Reminder of radiance quantities

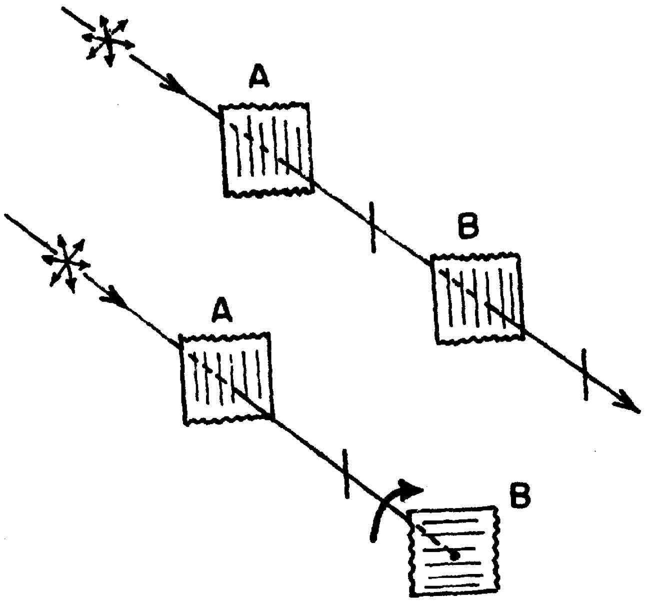
I_λ	Radiance Intensity (Monochromatic)	W m^{-2} μm^{-1} sr^{-1}
F_λ	Spectral Irradiance Monochromatic Flux	W m^{-2} μm^{-1}
F	(Broadband) Flux	W m^{-2}

$$F_\lambda = \int_{hemisphere} I_\lambda(\theta,\phi)\cos\theta\, d\Omega$$

$$= \int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi/2} I_\lambda(\theta,\phi)\cos\theta\sin\theta\, d\theta\, d\phi$$

$$F(\lambda_0,\lambda_1) = \int_{\lambda_0}^{\lambda_1} F_\lambda\, d\lambda$$

Polarization – a property of the transverse nature of EM radiation- doesn't affect energy transfer but it is altered by the way radiation interacts with matter



Simple illustration of the effects of two pieces of polarizing material (polarizers)

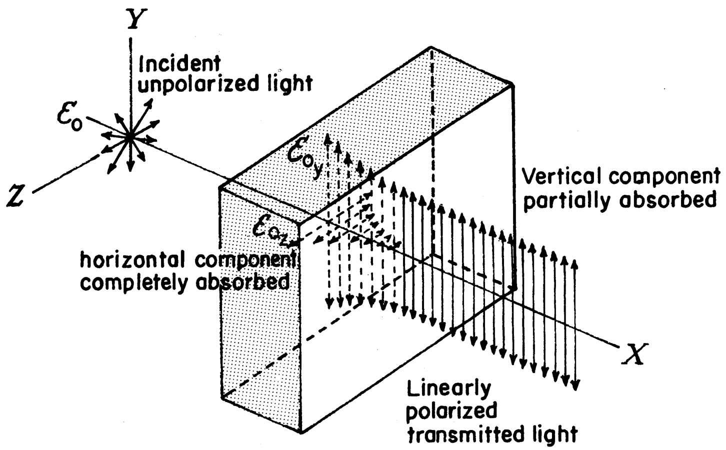
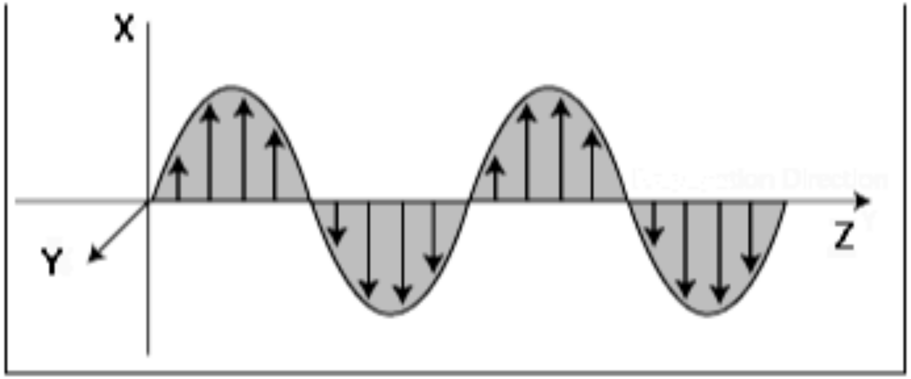


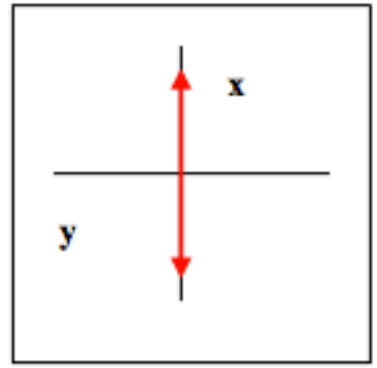
Figure 2.13 An illustration of dichroism.

Polarization is widely used in remote sensing:

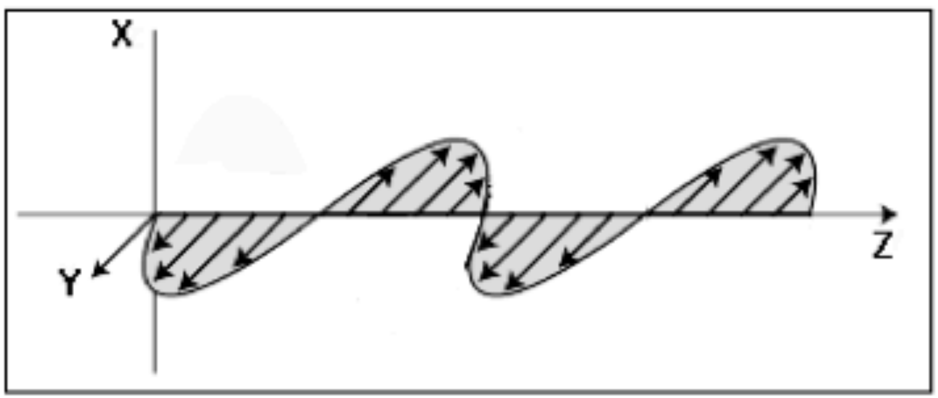
- 'multi-parameter' radar → particle characteristics
- microwave emission → cloud water and precipitation
- aerosol
- sea-ice extent
- design of instruments

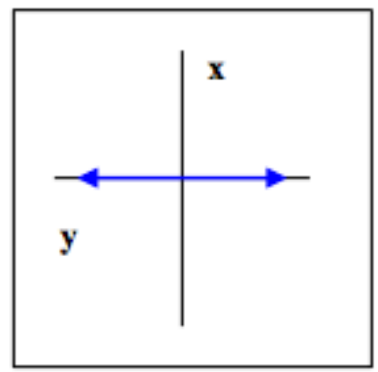
Vertically polarized wave is one for which the electric field lies only in the x-z plane.





Horizontally polarized wave is one for which the electric field lies only in the y-z plane.





- Horizontal and vertical polarizations are an example of **linear polarization**.

Stokes Parameters – an alternate set of 4 intensity (i.e. energy based) parameters that derive directly from experiments: can be Measured!

Stokes Vector

$$I = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

- **Stokes parameters** are defined via the intensities which can be measured:

I = total intensity

$Q = I_0 - I_{90}$ = differences in intensities between horizontal and vertical linearly polarized components;

$U = I_{+45} - I_{-45}$ = differences in intensities between linearly polarized components oriented at $+45^0$ and -45^0

$V = I_{rcl} - I_{lcr}$ = differences in intensities between right and left circular polarized components.

Stokes Parameters – an alternate set of 4 intensity (i.e. energy based) parameters that derive directly from experiments: can be Measured!

Stokes Vector

$$I = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \begin{matrix} \text{Total Intensity} \\ \text{Linear polarization} \\ \text{Linear pol at 45°} \\ \text{Circular Polarization} \end{matrix}$$

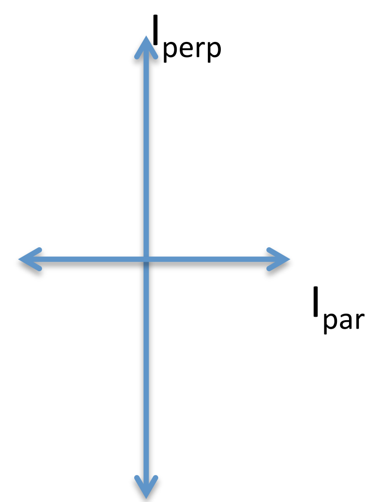
For a monochromatic wave:

$$I = I_{par} + I_{perp}$$

$$Q = I_{par} - I_{perp}$$

$$U = 2\sqrt{I_{par} I_{perp}} \cos(\varphi_{perp} - \varphi_{par})$$

$$V = 2\sqrt{I_{par} I_{perp}} \sin(\varphi_{perp} - \varphi_{par})$$



$$I \geq \sqrt{Q^2 + U^2 + V^2}$$ (in general)

$$\text{Degree of polarization} = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}$$

$$\text{Degree of linear polarization} = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\text{Degree of circ polarization} = \frac{V}{I}$$

NOTE:

