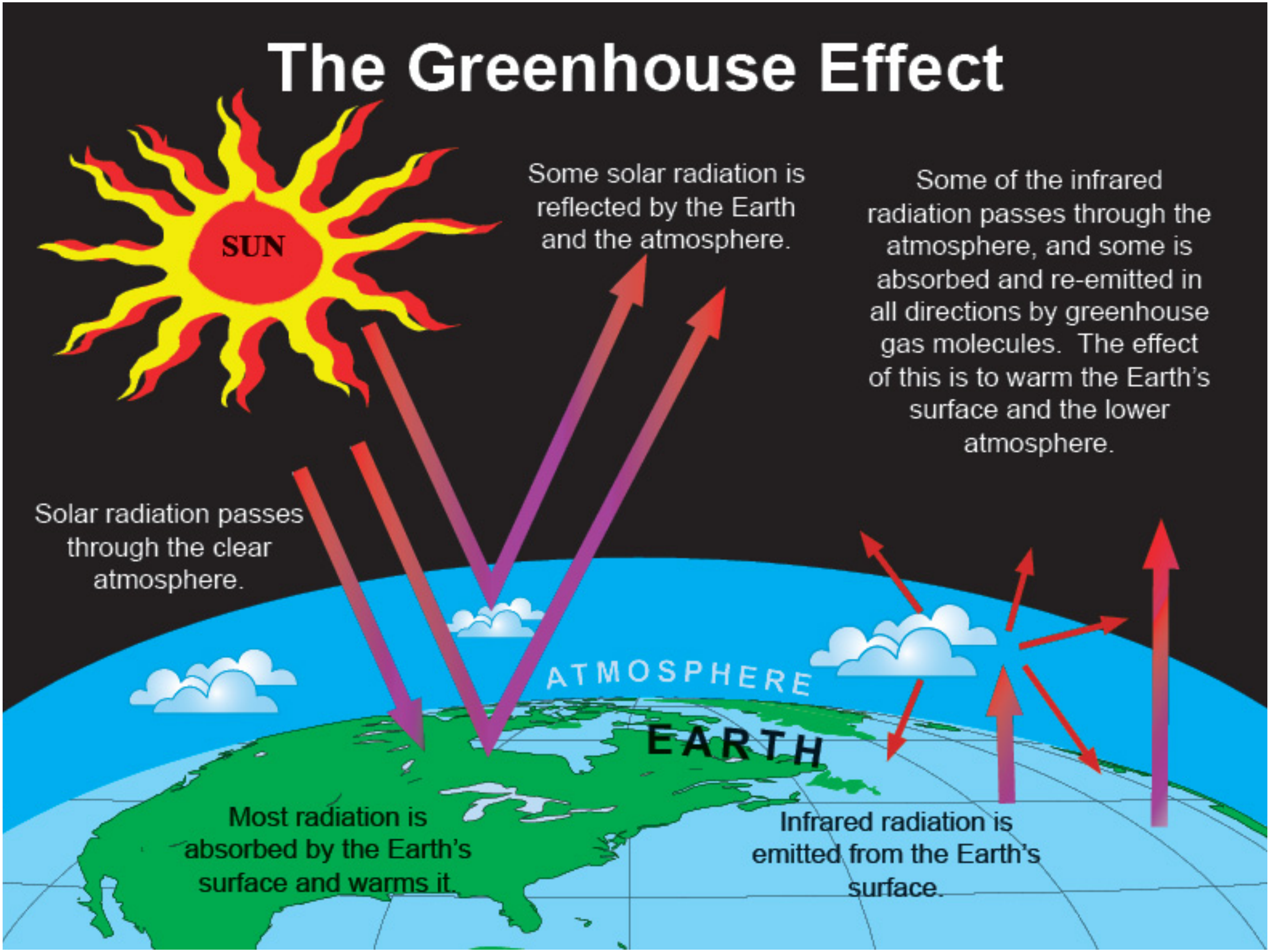
Without greenhouse effect

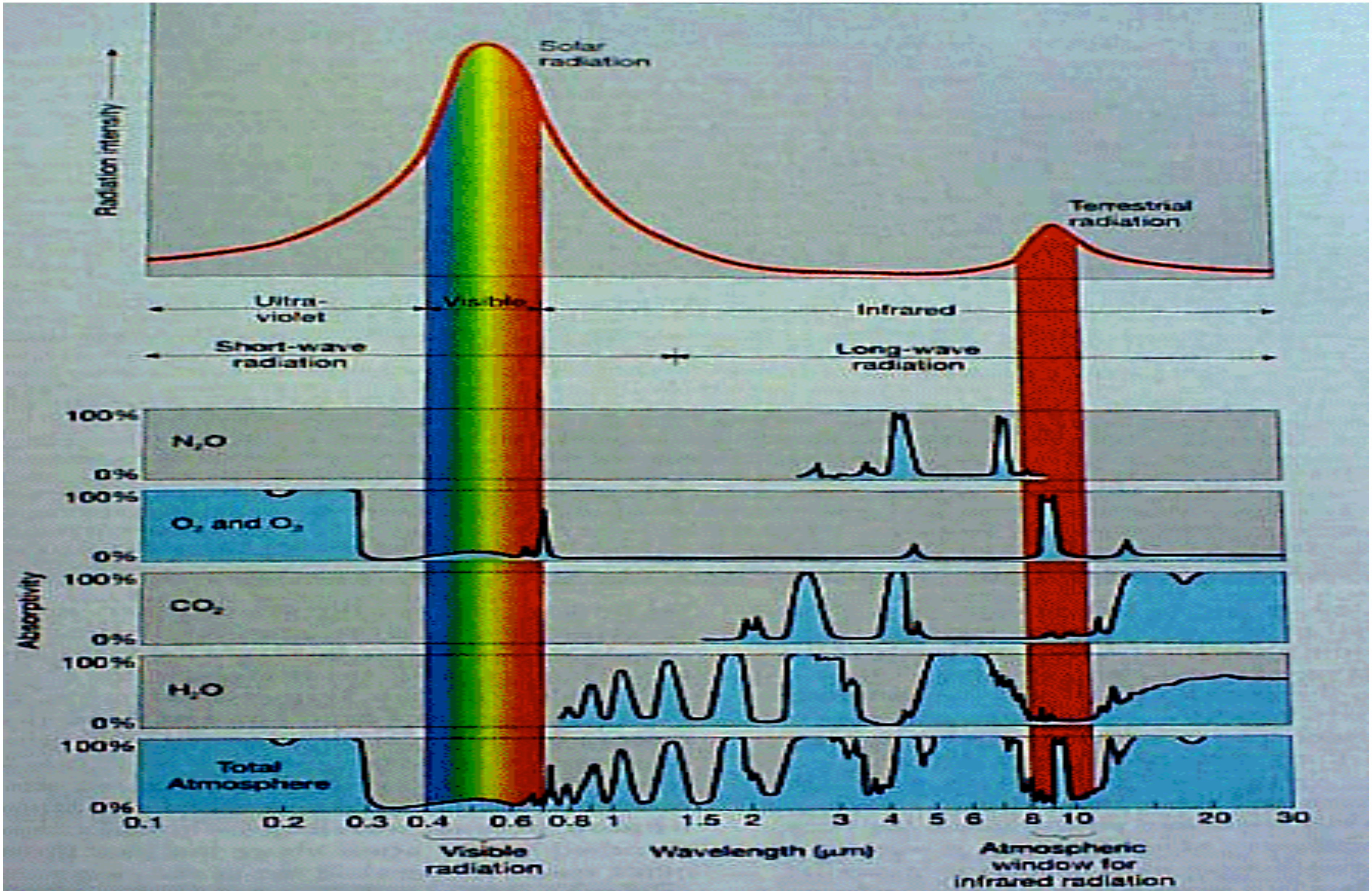
The earth is in a state of *radiative equilibrium* when incoming radiation is balanced by outgoing radiation.

Radiative equilibrium predicts surface temperature of ~ 255 K or ~ -18 degrees ^{o}C

But, the earth's observed average surface temperature is ~ 15 ^{o}C.

