Atmospheric Physics

Lecture 2

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Atmospheric radiation

To study the effects of atmospheric radiation, it is necessary to investigate the interaction between photons and atmospheric gases. One way in which solar photons may be lost is by

$$\Delta E = h\nu,$$

where ΔE is the difference in energy levels and h is Planck's constant.

$$\lambda = c/\nu = hc/\Delta E,$$

Absorption

The atmosphere does not absorb radiation the same for all wavelengths

Solar radiation (shortwave radiaiton) pass through quite easily

Most of the high-energy UV radiation is almost completely absorbed by Stratospheric Ozone

Water vapor and Carbon Dioxide absorb near infrared radiation

Scattering fundamentals

Scattering can be broadly defined as the redirection of radiation out of the original direction of propagation, usually due to interactions with molecules and particles

Reflection, refraction, diffraction etc. are actually all just forms of scattering

Matter is composed of discrete electrical charges (atoms and molecules – dipoles)

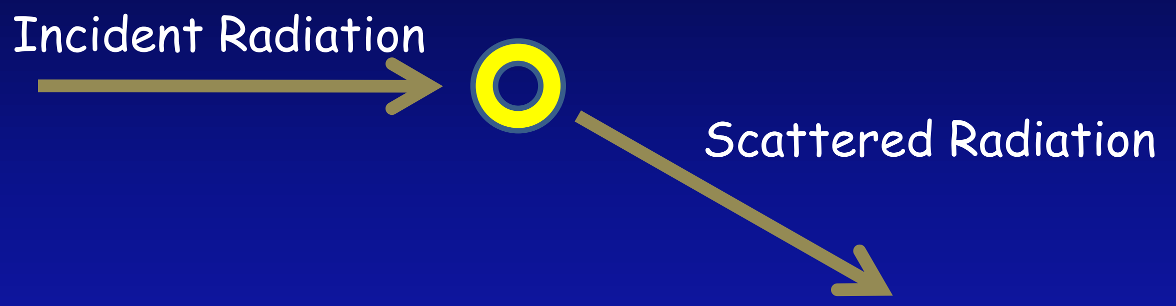
Light is an oscillating EM field – excites charges, which radiate EM waves

These radiated EM waves are scattered waves, excited by a source external to the scatterer

The superposition of incident and scattered EM waves is what is observed

Atmospheric Scattering

Scattering is the process where an atom, molecule, or particle redirects energy.



Types of Scattering

1) Rayleigh Scattering → Atmospheric atom and small molecule

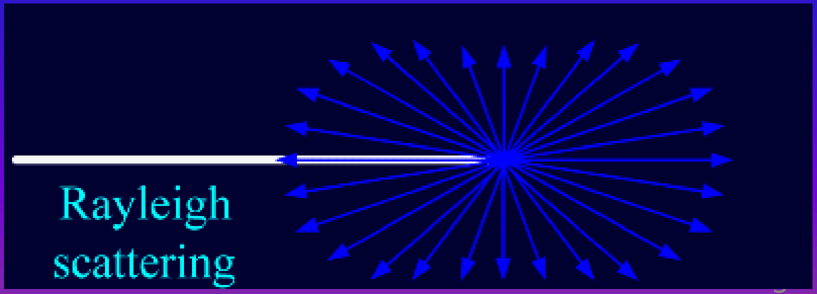
Atmospheric composition: N_2 (78%), O_2 (21%), Ar (1%)