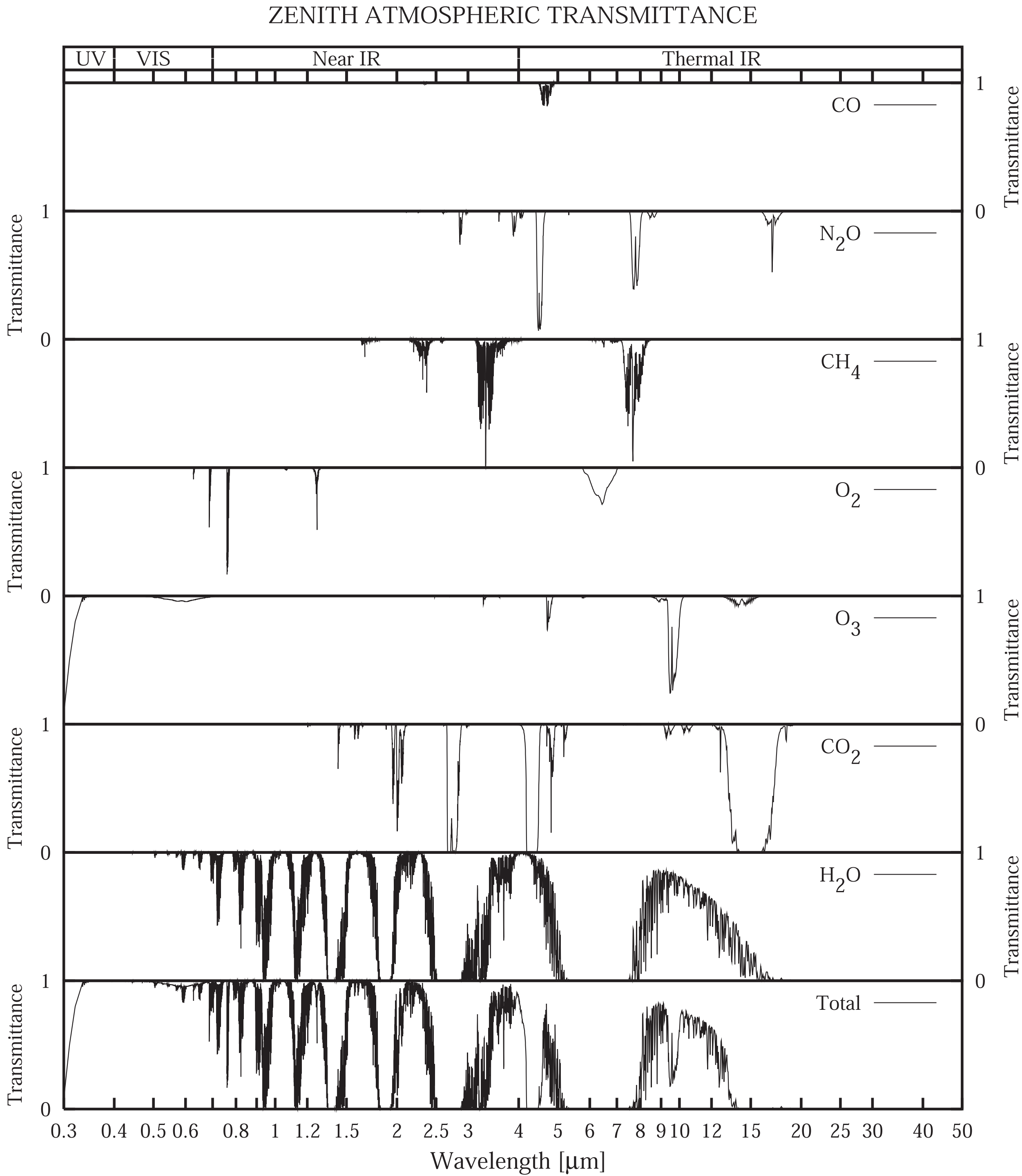
Measurements of polarization are actively used in remote sensing in the solar and microwave regions.

Polarization in the microwave–mainly due to reflection from the surface.

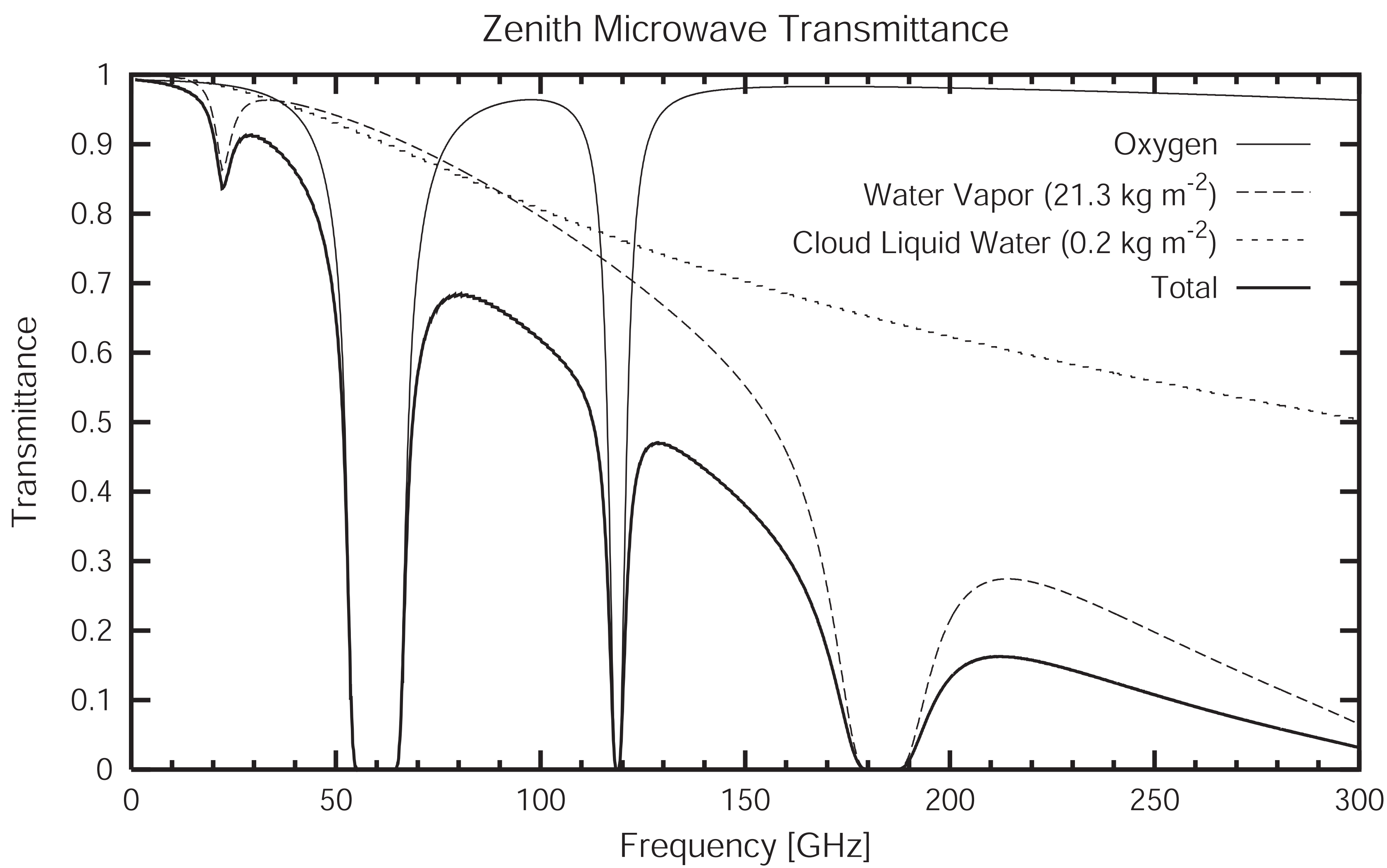
Polarization in the solar –reflection from the surface and scattering by molecules and particulates.

Active remote sensing (e.g., radar) commonly uses polarized radiation.

Region	Spectral Range	Fraction of solar output	Remarks
X-rays	λ < 0.01 μm		Photoionizes all species; absorbed in upper atmosphere.
Extreme UV	0.01 < λ < 0.1 μm		Photoionizes O_2 and N_2 ; absorbed above 90 km
Far UV	0.1 < λ < 0.2 μm	0.15%	Photodissociates O_2; absorbed above 50 km
UV-C	0.2 < λ < 0.28 μm	2%	Photodissociates O_2 and O_3; absorbed above 30 km
UV-B	0.28 < λ < 0.32 μm	2%	Mostly absorbed by O_3 in stratosphere; sunburn!
UV-A	0.32 < λ < 0.4 μm	8%	Reaches surface
Visible	0.4 < λ < 0.7 μm	37%	Atmosphere mostly transparent
Near IR	0.7 < λ < 4 μm	50%	Partially absorbed, H_2O, some useful RS lines (methane, CO_2, O_2)
Thermal IR	4 < λ < 50 μm	1%	Absorbed & emitted by wv, co2, ozone, other trace gases
Far IR	50 μm < λ < 1 mm		Absorbed by water vapor
Microwave	50 μm < λ < 30 cm		Clouds & rain; semi transparent; o2 & h2o lines
Radio	λ > 30 cm		



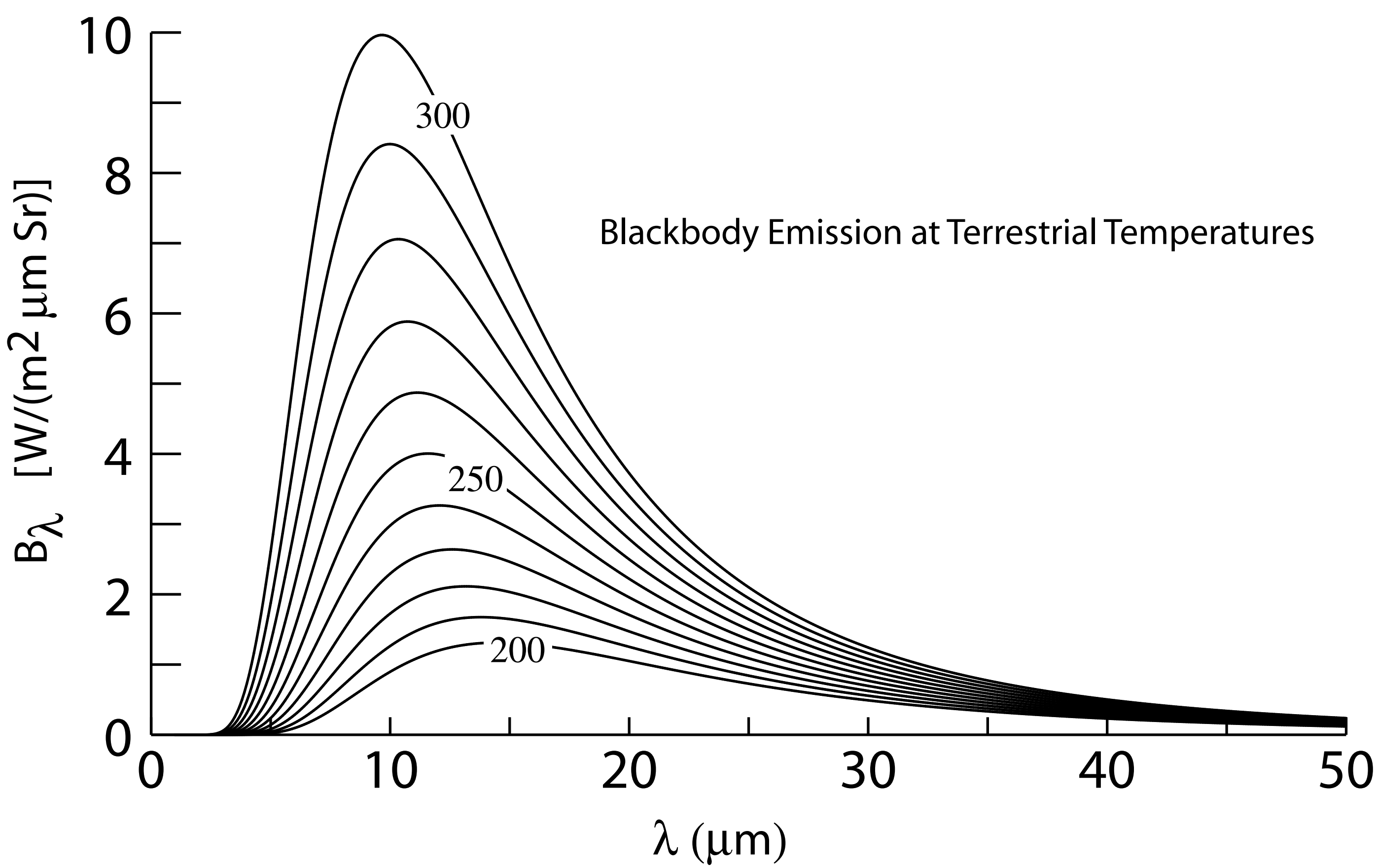
ZENITH ATMOSPHERIC TRANSMITTANCE
UV
VIS
Near IR
Thermal IR
CO
N2O
CH4
O2
O3
CO2
H2O
Total
Transmittance
1
0
0.3
0.4
0.5
0.6
0.8
1
1.2
1.5
2
2.5
3
4
5
6
7
8
9
10
12
15
20
25
30
40
50
Wavelength [μm]



Zenith Microwave Transmittance
Transmittance
Frequency [GHz]
Oxygen
Water Vapor (21.3 kg m-2)
Cloud Liquid Water (0.2 kg m-2)
Total
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300

Glowing wires in labs, when heated to high temperatures,
Had intensity that followed a characteristic shape!

