AOSC400-2015
September 24, Lecture # 7

- Supplementary comments on radiation units terminology

- Thermal radiation

  Basic long-wave (thermal) radiation laws:
  Plank; Stefan-Boltzmann; Wien
  Simple radiation balance climate model

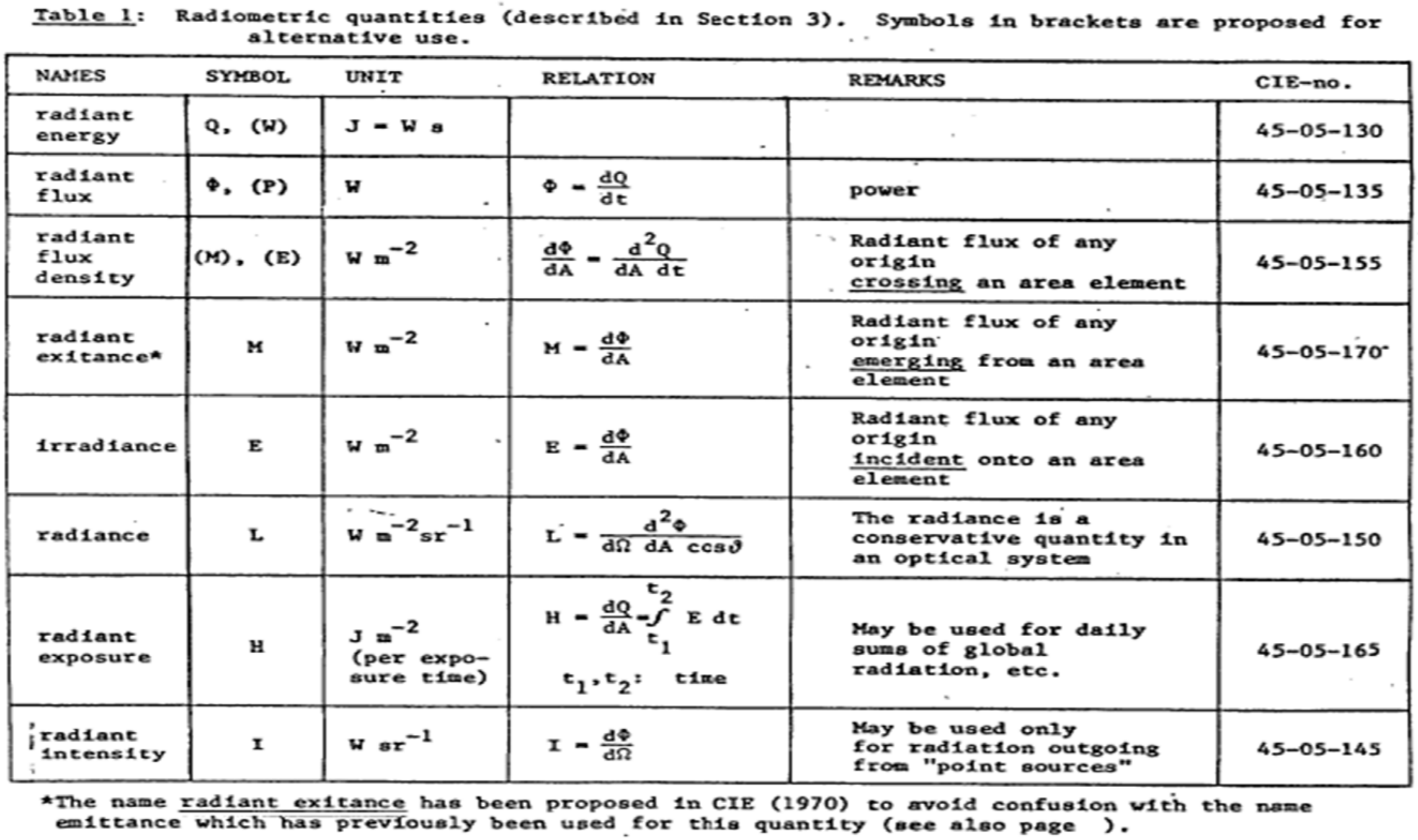


Table 1: Radiometric quantities (described in Section 3). Symbols in brackets are proposed for alternative use.

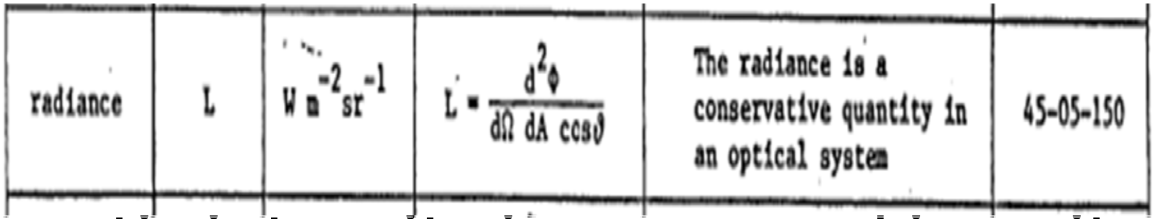
NAMES	SYMBOL	UNIT	RELATION	REMARKS	CIE-no.
radiant energy	Q, (W)	J = W s			45-05-130
radiant flux	Φ, (P)	W	$\Phi = \frac{dQ}{dt}$	power	45-05-135
radiant flux density	(M), (E)	$W\ m^{-2}$	$\frac{d\Phi}{dA} = \frac{d^2Q}{dA\ dt}$	Radiant flux of any origin crossing an area element	45-05-155
radiant exitance*	M	$W\ m^{-2}$	$M = \frac{d\Phi}{dA}$	Radiant flux of any origin emerging from an area element	45-05-170
irradiance	E	$W\ m^{-2}$	$E = \frac{d\Phi}{dA}$	Radiant flux of any origin incident onto an area element	45-05-160
radiance	L	$W\ m^{-2} sr^{-1}$	$L = \frac{d^2\Phi}{d\Omega\ dA\ \cos\vartheta}$	The radiance is a conservative quantity in an optical system	45-05-150
radiant exposure	H	$J\ m^{-2}$ (per exposure time)	$H = \frac{dQ}{dA} = \int_{t_1}^{t_2} E\ dt$ t_1, t_2: time	May be used for daily sums of global radiation, etc.	45-05-165
radiant intensity	I	$W\ sr^{-1}$	$I = \frac{d\Phi}{d\Omega}$	May be used only for radiation outgoing from "point sources"	45-05-145

*The name radiant exitance has been proposed in CIE (1970) to avoid confusion with the name emittance which has previously been used for this quantity (see also page).

From International Association of Meteorology and Atmospheric Physics (IAMAP) Radiation Comission

Quantitative Description of Radiation-from Textbook

The energy transferred by electromagnetic radiation in a specific direction passing through a unit area (normal to the direction considered) per unit time at a specific wavelength (or wave number) is called *monochromatic intensity* (or *spectral intensity* or *monochromatic radiance)* and is denoted by the symbol I_λ (or I_ν).



radiance	L	$W\ m^{-2}\ sr^{-1}$	$L = \frac{d^2\Phi}{d\Omega\ dA\ \cos\theta}$	The radiance is a conservative quantity in an optical system	45-05-150

Monochromatic intensity is expressed in units of watts per square meter per unit arc of solid angle, per unit wavelength in the electromagnetic spectrum.

The integral of the monochromatic intensity over some finite range of the electromagnetic spectrum is called the *intensity* (or *radiance) I,* which has units of W m^{-2} sr^{-1}

$$I = \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda = \int_{\nu_1}^{\nu_2} I_\nu d\nu$$

In Table, it is given as L.