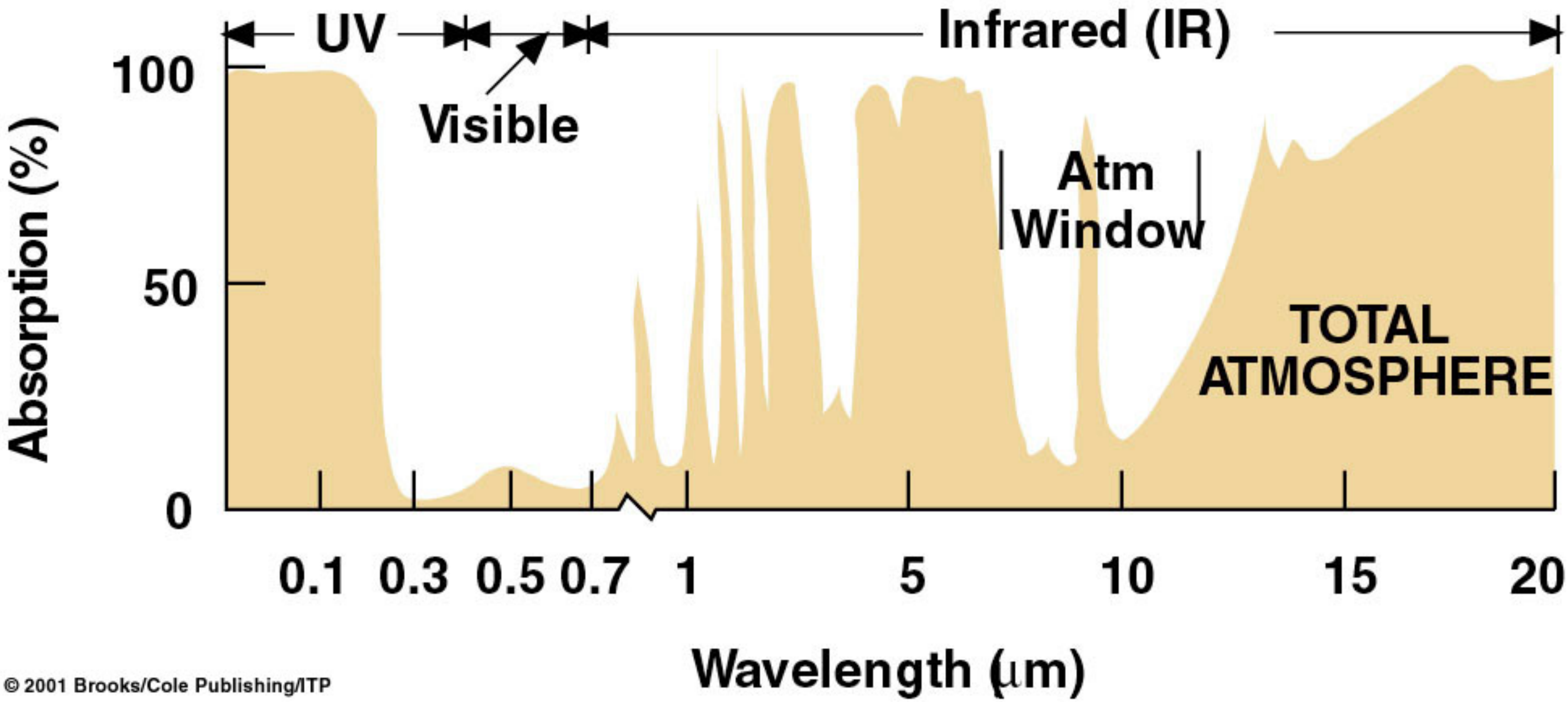
What happen?


The Greenhouse Effect
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation passes through the clear atmosphere.
ATMOSPHERE
EARTH
Most radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.



Solar radiation passes rather freely through earth's atmosphere, but earth's re-emitted longwave energy either passes through a narrow window or is absorbed by greenhouse gases and re-radiated toward earth.