Further, found that the total flux emitted (integrate over all wavelengths) depended ONLY on temperature.



Cavity radiation

Hot pottery kiln

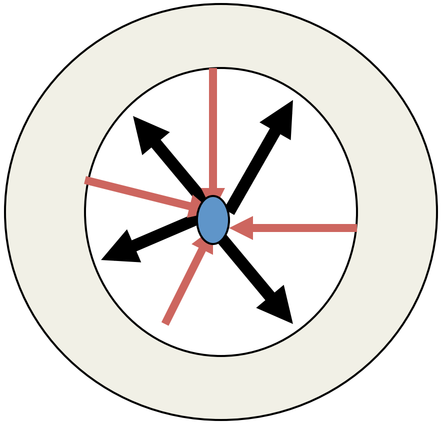
- In the hot kiln, all objects emit equally.
- There is a uniform glow of cavity radiation.
- All objects look the same.

Cooling pottery kiln

- As the kiln cools, reflected radiation is larger than emitted radiation.
- Objects can be distinguished.

Basic Laws of Emission

Consider an 'isolated cavity' and a hypothetical radiating body within it at temperature T.



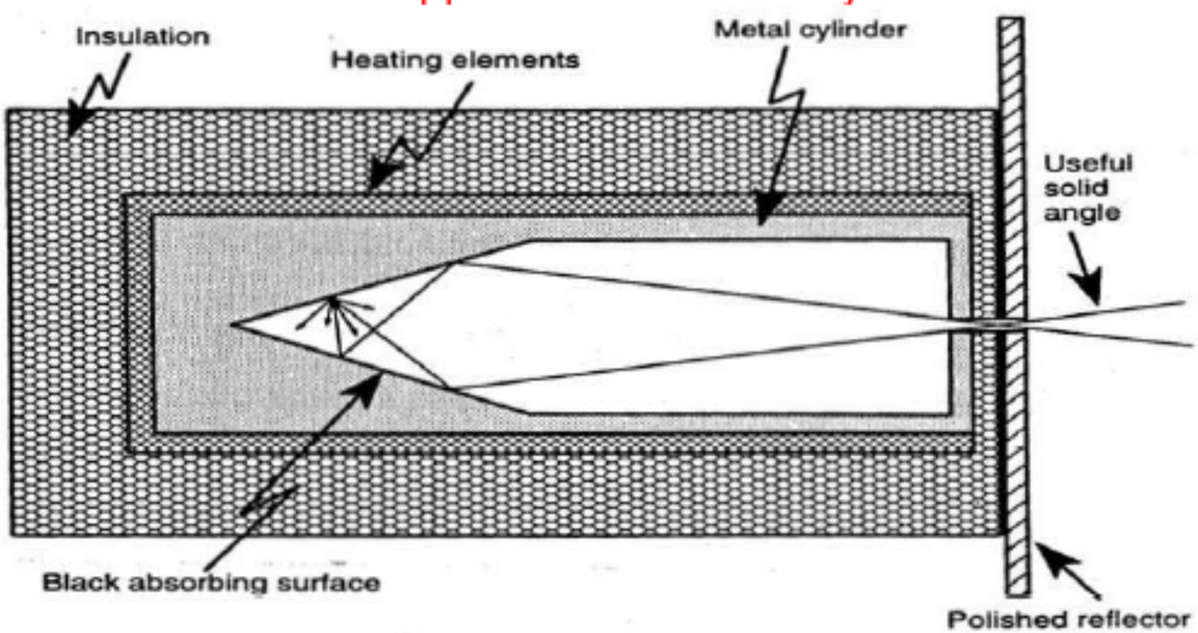
An equilibrium will exist between the radiation emitted from the body and the radiation that body receives from the walls of the cavity.

The 'equilibrium' radiation inside the cavity is determined solely by the temperature of the body. This radiation is referred to as black-body radiation. Two black-bodies of the same temperature emit precisely the same amount of radiation - proof 2nd law

Cavity radiation — experimental approximation to black-body radiation

- The radiance emitted by any body may be expressed in terms of the radiance emitted by a hypothetical black-body.
- In practice, an approximate black-body may be used as a source of radiation with known intensity to calibrate instruments.

An approximate black-body



- Cavities are designed to be light traps
- Radiation entering the cavity experiences many reflections before it can escape.
- If the reflectance of the walls is low, only a tiny amount of the incident energy escapes.
- Nearly all radiation leaving the cavity is emitted by the walls.

We can very closely approximate blackbody radiation by carefully constructing a cavity and observing the radiation within it.

Kirchhoff's challenge

- In 1859 Kirchhoff proved that the flux density W emitted by a black-body depends only on the temperature T and the frequency ν of the emitted energy.

  $$W = J(\nu, T).$$

  He challenged physicists to find the function J.

- In 1879 Josef Stefan proposed, on experimental grounds, that the total energy emitted by a hot body was proportional to the fourth power of the temperature.

  $$W = \sigma T^4$$

  where σ is now called the Stefan-Boltzmann constant.

- The same conclusion was reached in 1884 by Ludwig Boltzmann for black-body radiation from theoretical considerations using thermodynamics and Maxwell's theory of electromagnetism.

- The Stefan-Boltzmann law did not answer Kirchhoff's challenge, because it did not specify how the flux density depended upon frequency ν.

Rayleigh and Jeans 1900 — ultra-violet catastrophe

- Consider an evacuated and insulated cavity at temperature T
- Classical electromagnetism predicts that the energy density (energy per unit volume) of the radiation field inside the enclosure has the form

  $$U = NkT$$

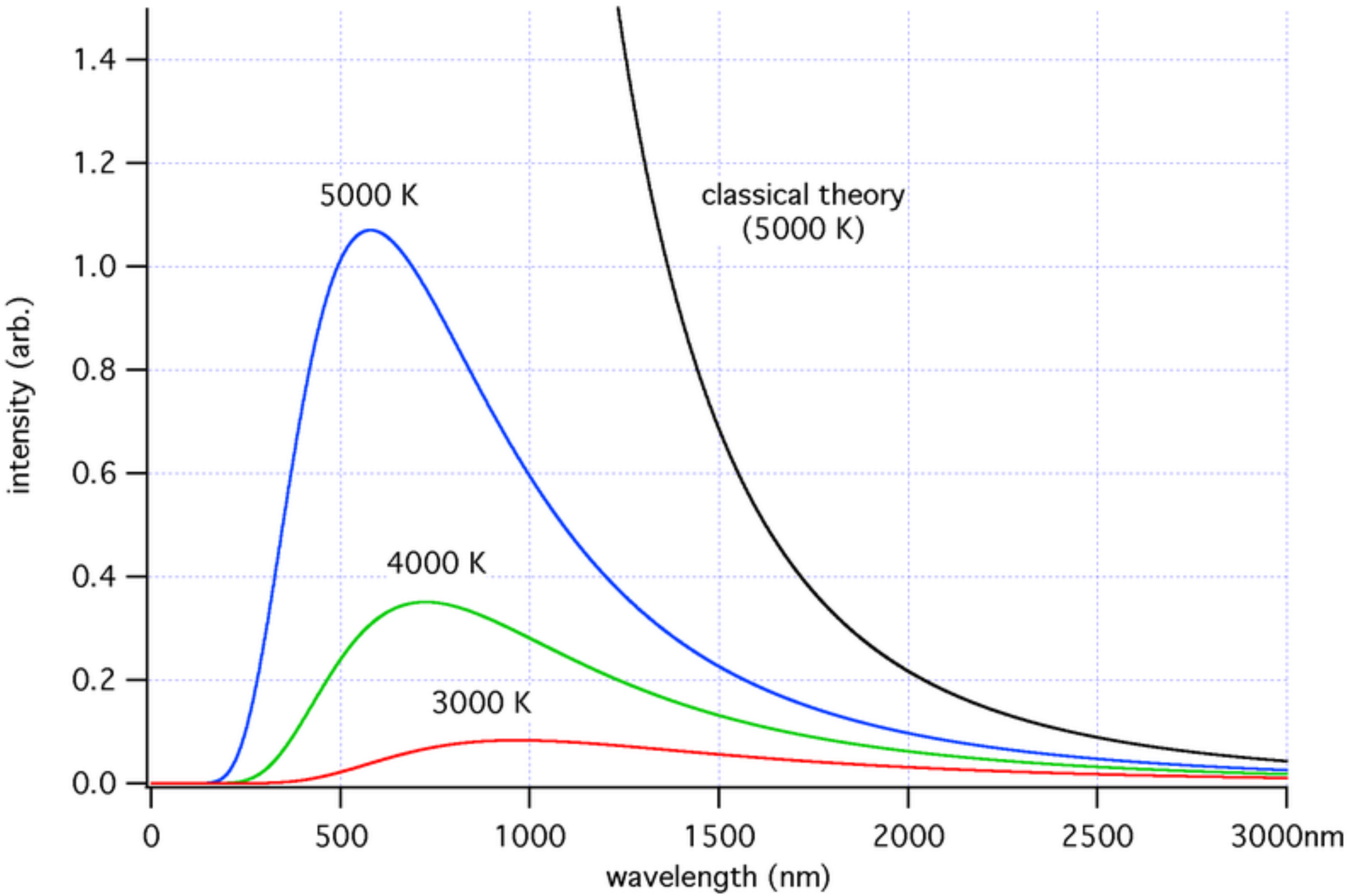
  where

  $N =$ number of electromagnetic modes and $kT =$ energy per mode
- All modes have the same energy kT in thermal equilibrium, a principle called equipartition of energy, derived from statistical mechanics of ensembles of particles.
- The number of modes depends on the frequency ν

  $$N = \left(\frac{8\pi\nu^2}{c^3}\right)$$

  so the energy density predicted by the classical theory is

  $$U = \left(\frac{8\pi\nu^2}{c^3}\right)kT$$
- This theory predicts that the energy density grows without limit as the frequency increases — 'the ultra-violet catastrophe'



