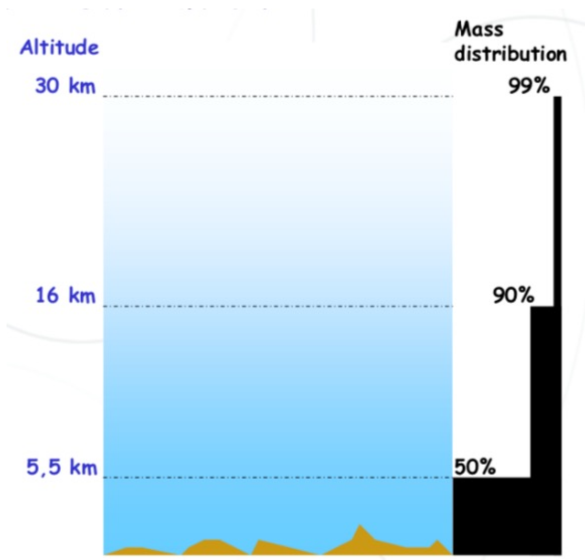
Introduction to Earth System

- Atmosphere (cont.)
- Radiation Balance of the Earth

The Atmosphere: vertical distribution



The Atmosphere: vertical distribution

- **Mass:**

The downward force of a unit volume of air:

$$F = \rho g$$

ρ: air density
g : gravitational acceleration

Integrating from the surface to the TOA → the atm. pressure on the Earth surface

$$p_s = \int_0^\infty \rho g dz$$

Assuming g equal to g_0=9.807 ms^{-2} → $p_s = m g_0$

where $m = \int_0^\infty \rho dz$ is the vertically integrated mass per unit area of the overlying air.

Q: The globally averaged surface pressure is 985 hPa. Estimate the mass of the atmosphere.

The Atmosphere: vertical distribution

- Pressure p (and density ρ) decreases nearly exponentially with height:

$$p \simeq p_0 e^{-z/H}$$

where H is the *scale height*; p_0 is the pressure at some reference level, usually taken as sea level.

- In the lowest 100 km of the atm., H~ 7-8km.

→
$$\ln \frac{p}{p_0} \simeq -\frac{z}{H}$$

→ useful for estimating the height of a pressure level in the atm.

E.g. H=8km.

Q. 50% mass of the atm. is at approximately what height above sea level?

Q. 90% mass of the atm. is at approximately what height above sea level?

Q. 99% mass of the atm. is at approximately what height above sea level?

Vertical distribution of pressure

- Q: How can we demonstrate the relationship?

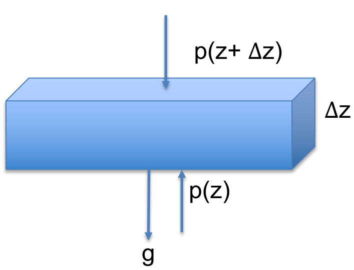
$$p \simeq p_0 e^{-z/H}$$

Hint: the hydrostatic equation & the equation of state

5

The hydrostatic equation

- In an air parcel at rest



- Force downward: $-[p(z+\Delta z)\Delta x \Delta y + mg]$
- Force upward: $+[p(z)\Delta x \Delta y]$
- Equilibrium:

$$\frac{p(z+\Delta z) - p(z)}{\Delta z}\Delta x \Delta y \Delta z + mg = 0$$

→ $$\frac{\partial p}{\partial z} + \rho g = 0$$

→ **Hydrostatic balance equation:** balance between the **vertical pressure gradient** and **gravity**

6

Vertical distribution of pressure

- We consider an isothermal atmosphere of temperature T_0 at rest.