Total Absorption by the Atmosphere



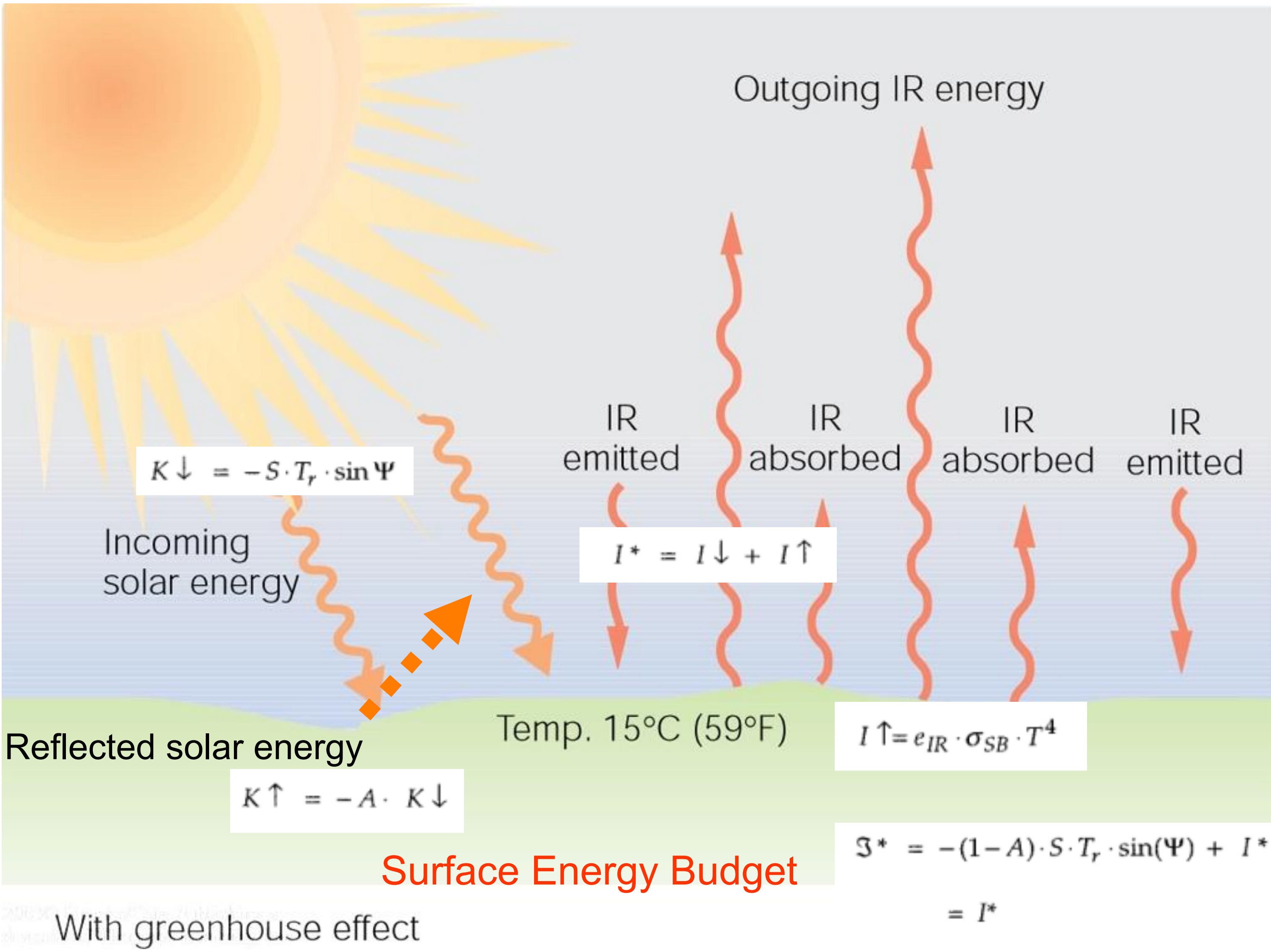
Atmospheric windows

Portions of the electromagnetic spectrum where atmospheric gases absorb relatively little energy

- Visible band (0.25-0.8 micrometers) - vision has evolved to use these wavelengths
- Terrestrial band (wavelength range between 8-11 μm) where little absorption of infrared radiation takes place, allowing earth's radiation to escape to space

Clouds are good absorbers of infrared radiation, even in the wavelengths range of 8-11 micrometers

Earth's atmosphere absorbs and emit infrared radiation that keeps atmosphere warm



$$\Im^* = -(1-A) \cdot S \cdot T_r \cdot \sin(\Psi) + I^* \quad \text{daytime}$$

$$= I^* \quad \text{nighttime}$$

Incoming Solar Radiation

- When solar radiation enters the atmosphere, a number of interactions take place.
- Some energy is absorbed by gases.
- When sunlight strikes small objects (e.g. air molecules and dust particles), the light is deflected in all directions -- called scattering.
- Sunlight can be reflected from objects. Reflection differs from scattering in that more light is sent backwards.

Albedo

- Albedo is the percent of radiation returning from a given surface compared to the amount of radiation initially striking that surface.