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
intensity (arb.)
5000 K
4000 K
3000 K
classical theory
(5000 K)
0
500
1000
1500
2000
2500
3000nm
wavelength (nm)

Wilhelm Wien 1864–1928

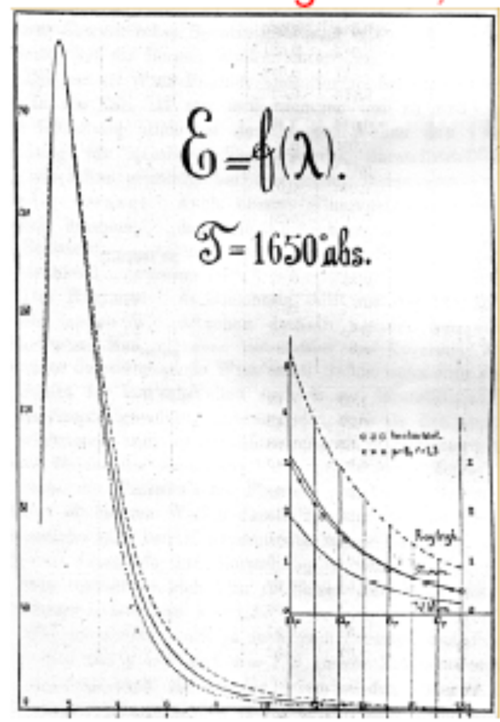
- Professor of Physics, Giessen 1899
  Professor of Physics, Munich 1920
- Major contributions:
  - spectrum of black-body radiation
  - displacement law for black-body radiation
  - in 1898 discovered the proton in streams of ionized gas — laid foundations for mass spectrometry
- Nobel prize in 1911 for work on heat radiation

- Wien proposed

$$J(\nu,T) = c_1\nu^3/\exp(c_2\nu/T)$$

with c_1 and c_2 adjusted to fit the data.

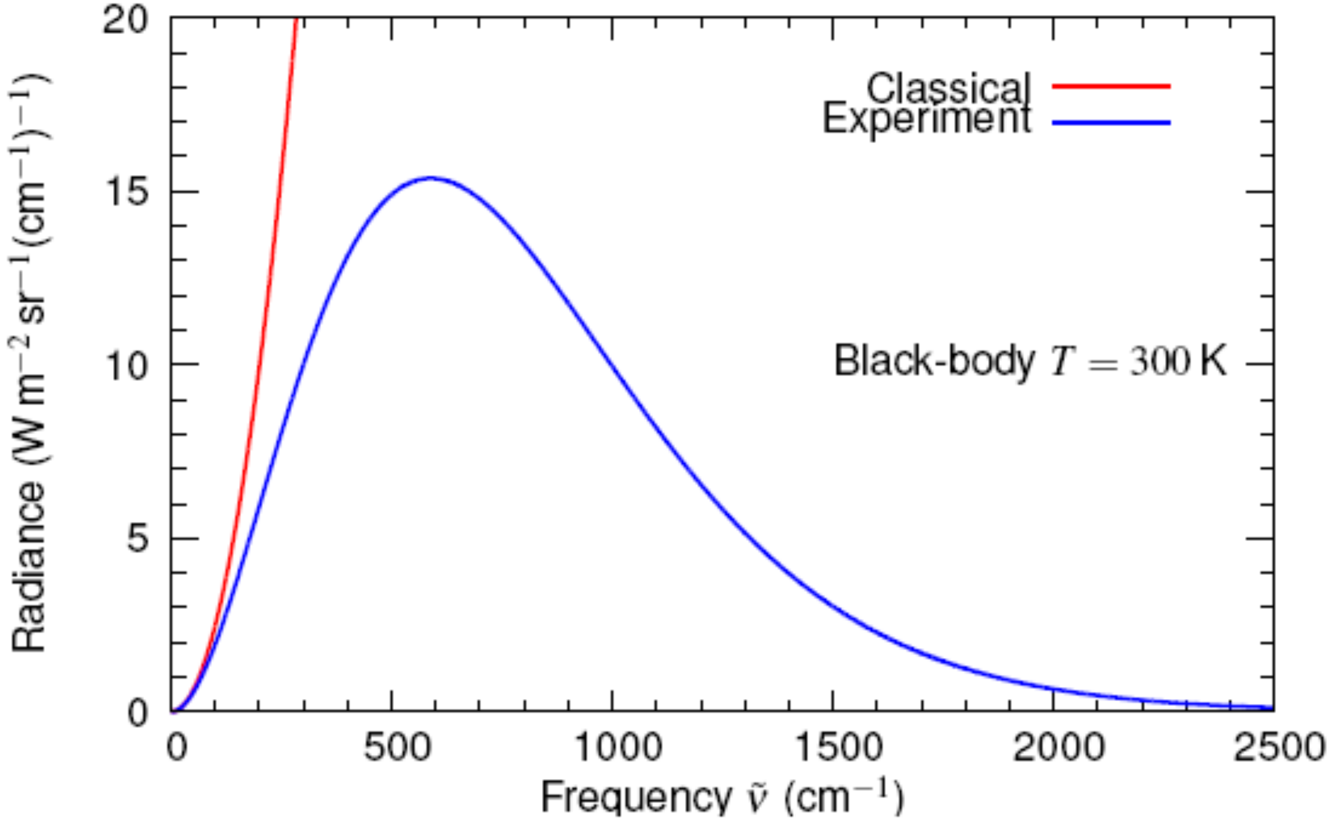
Lummer and Pringsheim, 1900



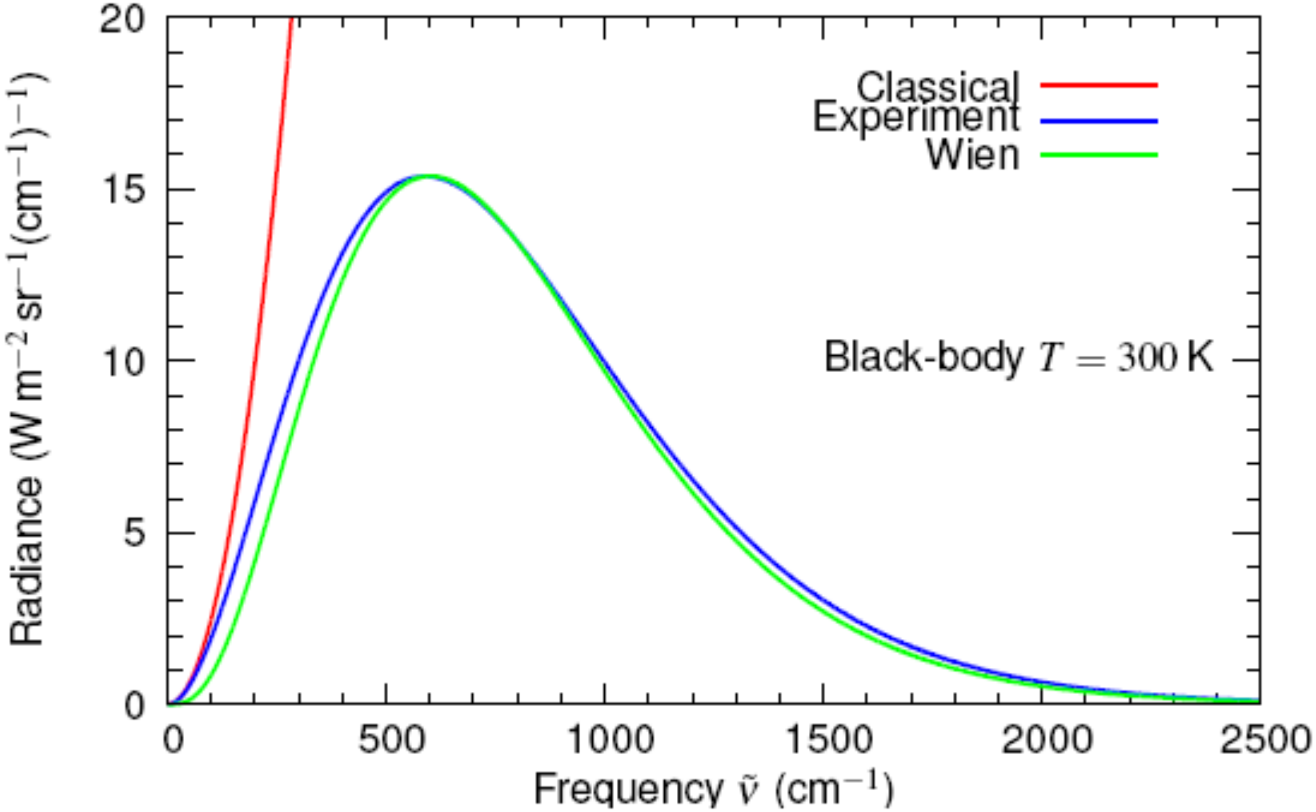
Wavelength λ

- The model is close but not perfect

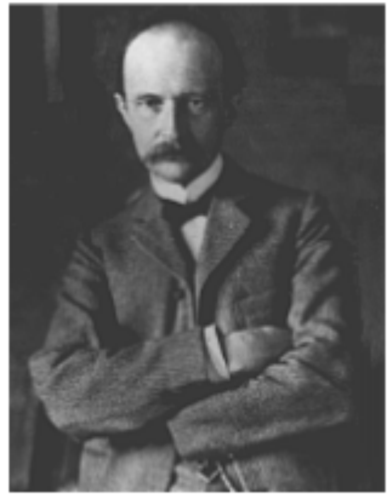
The situation in June 1900



The situation in June 1900



Max Karl Ernst Ludwig Planck 1858–1947



Instructor in Physics, University of Berlin 1880
Associate Professor of Physics, University of Kiel 1885
Professor of Physics, University of Berlin 1888

- Major contributions:
  - thermodynamics
  - electromagnetic radiation
  - black body radiation
  - quantum hypothesis
- Nobel prize in 1918
- Active in organizing German science
- Lost eldest son in World War I
- Openly opposed the Nazi policies and persecution of the Jews
- Second son executed by the Nazis for complicity in a plot to assassinate Hitler
- House, personal belongings and scientific papers destroyed by fire during Allied bombing in 1944

Planck's hypothesis presented on October 19, 1900

- After hearing of Wien's approximate radiation formula, Planck suggested

$$J(\nu,T) = \frac{c_1\nu^3}{\exp(c_2\nu/T)-1}$$

on the basis of his intuition and experience with Boltzmann's statistical mechanics.