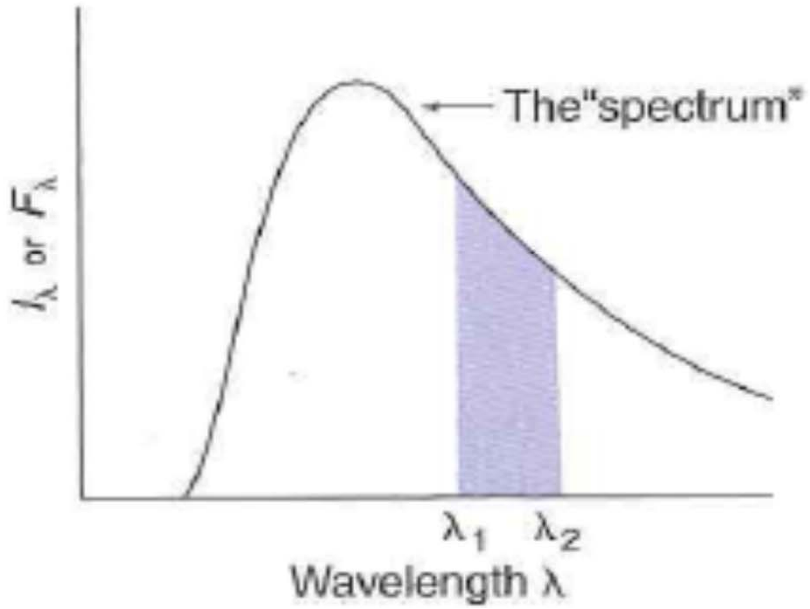
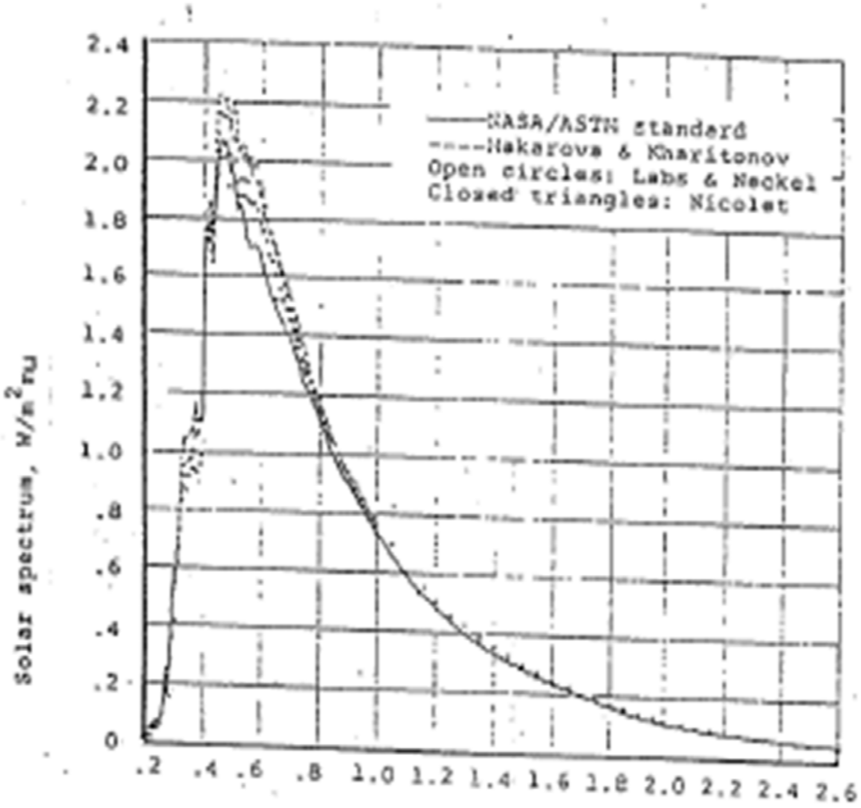
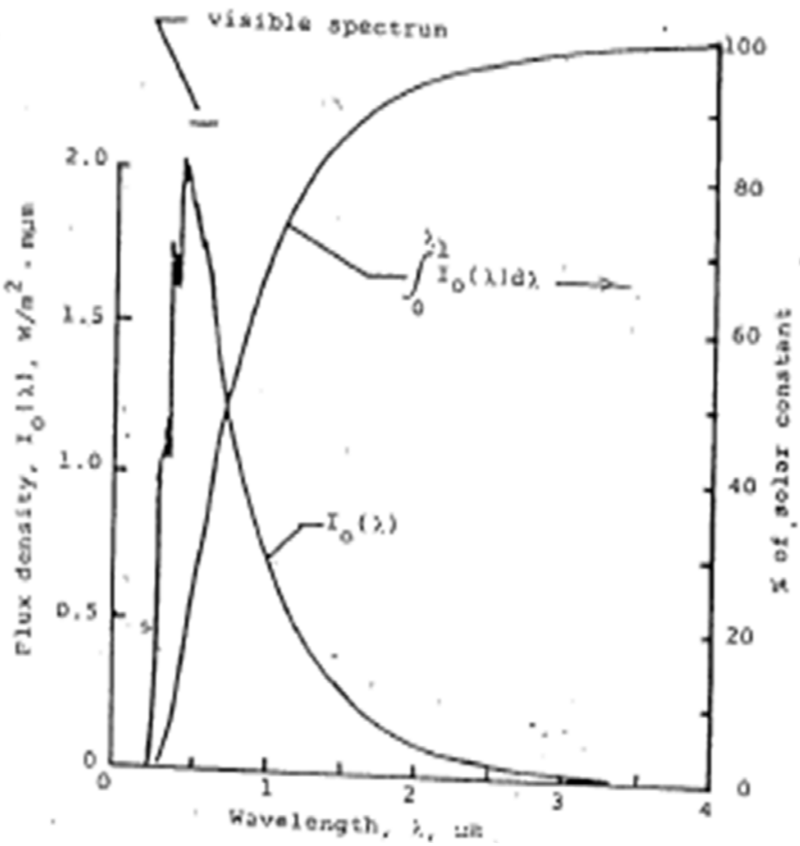


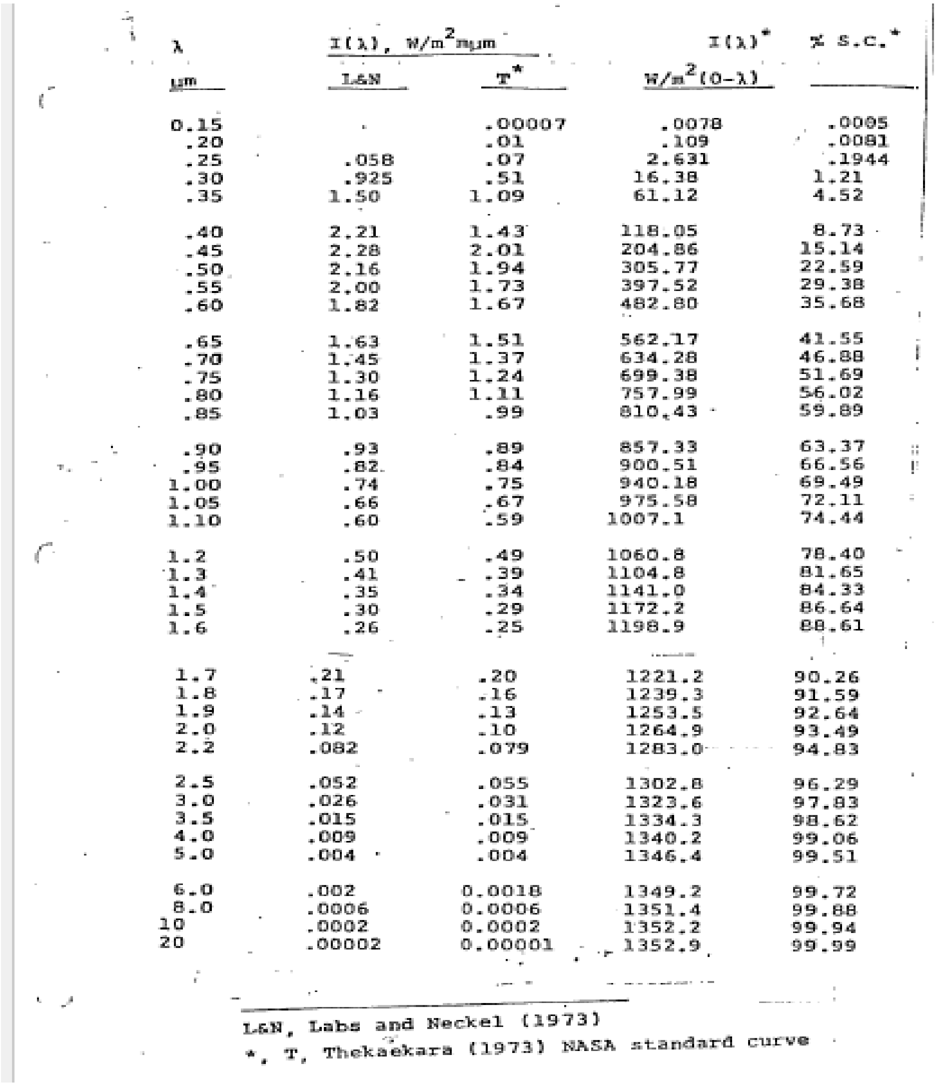
Fig. 4 .2 The curve represents a hypothetical spectrum of monochromatic intensity I_λ as a function of wavelength λ.

The intensity is the area under some finite segment of the spectrum of monochromatic intensity (i.e., the plot of I_λ. as a function of λ).

Given as handout







λ µm	I(λ), W/m^{2}mµm L&N	I(λ), W/m^{2}mµm T*	I(λ)* W/m^2(0–λ)	% S.C.*
0.15		.00007	.0078	.0005
.20		.01	.109	.0081
.25	.058	.07	2.631	.1944
.30	.925	.51	16.38	1.21
.35	1.50	1.09	61.12	4.52
.40	2.21	1.43	118.05	8.73
.45	2.28	2.01	204.86	15.14
.50	2.16	1.94	305.77	22.59
.55	2.00	1.73	397.52	29.38
.60	1.82	1.67	482.80	35.68
.65	1.63	1.51	562.17	41.55
.70	1.45	1.37	634.28	46.88
.75	1.30	1.24	699.38	51.69
.80	1.16	1.11	757.99	56.02
.85	1.03	.99	810.43	59.89
.90	.93	.89	857.33	63.37
.95	.82	.84	900.51	66.56
1.00	.74	.75	940.18	69.49
1.05	.66	.67	975.58	72.11
1.10	.60	.59	1007.1	74.44
1.2	.50	.49	1060.8	78.40
1.3	.41	.39	1104.8	81.65
1.4	.35	.34	1141.0	84.33
1.5	.30	.29	1172.2	86.64
1.6	.26	.25	1198.9	88.61
1.7	.21	.20	1221.2	90.26
1.8	.17	.16	1239.3	91.59
1.9	.14	.13	1253.5	92.64
2.0	.12	.10	1264.9	93.49
2.2	.082	.079	1283.0	94.83
2.5	.052	.055	1302.8	96.29
3.0	.026	.031	1323.6	97.83
3.5	.015	.015	1334.3	98.62
4.0	.009	.009	1340.2	99.06
5.0	.004	.004	1346.4	99.51
6.0	.002	0.0018	1349.2	99.72
8.0	.0006	0.0006	1351.4	99.88
10	.0002	0.0002	1352.2	99.94
20	.00002	0.00001	1352.9	99.99

L&N, Labs and Neckel (1973)

*, T, Thekaekara (1973) NASA standard curve

Given as handout

The *monochroniatic flux density* (or *monochromatic irradiance)* F_λ is a measure of the rate of energy transfer per unit area by radiation with a given wavelength through a plane surface with a specified orientation in three-dimensional space

$$F_\lambda = \int_{2\pi} I_\lambda \cos\theta \, d\omega \qquad (4.5)$$

(in Table it is M or E)

$$F_\lambda = \int_{2\pi} I_\lambda \cos\theta \, d\omega \qquad (4.5)$$

The limit on the bottom of the integral operator indicates that the integration extends over the entire hemisphere of solid angles lying above the plane, $d\omega$ represents an elemental arc of solid angle, and ϑ is the angle between the incident radiation and the direction normal to dA. The factor cos θ represents the spreading and resulting dilution of radiation with a slanted orientation relative to the surface. Monochromatic flux density F_λ. has units of W m- 2 µm $^{-1}$.