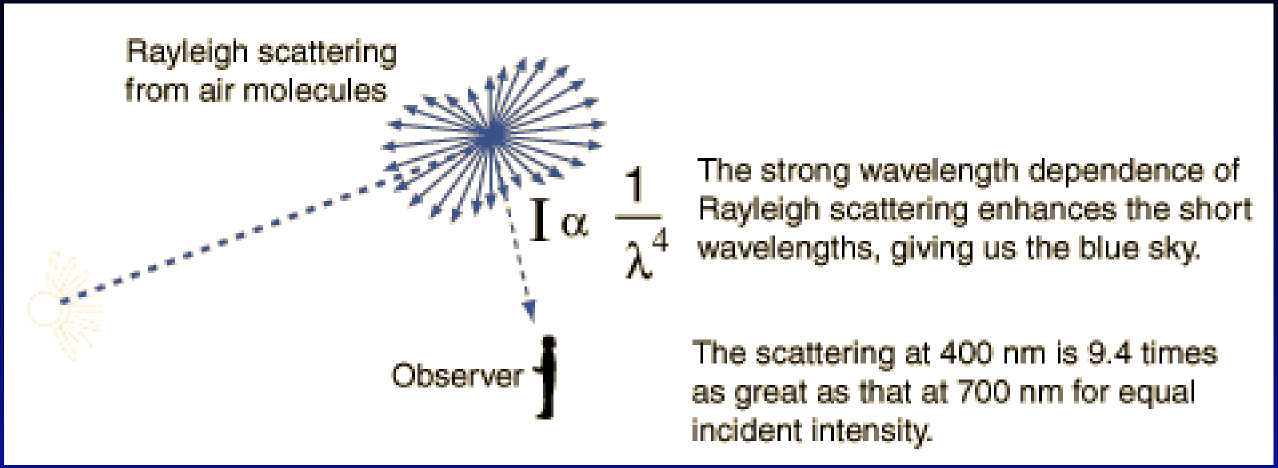
Size of N_2 molecule: 0.31 nm

Size of O_2 molecule: 0.29 nm

Size of Ar molecule: 0.3 nm

Visible wavelengths ~400-700 nm

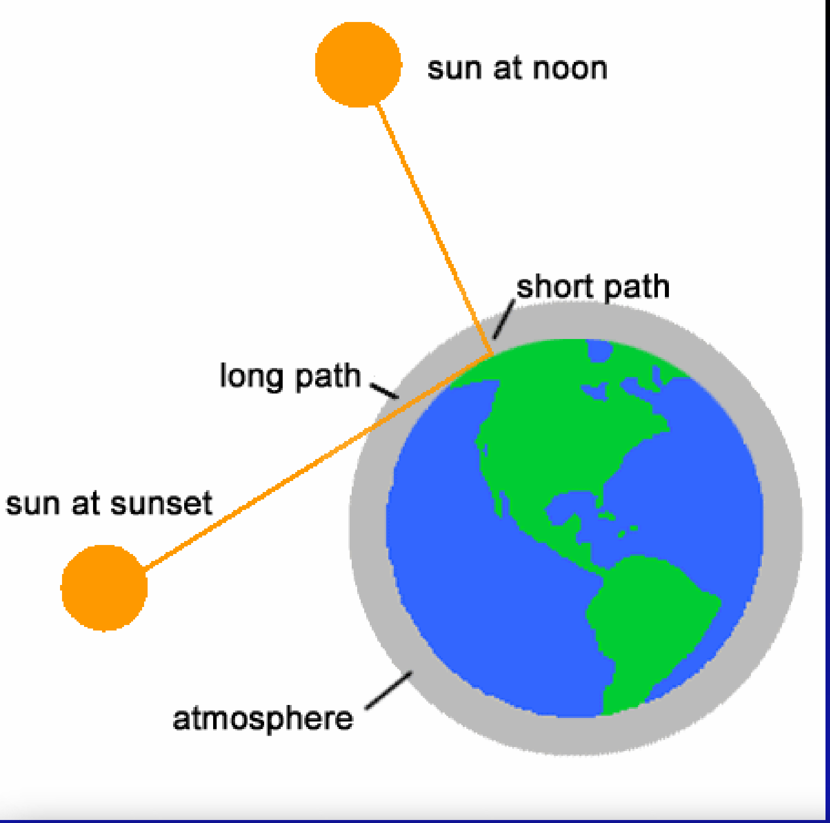


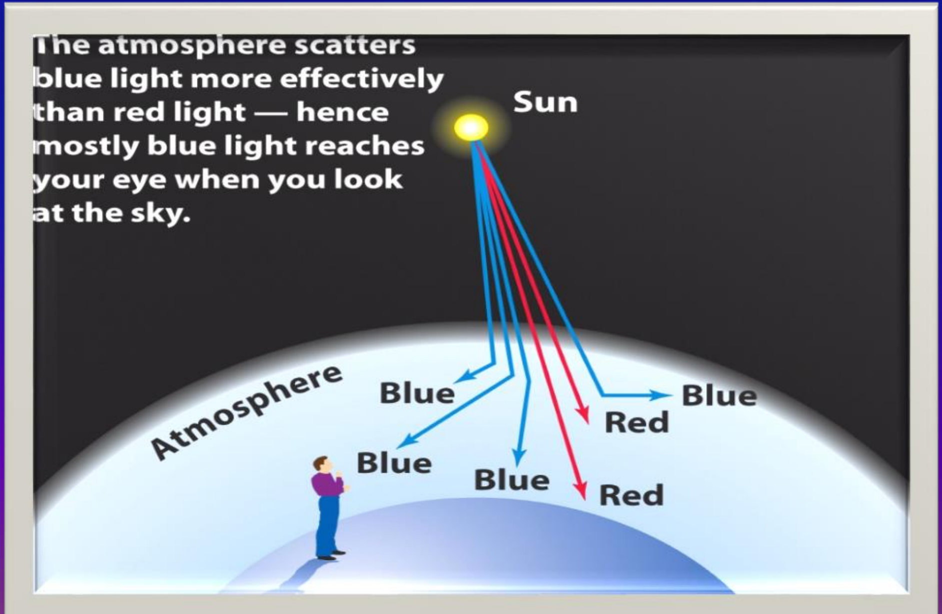


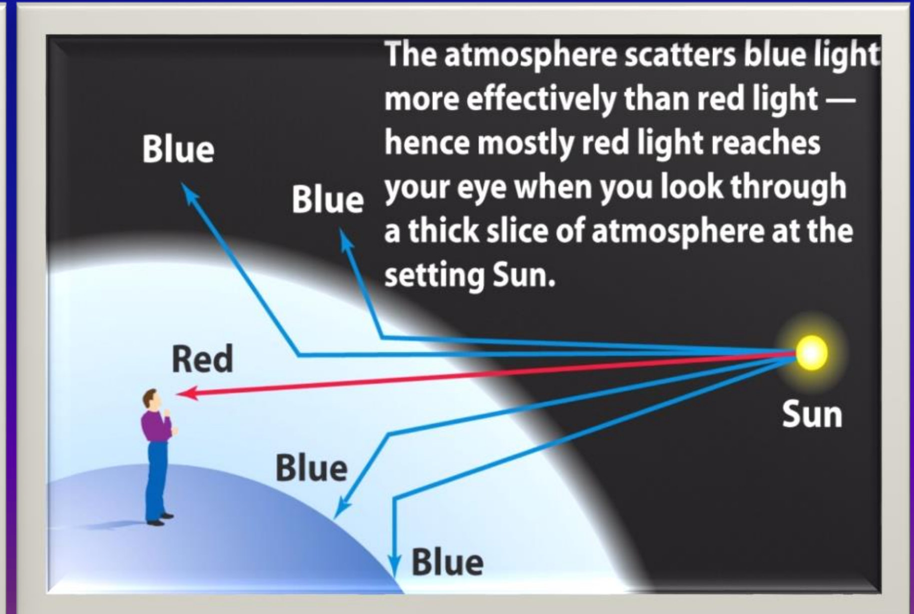
Scattering of light off air molecules is called Rayleigh Scattering

