# 講義の要領

- 中島映至(teruyuki@ccsr.u-tokyo.ac.jp)
- 大気放射学、リモートセンシング、大気組成と気候
- ノート(pdf)はウェブにアップ
  - http://157.82.240.167/index.html
- なるべく数値的に理解して欲しい
  - 全部はカバーしない
  - 電卓とかエクセルがあればうれしい



# 1. Atmospheric Radiation

# Radiation (放射)

- Radiation: electromagnetic wave
- Light, photon, visible light, infrared light, solar radiation,
- Maxwell equation
- Velocity, wavelength, frequency (/time), wavenumber (/distance) : $\nu = c/\lambda$, $E = h\nu$
- Electric permitivity, magnetic permiability
- Poynting vector

$$\mathbf{P} = \mathbf{E} \times \mathbf{H}^*$$

$$E = E_0 e^{i(\omega t - kx)}$$

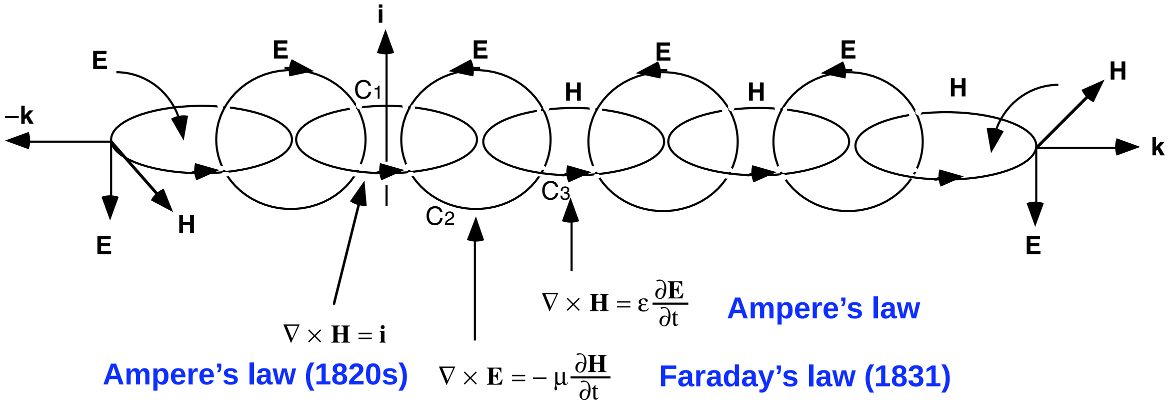
$$\omega = k\frac{dx}{dt} = kc$$

$$P = \sqrt{\frac{\varepsilon}{\mu}} E^2 = c\varepsilon E^2 \qquad c = \frac{1}{\sqrt{\varepsilon\mu}}$$

位相、波面の式、分散関係

$$k\lambda = 2\pi$$

$$\omega dt - kdx = const$$






# Radiance

**Radiance (輝度, W/m²/str/μm): *L***

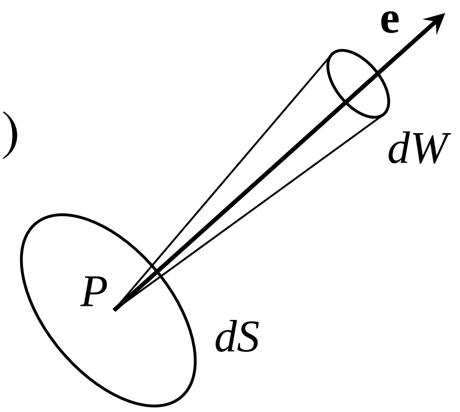
$$dE = L_\lambda(\mathbf{e}) d\lambda dt dS d\Omega$$