Properties of objects: Blackbody

- The ***blackbody*** concept serves as a useful standard for comparing the radiative properties of real surfaces with an ideal surface.
- A real surface will partly reflect and partly absorb incident radiation. It can also partly transmit the incident radiation, namely:
- $1= \alpha_\lambda + \rho_\lambda + \tau_\lambda$
- α_λ is the monochromatic absorption, namely, the ratio of energy absorbed to incident energy
- ρ_λ is the monochromatic reflectance, namely, the ratio of energy reflected to incident
- τ_λ is the monochromatic transmittance, namely, the ratio of energy transmitted to incident.

Radiation Laws

The average or bulk properties of electromagnetic radiation interacting with matter can be summarized in a simple set of rules called *radiation laws*.

These laws apply when the radiating body is what physicists call a *blackbody radiator*. Generally, blackbody conditions apply when the radiator has very weak interaction with the surrounding environment and can be considered to be in a state of equilibrium.

All objects with a temperature above absolute zero emit radiation

Planck Radiation Law

The primary law governing *blackbody* radiation is the *Planck Radiation Law,* which governs the intensity of radiation emitted by unit surface area into a fixed direction (solid angle) from the blackbody as a function of wavelength for a fixed temperature.

The law is named after Max Planck, who originally proposed it in 1900. Namely, **Planck's law** describes the amount of electromagnetic energy with a certain wavelength radiated by a black body in thermal equilibrium (i.e. the spectral radiance of a black body).

The Planck Law can be expressed through the following equation:

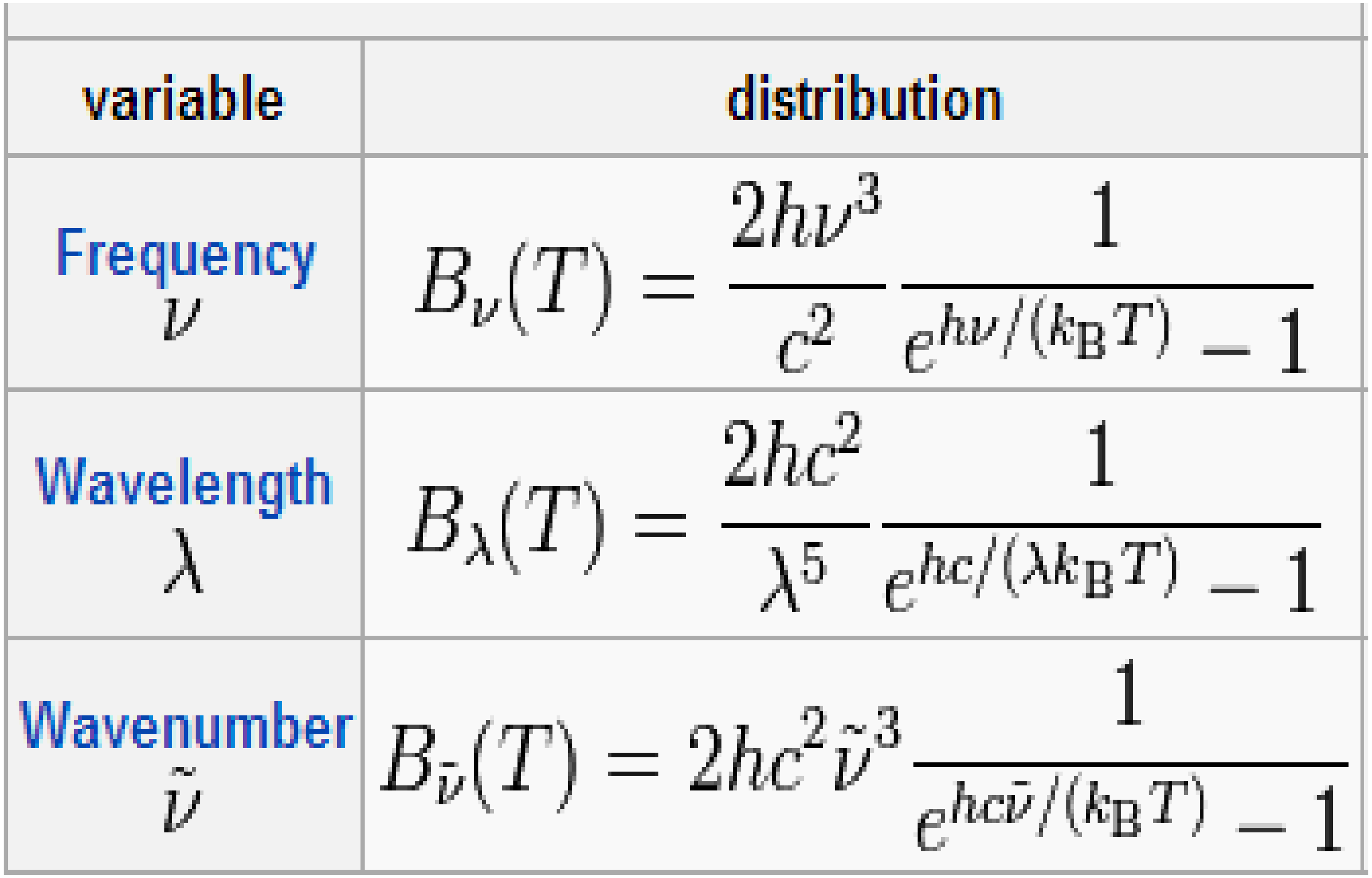
$$E(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

$$h = 6.625 \times 10^{-27} \text{ erg-sec} \quad \text{(Planck Constant)}$$

$$k = 1.38 \times 10^{-16} \text{ erg/K} \quad \text{(Boltzmann Constant)}$$

$$c = 3 \times 10^{10} \text{ cm/sec} \quad \text{(Speed of Light)}$$

Planck's law expressed in terms of different spectral variables



variable	distribution
Frequency ν	$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/(k_\mathrm{B}T)} - 1}$
Wavelength λ	$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/(\lambda k_\mathrm{B}T)} - 1}$
Wavenumber $\tilde{\nu}$	$B_{\tilde{\nu}}(T) = 2hc^2\tilde{\nu}^3\frac{1}{e^{hc\tilde{\nu}/(k_\mathrm{B}T)} - 1}$

The Wien and Stefan-Boltzmann Laws

The behavior of blackbody radiation is described by the Planck Law, but we can derive from the Planck Law two other radiation laws that are very useful.

- The Wien Displacement Law, and the
- Stefan-Boltzmann Law

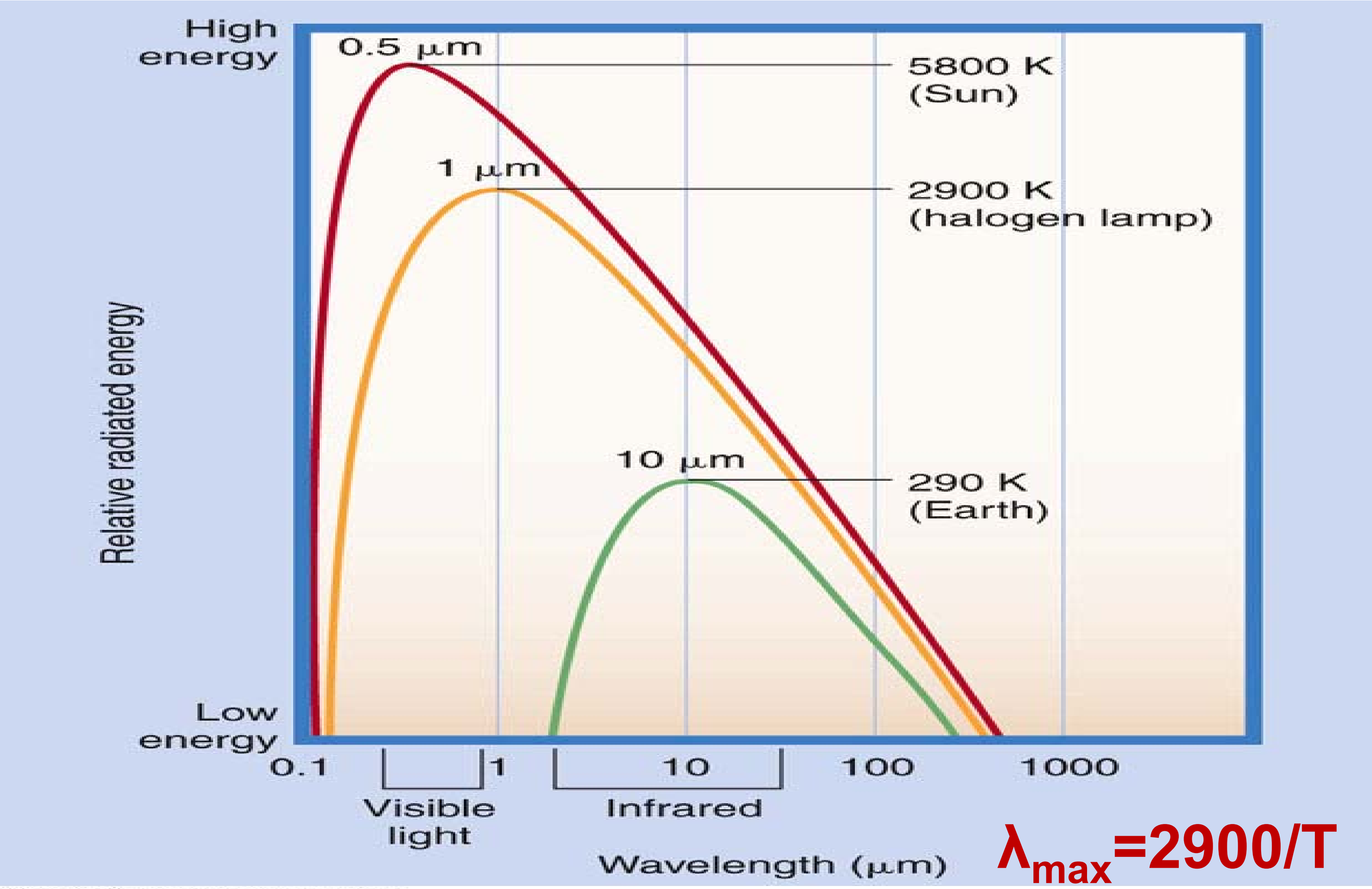
to be illustrated in the following equations.