Involves particles much smaller than the wavelength of incident light

Responsible for the blue color of clear sky

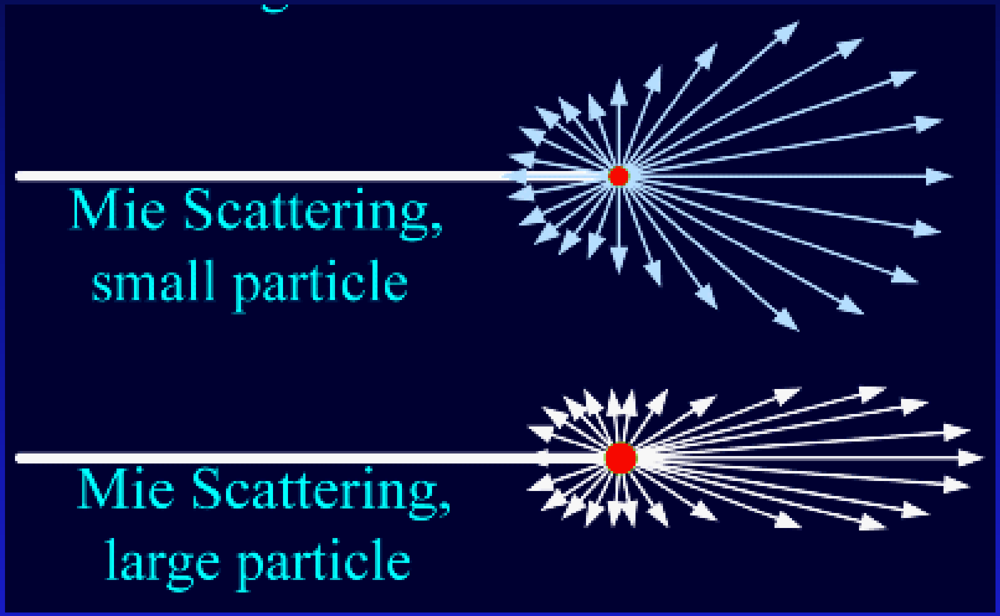

sun at noon
short path
long path
sun at sunset
atmosphere


The atmosphere scatters blue light more effectively than red light — hence mostly blue light reaches your eye when you look at the sky.
Sun
Atmosphere
Blue
Blue
Blue
Blue
Red
Red


The atmosphere scatters blue light more effectively than red light — hence mostly red light reaches your eye when you look through a thick slice of atmosphere at the setting Sun.
Blue
Blue
Red
Sun
Blue
Blue

2) Mie Scattering → **Aerosol**

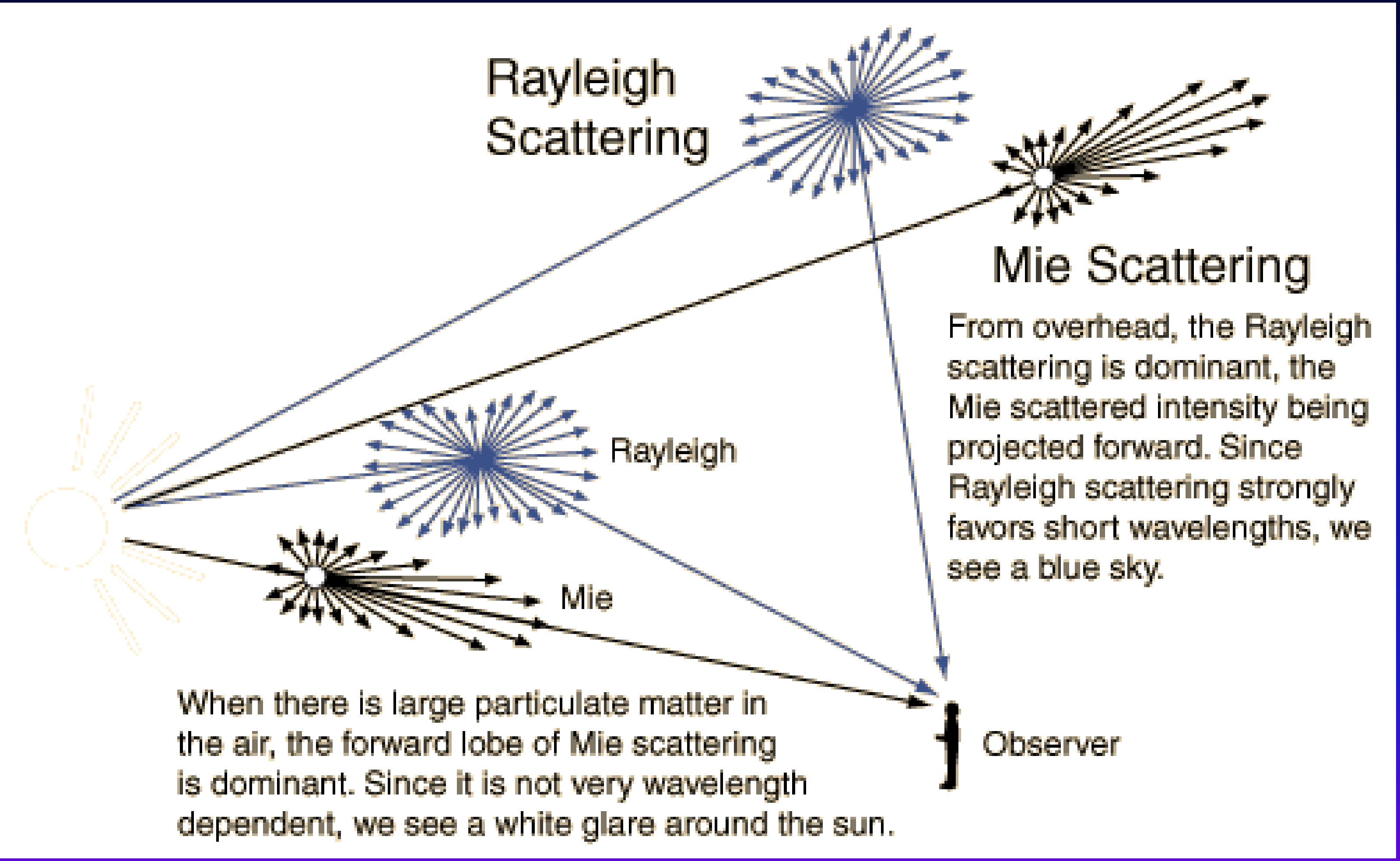
Aerosols $\sim 1\mu m$



Predominantly scatters light (radiation) in the forward direction.