- Within hours of Planck's lecture, Heinrich Rubens from the Berlin State Physical-Technical Institute (PTR) had checked that Planck's formula agreed with the best available data over the whole frequency range.
- Within two months, Planck had found a theoretical explanation that shook the foundations of physics, for it required quantization of energy.
- In Planck's theory, the energy density inside the enclosure again has the form

$$U = N\varepsilon(\nu)$$

where N is the number of electromagnetic modes and $\varepsilon(\nu)$ is the energy per mode,

$$N = \left(\frac{8\pi\nu^2}{c^3}\right) \qquad \text{and} \qquad \varepsilon(\nu) = \frac{h\nu}{\exp(h\nu/kT)-1}$$

Thus

$$U = \left(\frac{8\pi\nu^2}{c^3}\right)\left(\frac{h\nu}{\exp(h\nu/kT)-1}\right)$$

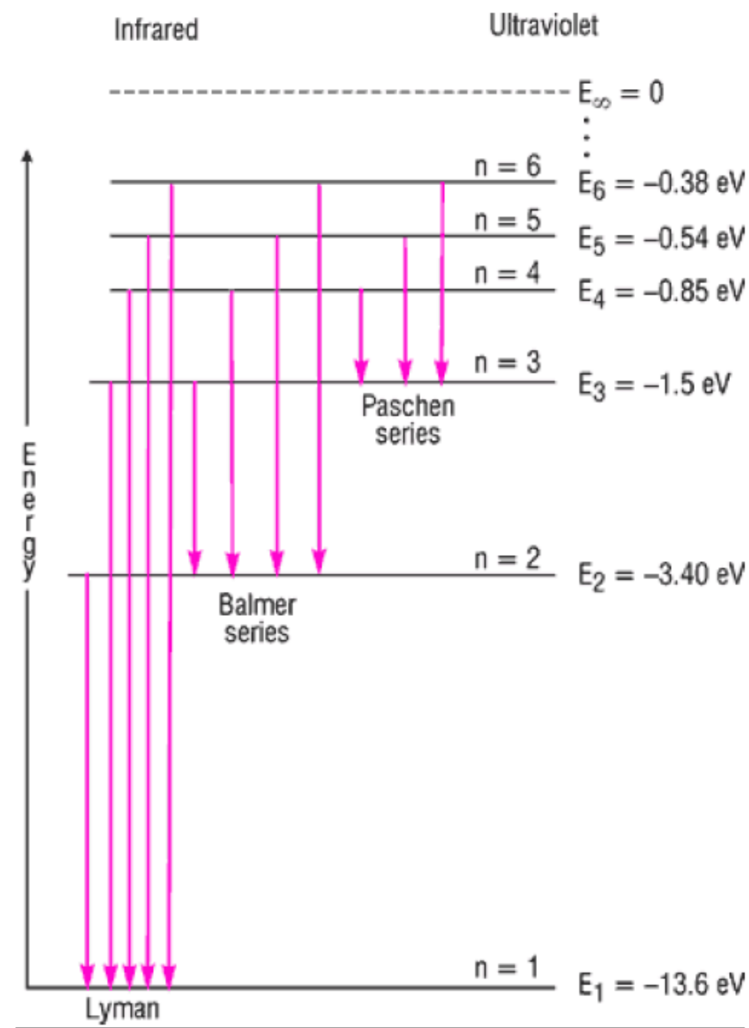
- The radiance emerging from a small aperture in the enclosure differs by a factor of $c/(4\pi)$

$$B_\nu = \frac{2hc^{-2}\nu^3}{\exp(h\nu/kT)-1}$$

Planck's radiance distribution
(in units of frequency, $\nu = c/\lambda$)

Planck's "Quantum Leap" of Faith

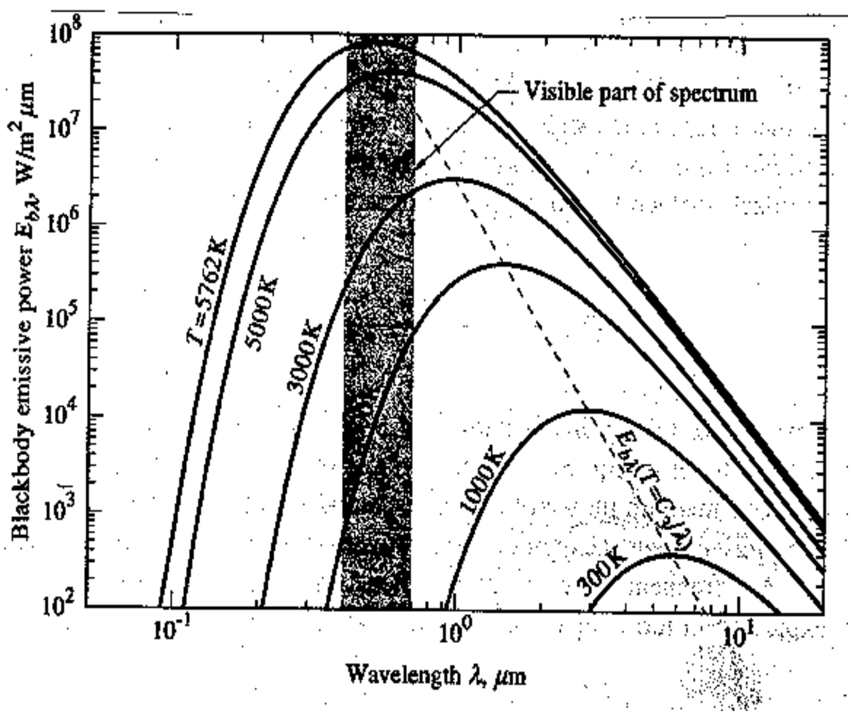
- Max Planck discovered via hypothesis that there is a discrete number of permitted energy levels for an oscillator.
- Classical physics would suggest a that there should exist a smooth continuum of possible energy values.
- Planck's Constant (h) is a proportionality constant relating the permitted energy levels to the frequency of the oscillator ($\nu = c/\lambda$).
- The discrete energy levels can then be expressed as: $E = n\ h\ \nu$



Above: discrete energy levels of the hydrogen atom

Planck's Blackbody Function

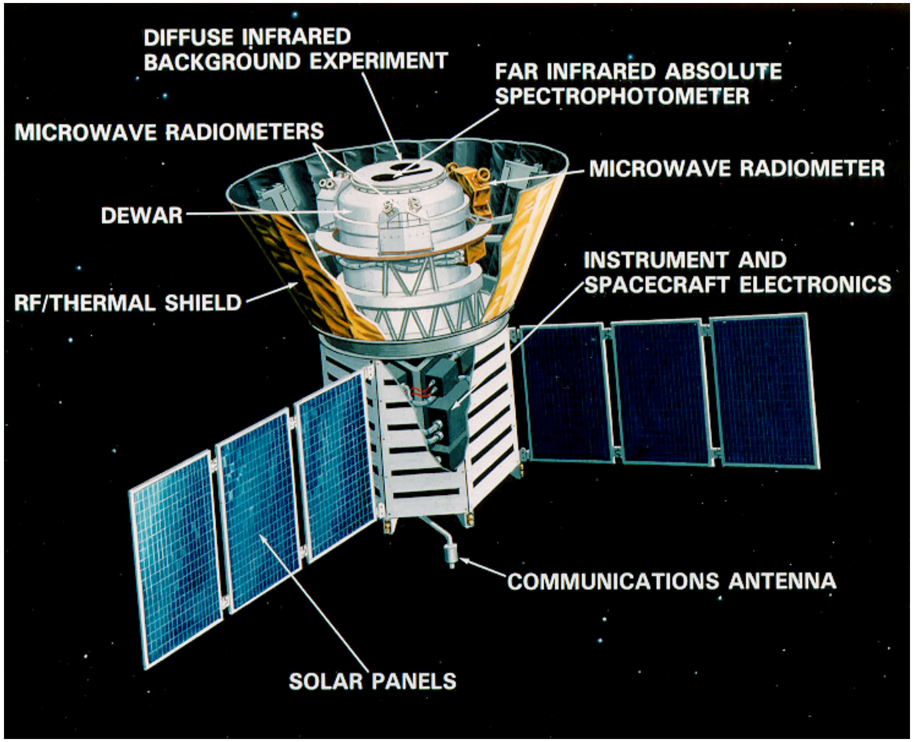
The nature of $B_\lambda(T)$ was one of the great findings of the latter part of the 19th century and led to entirely new ways of thinking about energy and matter.

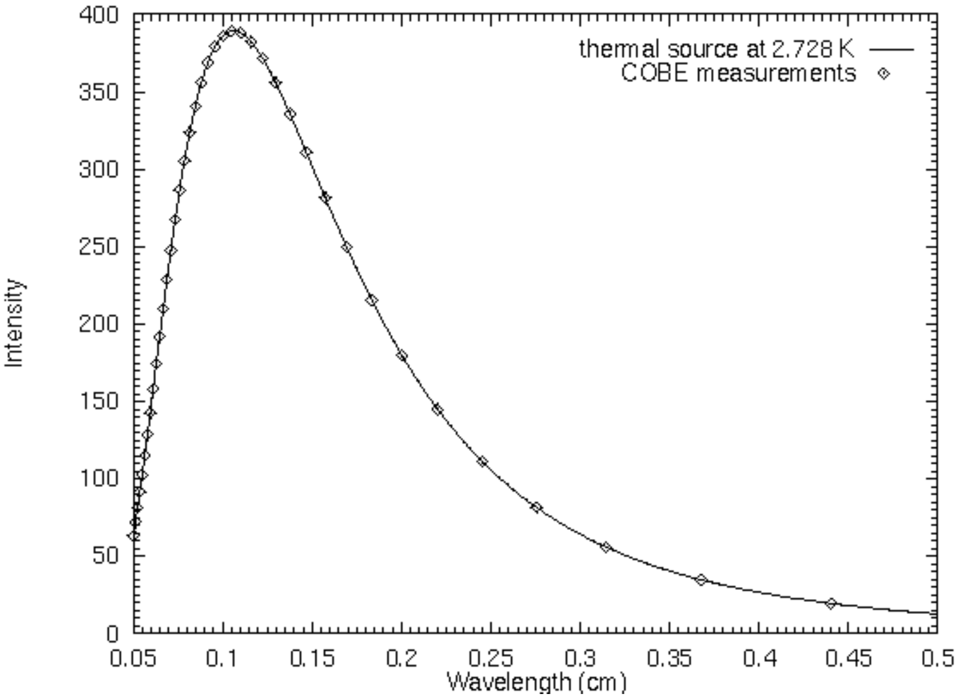


$$\mathbf{B}_\lambda = \frac{2hc^2}{\lambda^5\left(e^{hc/\lambda kT} - 1\right)}$$

