UNIT 1: Basics of Radiation

- Energy transfer through radiation
- Concept of blackbody radiation, Kirchhoff's law
- Radiation laws of Planck, Stefan-Boltzmann and Wien
- Radiation quantities
- Examples

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Radiative energy transfer

- Radiation is one of three basic **energy transfer** processes
- Transfer is performed by **electromagnetic waves**
- expressed in terms of **photon energy**
- Quantum mechanics: Photon energy is quantized and related to discrete **energy states** in the emitting source

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Electromagnetic Radiation

Light can be characterized by

- **Wavelength** λ, measured in μm, nm, Å
- **Frequency** ν, measured in s^{-1} (Hz)
- **Energy** E, measured in J, eV
- **Temperature** T, measured in K

These quantities are related by

$$\lambda\nu = c$$

$$E = h\nu$$

$$T = E/k$$

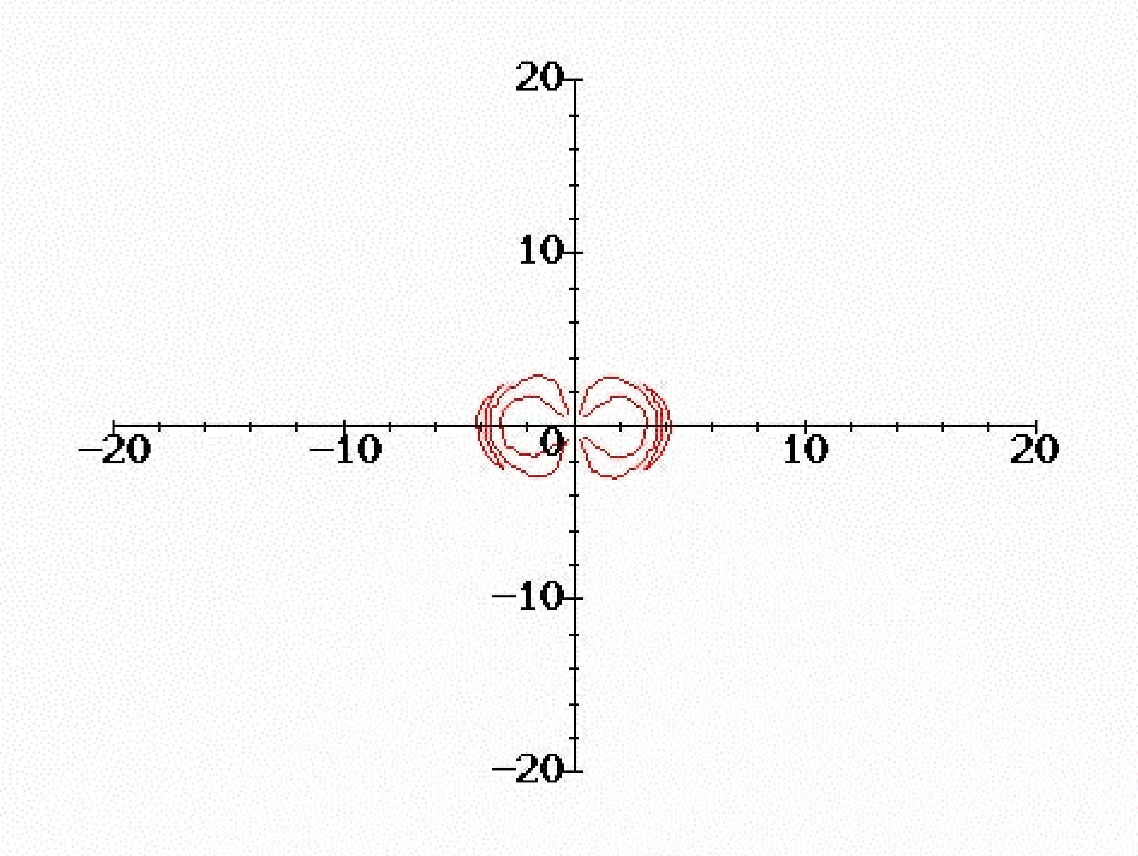
where

$c = 2.9979245800 \times 10^{8}\ ms^{-1}$

$h = 6.62606876 \times 10^{-34}\ Js$

$k = 1.3806503 \times 10^{-23}\ JK^{-1}$

Radiation from an Oscillating Electric Dipole



http://physics.usask.ca/~hirose/ep225/radiation.htm

Electric field lines due to an electric dipole oscillating vertically at the origin.

Near the dipole, the field lines are essentially those of a static dipole leaving a positive charge and ending up at a negative charge. At a distance greater than half the wavelength, the field lines are completely detached from the dipole. The radiation field propagates *freely* (without being attached to charges) in free space at the speed *c*.