**Plane parallel light（平行光）**

$$L(\mu, \phi) = F_0 \delta(\mu - \mu_0)\delta(\phi - \phi_0)$$

**Isotropic light（等方場）**

$$L(\mu, \phi) = L$$




***dS*: Receiver area**
***dΩ*: Solid view angle**

# Flux, irradiance (照度)

- Plane flux, hemispherical flux, irradiance

$$F = \int_0^1 d\mu \int_0^{2\pi} d\phi L(\mu,\phi)\mu$$

- Plane parallel radiation field

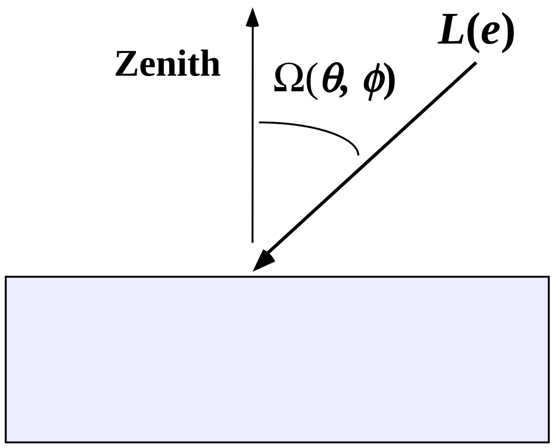
$$F = \mu_0 F_0$$

- Isotropic field

$$F = \pi L$$

- Wavelength integration, broadband fluxes

$$F = \int d\lambda F_\lambda, \quad L = \int d\lambda L_\lambda$$






# Reflectance and transmittance

- Flux reflectivity(反射率), reflectance, albedo

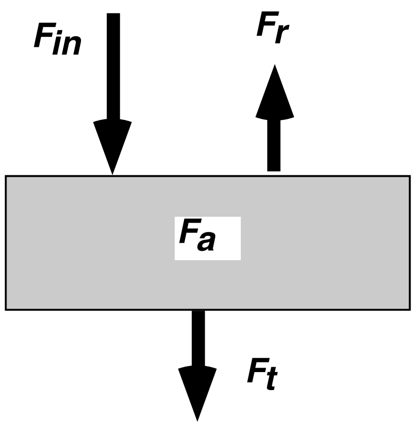
$$r = \frac{F_r}{F_{in}}$$

- Transmissivity (透過率), absorptivity (吸収率)

$$t = \frac{F_t}{F_{in}}, \quad a = \frac{F_a}{F_{in}}$$

- Radiant energy conservation law

$$r+t+a = 1$$



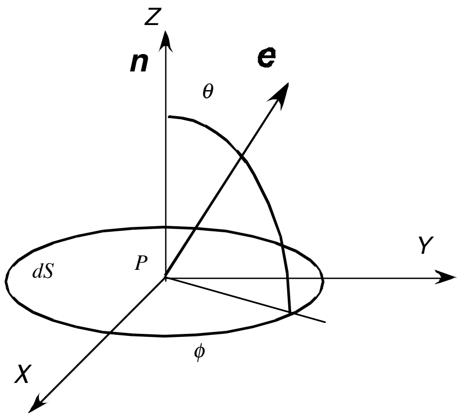
# Coordinates

- **Polar coordinates**

$$\mathbf{e} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$d\Omega = \sin\theta d\phi d\theta = d\phi d\mu$$

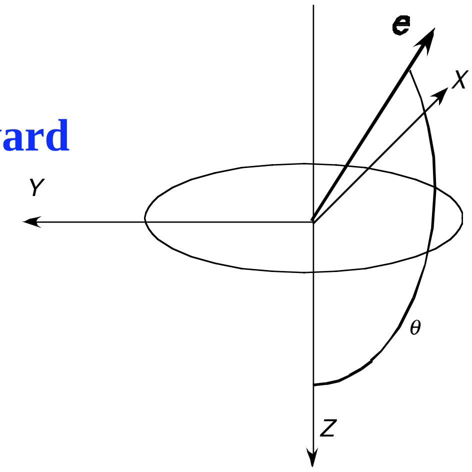
$$\mu = \cos\theta$$




- **Nadir (天底) and zenith (天頂)**
- **Upward (welling) and downward (welling)**
- **Nadir system**

  **μ < 0: upward**

  **μ > 0 : downward**





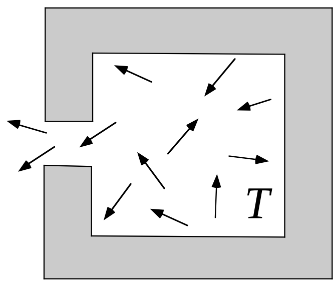

# Blackbody radiation 1

- **Quantum photon theory by M. Plank's in 1902**

$$e = 0,\ h\nu, 2h\nu, 3h\nu, \ldots \qquad \nu = \frac{c}{\lambda}$$

- **Boltzman's law**
- **Definition of temperature**

$$p = \exp\left(-\frac{\varepsilon}{k_B T}\right)$$



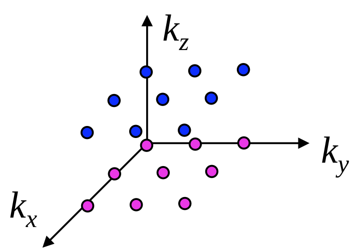

- **Mean energy is same for each degree of freedom (Equi-partition law of energy)**

$$<\varepsilon> = \frac{\sum nh\nu \exp(-nh\nu / k_B T)}{\sum \exp(-nh\nu / k_B T)} = \frac{h\nu \exp(-h\nu\beta)}{1-\exp(-h\nu\beta)} = \frac{h\nu}{\exp(h\nu\beta)-1} \qquad \beta = \frac{1}{k_B T}$$