For example, the solar radiation is typically scattered towards the surface and not back to space.

Rayleigh and Mie scattering

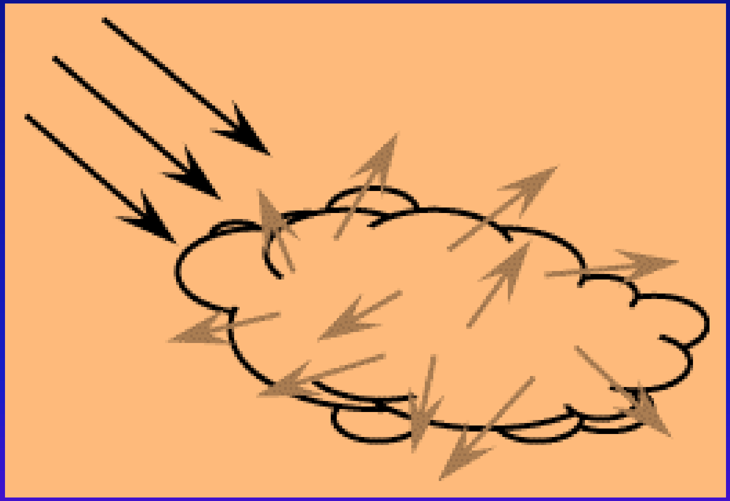


- Scattering determines the brightness and color of the sky

3) Non-selective Scattering $\longrightarrow$ Cloud

Water droplets $\sim 10\,\mu m$

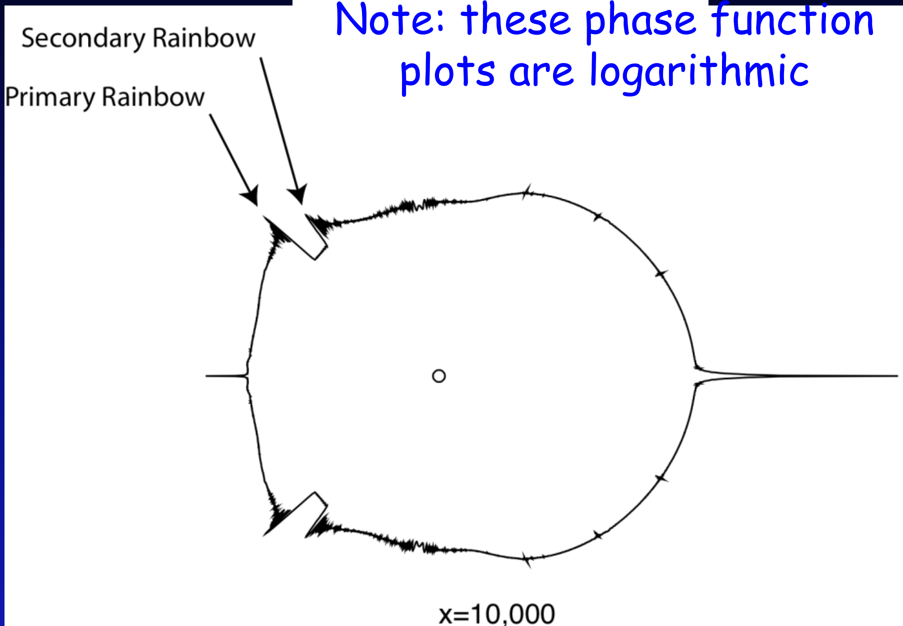
Ice crystals $\sim 100\,\mu m$

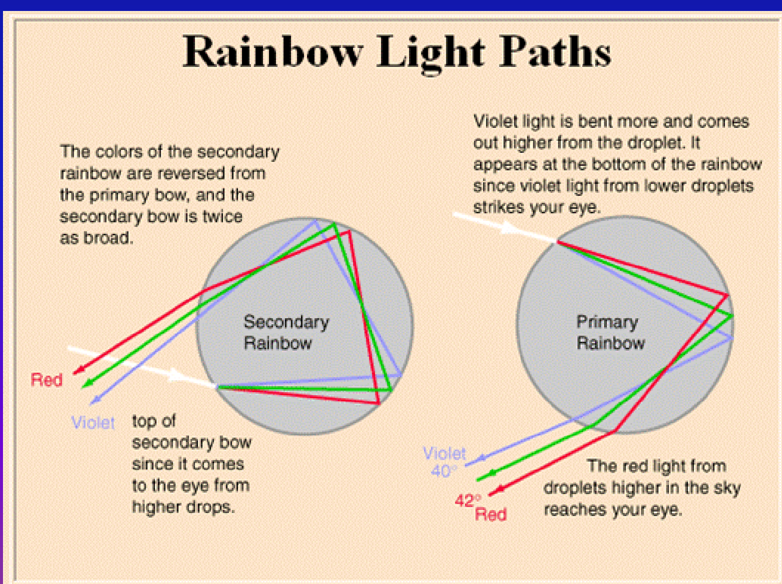


Light passing through clouds is an excellent example of nonselective scattering

Optical phenomena

Note: these phase function plots are logarithmic





Rainbow: for large particles (x = 10,0000), the forward and backward peaks in the scattering phase function become very narrow (almost non-existent). Light paths are best predicted using geometric optics and ray tracing

