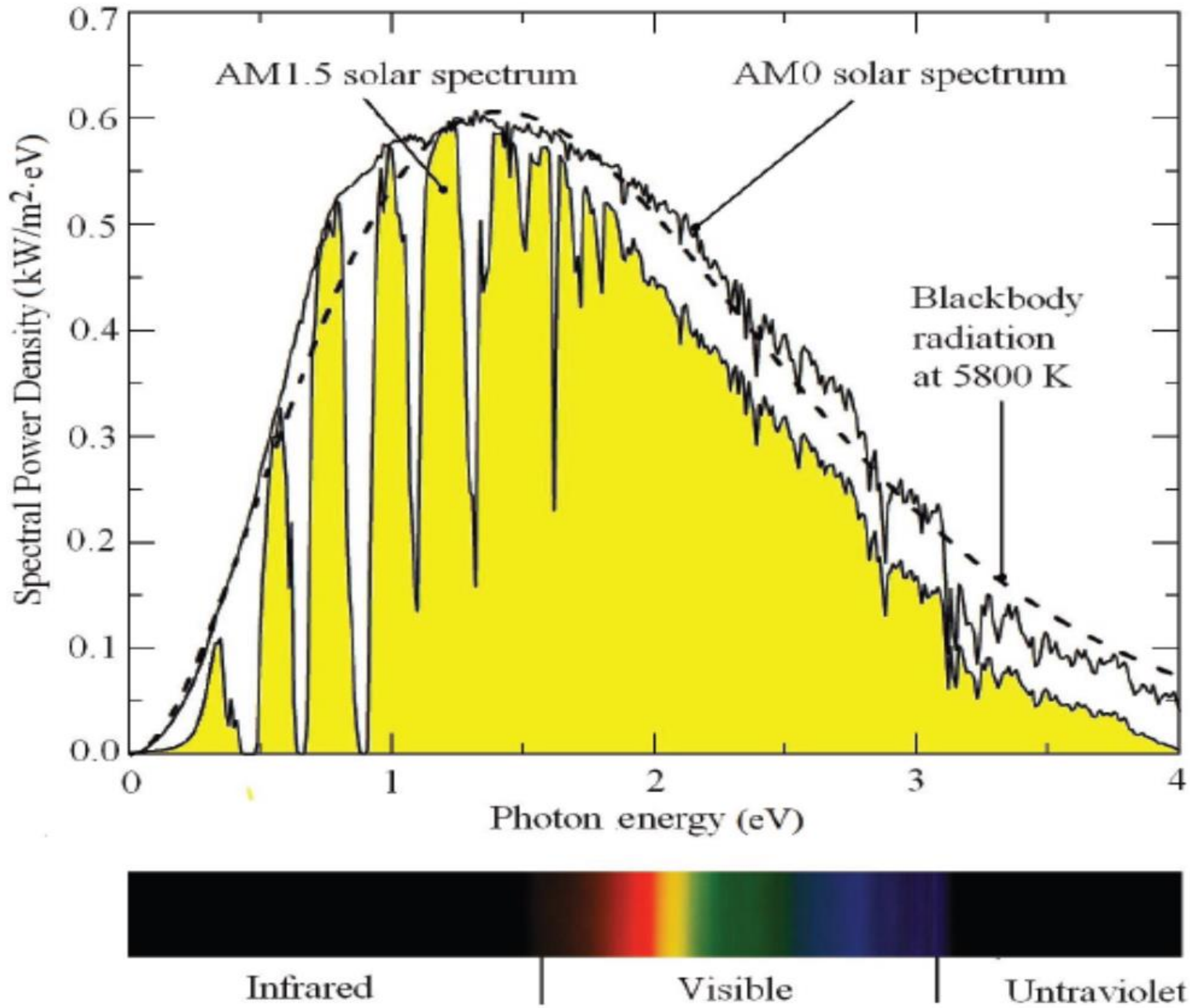
Solar Radiation



The Sun as a Fusion Reactor

Nuclear fusion processes

$$4\,{}^{1}_{1}\mathrm{p} \longrightarrow {}^{4}_{2}\alpha + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}} + \Delta E \tag{2.1}$$