- **Number of quantum sates of photon inside a box L^3**

$$k = \frac{2\pi}{\lambda} = \frac{2\pi n}{L}, \quad (n = 0, \pm 1, \pm 2, \ldots)$$

$$g(\nu) = \frac{4\pi k^2 dk}{(2\pi / L)^3} = \frac{V}{2\pi^2} k^2 dk = \frac{4\pi V}{c^3} \nu^2 d\nu$$




- **2 polarization states: 2g(ν)**

# Blackbody radiation 2

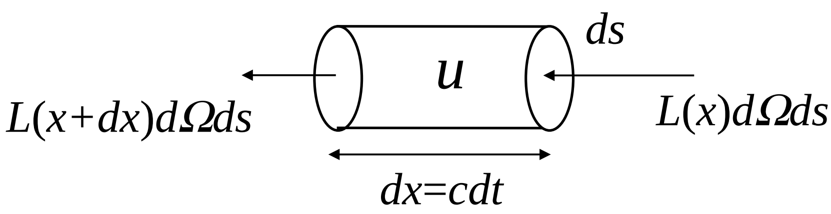
- **Radiant energy density with two polarization states**
- **Plank Function for Blackbody radiation**
- **Radiant energy density (W/m3)**

$$u_\nu(T)d\nu = 2 < \varepsilon > g(\nu)\frac{d\nu}{V} = \frac{8\pi}{c^3}\frac{h\nu}{\exp(h\nu / k_B T) - 1}\nu^2 d\nu$$

$$u_\nu dV = \int_{4\pi} d\Omega L d\sigma dt = \int_{4\pi} d\Omega \frac{L}{c} dV = \frac{4\pi}{c} L dV$$

$$L = B_\nu(T) = \frac{2h\nu^3}{c^2[\exp(h\nu / k_B T) - 1]}$$

**Plunk function**






# Blackbody radiation 3

- **Blackbody radiation**

$$L_\nu = B_\nu(T) = \frac{2h\nu^3}{c^2[\exp(h\nu / k_B T) - 1]}$$

**wavelength: $\lambda$**
**frequency: $\omega = 2\pi/\lambda$**
**wavenumber: $\nu = c/\lambda$, $\nu' = 1/\lambda$(cm)**

$$B_\lambda(T) = B_\nu(T)\frac{d\nu}{d\lambda} = \frac{c}{\lambda^2}B_\nu(T) = \frac{2hc^2}{\lambda^5[\exp(hc / k_B T\lambda) - 1]}$$

- **Wien's displacement law**
- **Stefan-Boltzman's law**

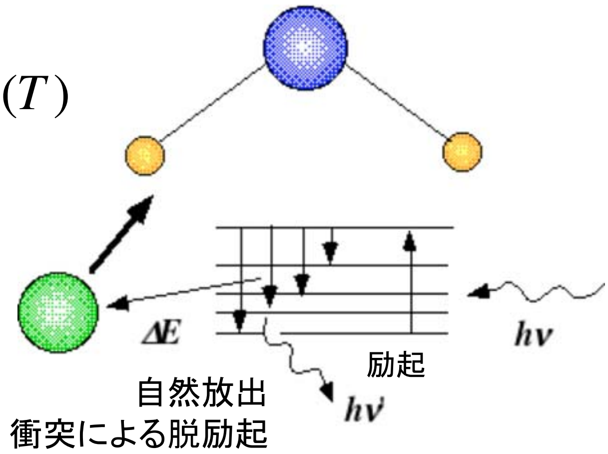
$$\lambda_{\max} T = 2900 \quad (\mu m K)$$

$$F = \pi \int_0^\infty B_\lambda d\lambda = \sigma T^4$$

$$\sigma = \frac{2\pi^5 k_B^4}{15h^3c^2} = 5.67 \times 10^{-8} W / m^2 K^4$$

# Emission (射出) of the radiation

- Local Thermodynamic Equillibrium (LTE) state z<50km
- Kinetic temperature $T$ = Internal state temperature $T_i$
  - ➢ *Electronic - Vibration - Rotation - Translation*
- Boltzman's law $$n(\varepsilon) \propto \exp(-\frac{\varepsilon}{k_B T})$$
- Kirchihoff's law; absorptivity $$E(T) = \tilde{a}B(T)$$
- Emissivity (射出率) $$E(T) = \varepsilon B(T)$$ $$\varepsilon = \tilde{a}$$