Primary rainbow: single internal reflection

Secondary rainbow: double internal reflection

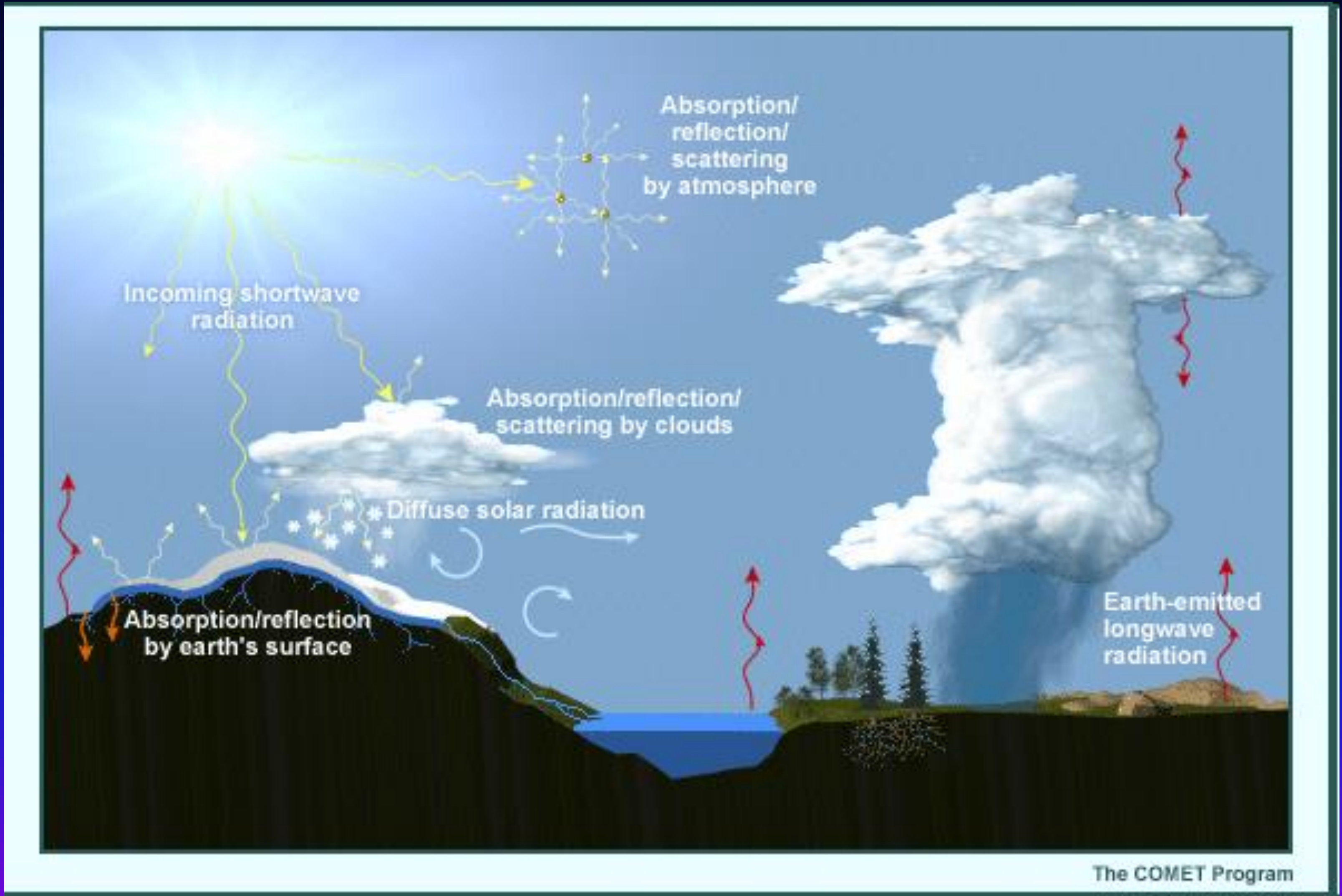
Reflected radiation

a = 0.6-0.8

a = 0.2-0.5

a < 0.2

Diffuse radiation



A schematic illustration of atmospheric processes

Wien's Displacement Law

This law expresses the relationship between the temperature of a radiating body and its wavelength of maximum emission

$$\lambda_{max} = C/T$$

C is the Wien's constant $C = 2898\ \mu mK$

Compare the difference between the sun and the Earth.

$$\lambda_{max}(Sun) = \frac{2898\ \mu mK}{6000\ K} = 0.483\ \mu m$$

$$\lambda_{max}(Earth) = \frac{2898\ \mu mK}{300\ K} = 9.66\ \mu m$$

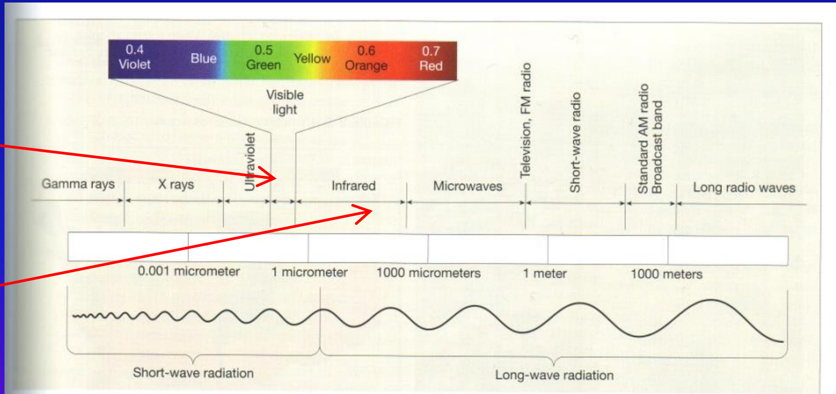


FIGURE 2-11 The electromagnetic spectrum, illustrating the wavelengths and names of various types of radiation.