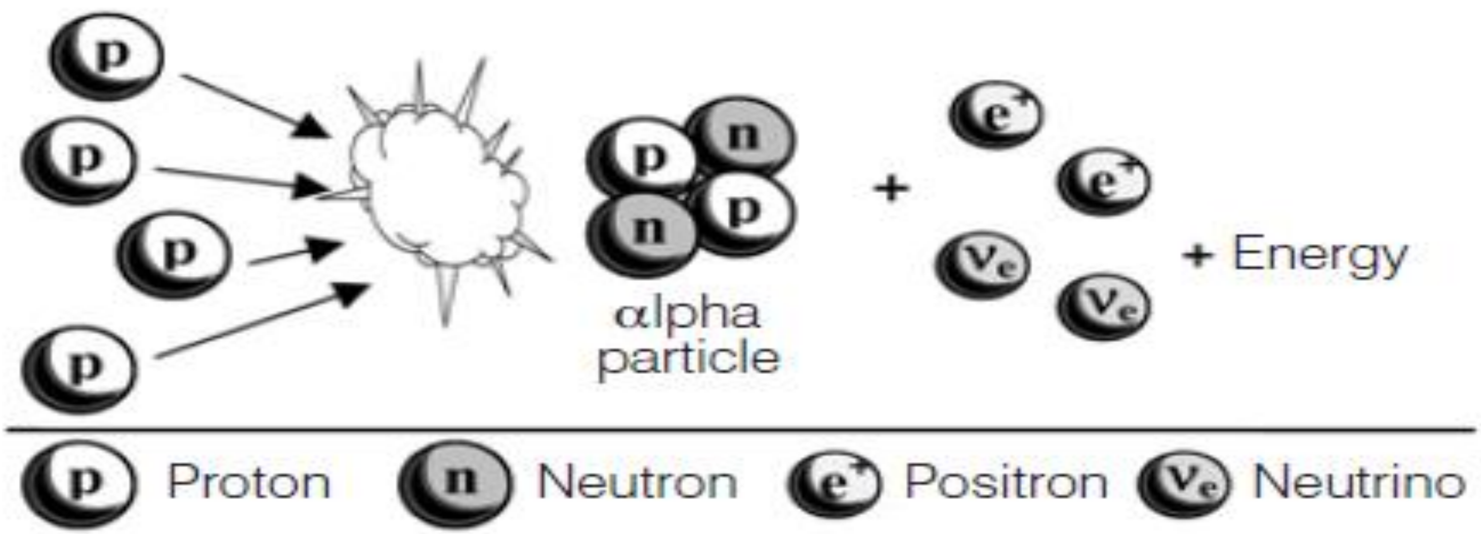


Figure 2.1 *Fusion of Four Hydrogen Nuclei to Form One Helium Nucleus (Alpha Particle)*

The mass difference Δm will be calculated by:

$$\Delta m = 4 \cdot m(^{1}\text{p}) - m(^{4}\alpha) - 2 \cdot m(e^{+})$$

Table 2.3 *Various Particle and Nuclide Masses (1 u = $1.660565 \cdot 10^{-27}$ kg)*

Particle or nuclide	*Mass*	*Particle or nuclide*	*Mass*
Electron (e^-)	0.00054858 u	Hydrogen (^{1}H)	1.007825032 u
Proton (^{1}p)	1.00727647 u	Helium (^{4}He)	4.002603250 u
Neutron (^{1}n)	1.008664923 u	Alpha particle ($^{4}\alpha$)	4.0015060883 u

$$\Delta m = 4 \cdot 1.00727647 \text{ u} - 4.0015060883 \text{ u} - 2 \cdot 0.00054858 \text{ u} = 0.02650263 \text{ u}$$

$$\Delta E = \Delta m \cdot c^2 \qquad c = 2.99792458 \cdot 10^{8} \text{ m/s}$$

$$\Delta E = 3.955 \cdot 10^{-12} \text{ J} = 24.687 \text{ MeV.}$$

The two other electrons and the positrons convert directly into energy. This radiative energy is four times the equivalent mass of an electron of 2.044 MeV.

The total energy released during the reaction is thus 26.731 MeV.

The sun loses 4.3 million metric tonnes of mass per second (Δm $4.3 \cdot 10^9$ kg/s). This results in the solar radiant power $\phi_{e,S}$ of:

$$\phi_{e,S} = \Delta m \cdot c^2 = 3.845 \cdot 10^{26}\ \mathrm{W} \tag{2.4}$$

This value divided by the sun's surface area, A_S, provides the *specific emission of the sun*:

$$M_{e,S} = \frac{\phi_{e,S}}{A_S} = 63.11\ \frac{\mathrm{MW}}{\mathrm{m}^2} \tag{2.5}$$

Radiant physical quantities			*Daylight quantities*		
Name	*Symbol*	*Unit*	*Name*	*Symbol*	*Unit*
Radiant energy	Q_e	Ws = J	Quantity of light	Q_v	lm s
Radiant flux/radiant power	Φ_e	W	Luminous flux	Φ_v	lm
Specific emission	M_e	W/m^2	Luminous exitance	M_v	lm/m^2
Radiant intensity	I_e	W/sr	Luminous intensity	I_v	cd = lm/sr
Radiance	L_e	W/(m^2 sr)	Luminance	L_v	cd/m^2
Irradiance	E_e G	W/m^2	Illuminance	E_v	lx = lm/m^2
Irradiation	H_e	Ws/m^2	Light exposure	H_v	lx s