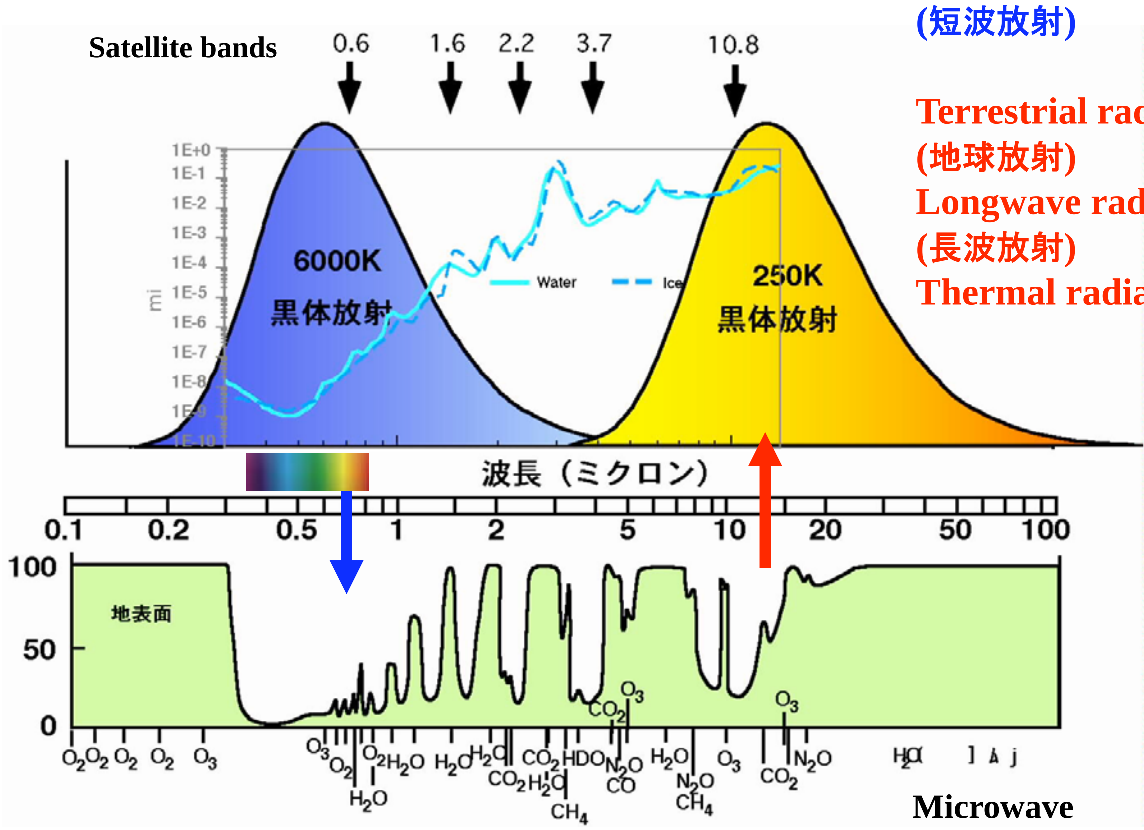





# Solar and terrestrial radiation

Solar radiation
Shortwave radiation
(短波放射)

Terrestrial radiation
(地球放射)
Longwave radiation
(長波放射)
Thermal radiation




UV Visible window IR window

Goody and Yung (1989)