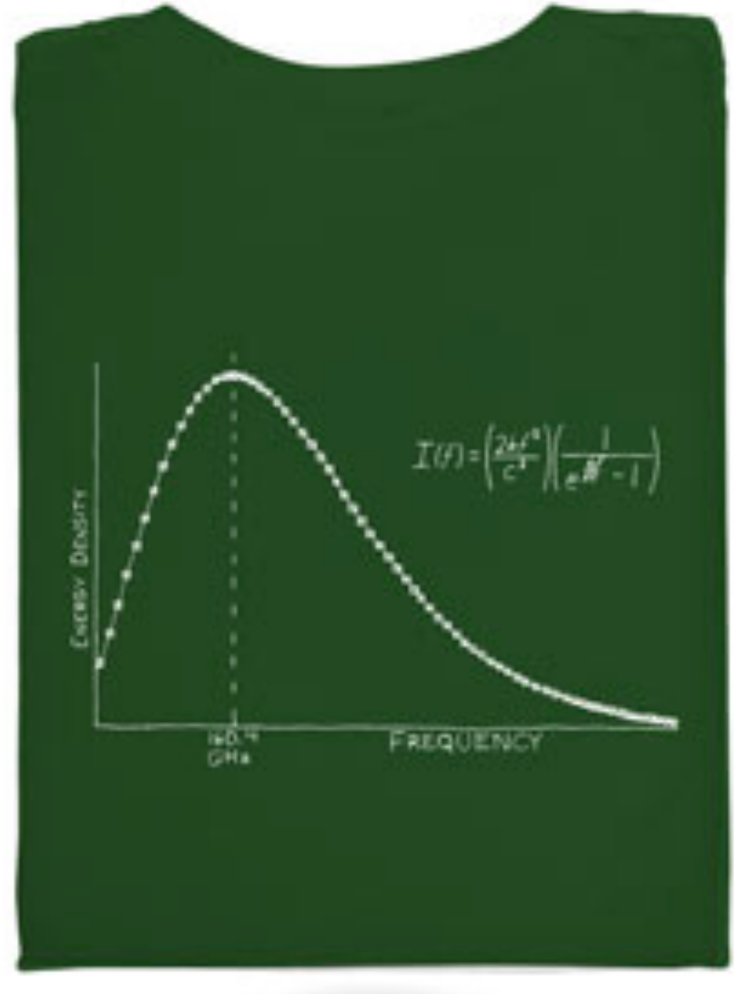
There are 4 'laws' or properties of the Planck function that have important consequences: (i) Wien displacement law; (ii) Stefan-Boltzmanm Law; (iii) Rayleigh-Jeans law and (iv) Wein radiation law

COLD SPACE – THE MOST PERFECT BLACKBODY EVER MEASURED:

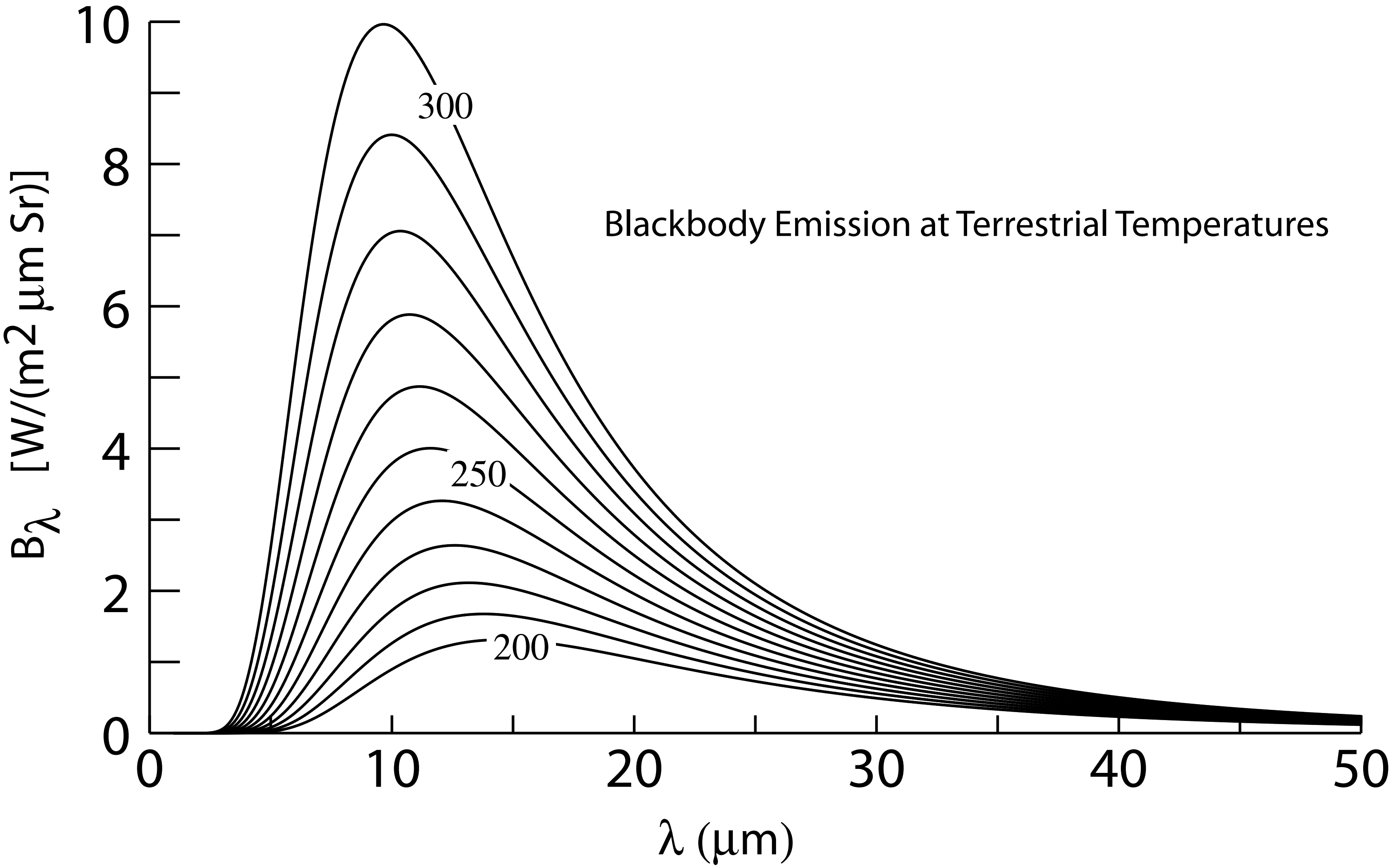




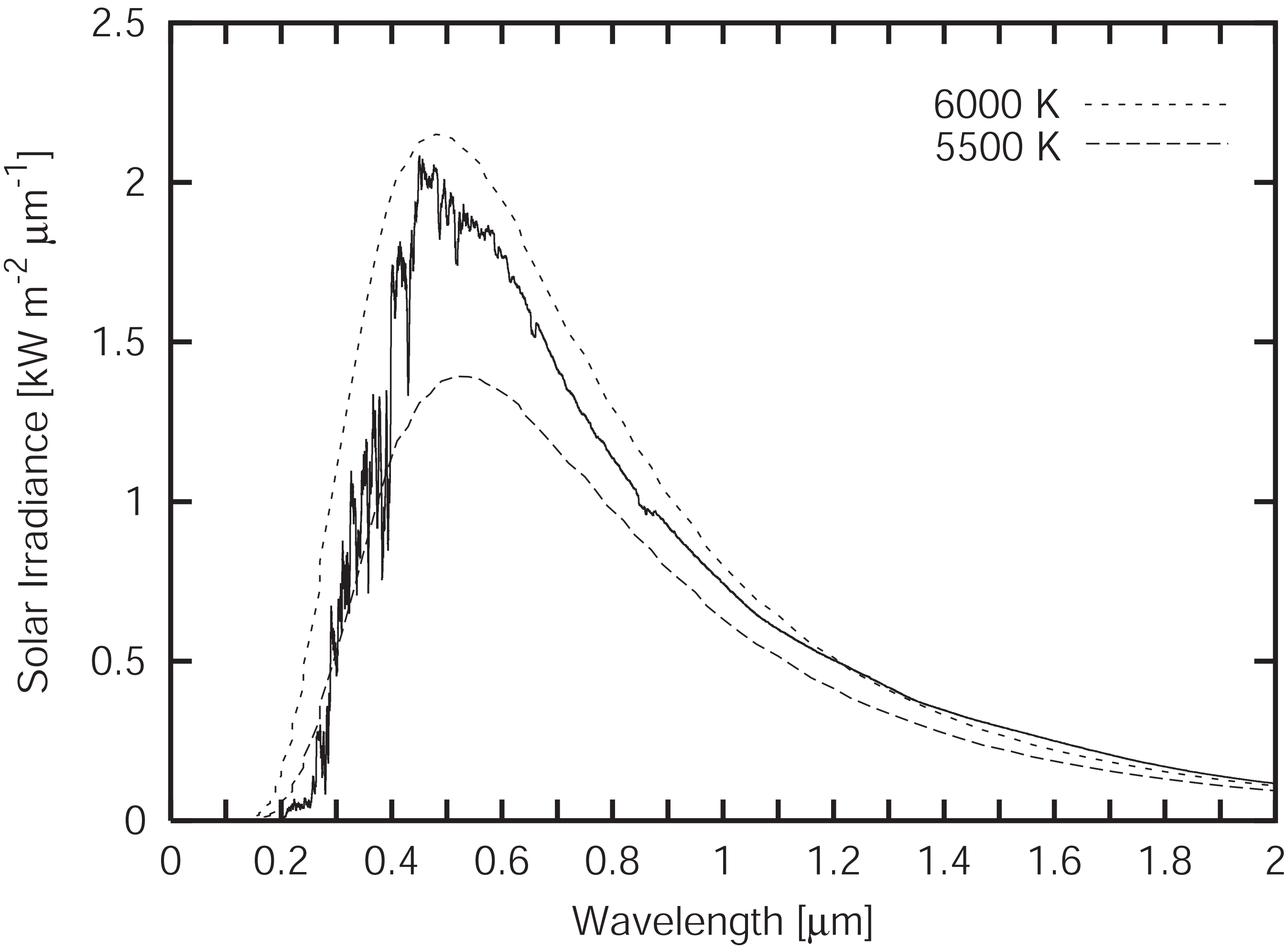

SCIENCE
IT WORKS, BITCHES.