Note: W = watt; m = metre; s = second; sr = steradian; lm = lumen; lx = lux; cd = candela

Source: DIN, 1982; ISO, 1993

Table 2.2 *Data for the Sun and the Earth*

	Sun	*Earth*	*Ratio*
Diameter (km)	1,392,520	12,756	1:109
Circumference (km)	4,373,097	40,075	1:109
Surface (km^2)	$6.0874 \cdot 10^{12}$	$5.101 \cdot 10^{8}$	1:11,934
Volume (km^3)	$1.4123 \cdot 10^{18}$	$1.0833 \cdot 10^{12}$	1:1,303,670
Mass (kg)	$1.9891 \cdot 10^{30}$	$5.9742 \cdot 10^{24}$	1:332,946
Average density (g/cm^3)	1.409	5.516	1:0.26
Gravity (surface) (m/s^2)	274.0	9.81	1:28
Surface temperature (K)	5777	288	1:367
Centre temperature (K)	15,000,000	6700	1:2200

The sun's irradiance can be approximated to that of a black body. The *Stefan–Boltzmann law*:

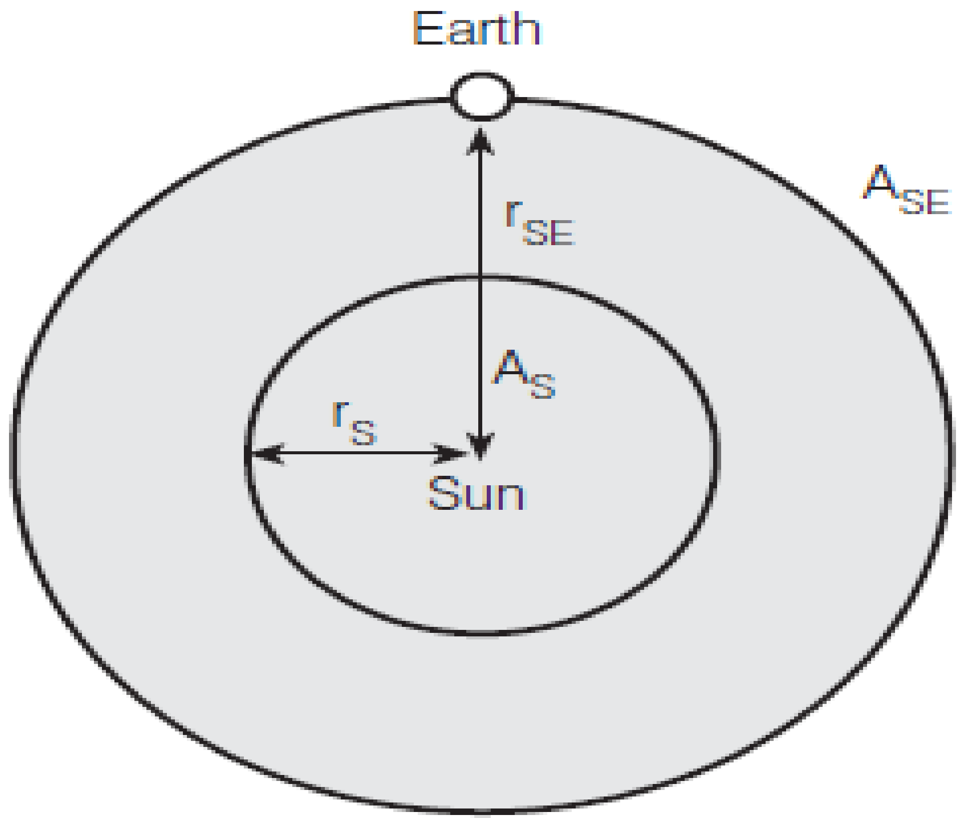
$$M_e(T) = \sigma \cdot T^4 \qquad (2.6)$$

can be used to estimate the *surface temperature of the sun*, T_{sun}. With the Stefan–Boltzmann constant $\sigma = 5.67051 \cdot 10^{-8}$ W/(m^2 K^4), it becomes:

$$T_{sun} = \sqrt[4]{\frac{M_{e,S}}{\sigma}} = 5777\ \text{K} \qquad (2.7)$$

With $M_{e,S} \cdot A_S = E_e \cdot A_{SE}$ and substituting $A_{SE} = 4 \cdot \pi \cdot r_{SE}^2$, the irradiance at the Earth, E_e, finally becomes:

$$E_e = M_{e,S} \cdot \frac{A_S}{A_{SE}} = M_{e,S} \cdot \frac{r_S^{\,2}}{r^2_{SE}} \qquad (2.8)$$