Radiative properties of natural surfaces

Natural surfaces are not perfect radiators or blackbodies, but are, in general, gray bodies. They are generally characterized by several different radiative properties, which are defined as follows

Emissivity is defined as the ratio of the energy flux emitted by the surface at a given wavelength and temperature to that emitted by a blackbody at the same wavelength and temperature

$$\varepsilon_\lambda = \frac{I_\lambda}{B_\lambda}$$

Absoptivity is defined as the ratio of the amount of radiant energy absorbed by the surface material to the total amount of energy incident on the surface

$$\alpha_\lambda = \frac{I_\lambda(absorbed)}{I_\lambda(incident)}$$

Reflectivity is defined as the ratio of the amount of radiation reflected to the total amount incident upon the surface

$$R_\lambda = \frac{I_\lambda(reflected)}{I_\lambda(incident)}$$

Transmissivity is defined as the ratio of the radiation transmitted to the subsurface medium to the total amount incident upon the surface

$$T_\lambda = \frac{I_\lambda(transmitted)}{I_\lambda(incident)}$$

$$\alpha_\lambda + T_\lambda + R_\lambda = 1$$

Kirchhoff's Law

A body absorbs and emits energy at a given wavelength with equal efficiency.

For a blackbody: $$\alpha_\lambda = \varepsilon_\lambda = 1$$

Where α_λ is the absorptivity, and ε_λ is the emissivity. If the object is not a blackbody, then:

$$\alpha_\lambda = \varepsilon_\lambda < 1$$

strong emitters ⇔ strong absorbers
weak emitters ⇔ weak absorbers

$$R_L = -\varepsilon \sigma T^4$$

Arya

Table 3.1

Radiative Properties of Natural Surfaces[a]

Surface type	Other specifications	Albedo (a)	Emissivity (ε)
Water	Small zenith angle	0.03–0.10	0.92–0.97
	Large zenith angle	0.10–0.50	0.92–0.97
Snow	Old	0.40–0.70	0.82–0.89
	Fresh	0.45–0.95	0.90–0.99
Bare sand	Dry	0.35–0.45	0.84–0.90
	Wet	0.20–0.30	0.91–0.95
Grass	Long (1 m) Short (0.02 m)	0.16–0.26	0.90–0.95

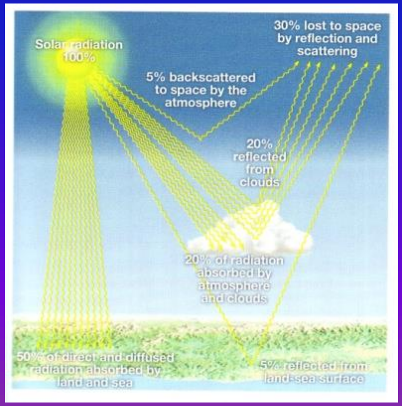
Shortwave Radiation

S_o = 1368 w m^{-2} is the **solar constant** for Earth

Insolation

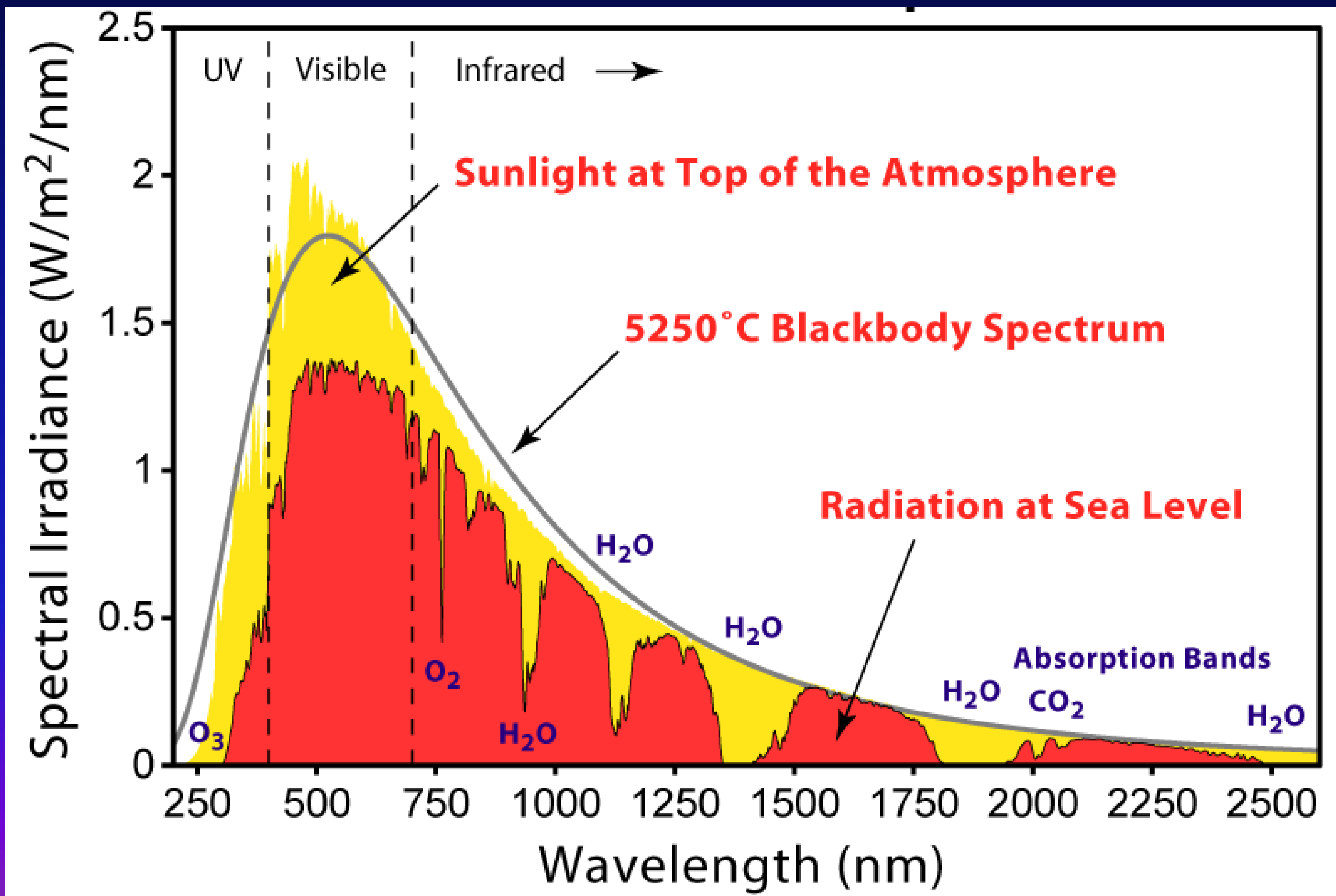
$$R_0 = S_0 \left(\frac{d_m}{d}\right)^2 \cos\gamma$$

$$I_0 = \int_{t_1}^{t_2} R_0(t)\,dt$$



Radiation in the Atmosphere

Deviations from blackbody due to absorption by the solar atmosphere, absorption and scattering by the earth's atmosphere (below).