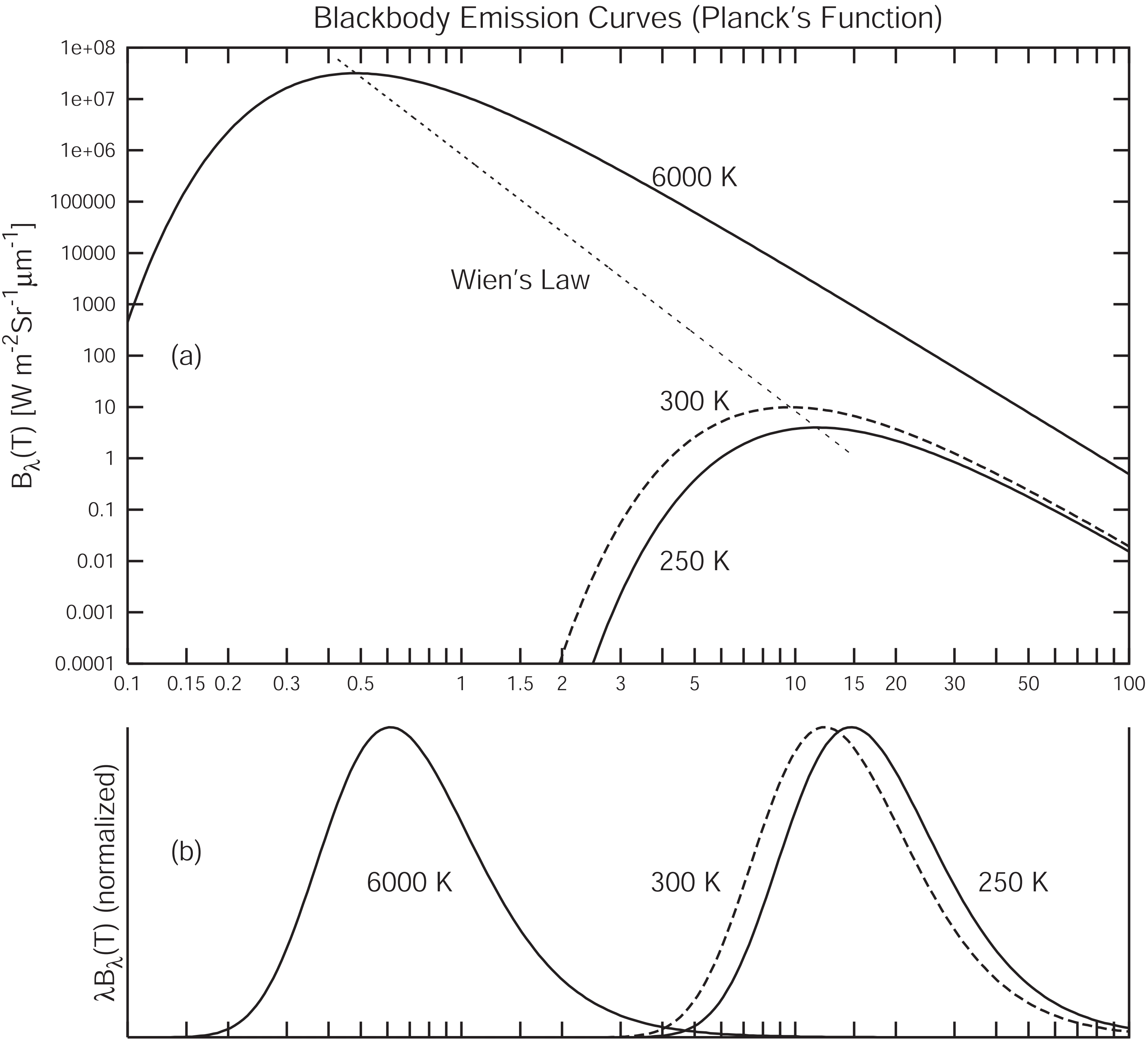

ENERGY DENSITY
160.4
GHz
FREQUENCY

Higher temperature blackbodies are higher at EVERY wavelength.



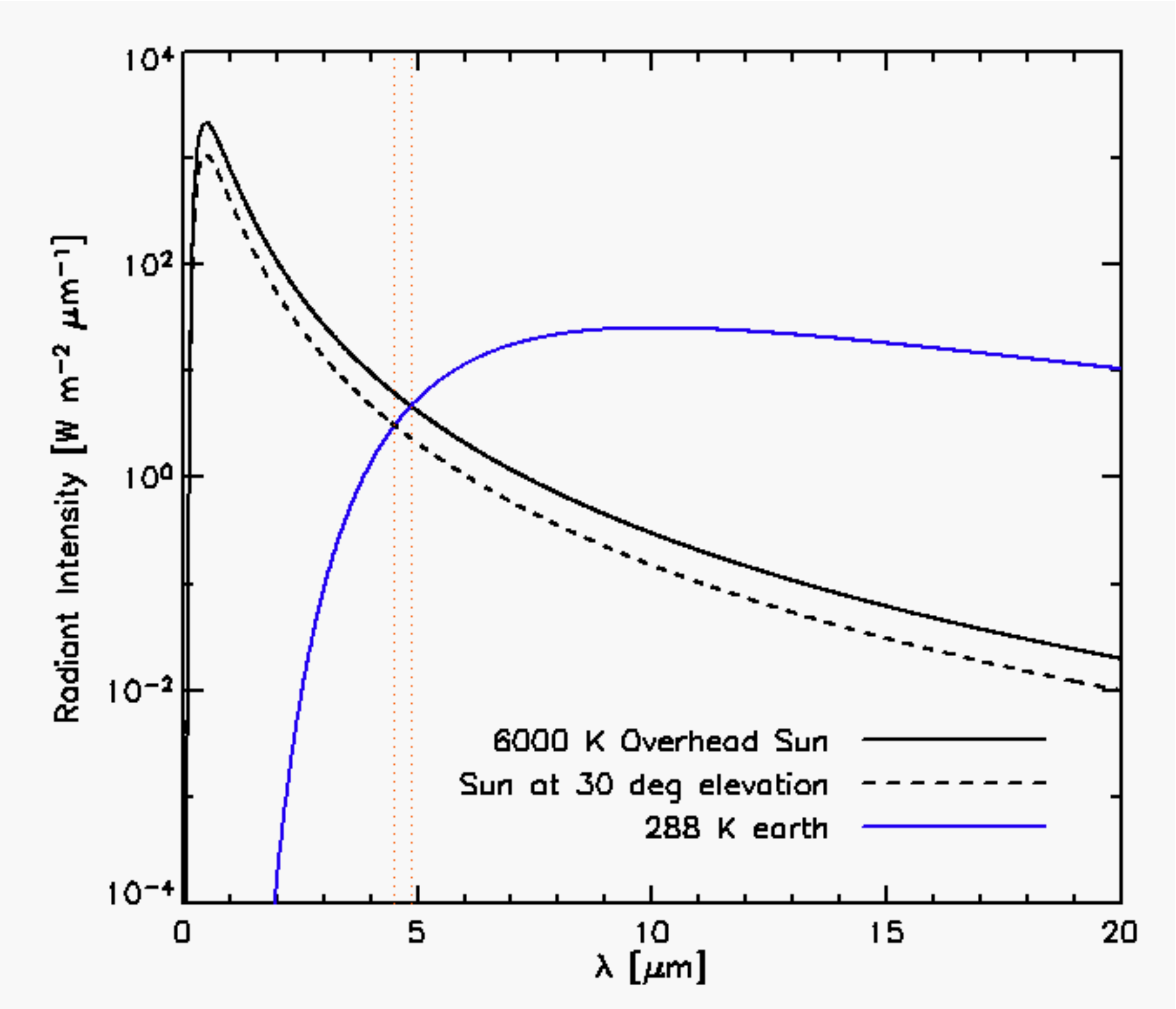
The solar spectrum is a near blackbody at 5762K.





Blackbody Emission Curves (Planck's Function)
1e+08
1e+07
1e+06
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
$B_\lambda(T)$ [W m^{-2}Sr^{-1}μm^{-1}]
6000 K
Wien's Law
(a)
300 K
250 K
0.1
0.15
0.2
0.3
0.5
1
1.5
2
3
5
10
15
20
30
50
100
$\lambda B_\lambda(T)$ (normalized)
(b)
6000 K
300 K
250 K

The sun & earth's spectra do not overlap much! Thank goodness.