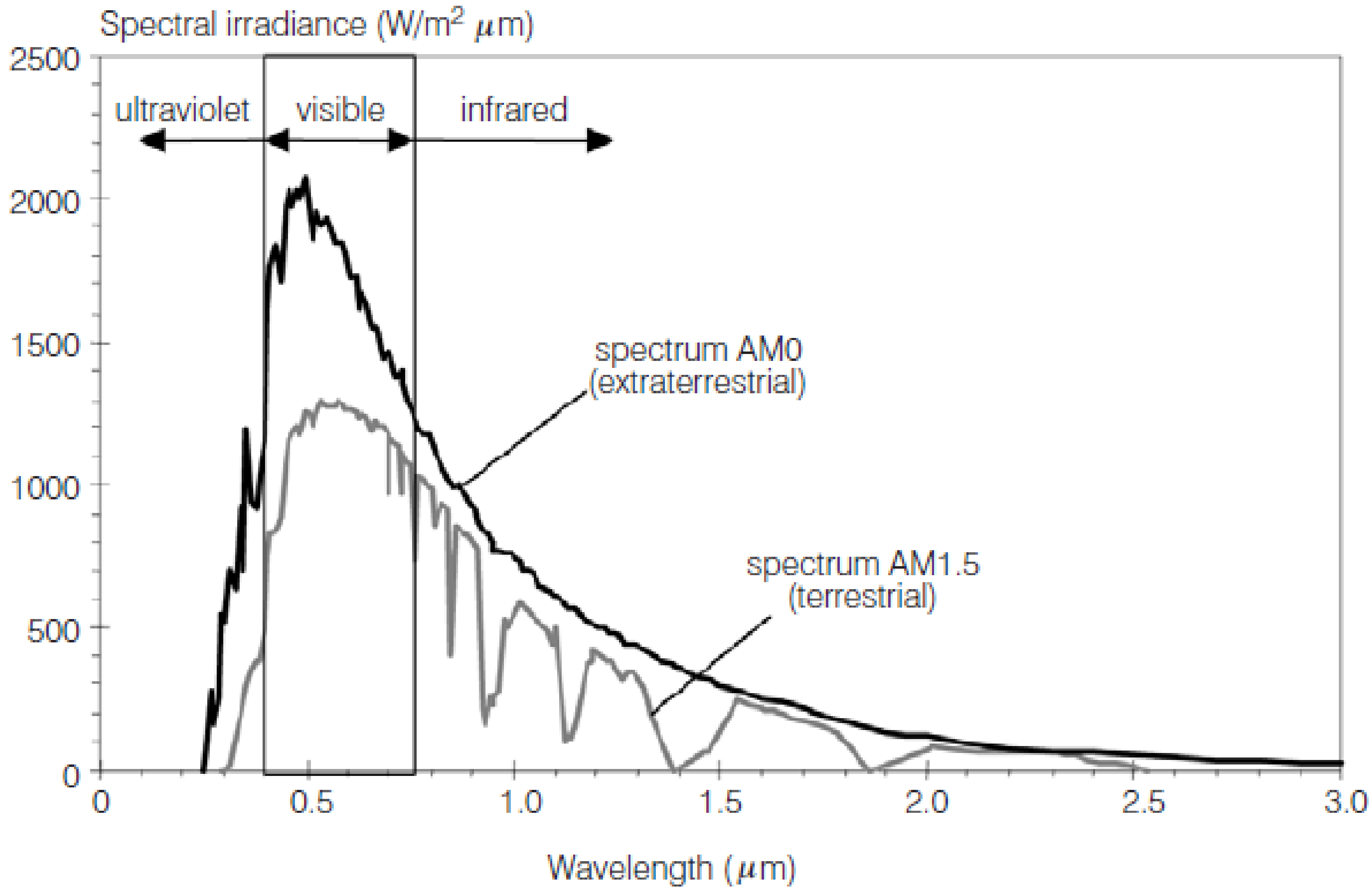
With $M_{e,S} \cdot A_S = E_e \cdot A_{SE}$ and substituting $A_{SE} = 4 \cdot \pi \cdot r_{SE}^2$, the irradiance at the Earth, E_e, finally becomes:

$$E_e = M_{e,S} \cdot \frac{A_S}{A_{SE}} = M_{e,S} \cdot \frac{r_S{}^2}{r^2{}_{SE}} \tag{2.8}$$