The hydrostatic equation $\frac{\partial p}{\partial z} + \rho g = 0$

The equation of state $p = R\rho T_0$

→ $p(z) = p_0 e^{-z/H}$

$$\frac{dp}{p} = -\frac{gdz}{RT_0} = -\frac{dz}{H}$$

where H is the scale-height= $\frac{RT_0}{g}$

→ Pressure and density decrease exponentially with height

- Suppose T_0 =0ºC~273.15K

→ H= $\frac{287 \times 273.15}{9.807} \approx 8$ (km)

- Suppose T_0 =-35ºC~238.15K

→ H= $\frac{287 \times 238.15}{9.807} \approx 7$ (km)

The Atmosphere: composition

- The **homosphere** and **heterosphere** are defined by whether the atmospheric gases are well mixed.

Homosphere
Lower atmosphere

The air is well mixed:
- 78.09%: Nitrogen (N_2);
- 20.95%: Oxygen (O_2);
- 0.93% Argon
- & other "**trace**" gases
  - CO_2 ~400 ppm (0.037%))
  - Methan CH_4 ~1.8ppm
  - Ozone O_3 ~0.1 ppm (90% between 20-50km)
  - Water (H_2O): various amount, on average around 1% at sea level, and 0.4% over the entire atmosphere

Heterosphere
upper atmosphere

- The air is not well mixed
- Atoms get sorted by atomic weight (by gravity)
- H_2 and He can sometimes escape gravity

The Atmosphere (by composition)

Greenhouse Gases

- N_2 and O_2 are transparent to both incoming solar radiation and OLR → do not play a role in establishing atmospheric temperature

- **Gases that absorb OLR are called greenhouse gases**

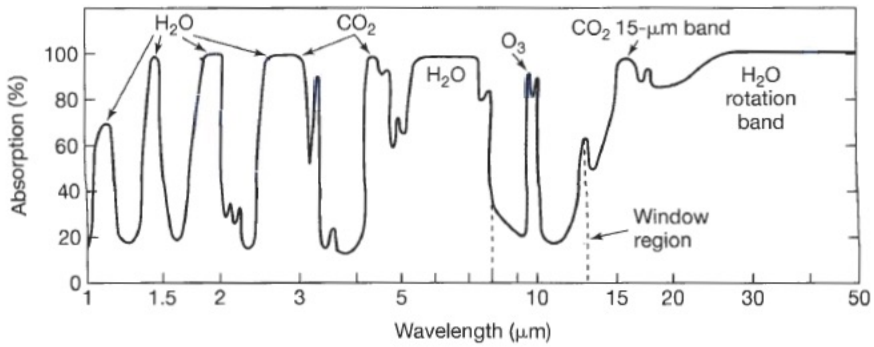
Q. What are the main GHGs?

1. water vapor (H_2O)
2. carbon dioxide (CO_2)
3. methane (CH_4)
4. nitrous oxide (N_2O)
5. ozone (O_3)
6. CFCs

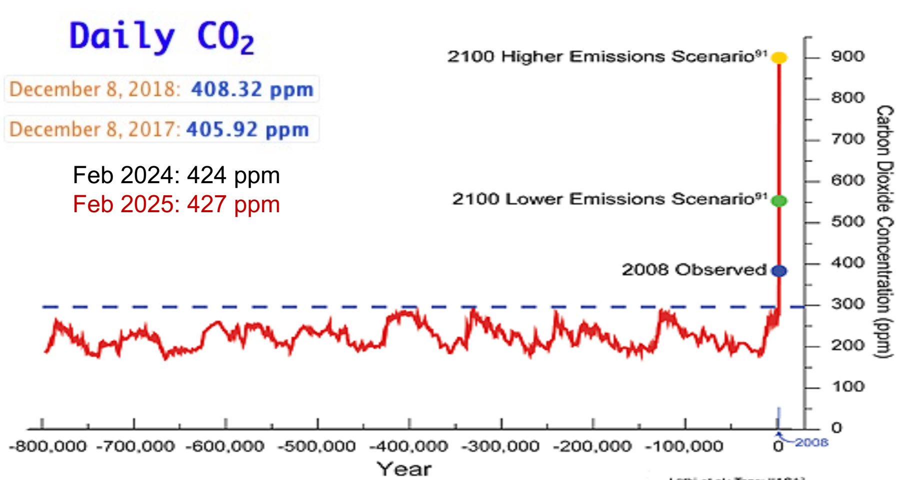
Important atmospheric greenhouse gases (2012)