Maxwell Equations

governing the the behavior of electric and magnetic fields

$$\nabla \cdot \varepsilon \mathbf{E} = \rho$$

$$\nabla \cdot \mu \mathbf{H} = 0$$

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}$$

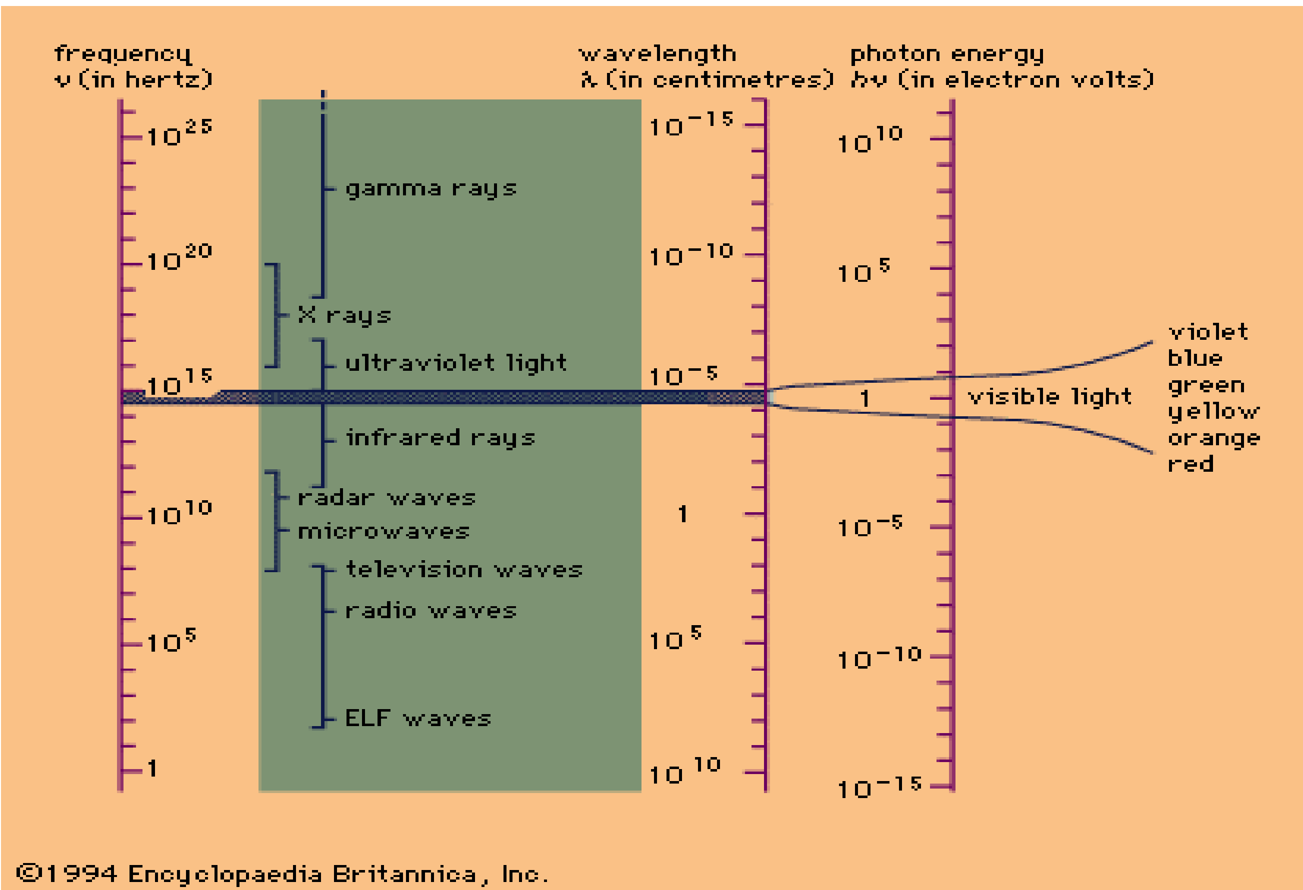
$$\nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t}$$

E electric field
H magnetic field
ρ free electric charge density
J free current density