This determines the extraterrestrial irradiance experienced at Earth's orbital distance from the sun. However, the distance between the sun and Earth is not constant throughout the year. It varies between $1.47 \cdot 10^8$ km and $1.52 \cdot 10^8$ km. This causes a variation in the irradiance, E_e, of between 1325 W/m^2 and 1420 W/m^2. The average value, called the *solar constant*, E_0, is:

$$E_0 = 1.367 \pm 2 \text{ W/m}^2 \tag{2.9}$$

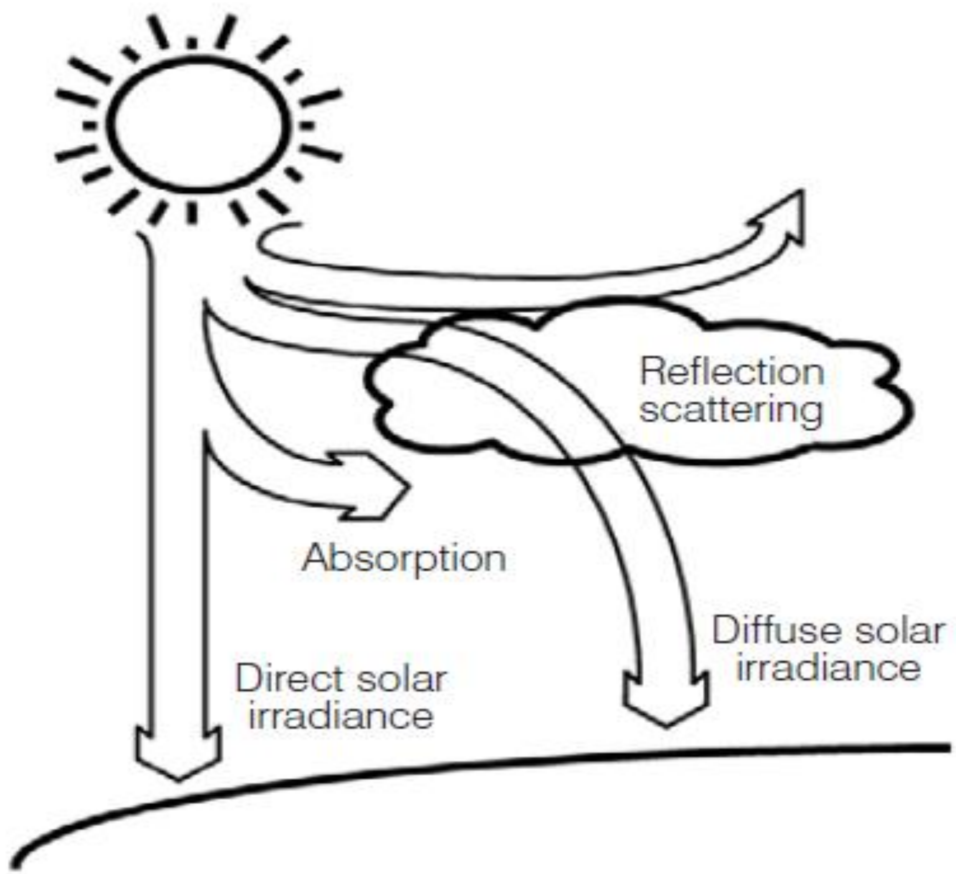
This value can be measured outside the Earth's atmosphere on a surface perpendicular to the solar radiation. The symbol I_0 is also used for the solar constant.



*Note: AM*0 is the extraterrestrial spectrum; *AM*1.5 is the spectrum on the Earth's surface at a sun height of 41.8°