The Wien displacement law

- Temperature of the emitting body affects the wavelength of the maximal radiant energy emitted.
- German physicist Wilhelm Wien won the 1911 Nobel Prize in physics for this discovery. Wien’s Law can be summarized as, *the hotter an object, the shorter the wavelength of maximum emission of radiation.*
- Wavelength (μm) of max energy= 2900/object temp (K)

$$\lambda_{max}=2900/T$$

Wien’s Law



λ_{max}=2900/T

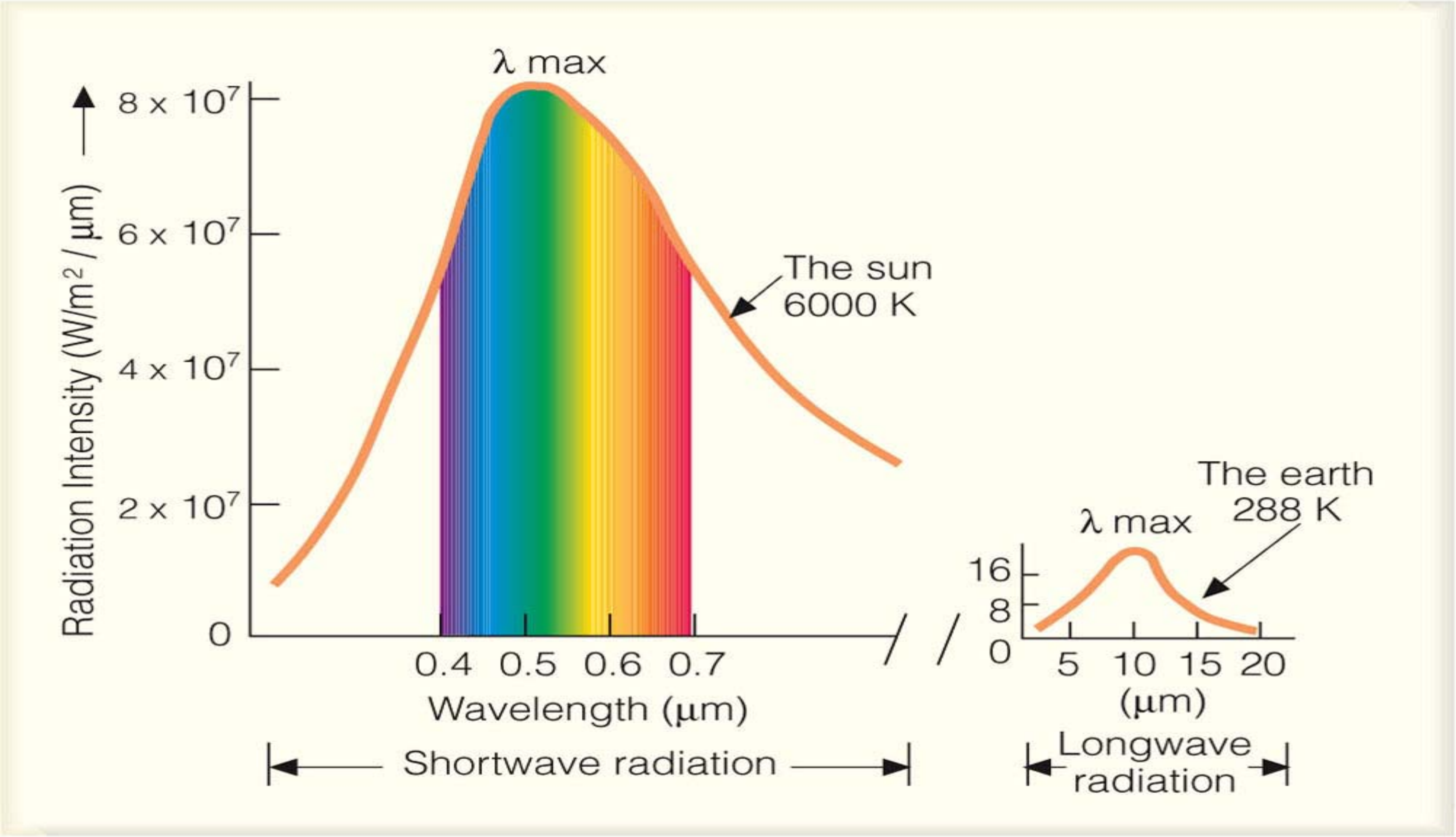
Stefan-Boltzman Law

- Stefan-Boltzmann Law states that the amount of energy per square meter per second that is emitted by an object is related to the fourth power of its Kelvin temperature: $E \sim T^4$

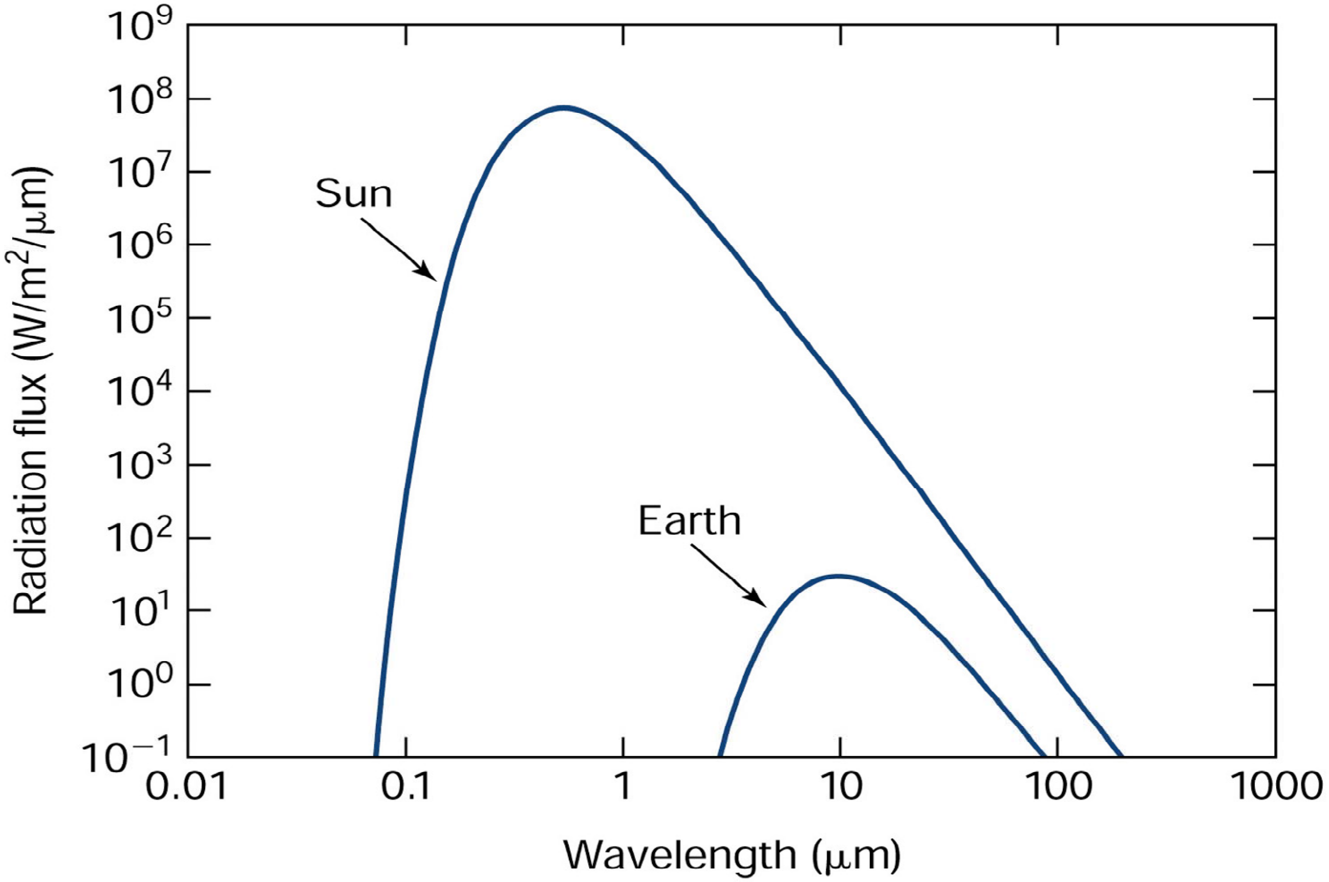
- Therefore, a warmer object emits significantly more radiation than a cooler object- the Sun emits more energy than the Earth.

Note: Sir William Herschel discovered the infrared portion of the spectrum when he placed thermometers above the red portion of a projected spectrum.

Implications of the Stefan-Boltzmann Law: Since the temperature of the sun is much higher than the temperature of the Earth, the amount of energy emitted from the Earth is much less when compared to that from the sun.