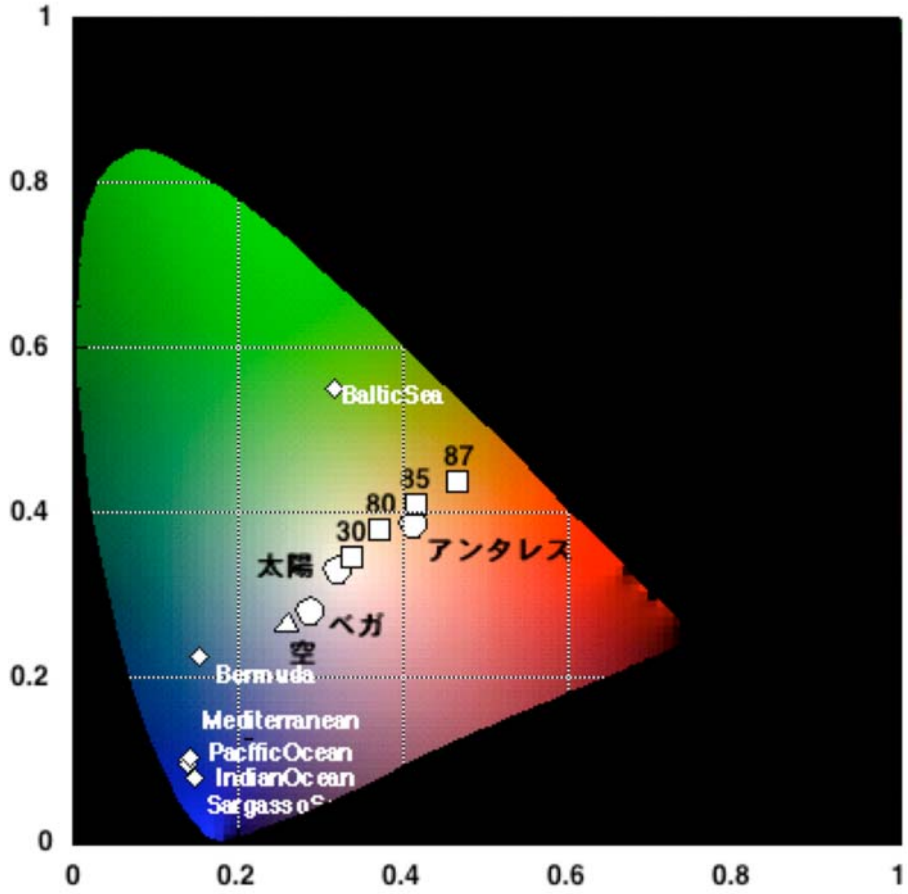
# 月




# 質問

- 6000Kは緑色、だけど太陽は緑には見えないのはなぜ?

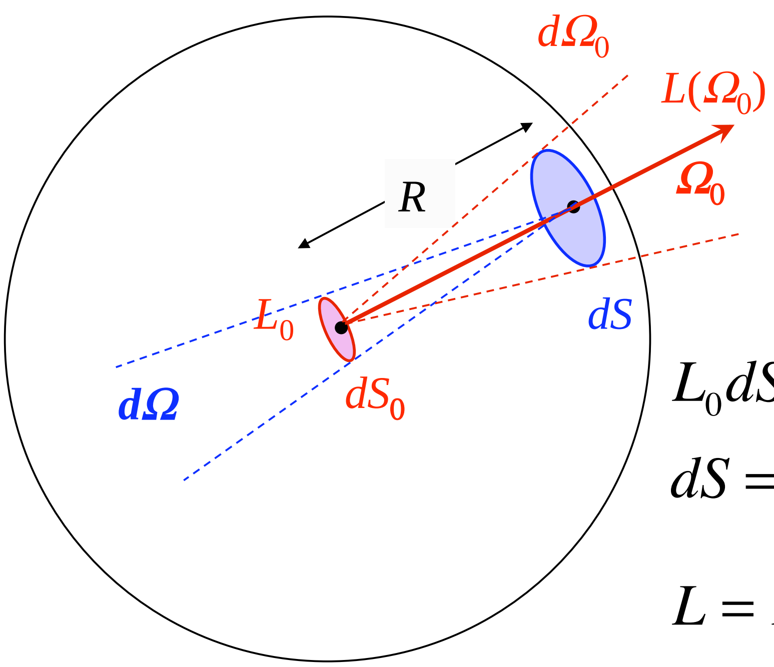
## Color of the environment






## Invariance principle of radiance

- Emitted radiation and recieved radiance
- Point source problem



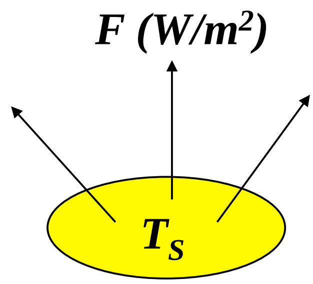

$$L_0 dS_0 d\Omega_0 = L dS d\Omega$$

$$dS = R^2 d\Omega_0, \quad dS_0 = R^2 d\Omega$$

$$L = L_0, \quad F = L d\Omega = L_0 \frac{dS_0}{R^2}$$

# Solar constant (太陽定数)

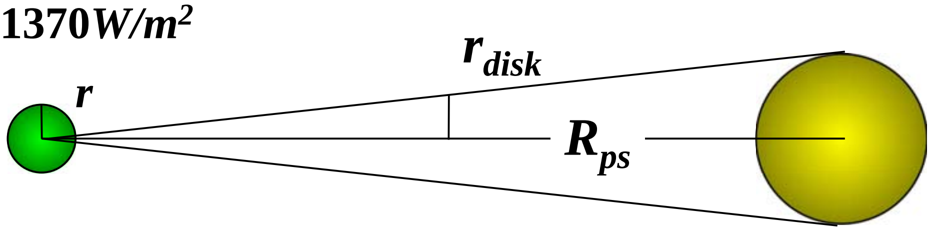
- Radiative flux at the sun surface: $F$ (W/m$^2$)
- Radiative flux at the earth's orbit: $S$ (W/m$^2$)
- Radius of the solar disk: $r$
- Angular radius (視半径) of the solar disk: $r_{disk}$
- Distance between earth and sun: $R_{ps}$




$$S = \frac{E_s}{4\pi R_{ps}^2} = \frac{4\pi r^2 F}{4\pi R_{ps}^2} = r_{disc}^2 F = r_{disc}^2 \sigma T_{sun}^4$$