Name	Concentration (ppm by volume)
Water vapor, H_2O	0.1 (South Pole) – 40000 (tropics)
Carbon dioxide, CO_2	370 (427 as of Feb 2025)
Methane, CH_4	1.7 (1.94 as of Nov 2023)
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

Percentage of radiation absorbed during vertical passage through the atmosphere



Are GHGs increasing?



Feb 2024: 424 ppm
Feb 2025: 427 ppm

At 2 ppm rise per year
→ **increasing rate of ~80 times that of the fastest natural rate and almost 2000 times the average rate** over the past hundreds of thousands of years

Radiative Forcings

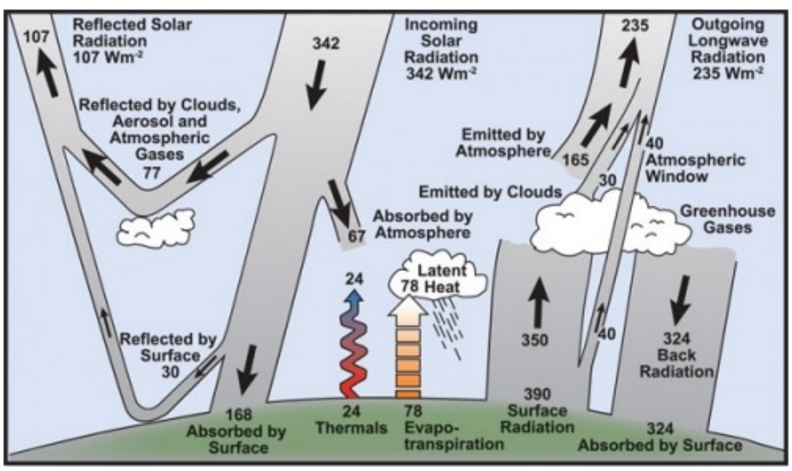
– is the change in the net irradiance (Wm^{-2}) at the tropopause
– usually defined as the change relative to the year 1750

Surface temperature can be linked to radiative forcing:

$$\Delta T_s = \lambda \cdot \Delta F$$

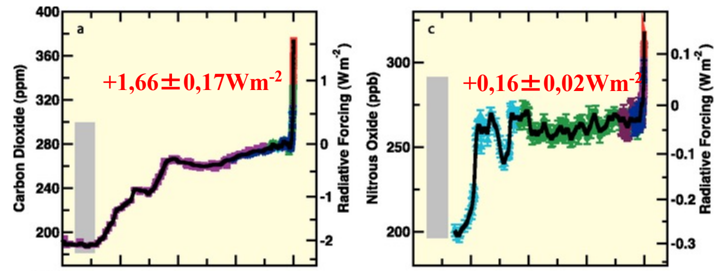
where λ is the climate sensitivity ($K/(W/m^2)$)
a typical value of λ is $0.8K/(W/m^2)$

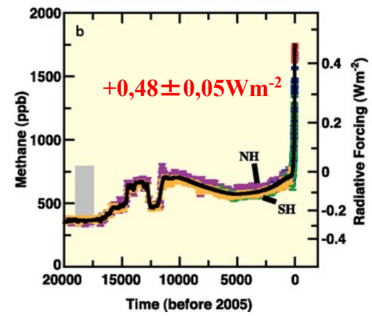
Energy balance



- When the climate system reaches a steady state, i.e. temperature stops changing → amount of energy going out = amount of energy coming in
- **Radiative forcing**