Stefan-Boltzmann Law

This law expresses the rate of radiation emission per unit area

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

Compare the difference between the radiation emission from the sun and the Earth.

The sun with an average temperature of 6000 K emits 73,483,200 W/m^2

By contrast, Earth with an average temperature of 300 K emits 459 W/m^2

The sun has a temperature 20 times higher than Earth and thus emits about 160,000 times more radiation

This makes sense,

$$20^4 = 160,000$$

The Planck law

$$u_\nu(T) = \frac{8\pi h\nu^3}{c^3(e^{h\nu/k_B T} - 1)}$$

h = 6.6262x10^{-34} joule sec
k =1.3806x10^{-23} joule deg^{-1}
c =2.99793x10^{+8} m/s
T = object temperature in Kelvins

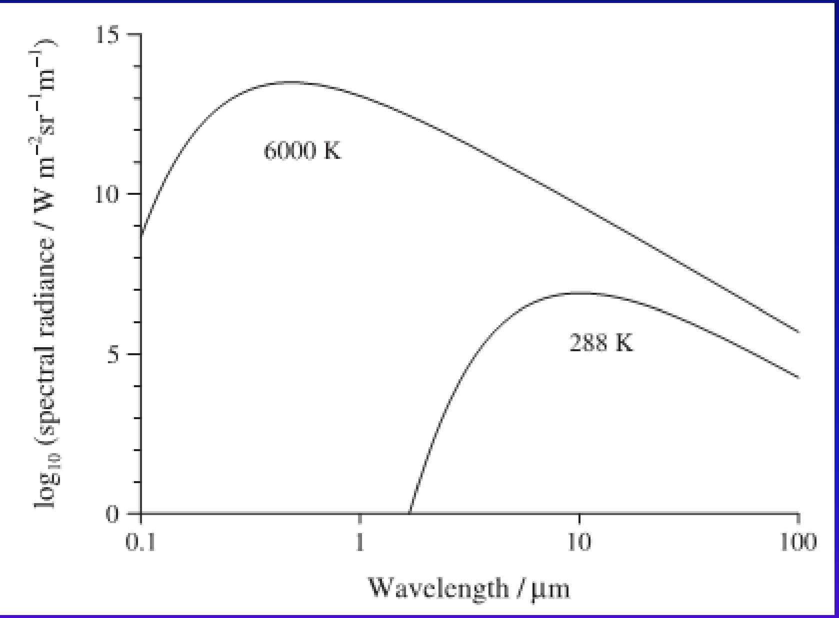
$u_\nu \, \Delta\Omega/(4\pi)$.

$$B_\nu(T) = \frac{2h\nu^3}{c^2\{\exp[h\nu/(k_\mathrm{B}T)] - 1\}};$$

this is called the Planck function

The black-body spectral radiance can also be written in terms of the power per unit area, per unit solid angle, per unit wavelength interval,

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5\{\exp[hc/(\lambda k_B T)] - 1\}};$$



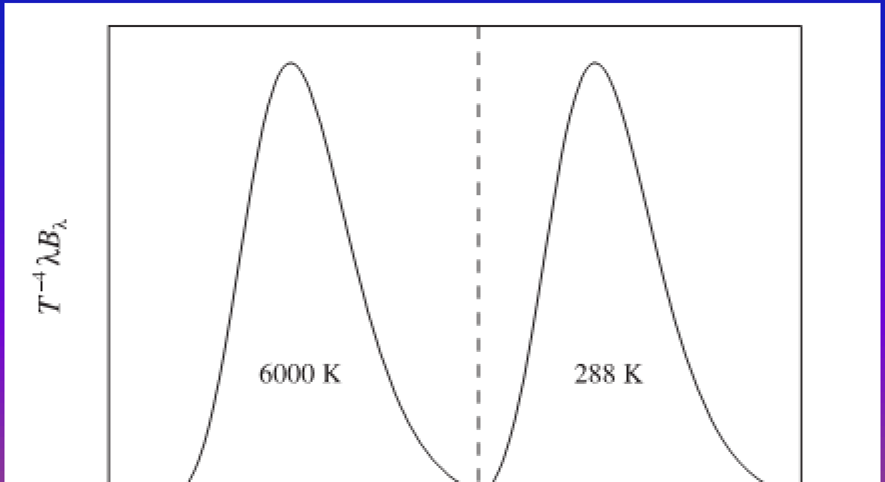
If B_λ is integrated over all wavelengths, we obtain the black-body radiance