- In case of $R_{ps}$= mean orbit: $S$ is called Solar constant

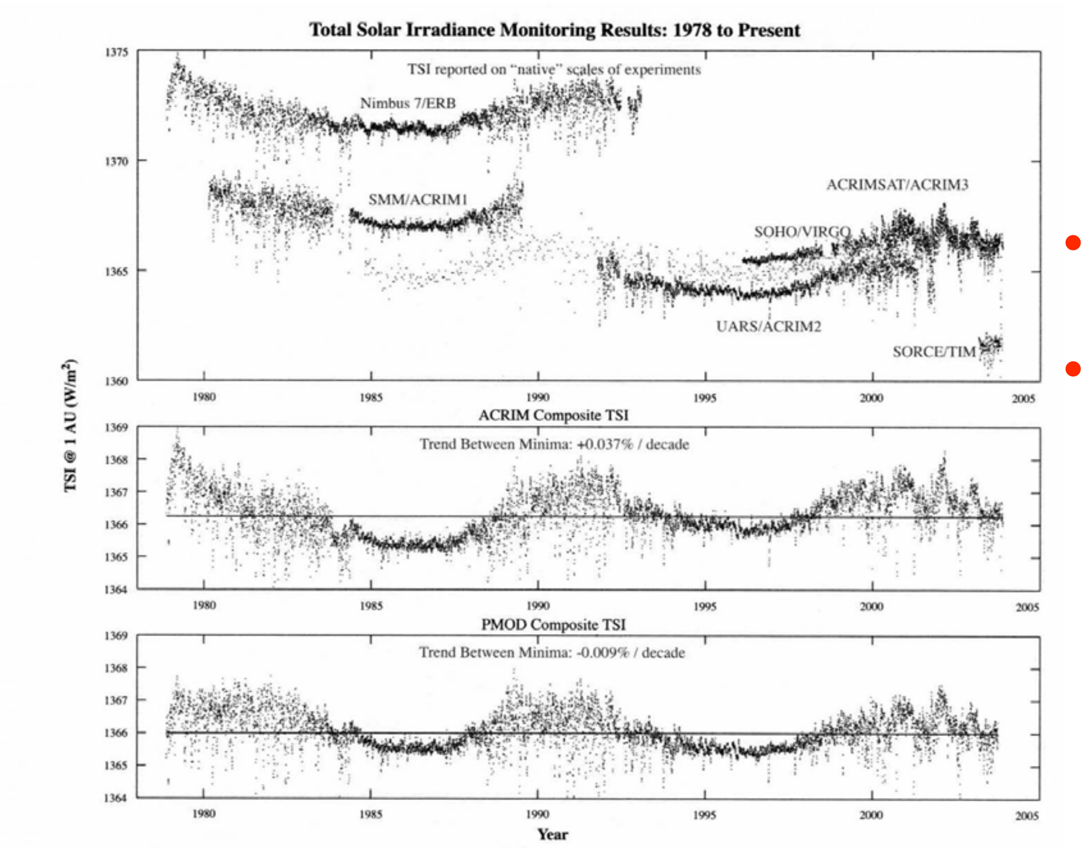
$r_{disk}$=D/2=16'
$T_s$=5790$K$, $S$=1370$W/m^2$