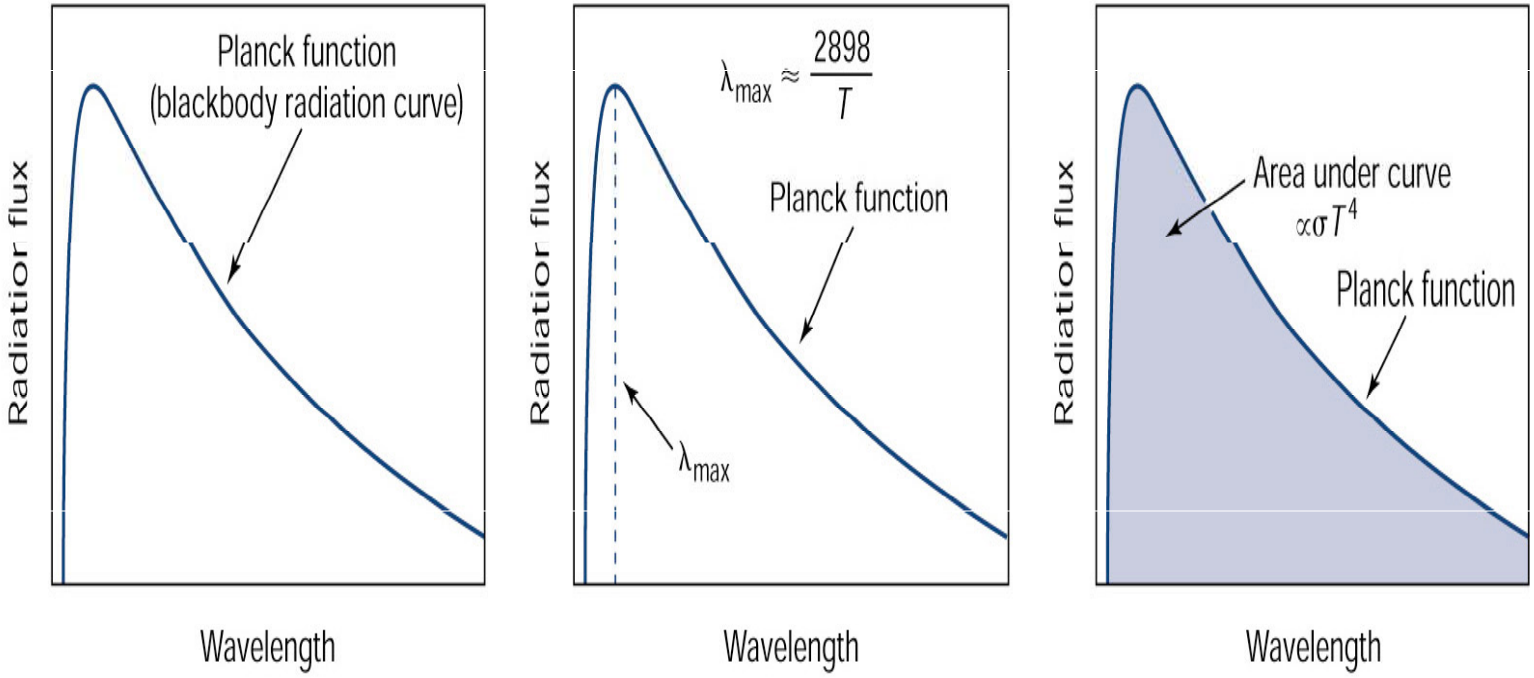
The earth emits radiation called terrestrial or long wave radiation which is less energetic than solar radiation and therefore characterized by longer wavelengths *(similar message as previous slide)*



The *Wien Law* gives the wavelength of the peak of the radiation distribution, while the Stefan-Boltzmann Law gives the total energy being emitted at all wavelengths by the blackbody (which is the area under the Planck Law curve). Thus, the Wien Law explains the shift of the peak to shorter wavelengths as the temperature increases,

while the Stefan-Boltzmann Law explains the growth in the height of the curve as the temperature increases.

a) The Planck function, or blackbody radiation curve; (b) Wien’s law; (c) the Stefan–Boltzmann law



(a) (b) (c)

SIMPLE GLOBAL RADIATIVE EQUILIBRIUM MODEL

Over a long period of time the energy absorbed and emitted balance each other so that equilibrium temperature is maintained.

Can evaluate the global radiative equilibrium temperature from the balance of the incoming solar flux and outgoing thermal infrared flux:

R = Global Albedo

S =Solar Constant

a = Radius of the Earth

T = Temperature

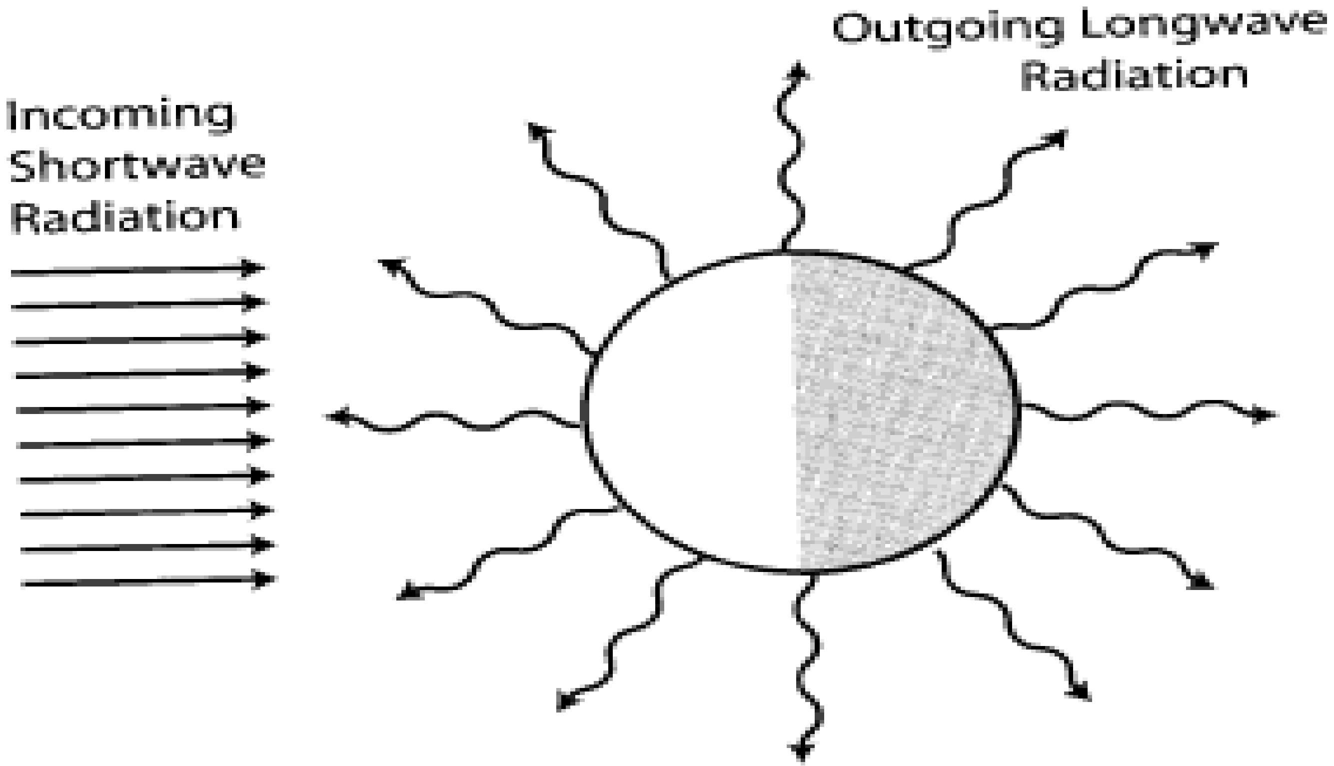
σ= Stephan-Boltzman Constant

Stefan-Boltzmann Law states that total energy per square meter per second that is emitted by an object is related to the fourth power of its Kelvin temperature: $E=\sigma T^4$

From earth emitted:

$$E=\sigma T^4 \text{ x area of earth} = E=\sigma T^4 \text{ x } 4\pi r^2$$

We can derive the equilibrium temperature T_E of Earth by requiring a balance between incoming solar (SW) and outgoing longwave (LW) radiation.



Relationship between incoming solar radiation and outgoing thermal infrared radiation for a spherical object.

The SW is given by the area of the shadow of the object (i.e., its cross-sectional area) times the solar flux:

$$\pi R^2 S_0$$

Part of the incoming SW is reflected back. If the albedo (capacity to reflect) is A:

Reflected part is: $\pi R^2 S_0 \, x A$

We subtract what comes down and what goes back:

$$\pi R^2 S_0 - \pi R^2 S_0 x A = \pi R^2 S_0 (1-A)$$

The second is given by the Stefan-Boltzmann relationship times the surface area:

$$\sigma T^4 \times 4\pi r^2$$

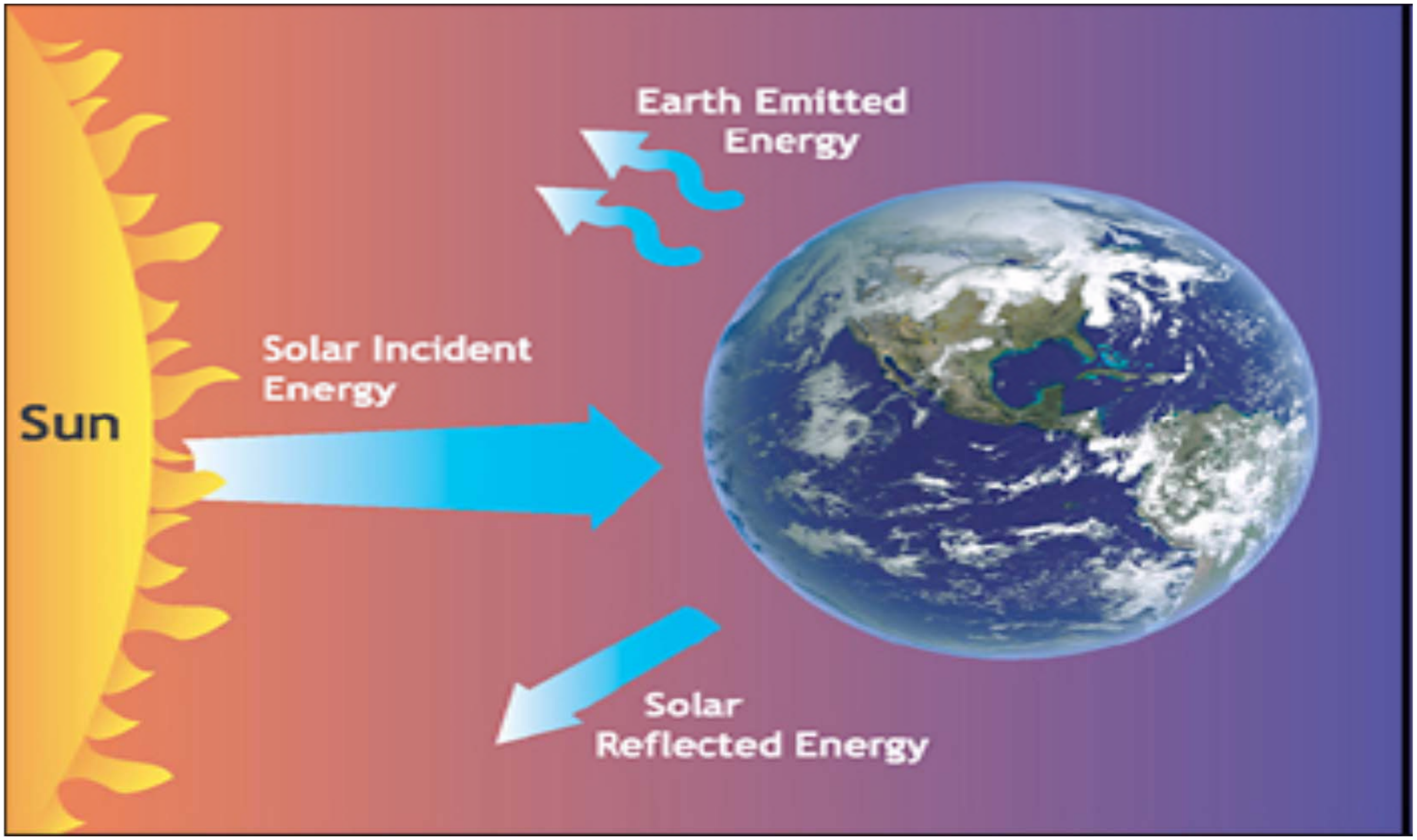
Setting the two fluxes equal to each other:

$$4\pi R^2 \sigma T^4 = \pi R^2 S_0(1-A)$$

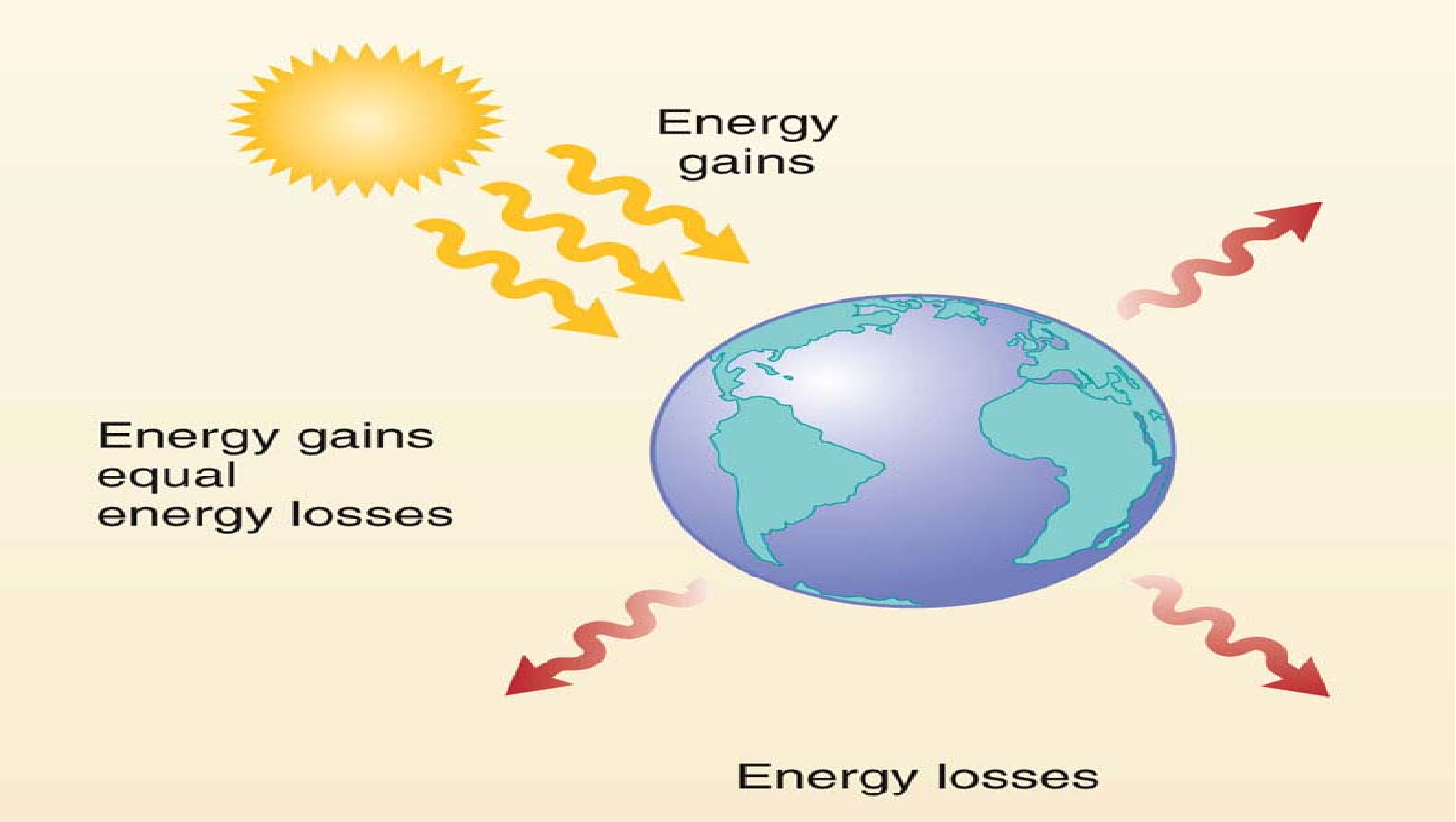
Solve for T:

Average Temperature of Earth -18^0 C

Assumptions for formulating a simple radiation balance climate model: SW and LW fluxes balance each other