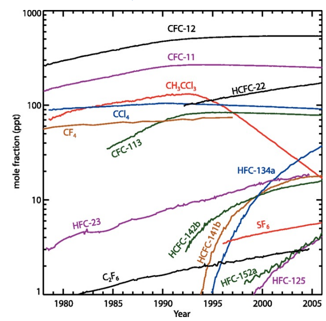
Changes in CO2, CH4 & N2O concentrations





Question: ? ΔT

CFCs, HCFCs +0,32±0,03Wm-2



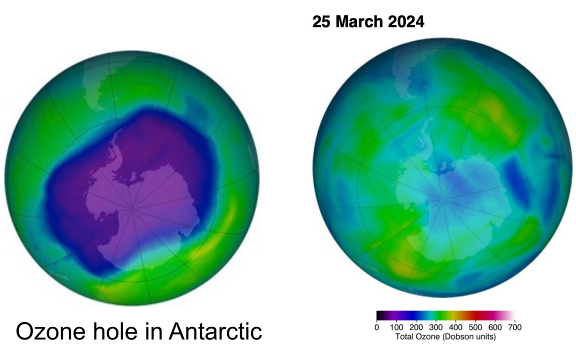
- Ice core data & direct observation (red line)
- Gray bar: natural variability within 650000 yrs

15

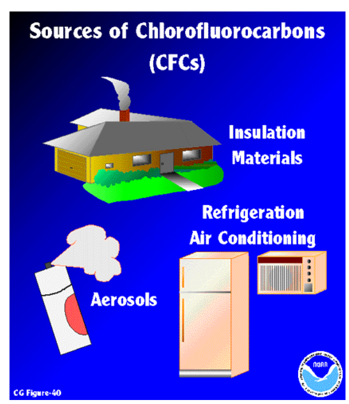
15

CFCs, HCFCs

- CFCs & HCFCs → man-made GHG
- Montreal Protocol (1989, 196 countries)



Ozone hole in Antarctic



Kofi Annan "perhaps the single most successful international agreement to date has been the Montreal Protocol"

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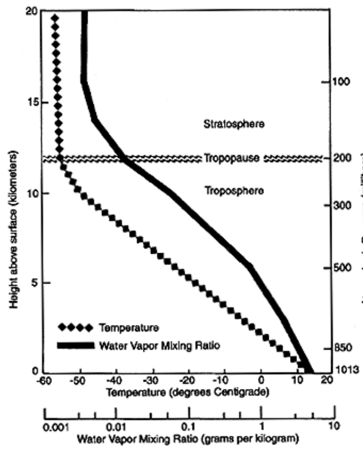
16

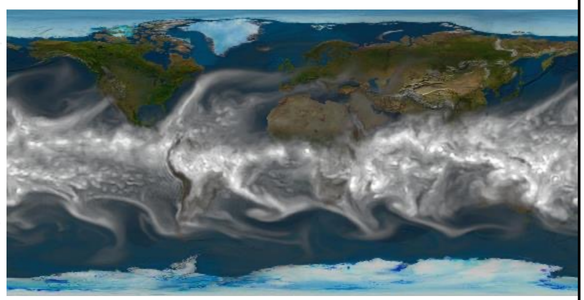
16

The Atmosphere: water vapor

Close to the surface:

- from 1 g per kg of dry air in the very cold continental regions to 30 g per kg of dry air in hot maritime regions
- rare above 8000/9000 m