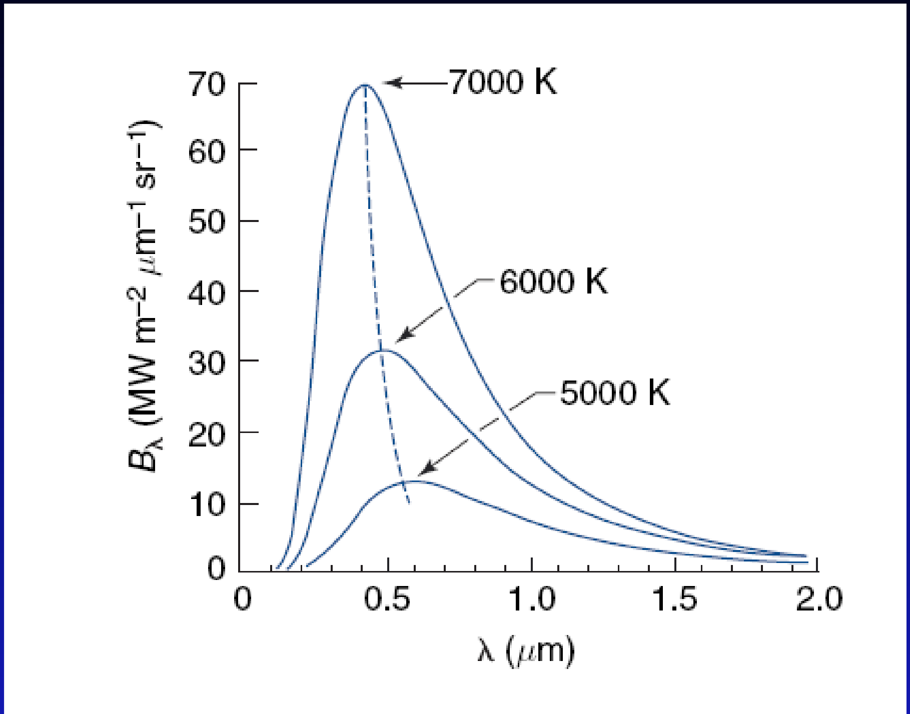
$$\int_0^\infty B_\lambda(T)\,d\lambda = \frac{\sigma}{\pi}T^4,$$

where σ is the Stefan–Boltzmann constant.

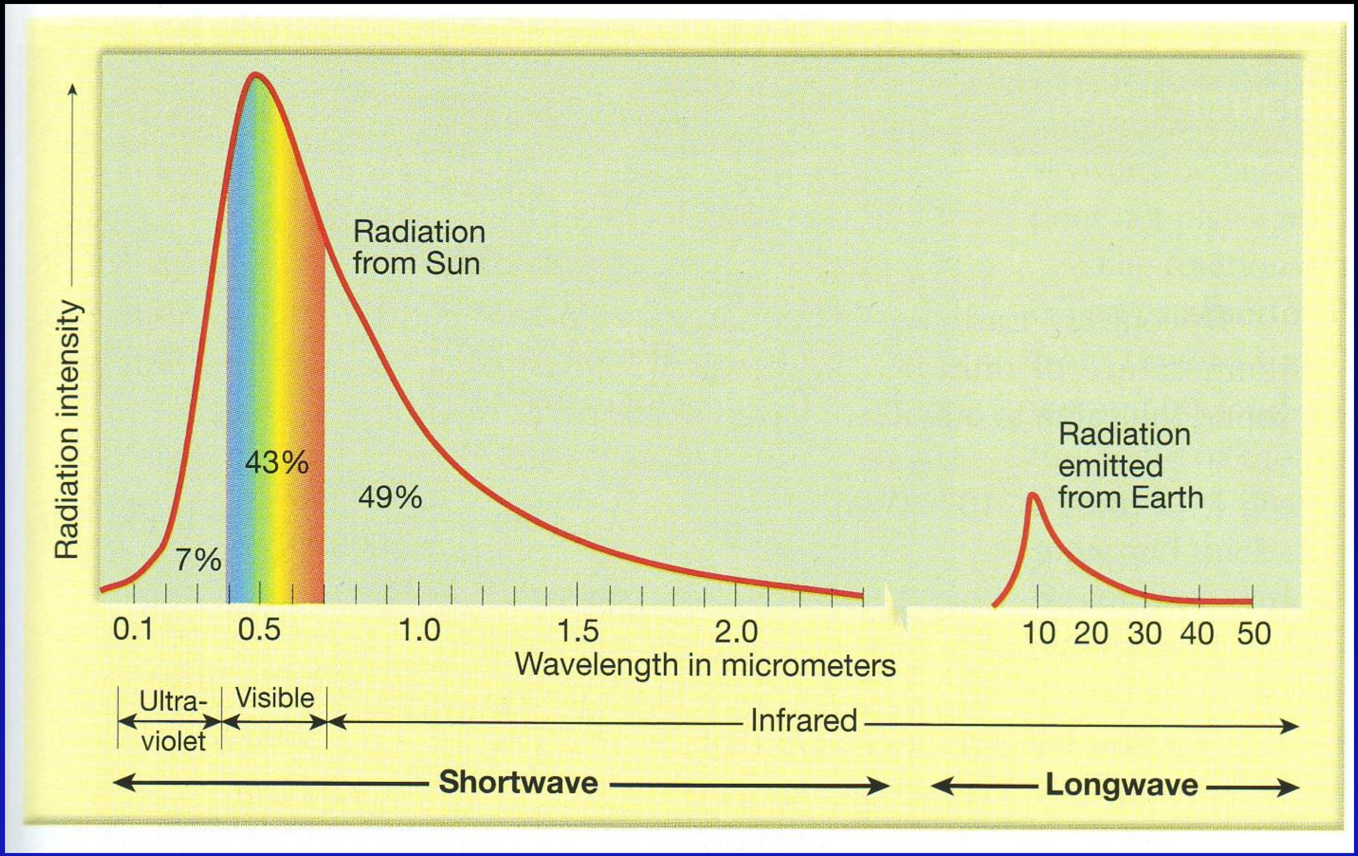
In terms of an integral over ln(λ),this gives

$$T^{-4}\int_{-\infty}^{\infty} \lambda B_\lambda(T)\,d(\ln\lambda) = \frac{\sigma}{\pi}.$$





Blackbody radiation curves at three different temperatures (K; see legend in upper right corner).


Radiation intensity
Radiation from Sun
43%
49%
7%
Radiation emitted from Earth
0.1
0.5
1.0
1.5
2.0
10 20 30 40 50
Wavelength in micrometers
Ultra-violet
Visible
Infrared
Shortwave
Longwave