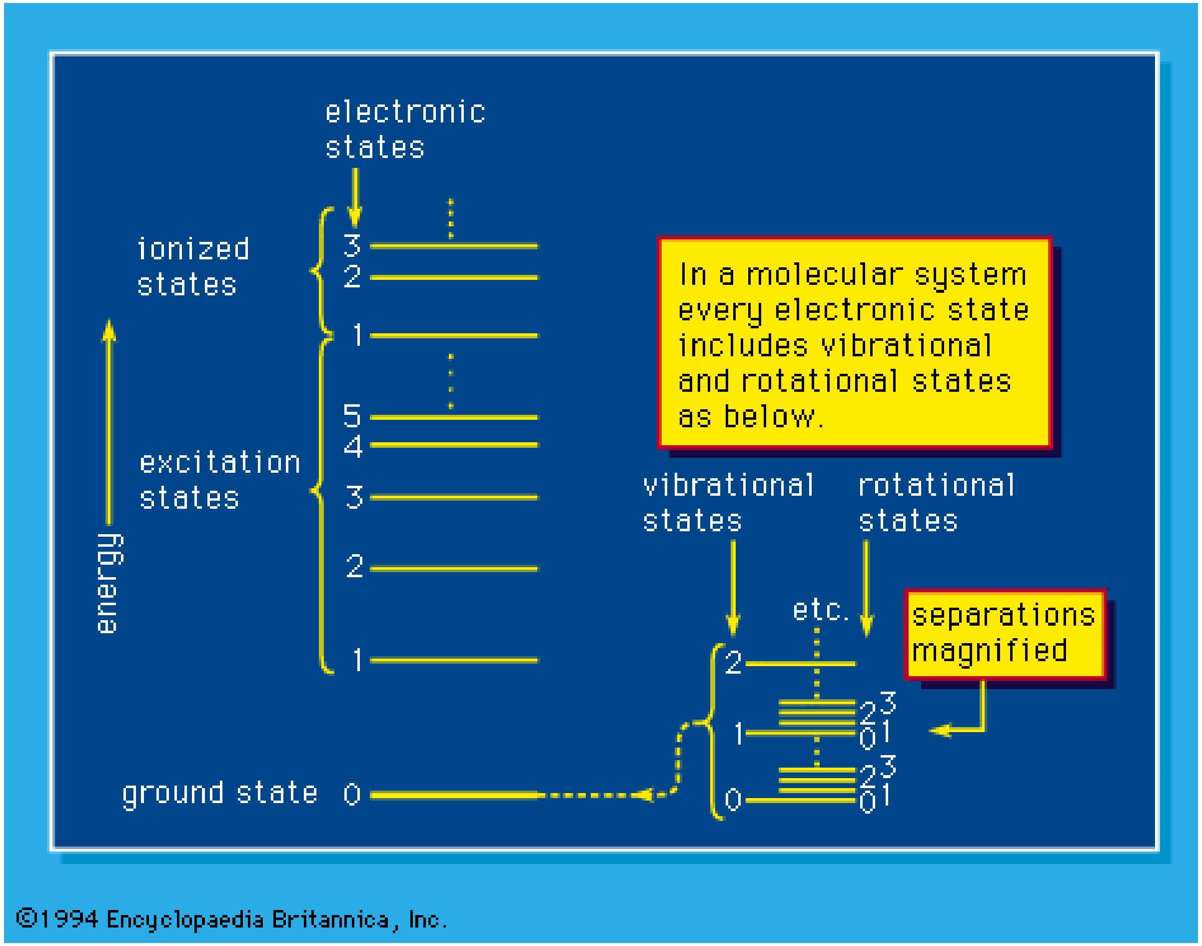
ε electrical permittivity of the material
μ magnetic permeability of the material

Maxwell's theory describes light as an electromagnetic oscillation.

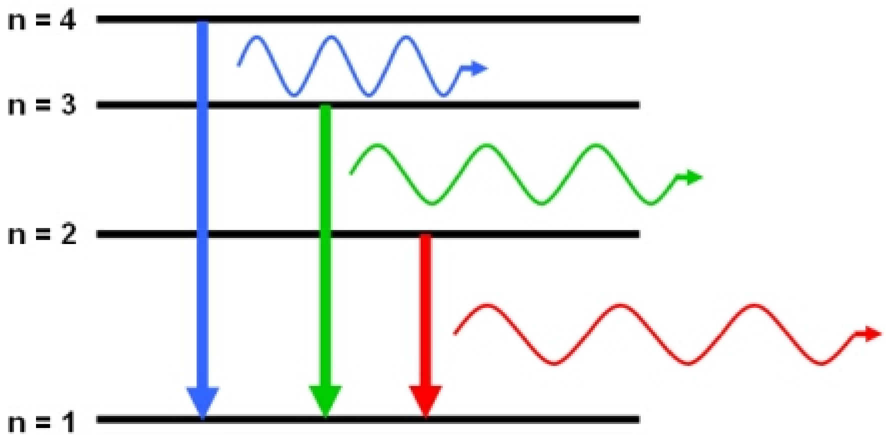
Electromagnetic spectrum



Energy states in molecular systems



Photon Emission



The **spectrum** of a material in an excited state shows **emission lines** at discrete frequencies.

Photons with specific energies will be emitted by an atom, ion or molecule in an **excited state**. The energy is equal to the difference between the higher and lower **energy levels**. In this example, three different photon energies are emitted as electrons move from excited states (n=2,3 and 4) to the ground state (n=1).

http://cosmos.swin.edu.au

Emission of radiation

All matter with T > 0 K shows a lot of changes of energetic levels mainly due to molecular activities

→ Emission of radiation

Questions:

- How can this emission be described?
- Which are the relevant parameters?

→ Radiation laws

Kirchhoff's law

Assumption: A body emits radiation $\mathbf{E_\lambda}$ **[Wm $^{-2}$ sr $^{-1}$ μm $^{-1}$]** in a certain direction (from ist unit area and per wavelength interval) and absorbs radiation from the same direction in relative amounts α_λ.