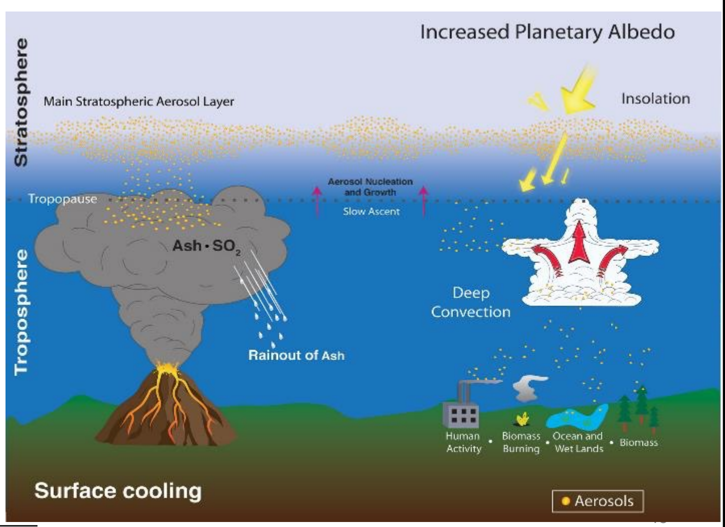
Q: Observed with which channel?

The Atmosphere: aerosols

- **Hydrometeors**: water droplets and ice particles
- **Lithometeors**: vegetable and mineral wastes, bacteria, carbon particles,...

- exponential decay with increasing altitude
- light diffusion
- condensation nuclei

Q. Warming or cooling effect?

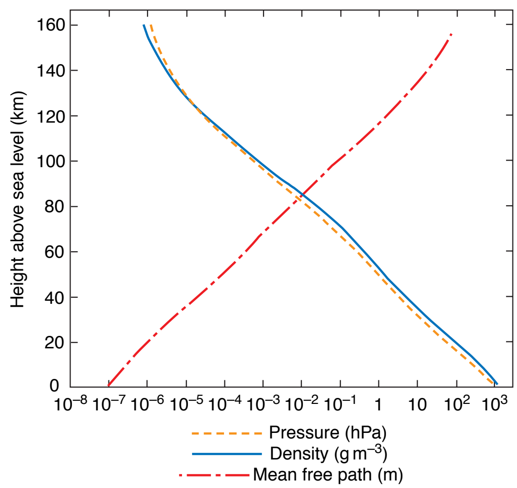


The Atmosphere (Vertical structure)

→ Density decreases with height in the same manner at pressure. Q. Why?

→ the outermost reaches of the atm.: dominated by the lightest molecular species (H, H_2, and He)

→ Above ~ 105km, the **mean free path** exceeds 1m



Vertical profiles of pressure in units of hPa, density in units of kg m^{-3}, and mean free path (in meters) for the *U.S. Standard Atmosphere*.

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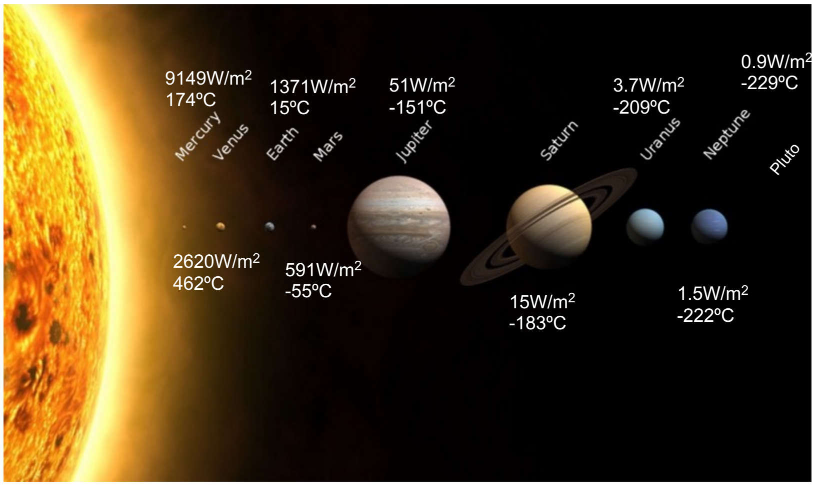
Solar system

Q: Does the radiation amount a planet receives determine its surface temperature?