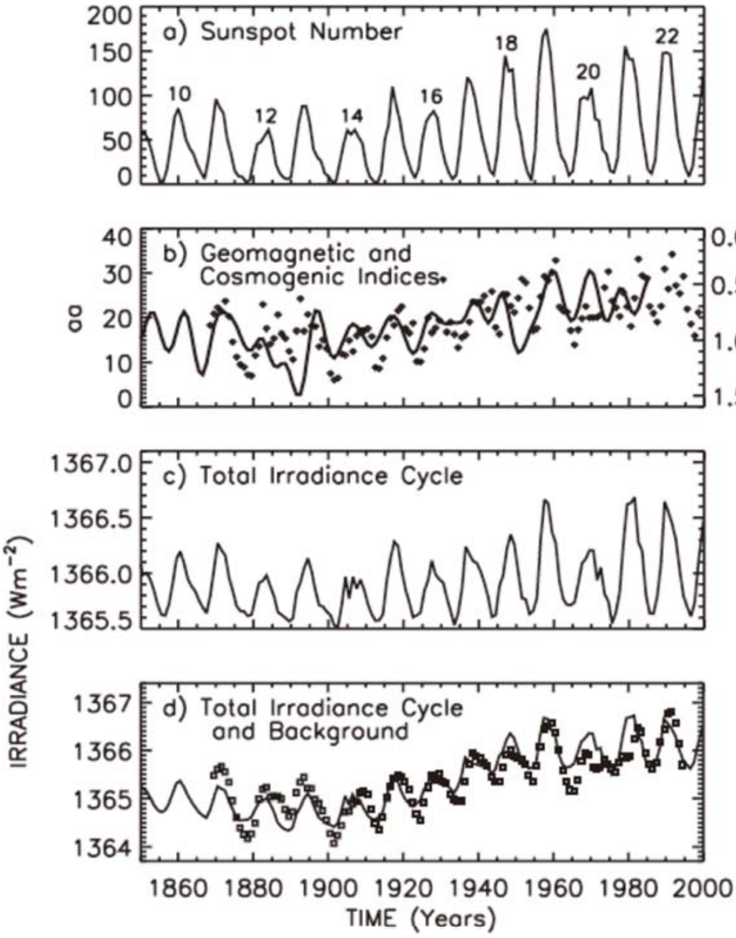



# Variation of the solar output

NASA (EO 2004)




- 太陽活動が高いときほどばらつきが大きいことがわかる。
- なぜ衛星の結果が異なるの？




**Lean et al. (2002)**

$\Delta U$= 70
$\Delta S$= 1.5 W/m$^2$

Sunspots cause spectral irradiance to change by

$$\Delta F_S(\lambda, t) = \alpha_S F(\lambda)_{quiet} \frac{C_S(\lambda) - 1}{C_S^{bol} - 1} P_S(t) \qquad (3)$$

where $C_S(\lambda) - 1$ are the contrasts in Figure 1, $C_S^{bol} = 0.68$, and $P_S(t)$ are $10^{-6}$ of the values in Figure 3. The constant $\alpha_S = 0.99$ ensures that $\int(\Delta F_S(\lambda, t_{cmax}) - \Delta F_S(\lambda, t_{cmin}))d\lambda = -1.1\ Wm^{-2}$, which is the bolometric solar cycle change determined independently from modeling total solar irradiance [*Fröhlich and Lean*, 1998].

**Lean et al. (2000)**



# Sun spot variation

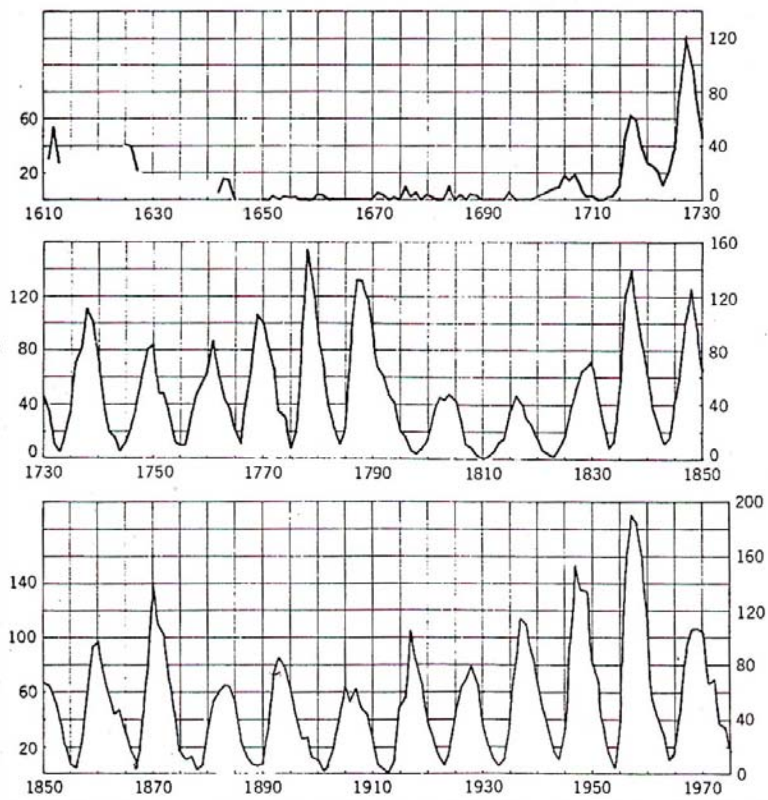


Fig. 2. Annual mean sunspot number, 1610 through 1975. Values for 1610 through 1715 are those estimated by Eddy (9). Data for 1642 through 1644 were derived from Hevelius's *Selenographia* (8); those for 1625 through 1627 are from the *Rosa Ursina* (10).