- Experiments showed: E_λ **/** $\alpha_\lambda = f(\lambda,T)$
- Emission only occurs for wavelengths for which absorption occurs
- For complete absorption ($\alpha_\lambda = 1$) it is: $E_\lambda = E_{max} = f(\lambda,T)$
- A body showing this behavior (α_λ=1, E_λ=E_{max}) is called a **blackbody**

Question: Explicit form of f (λ,T)

Radiation laws

$$L(\lambda,T)\,d\lambda = \frac{2\,h\,c^2}{\lambda^5}\left(\exp\left(\frac{h\,c}{\lambda\,k\,T}\right)-1\right)^{-1} d\lambda$$

Planck's law

integration ↓

$$M = \sigma\,T^4$$

Stefan-Boltzmann (Stefan's) law

differentiation ↓

$$T\,\lambda_{max} = const = 2898\ (\mu m\ K)$$

Wien's law

$L(\lambda,T)$	spectral radiance	$(Wm^{-2}sr^{-1}\mu m^{-1})$
$M(T)$	specific emittance of a blackbody	(Wm^{-2})
λ	wavelenght of radiation	(μm)
T	absolute temperature	(K)

k	Boltzmann-Konstante	$1.381 \cdot 10\text{-}23\ (JK^{-1})$
h	Planck-Konstante	$6.626 \cdot 10\text{-}34\ (Js)$
c	velocity of light in vacuum	$2.9979 \cdot 108\ (ms^{-1})$
σ	Stefan-Boltzmann constant	$5.67 \cdot 10\text{-}8\ (Wm^{-2}K^{-4})$

Planck‘s Law

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

Spectral photon energy density, i.e. per volume element

$$L_\nu(T)d\nu = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1}d\nu$$

Spectral radiance per frequency interval

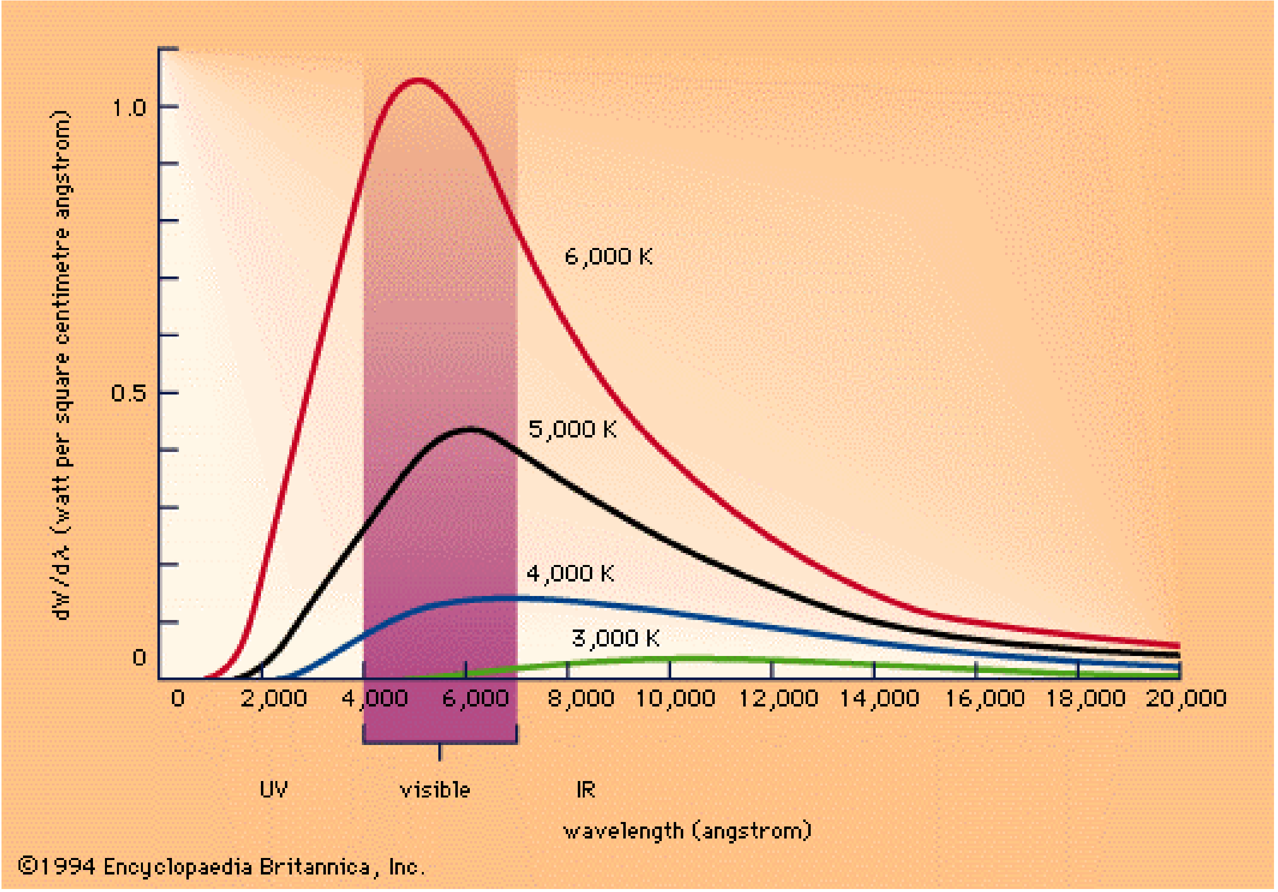
$$L_\lambda(T)d\lambda = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}d\lambda$$

Spectral radiance per wavelength interval

$$M_\lambda(T) = \pi L_\lambda(T)$$

Spectral radiant flux density per wavelength interval

Blackbody Radiation



Electromagnetic energy *dW* emitted per unit area and per second into a wavelength interval, $d\lambda = 1$ Å, by a blackbody at various temperatures between 3000 and 6000 K as a function of wavelength.