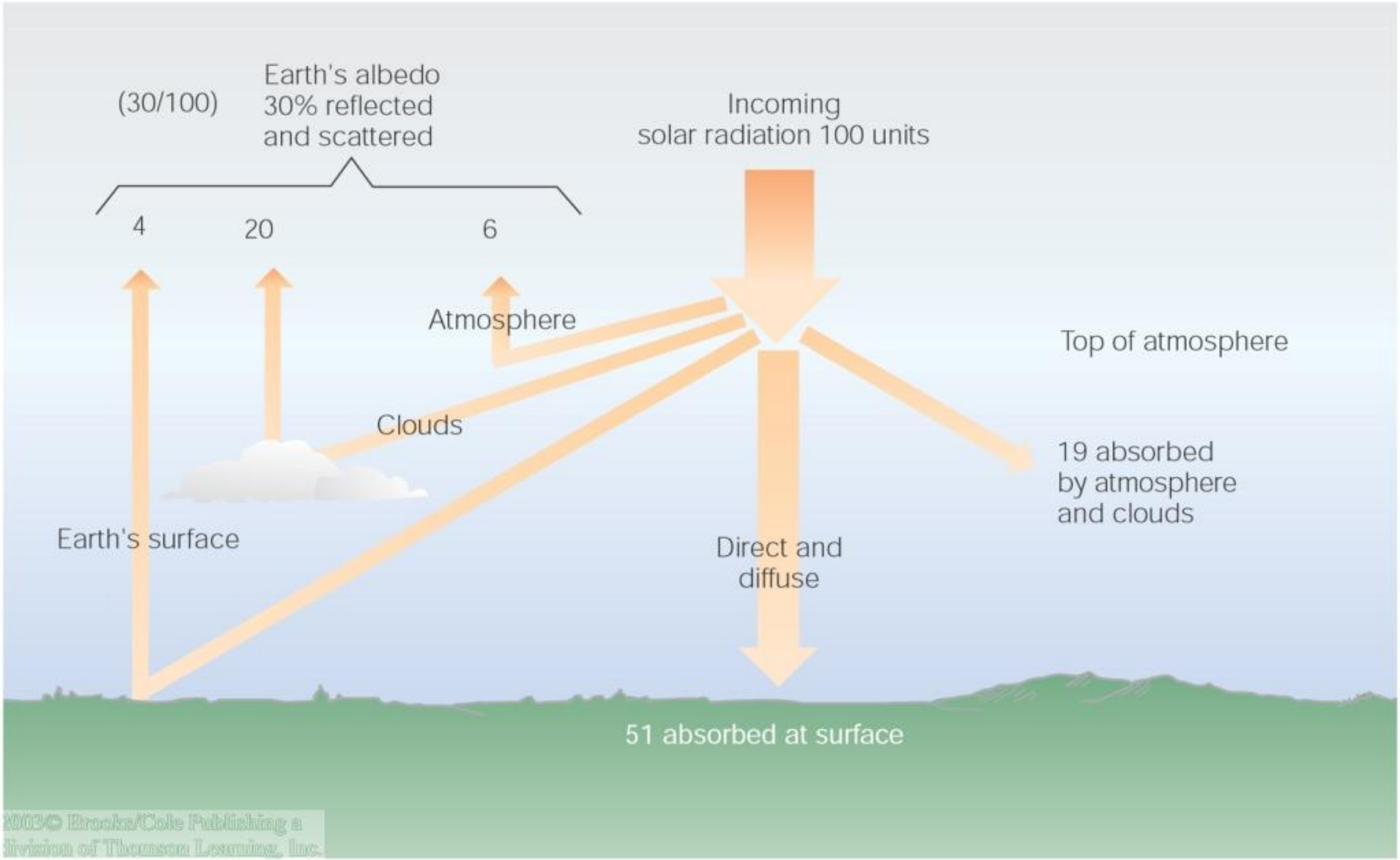
Albedo

SURFACE	ALBEDO (PERCENT)
Fresh snow	75 to 95
Clouds (thick)	60 to 90
Clouds (thin)	30 to 50
Venus	78
Ice	30 to 40
Sand	15 to 45
Earth and atmosphere	30
Mars	17
Grassy field	10 to 30
Dry, plowed field	5 to 20
Water	10*
Forest	3 to 10
Moon	7

*Daily average.