$\Delta U$= 100
$\Delta S$= ? W/m$^2$

## Solar activity periods

**11, 22 year cycles < 2 W/m$^2$**
**Large UV variation**
**55, 80 year cycles**
**太陽磁気活動の極小期、静かな太陽**
**シュペラー極小期:16世紀**
**マウンダー極小期:17世紀**

**寒冷な中世の気候と時期的に重なる**

**マウンダーミニマム**
**ΔS =˜ −4 W/m$^2$**

## 物理学の美しさ



1948


Statue of Prof. Boltzman


Prof. Helmuth Horvath

- ランダウ･リフシッツ　シリーズ



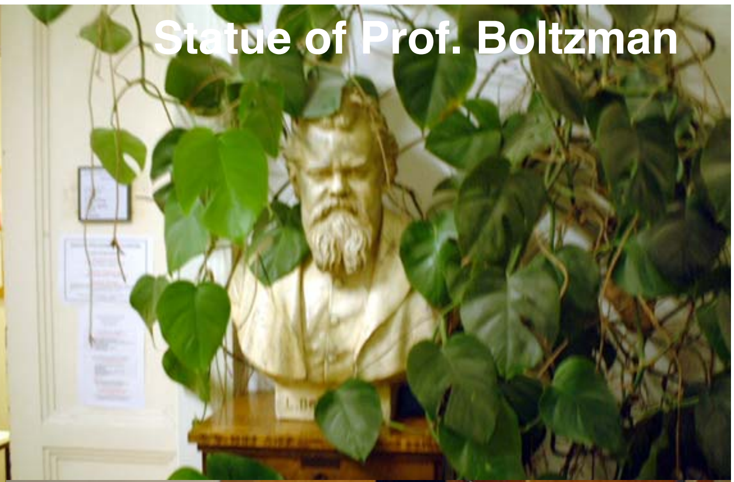
**Newton's 2nd law**

$$m\frac{d\mathbf{v}}{dt} = \mathbf{F}$$

**Boltzman's law**

$$n(\varepsilon) \propto \exp(-\frac{\varepsilon}{k_B T})$$


Prof. Helmuth Horvath


Statue of Prof. Boltzman


LUDWIG BOLTZMANN'S VORLESUNGSTAFEL

# The University of Vienna since 1365

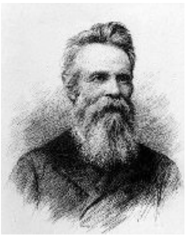


Ludwig Boltzmann (1844-1906)

Ernst Mach (1838-1916)

Christian Doppler (1803-1853)

Erwin Schrödinger (1887-1961)
Nobel prize



Johann Josef Loschmidt (1821-1895)

# John William Strutt Lord Rayleigh

**1842-1919, Essex, England**

**Trinity College, Cambridge**

**Prof. Stokes**

**Maxwell’s 1865 paper**

**Rayleigh's theory of scattering, published in 1871, was the first correct explanation of why the sky is blue. In the same year he married Evelyn Balfour, the sister of Arthur James Balfour who was to be a leading member of the Conservative Party for 50 years and Prime Minister of Britain 30 years later. Rayleigh had been a student at Cambridge with Arthur James Balfour and through him had met Evelyn. Shortly after their marriage Rayleigh had an attack of rheumatic fever which nearly brought his scientific activities to a premature end. He was advised to travel to Egypt and indeed he did just this with his wife. They sailed down the Nile during the last months of 1872 and early 1873, returning to England in the spring of 1873.**

## Constants

| | |
|---|---|
| Acceraration of gravity | 9.80665 m/sec2 |
| Speed of light | 2.9979e8 m/sec |
| Boltzman constant | 1.3807e-23 J/K |
| Plank constant | 6.6261e-34 Jsec |
| Avogadro number | 6.0221e23 /mol |
| Volume of ideal gas at $0_{\circ}$C and 1 atom | 2.241e4 cm3/mol |
| Absolute temperature | 273.15 K (0C) |
| Gas constant | 8.314 J /deg/mole |
| Stephan-Boltzman constant | 5.670e-8 W /m2 K4 |
| Molecular weight of dry air | 28.964 g/mol |
| Latent heat of vaporization at 273K | 2.500E6 J/Kg |
| 1 bar 10^6 dyne/cm2 = 10^5 N/m2 = 10^5 Pa | |
| Earth's radius | 6370 km |
| Mean solar angular diameter | 31.99 minutes of arc |
| Air= 0.78083 (N2)+0.20947 (O2)+ 0.00934 (Ar)+0.00033 (CO2) by volume ratio | |
| Globe= 0.708 (Ocean)+ 0.292 (Land) by area ratio | |
| Molecular weight of air | 29 g/mole |



## Textbooks and reviews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