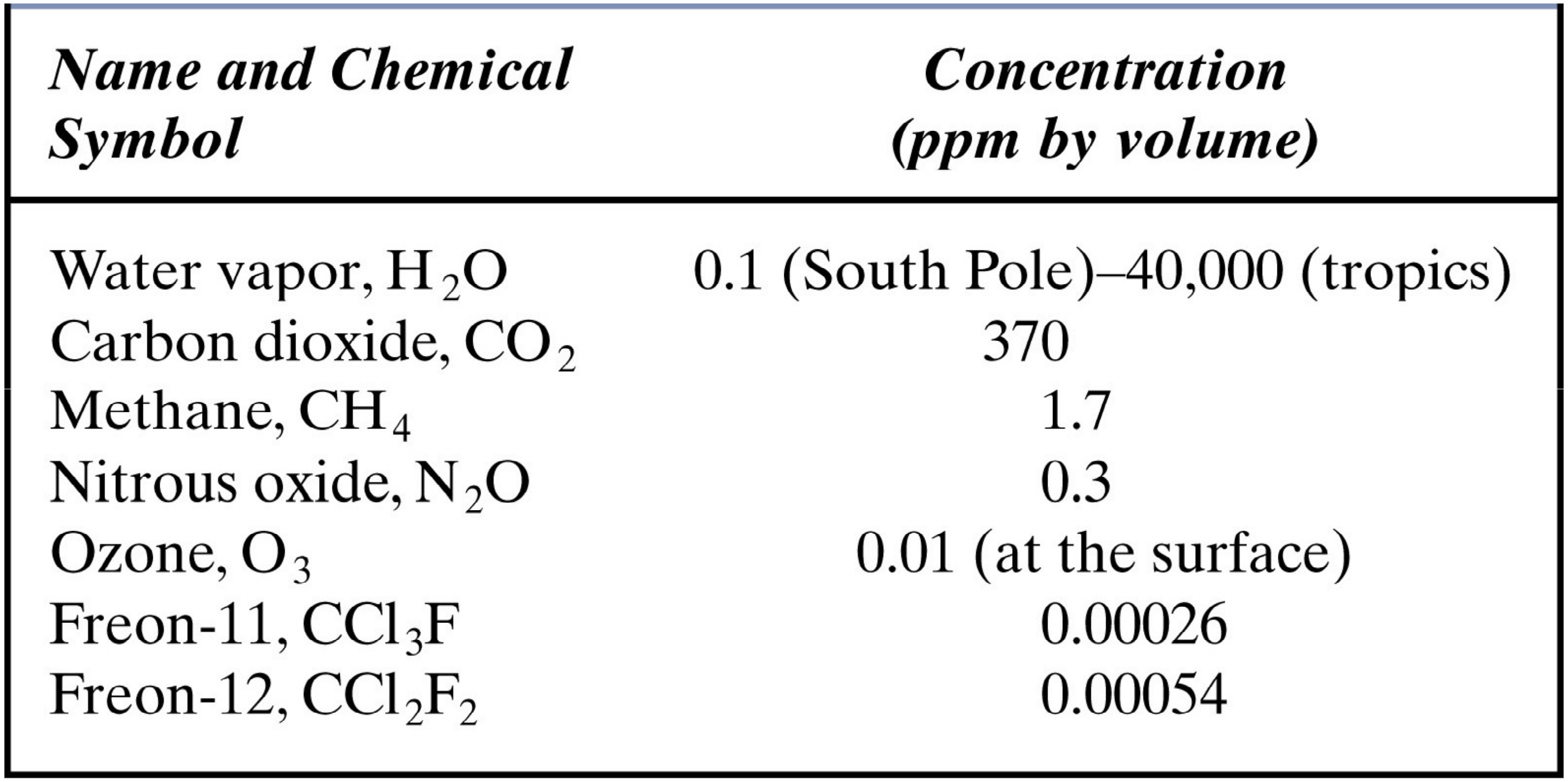


Basic Climate Model



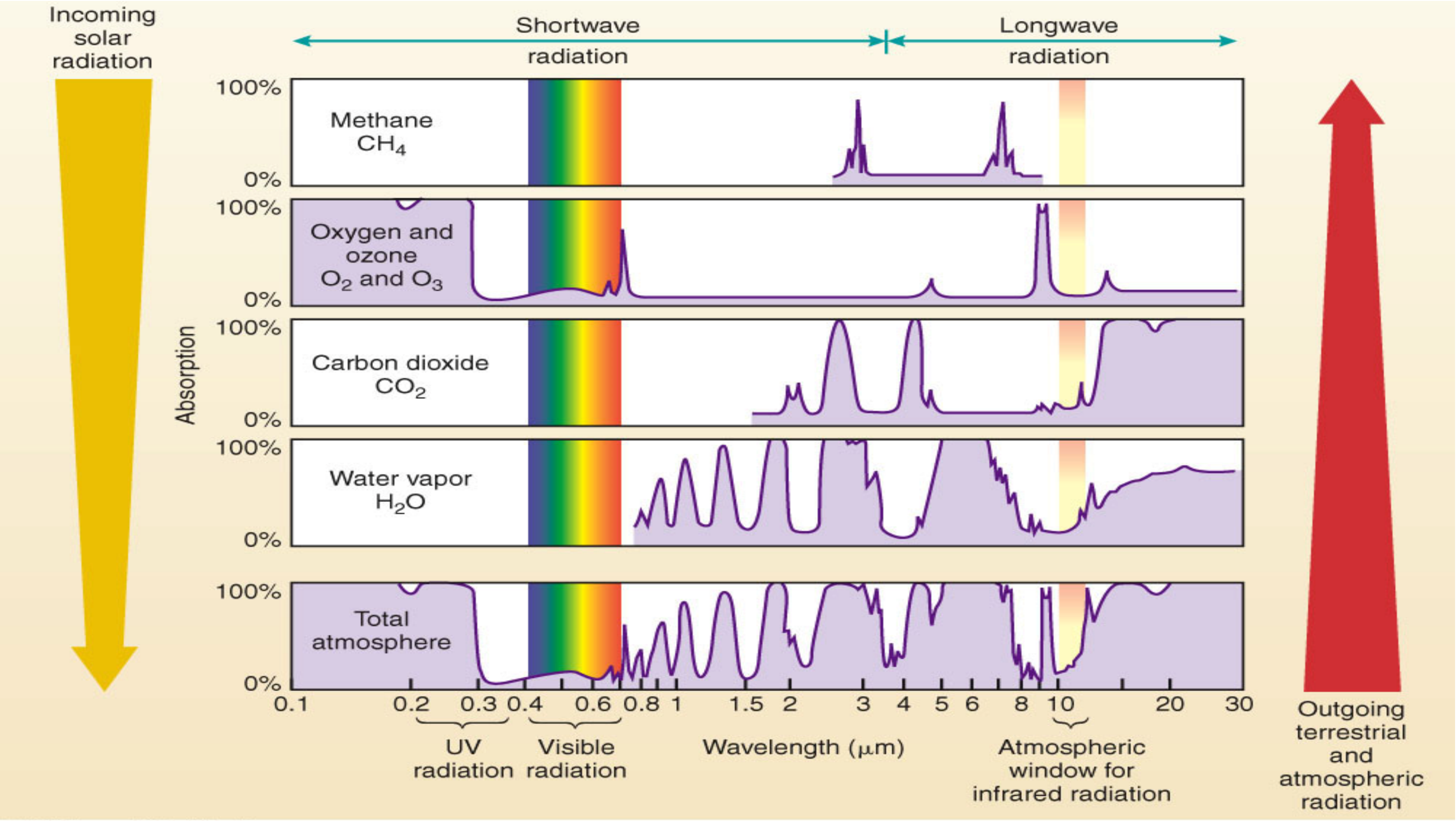
This model yields an average earth temperature of -18^0 C ; Actual value is 15^0 C.

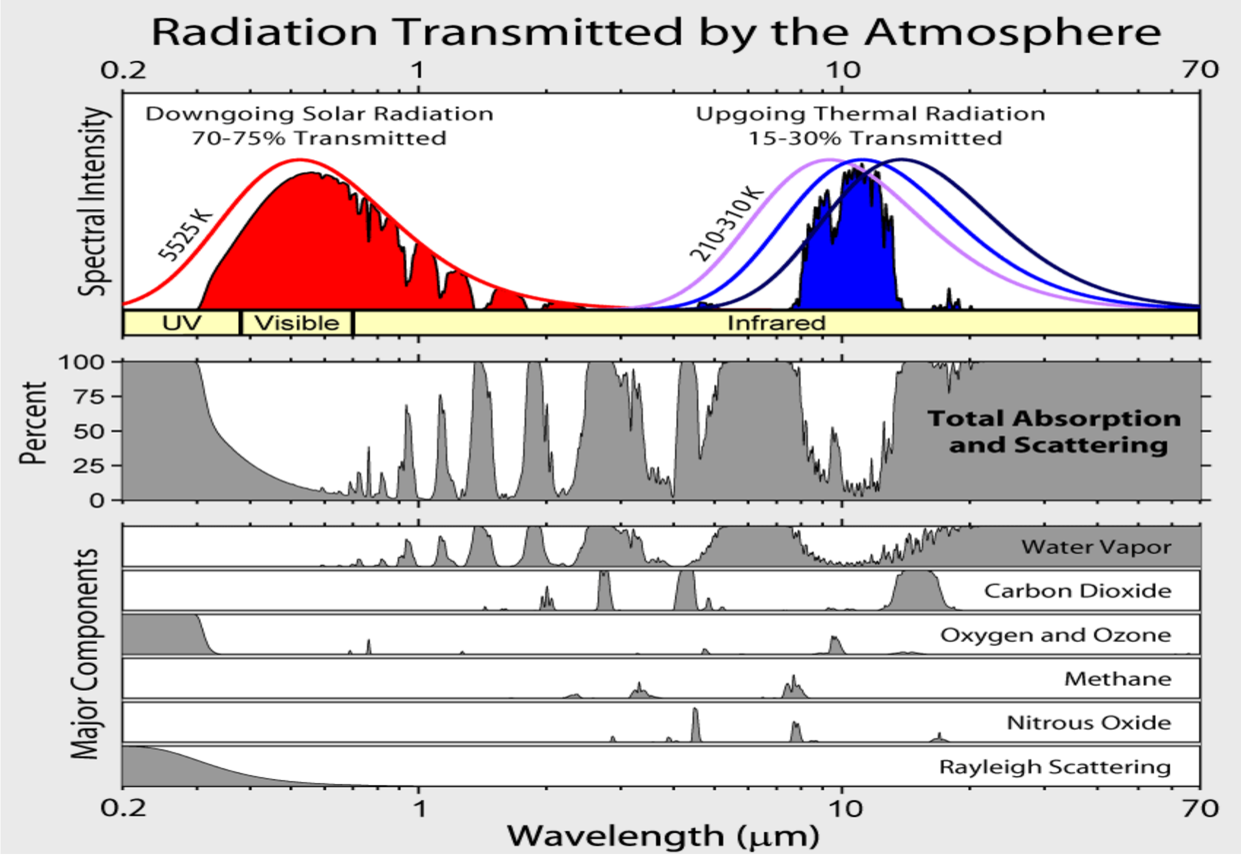
The reason that the actual average Earth temperature is about 15^0 C is due to the role of Atmospheric Greenhouse Gases



Name and Chemical Symbol	*Concentration (ppm by volume)*
Water vapor, H_2O	0.1 (South Pole)–40,000 (tropics)
Carbon dioxide, CO_2	370
Methane, CH_4	1.7
Nitrous oxide, N_2O	0.3
Ozone, O_3	0.01 (at the surface)
Freon-11, CCl_3F	0.00026
Freon-12, CCl_2F_2	0.00054