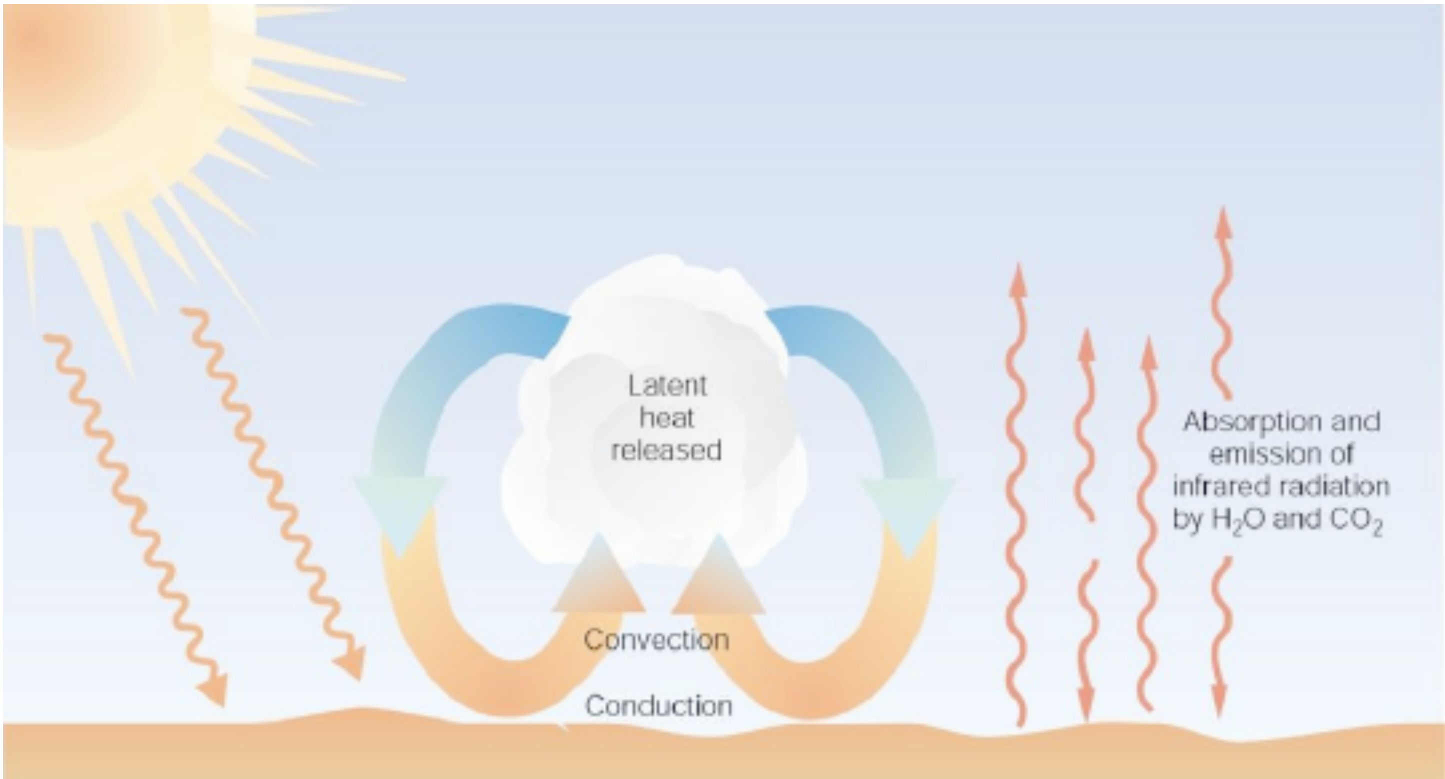
- **Thick clouds have a higher albedo than thin clouds**

