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 permeability
- Poynting vector

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

\[
\omega = k \frac{dx}{dt} = kc
\]

\[
P = E \times H^* = \sqrt{\frac{E^2}{\mu}} = cE^2
\]

\[
c = \frac{1}{\sqrt{\varepsilon\mu}}
\]

- Faraday's law (1831)
- Ampere's law (1820s)

**Radiance**

Radiance (輝度, \( \text{W/m}^2/\text{str}/\mu\text{m} \)): \( L \)

\[
dE = L_\lambda(e) d\lambda dt dS d\Omega
\]

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
\( d\Omega \): 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
  \[ r + t + a = 1 \]
Polar coordinates

Nadir (天底) and zenith (天顶)
Upward (welling) and downward (welling)

Nadir system
\( \mu < 0: \) upward
\( \mu > 0: \) downward

Blackbody radiation 1

Quantum photon theory by M. Plank’s in 1902
\( e = 0, \ h\nu, \ 2h\nu, \ 3h\nu, \ldots \)

Boltzman’s law
\( p = \exp\left(-\frac{\varepsilon}{k_B T}\right) \)

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

\[
<\varepsilon> = \frac{\sum n \hbar \nu \exp(-n\hbar \nu / k_B T)}{\sum \exp(-n\hbar \nu / k_B T)} = \frac{\hbar \nu \exp(-\hbar \nu \beta)}{1 - \exp(-\hbar \nu \beta)} = \frac{\hbar \nu}{\exp(\hbar \nu \beta) - 1}
\]

Number of quantum states 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: \( 2g(\nu) \)
Blackbody radiation 2
- Radiant energy density with two polarization states
- Plank Function for Blackbody radiation
- Radiant energy density (W/m3)

\[ u_v(T)dv = 2 < \varepsilon > g(v) \frac{dv}{V} = \frac{8\pi}{c^3} \frac{h\nu}{\exp(h\nu/k_BT)-1} \nu^2 dv \]

\[ u_vdv = \int d\Omega Ld\sigma dt = \int d\Omega \frac{L}{c} dV = \frac{4\pi}{c} LdV \]

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

Plank function

\[ L(x+dx)d\Omega ds \]

\[ dx = cd\tau \]

\[ L(x)d\Omega ds \]

Blackbody radiation 3
- Blackbody radiation

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

\[ \text{wavelength: } \lambda \]
\[ \text{frequency: } \omega = 2\pi/\lambda \]
\[ \text{wavenumber: } \nu = c/\lambda, \nu' = 1/\lambda (\text{cm}) \]

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

- Wien’s displacement law
- Stefan-Boltzmann’s law

\[ \lambda_{max} T = 2900 \quad (\mu mK) \]

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

\[ \sigma = \frac{2\pi^5 k_B^4}{15h^3 c^2} = 5.67 \times 10^{-8} \text{ W} / \text{m}^2 \text{K}^4 \]
Emission (射出) of the radiation

- Local Thermodynamic Equilibrium (LTE) state \( z < 50 \text{km} \)
- Kinetic temperature \( T = \) Internal state temperature \( T_i \)
  - Electronic - Vibration - Rotation - Translation

- Boltzmann’s law
  \[ n(\varepsilon) \propto \exp\left(-\frac{\varepsilon}{k_BT}\right) \]

- Kirchhoff’s law; absorptivity
  \[ E(T) = \tilde{\alpha}B(T) \]

- Emissivity (射出率)
  \[ E(T) = \varepsilon B(T) \]
  \[ \varepsilon = \tilde{\alpha} \]

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

Goody and Yung (1989)
質問

・6000Kは緑色、だけど太陽は緑には見えないのはなぜ？
Invariance principle of radiance

- Emitted radiation and received 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 (視半徑) of the solar disk: \( r_{\text{disk}} \)
- Distance between earth and sun: \( R_{ps} \)

\[
S = \frac{E_s}{4\pi R_{ps}^2} = \frac{4\pi r^2 F}{4\pi R_{ps}^2} = r_{\text{disk}}^2 F = r_{\text{disk}}^2 \sigma T_{\text{sun}}^4
\]

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

\[
r_{\text{disk}} = D/2 = 16'
\]
\[
T_s = 5790K, \ S = 1370W/m^2
\]

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？
\[ \Delta U = 70 \]
\[ \Delta S = 1.5 \text{ W/m}^2 \]

Sun spot variation
\[ \Delta U = 100 \]
\[ \Delta S = ? \text{ W/m}^2 \]

Solar activity periods
- 11, 22 year cycles < 2 W/m^2
- Large UV variation
- 55, 80 year cycles

16th century solar minimum
17th century solar maximum

\[ \Delta S \approx -4 \text{ W/m}^2 \]

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 Hevelin’s Solenographic (9); those for 1655 through 1657 are from the Rose Kraush (50).
Newton’s 2nd law \[ m \frac{dv}{dt} = F \]

Boltzmann’s law \[ n(\varepsilon) \propto \exp\left(-\frac{\varepsilon}{k_B T}\right) \]
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**

- Acceleration of gravity: 9.80665 m/sec\(^2\)
- Speed of light: 2.9979e8 m/sec
- Boltzmann constant: 1.3807e-23 J/K
- Plank constant: 6.6261e-34 J/sec
- Avogadro number: 6.0221e23 /mol
- Volume of ideal gas at 0°C and 1 atom: 2.241e4 cm³/mol
- Absolute temperature: 273.15 K (0°C)
- Gas constant: 8.314 J /deg/mole
- Stephan-Boltzmann 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 (N\(_2\)) + 0.20947 (O\(_2\)) + 0.00934 (Ar) + 0.00033 (CO\(_2\)) by volume ratio
- Globe: 0.708 (Ocean) + 0.292 (Land) by area ratio
- Molecular weight of air: 29 g/mole

**Textbooks and reviews**

- **柴田清孝, 1982**: 大気と放射過程、気象学のプロムナード、東京堂出版。
- IPCC, 2007
- **柴田 清孝, 光の気象学（応用気象学シリーズ）、朝倉書店