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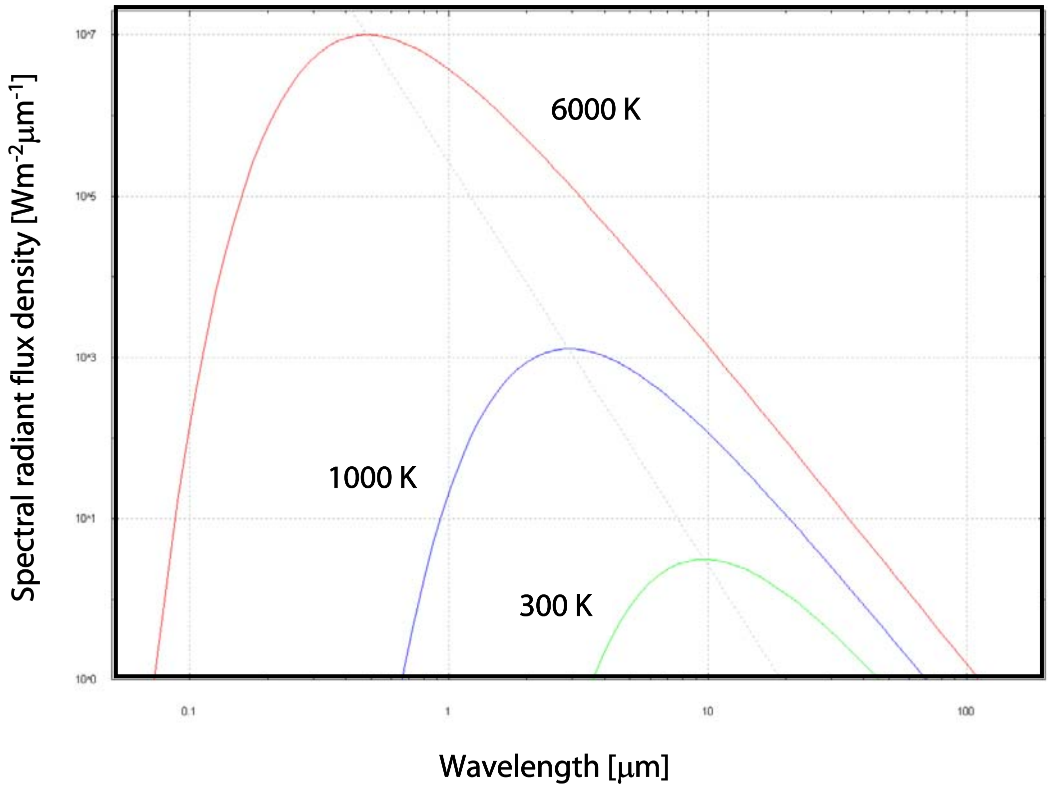
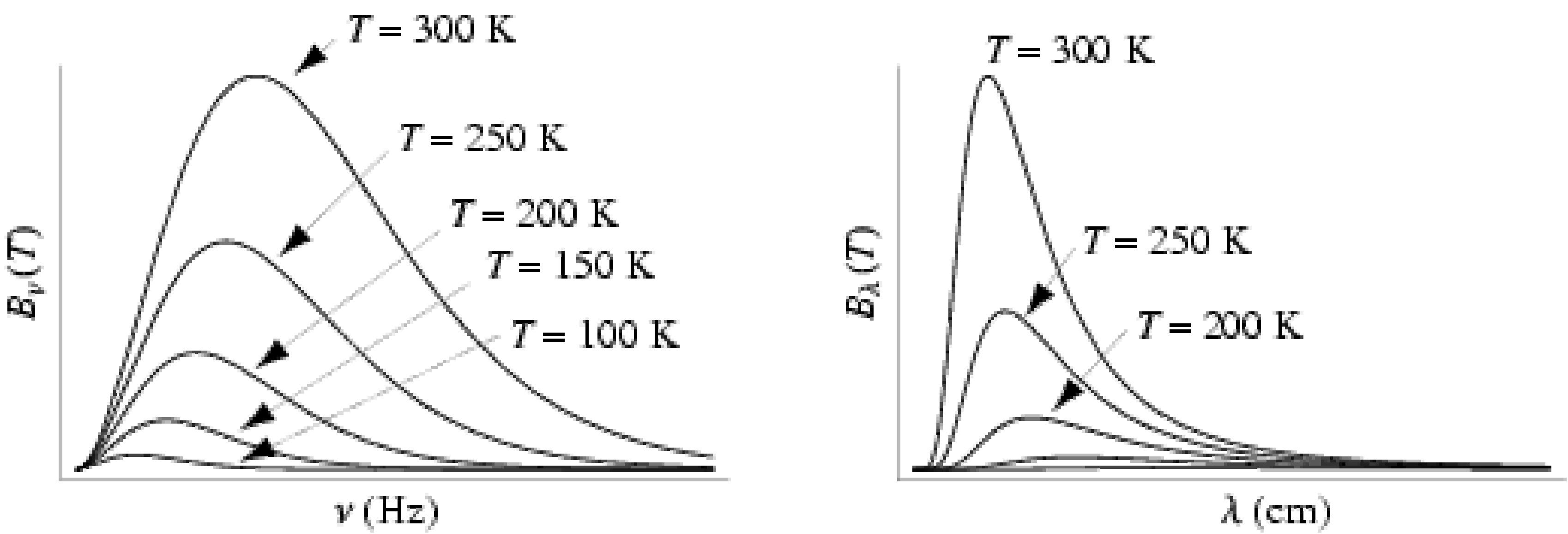
Blackbody Radiation