The Fate of Incoming Solar Radiation



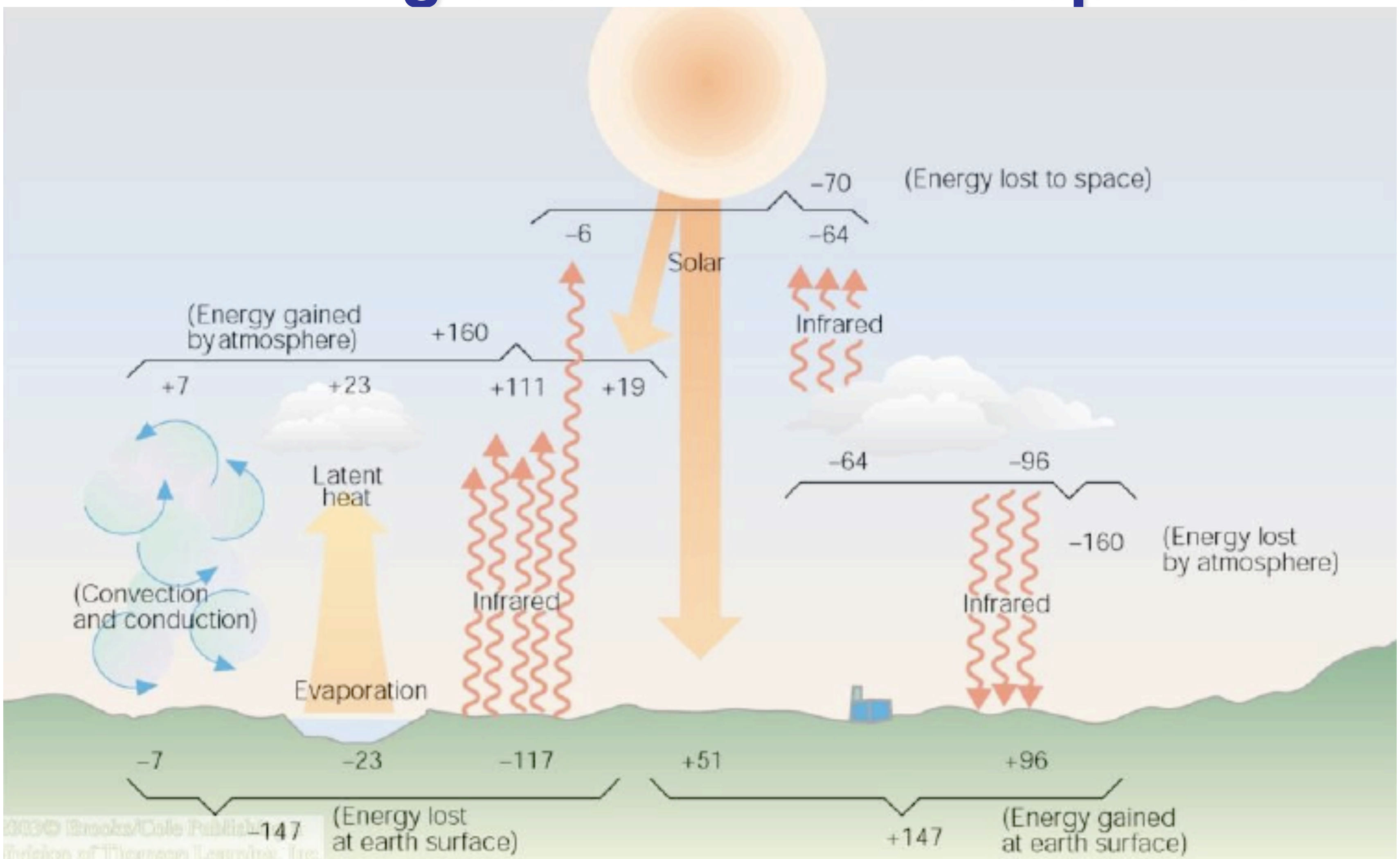
Solar radiation is scattered and reflected by the atmosphere, clouds, and earth's surface, creating an average albedo of 30%. Atmospheric gases and clouds absorb another 19 units, leaving 51 units of shortwave absorbed by the earth's surface.

Warming the Earth & Atmosphere



- Sunlight warms the ground, and the air above is warmed by conduction (small impact), convection, and radiation.
- Further warming occurs during condensation as latent heat is given up to the air inside the cloud.

Warming the Earth & Atmosphere



Earth's surface absorbs 51 units of SW and 96 units of LW. Earth's surface loses 147 units by convection, conduction, evaporation, and radiation.

Summary

1. The Sun emits most of its radiation as short-wave radiation. The earth emits most of its radiation as longwave infrared energy.
2. The higher an object's temperature, the greater the amount of radiation emitted per unit surface area and the shorter are the wavelengths of emitted radiation.
3. Selective absorbers in the atmosphere, such as water vapor and carbon dioxide, absorb some infrared radiation from the earth and radiate a portion of it back to the surface, producing the atmospheric greenhouse effect.
4. Latent heat is an important source of atmospheric energy.