Figure 2.3 ***Spectrum of Sunlight***

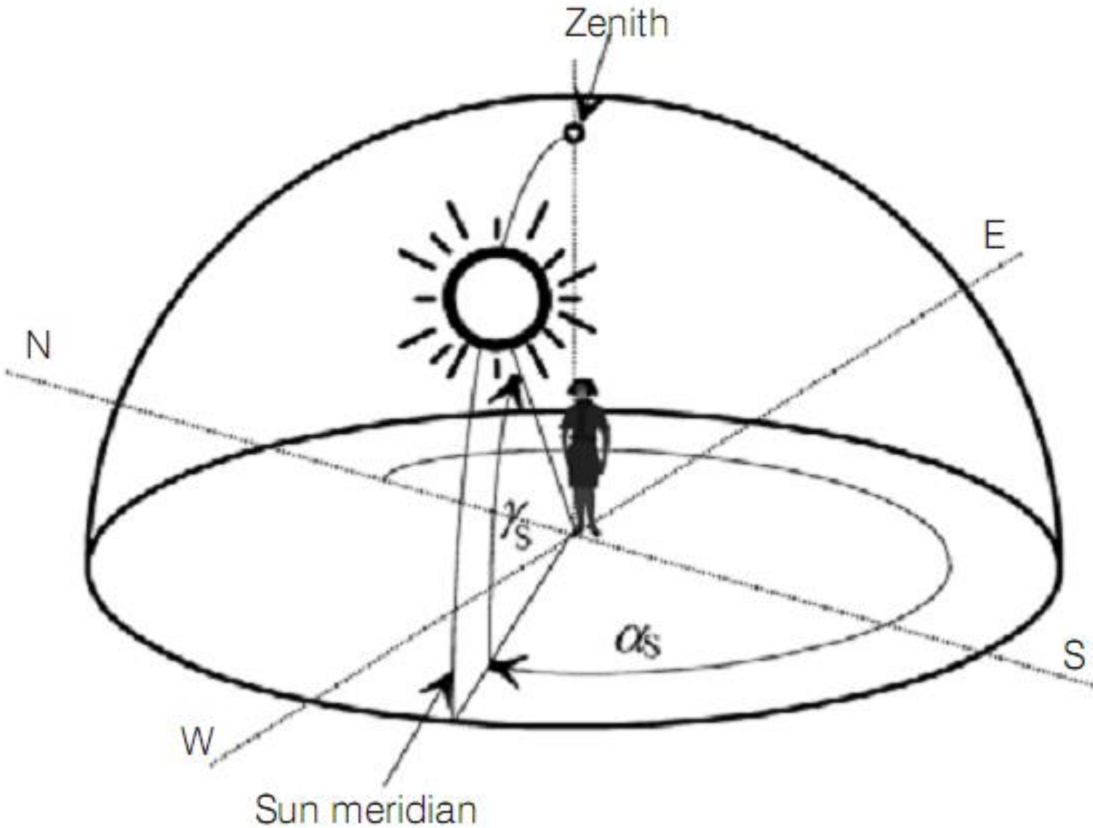
- reduction due to reflection by the atmosphere
- reduction due to absorption in the atmosphere (mainly O_3, H_2O, O_2 and CO_2)
- reduction due to Rayleigh scattering
- reduction due to Mie scattering.