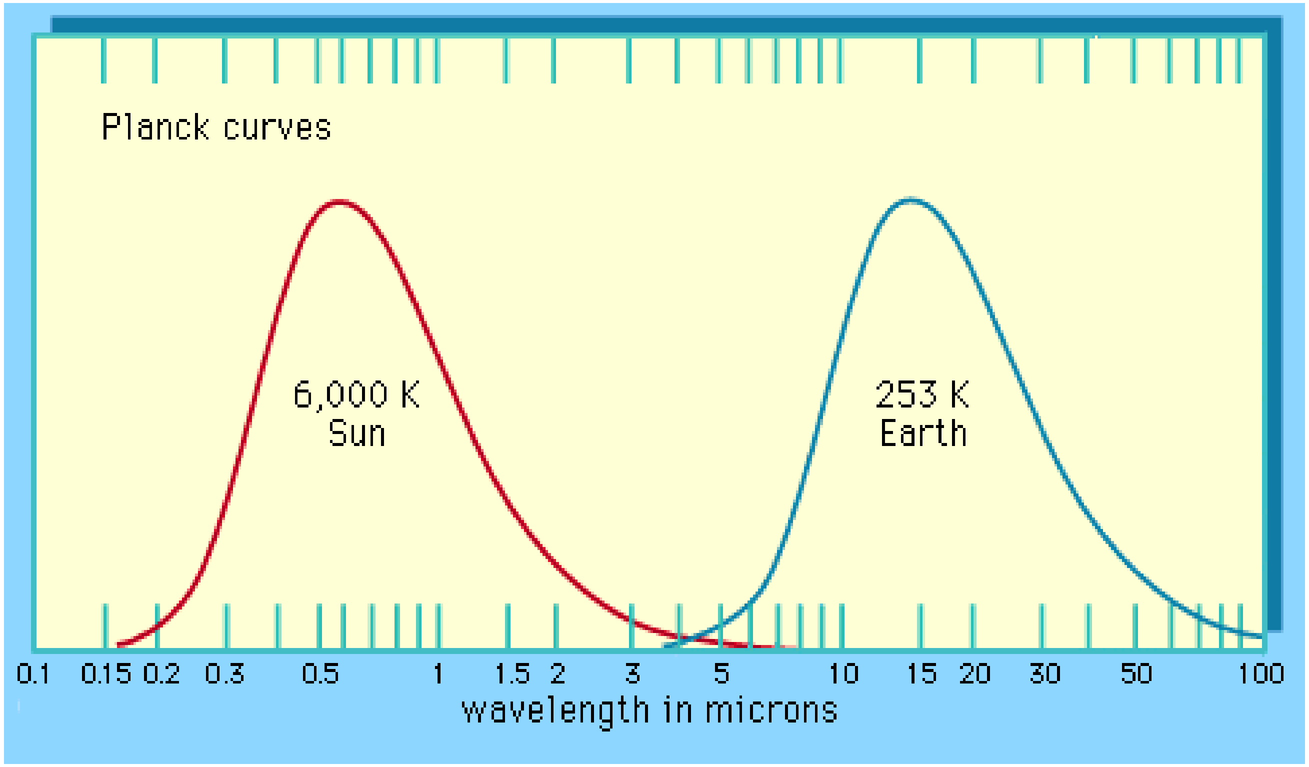


Planck's Law



Intensity radiated by a blackbody as a function of frequency (left) or wavelength (right)