Another perspective: normalized area under BB curves

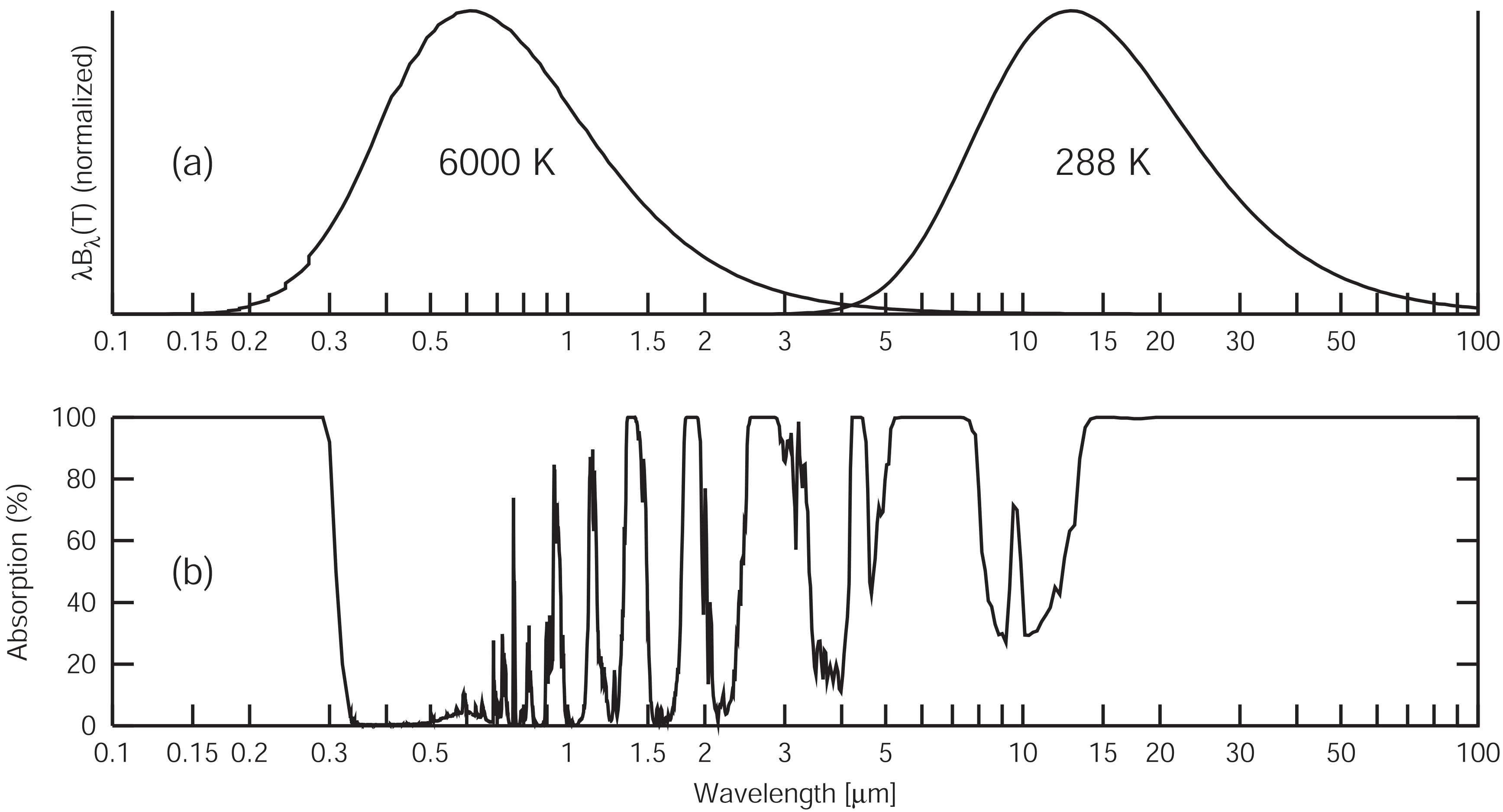
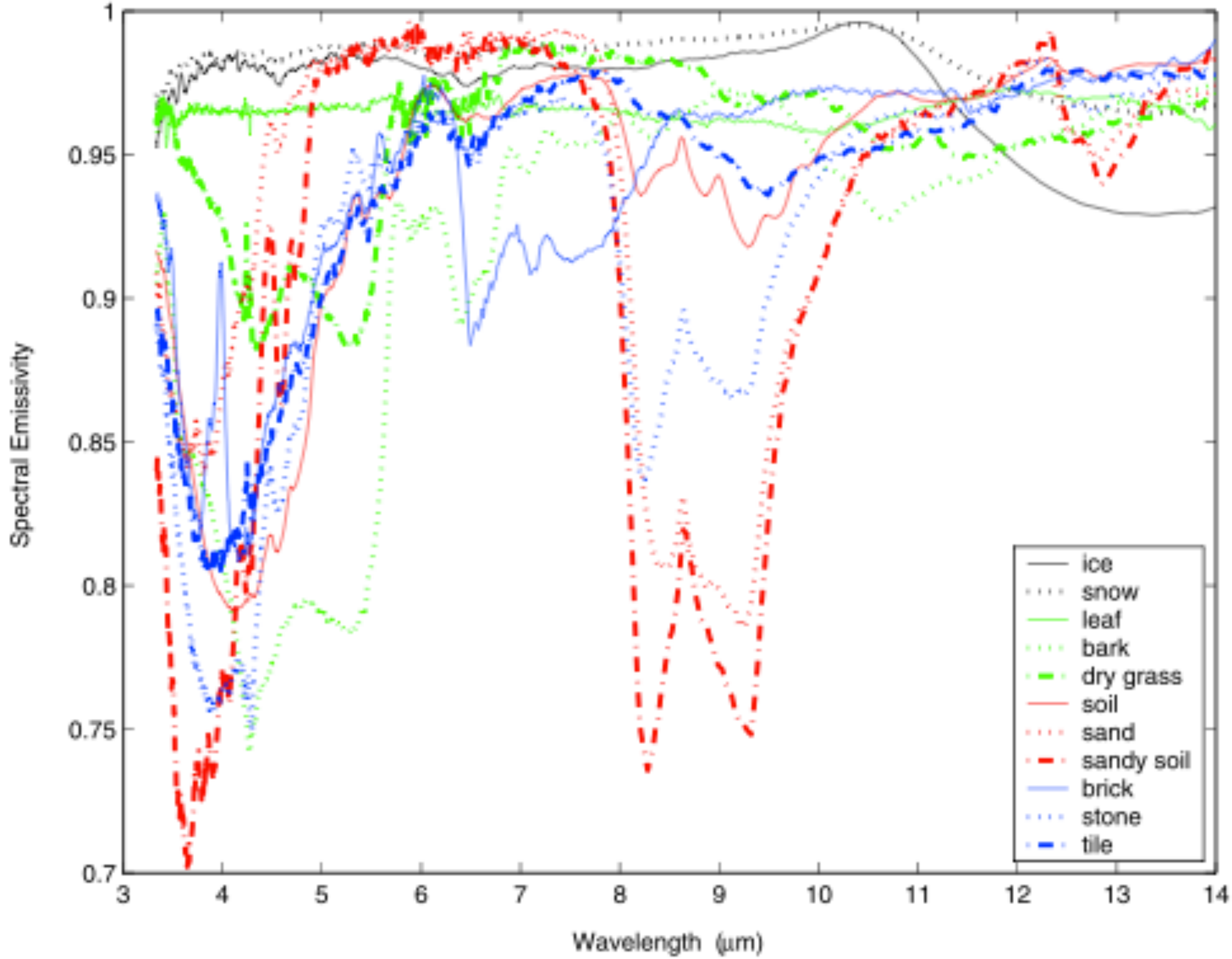


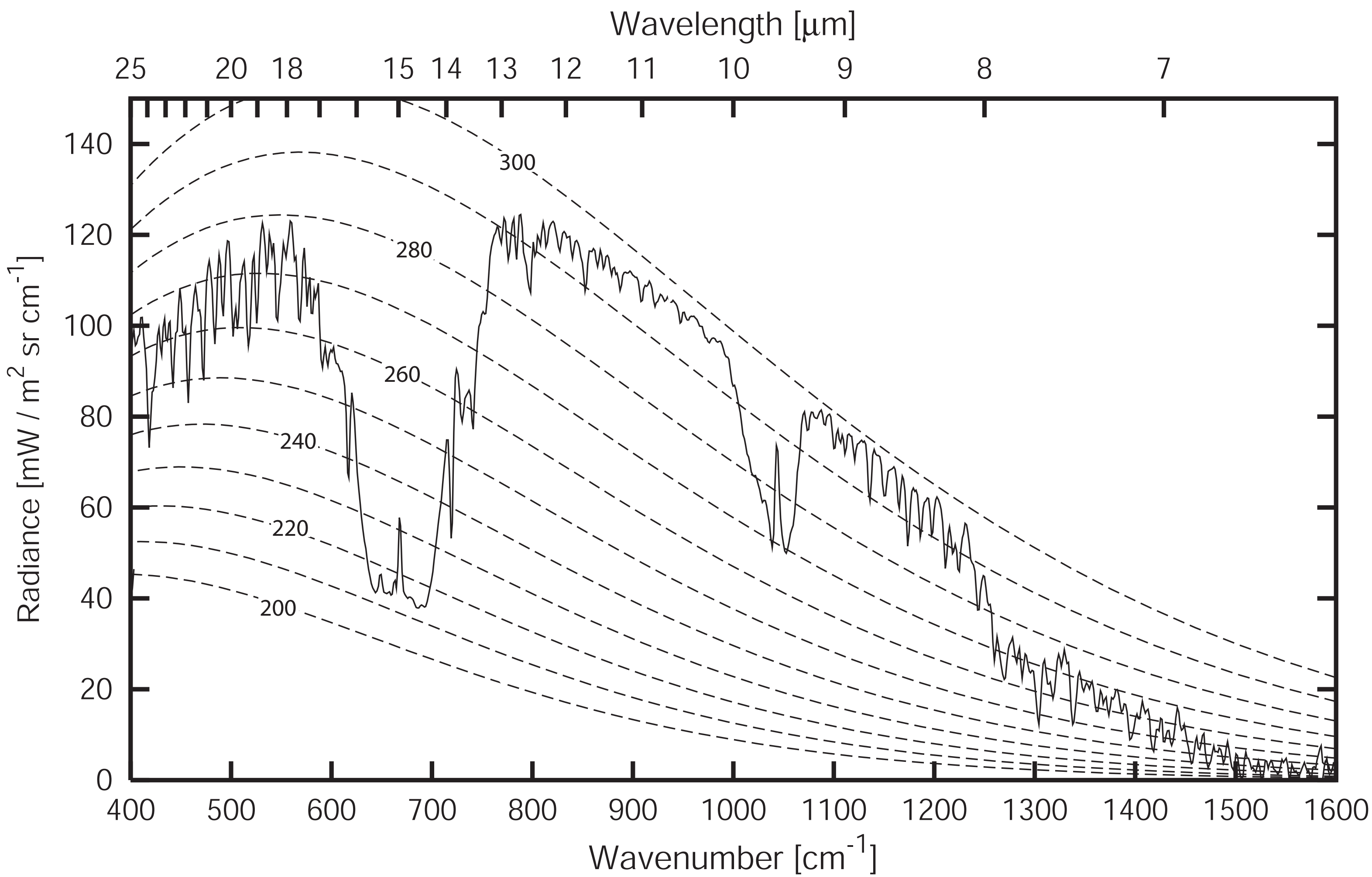
Table 4-1. Emissivity of natural surfaces expressed as a fraction of the radiant energy of a blackbody at the same temperature for the spectral region from 9 to 12 μ. (From U. L. Gayevsky [210])

Water	0.960
Fresh snow	0.986
Coniferous needles	0.971
Leaves	
Corn, Beans	0.940
Cotton, Tobacco	0.980
Sugar Cane	0.940
Dry peat	0.970
Wet peat	0.983
Dry fine sand	0.949
Wet fine sand	0.962
Thick green grass	0.986
Thin green grass on wet clay soil	0.975
Forest, Deciduous	0.950
Forest, Coniferous	0.970
Fur, Hair	
Mouse	0.940
Squirrel	0.980
Hare, Wolf	0.990
Human Skin	0.980
Glass	0.940

From *The Climate Near the Ground* (Geiger, Aron, and Todhunter)



Spectral Emissivity
Wavelength (μm)
1
0.95
0.9
0.85
0.8
0.75
0.7
3
4
5
6
7
8
9
10
11
12
13
14
ice
snow
leaf
bark
dry grass
soil
sand
sandy soil
brick
stone
tile



Satellite spectrum over tropical Pacific.