Source: wiki, distances not to scale

Answer: It's not only the sunlight

21

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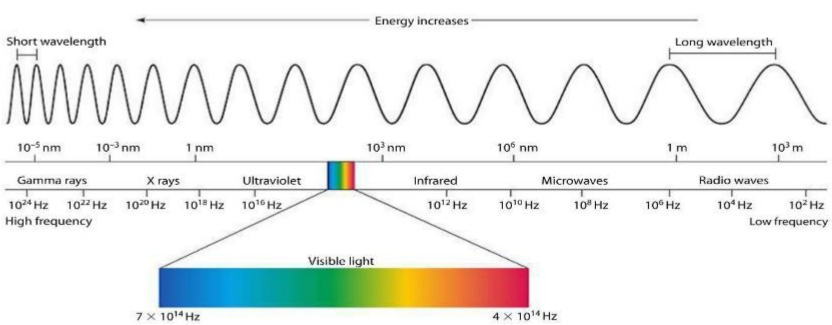
21

Some basic definitions

- **Electromagnetic Spectrum**: full range of forms of electromagnetic radiation, which differ by their wavelengths



- Q: In which wave bands do the most common remote sensing systems operate?

22

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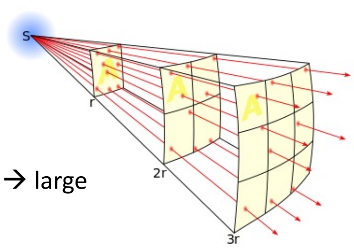
22

Some basic definitions

- In electromagnetic radiation, **flux (F)**: amount of energy in an electromagnetic wave that passes **perpendicularly** through a unit surface area per unit time
  - Polar regions are cooler than the tropics
  - Summer temperature are warmer than winter temperature

- Inverse-square law: $S = S_0 \left(\frac{r_0}{r}\right)^2$
  (S: solar flux)



→ Small variations in the shape of Earth's orbit → large changes in the climate of the polar regions

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23

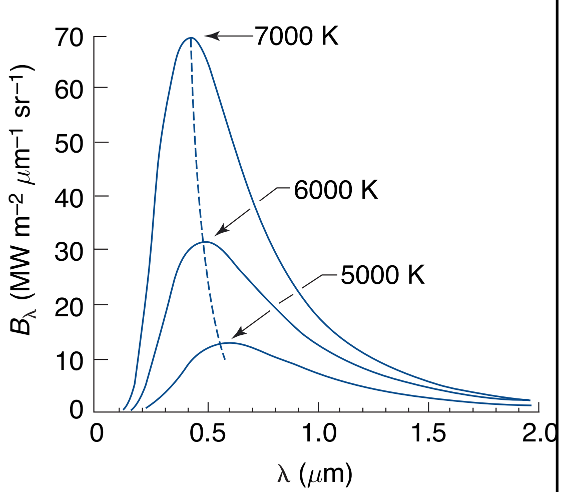
Blackbody radiation

- A **blackbody** is something that completely absorbs all incident radiation
- The radiation emitted by a blackbody is called **blackbody radiation**
- **Planck function**:

$$B_\lambda(T) = \frac{c_1 \lambda^{-5}}{\pi \left(e^{c_2/\lambda T} - 1\right)}$$

where $B_\lambda(T)$ is the intensity of radiation emitted by a blackbody;
$c_1 = 3.74 \times 10^{-16}$ W m^2
$c_2 = 1.45 \times 10^{-2}$ m K.