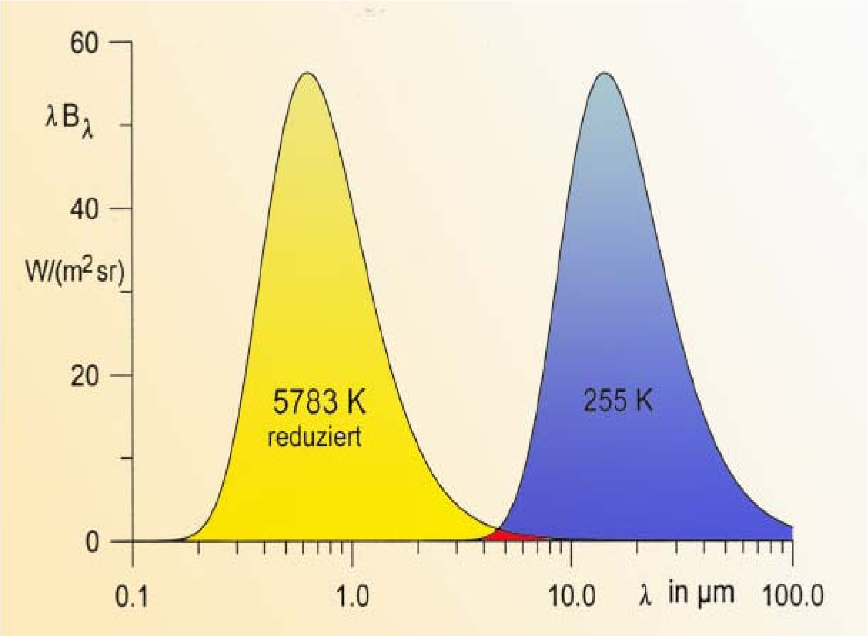
Solar and terrestrial spectrum



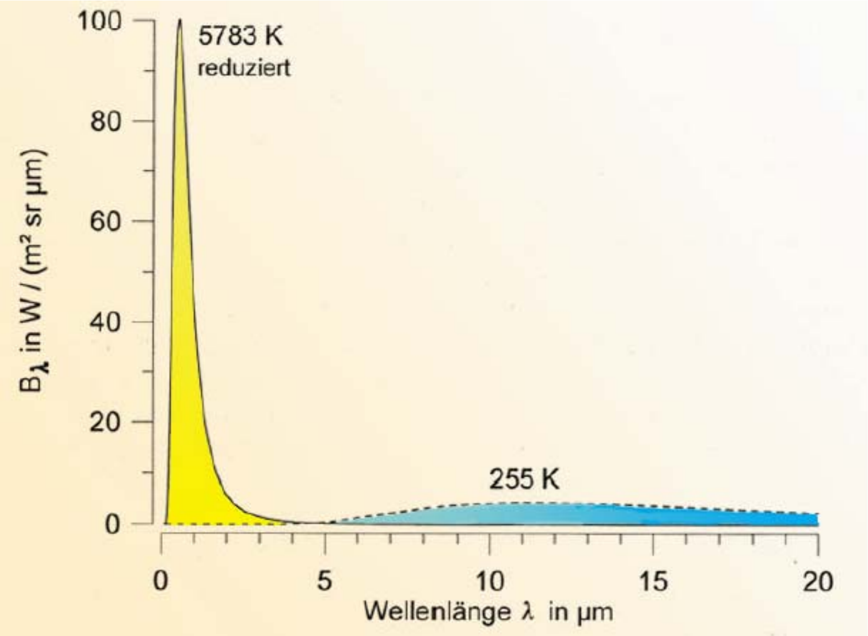
Spectrum of the Earth as viewed from space showing distinction between reflected sunlight and planetary radiation. The Earth is assumed to emit as a blackbody at an average temperature of 253 K.

Royal Meteorological Society.

Solar and terrestrial spectrum



logarithmic



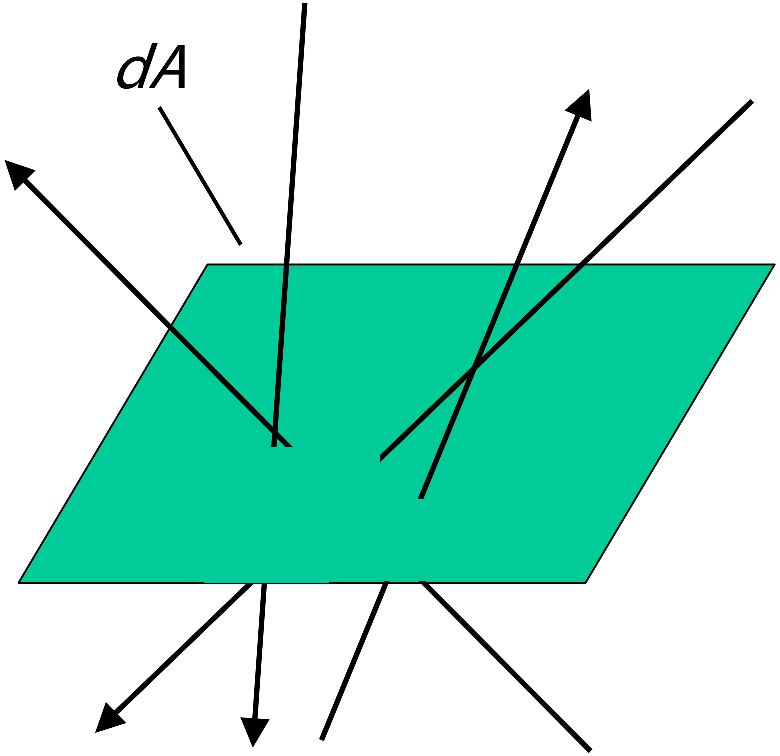
linear

Source: Vogt

Radiometric Quantities

	Symbol	*Unit*	
Wavelength	λ	m, μm, nm, Å	
Frequency ($\nu = c/\lambda$)	ν	s^{-1}	
Wavenumber ($k = 1/\lambda$)	k	m^{-1}, cm^{-1}	
Radiant energy	Q, W	J = Ws	
Radiant flux	Φ	W	$\Phi = dQ/dt$
Radiant flux density (general)	F	Wm^{-2}	$F = d\Phi/ds$
Irradiance (incident onto a surface)	E	Wm^{-2}	
Radiant exitance, emittance (emerging from a surface)	M	Wm^{-2}	
Solar radiant flux density (global irradiance)	G	Wm^{-2}	
Radiant intensity (radiant flux propagating in a given direction within a solid angle)		Wsr^{-1}	$= d\Phi/d\omega$
Radiance (same, but for radiant flux density)	L	$Wm^{-2} sr^{-1}$	$L = d^2\Phi/d\omega ds$