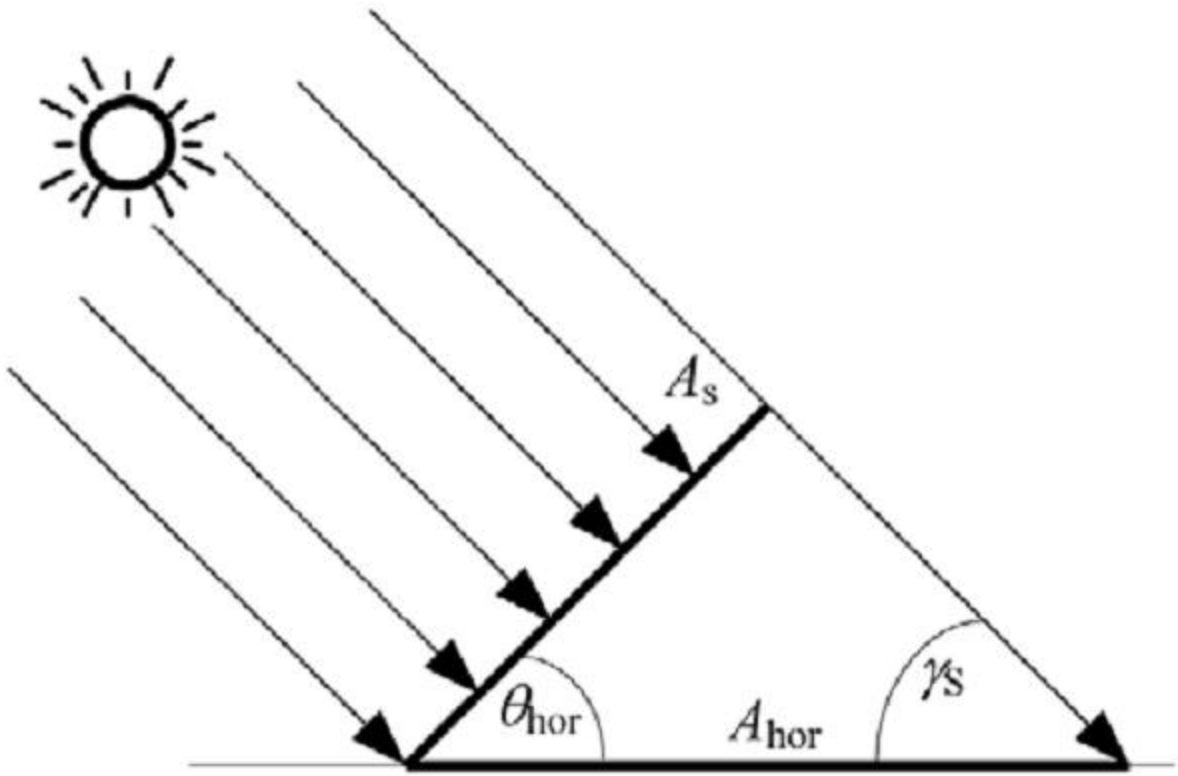


Molecular air particles with diameters smaller than the wavelength of light cause *Rayleigh scattering*. The influence of Rayleigh scattering rises with decreasing light wavelength.

Dust particles and other air pollution cause *Mie scattering*. The diameter of these particles is larger than the wavelength of the light. Mie scattering depends significantly on location; in high mountain regions it is relatively low, whereas in industrial regions it is usually high.