- The Sun emits ~50% of its energy in the visible interval; ~40% in IR; ~10% as ultraviolet radiation



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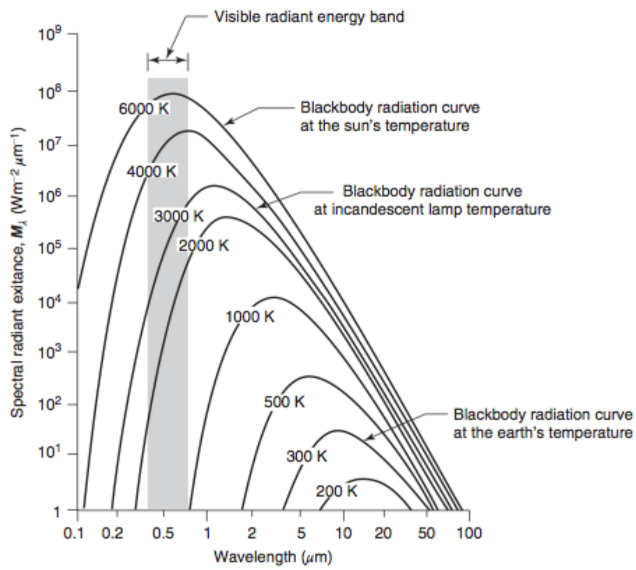
24

Wien's law

Wien's displacement law: the wavelength of peak emission for a blackbody at T

$$\lambda_m = \frac{2897}{T}$$



Prove the Wien's law?

- Peak emission of the Sun (5780K) ?
- Peak emission of the Earth (288K) ?

To find the peak of the blackbody radiation curve → take the derivative of the Plank function

$$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\pi\,(e^{c_2/\lambda T} - 1)}$$

$$\frac{d}{d\lambda}\left[\frac{1}{\lambda^5}\frac{1}{e^{a/\lambda T}-1}\right] = 0$$

$$\left[\frac{-5}{\lambda^6}\frac{1}{e^{a/\lambda T}-1} + \frac{1}{\lambda^5}\frac{-e^{a/\lambda T}\,\frac{a}{T}\frac{-1}{\lambda^2}}{\left[e^{a/\lambda T}-1\right]^2}\right] = 0$$

$$\lambda T = \frac{a e^{a/\lambda T}}{5\left[e^{a/\lambda T}-1\right]} = \frac{a}{5\left[1-e^{-a/\lambda T}\right]}$$

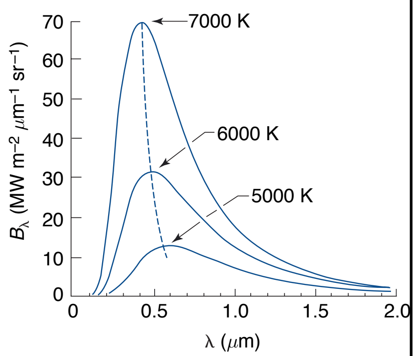
$$\lambda_m = \frac{2897}{T}$$

The Stefan-Boltzmann Law

The Stefan-Boltzmann Law: the black body irradiance → integrating the Plank function over all wave lengths

$$F = \sigma T^4$$

where σ is the Stefan-Boltzmann constant, equal to 5.67 × 10^{-8} W m^{-2} K^{-4}



- For a nonblack body (grey body) → estimate T_E
- T_E is called **equivalent blackbody temperature**; or **effective radiating temperature**

Energy emitted from an object is primarily a function of its temperature

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27

Kirchhoff's law

Kirchhoff's law

- For an arbitrary body emitting and absorbing thermal radiation in **thermodynamic equilibrium**, the **emissivity** is equal to the **absorptivity**.

→ **Corollary?**

- ❑ An arbitrary body emit ≤ a black body of the same size and shape at the same fixed temperature
- ❑ An arbitrary body can emit only at the wavelengths it absorbs
- ❑ a good/poor absorber is a good/poor emitter

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28

Practice #2

1. Plot the Planck curves for different black body temperatures T=6000K, 5000K, 4000K, 3000K
2. Print out the wavelength of peak emission for each body
3. Print out the total energy emitted by each body by using 1) the Stefan-Boltzmann Law, and 2) the Plank function

$$B_\lambda(T) = \frac{c_1 \lambda^{-5}}{\pi \left(e^{c_2/\lambda T} - 1\right)}$$

c_1=3.74 × 10^{-16} W m^2
c_2=1.45 x 10^{-2} m K.