Definition: Radiant flux density



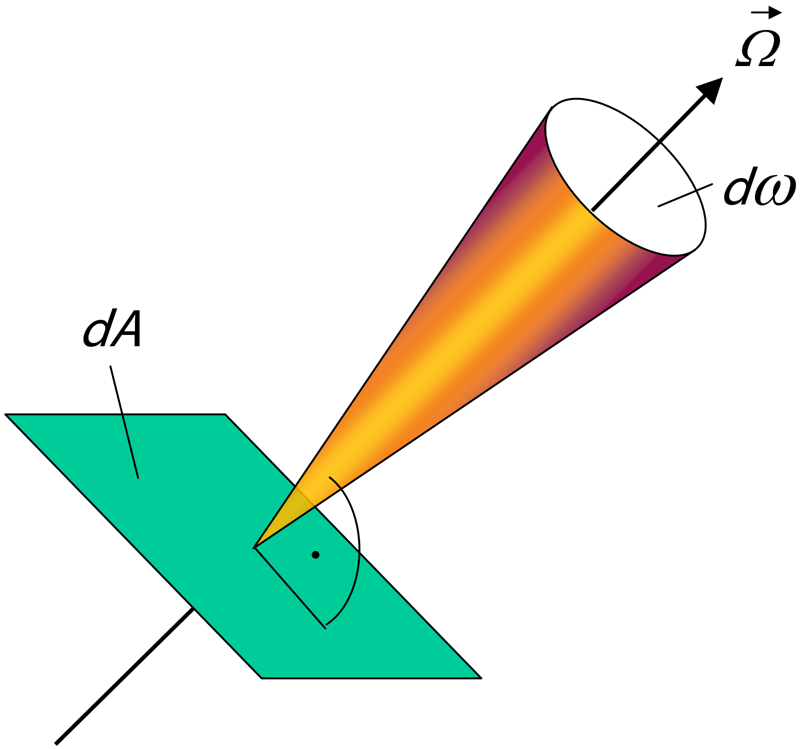
Energy flux density *F*

defines the radiant energy dQ passing through an area dA in the time interval t, $t+dt$:

$$d^2Q = F\,dA\,dt$$

Units of F are Wm^{-2}.

Definition: Radiance



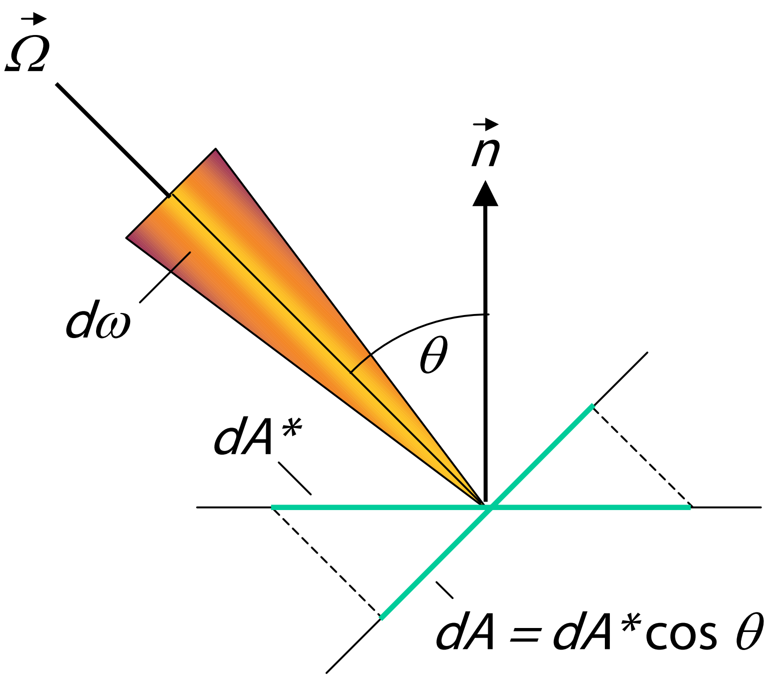
Radiance L

defines the radiant energy flux $d\Phi = dQ/dt$ passing through an area dA perpendicular to the direction Ω into by the solid angle $d\omega$:

$$d^3Q = L\, dA\, dt\, d\omega$$

Units of L are $Wm^{-2}sr^{-1}$.

Relation between Radiance and Radiant Flux Density



According to the cosine law, the radiance crossing a surface *dA**, whose normal *n* makes an angle θ with the beam axis Ω, is:

$$L^* = \cos\theta \, L$$

and the radiant flux density calculates to

$$F = \iint_{4\pi} L \cos\theta \, d\omega$$