Visible Light


Zenith
E
N
γ_S
α_S
S
W
Sun meridian


A_s
θ_{hor}
A_{hor}
γ_S

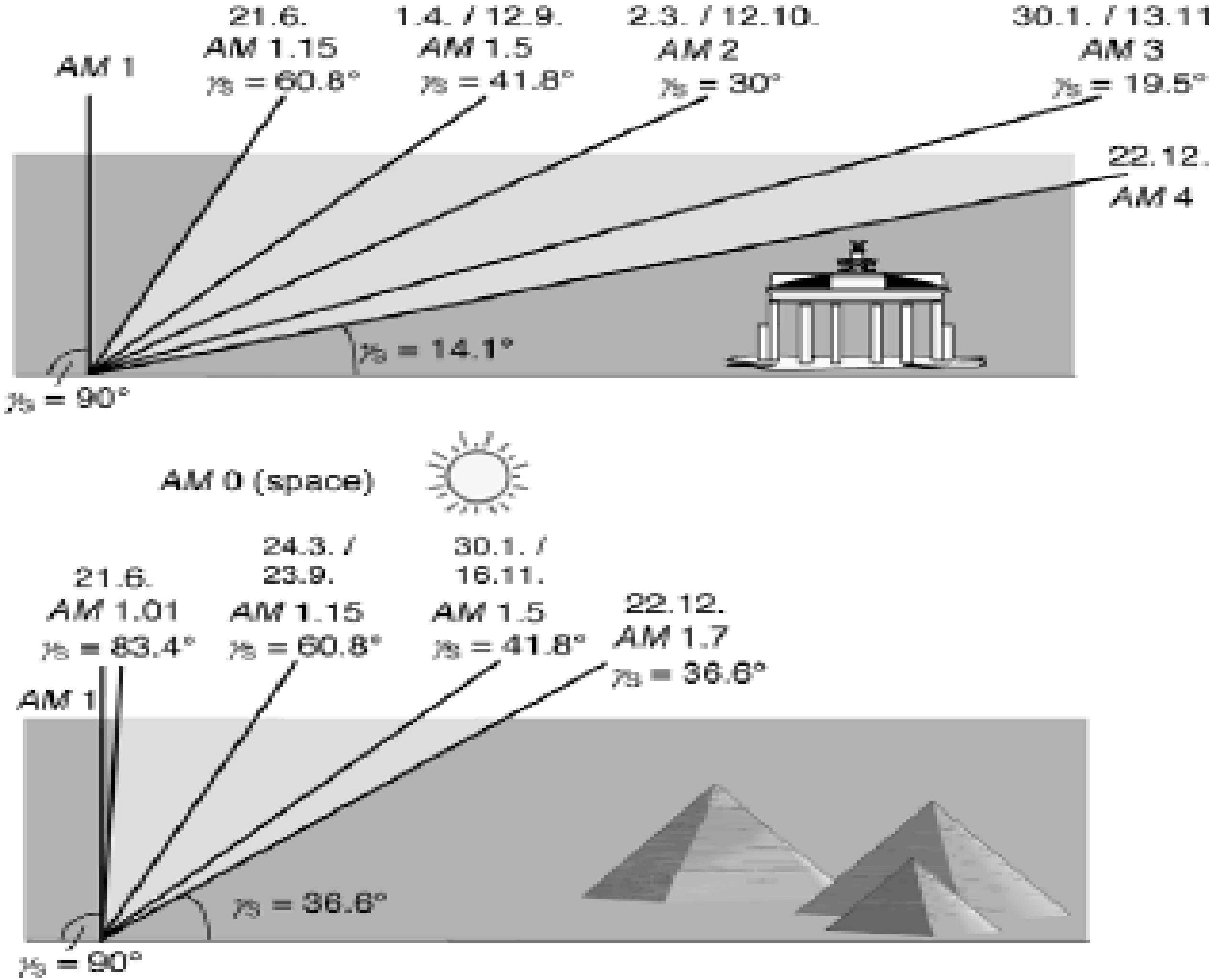
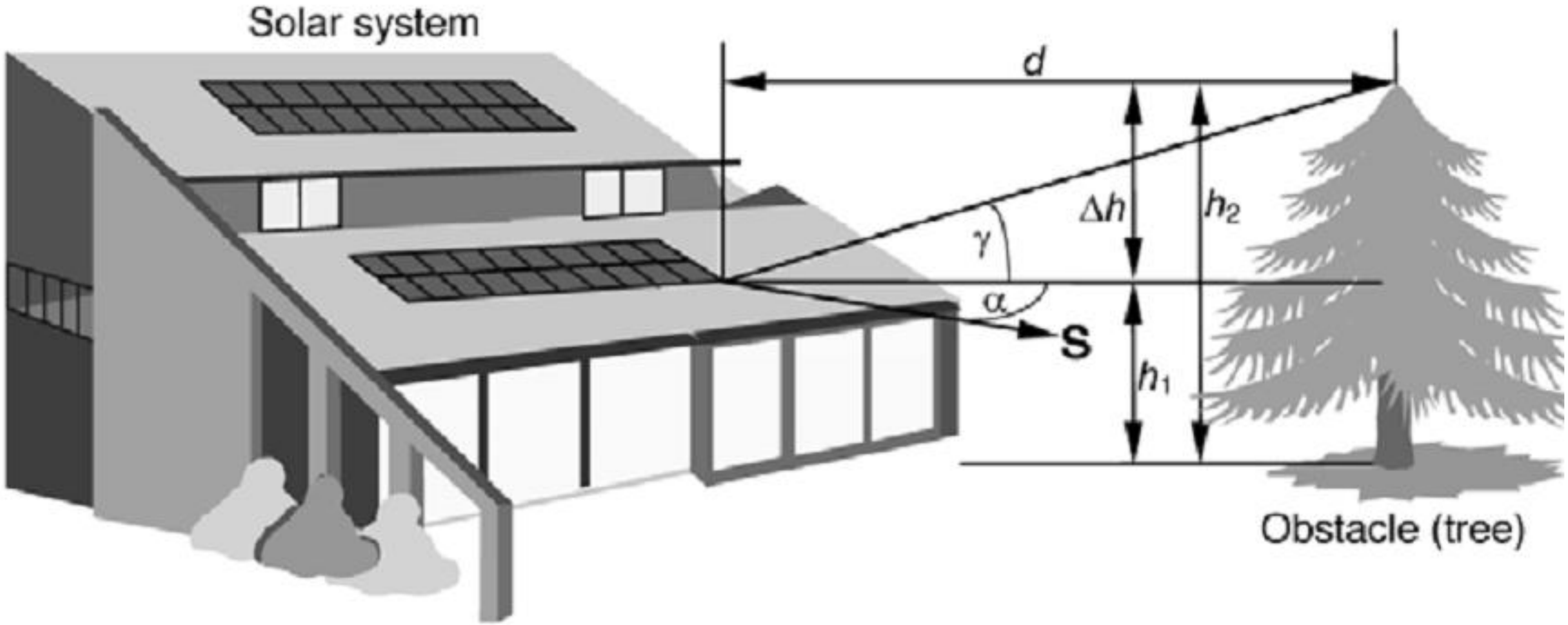


Figure 2.4 *Sun Height at Solar Noon and Air Mass (AM) Values for Variou Dates in Berlin (top) and Cairo (bottom)*


Solar system
d
Δh
h2
γ
α
S
h1
Obstacle (tree)

Solar thermal

power plants. The main operational areas are:

- solar swimming pool heating
- solar domestic water heating
- solar low-temperature heat for space heating in buildings
- solar process heat
- solar thermal electricity generation.

Table 3.1 *Thermodynamic Quantities for Thermal Calculations*

Name	*Symbol*	*Unit*
Heat, energy	Q	Ws (= J) or kWh
Heat flow	$\dot{Q}$	W
Temperature	ϑ	°C
Thermodynamic temperature	T	K (Kelvin, 0 K = –273.15°C)
Specific heat capacity	c	J/(kg K)
Thermal conductivity	λ	W/(m K)
Heat transition coefficient	K'	W/(m K)
Coefficient of heat transfer	k	W/(m^2 K)
Surface coefficient of heat transfer	α	W/(m^2 K)