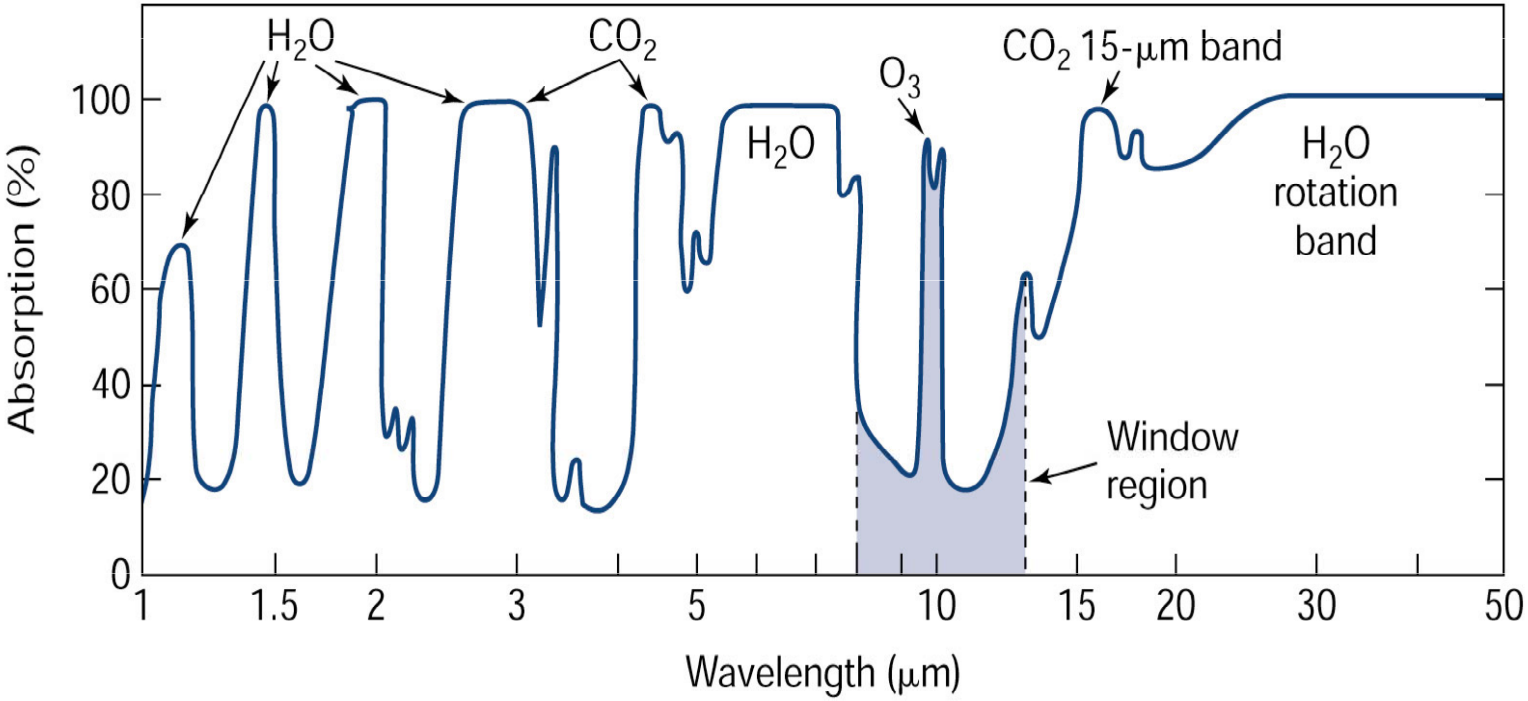
Properties of the atmosphere



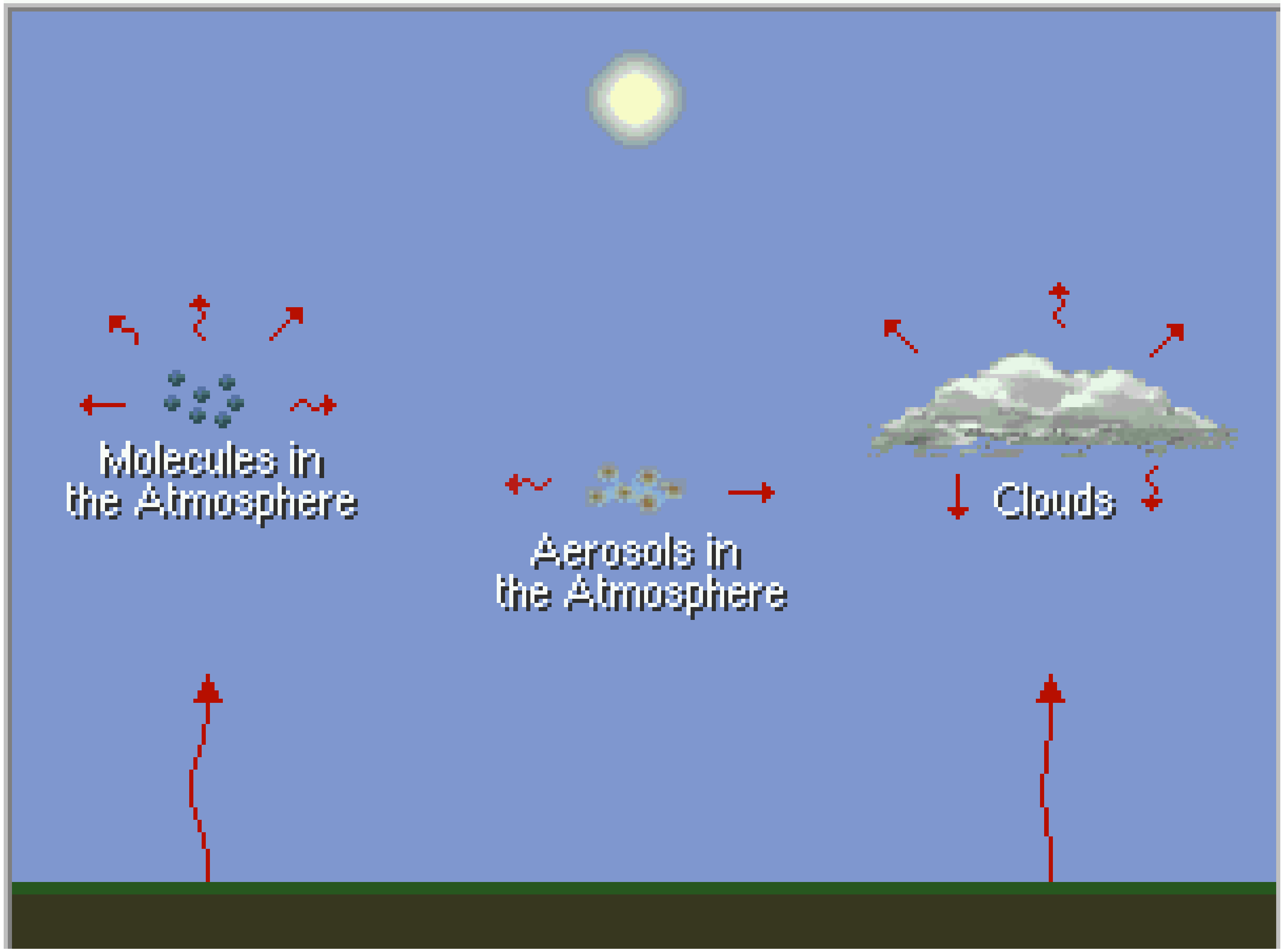


Transformation of radiation that reaches the earth, the Red line indicates radiation that reaches the outer atmosphere, whereas the painted red area is the radiation as it reaches the surface, Aerosols can lower this even more.

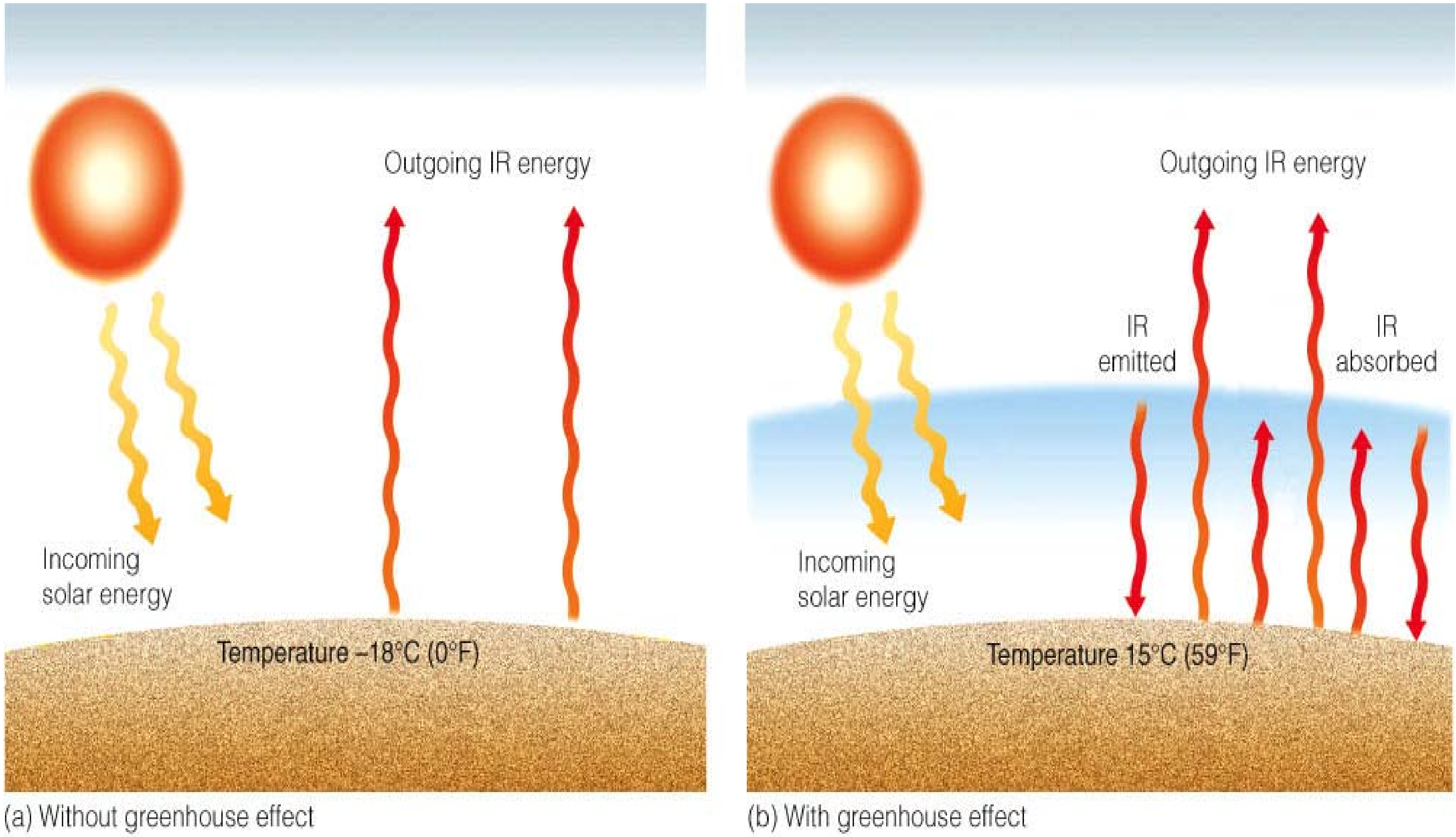
Absorption of 100% - no radiation penetrates the atmosphere. The large absorption beyond 13 μm is caused by CO_2 and H_2O. Both gases also absorb solar radiation in the near infrared (wavelengths between about 0.7 and 5 μm). The absorption at 9.6 μm is caused by ozone.



Re-emission of Infrared Radiation



“The Greenhouse Effect”



(a) Without greenhouse effect

(b) With greenhouse effect

$T_e=[(1-r)S/4\sigma]^{1/4}$; **Actual value of T_e is 15^0 C.**

What drives climate to change? - **“radiative forcing”**: A small change in the energy balance of the earth can change surface temperatures, winds, precipitation patterns => **its climate**