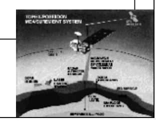
Microwave Radiometry

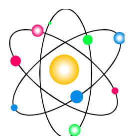
Ch6 Ulaby & Long
INEL 6669
Dr. X-Pol

Outline

- Introduction
- Thermal Radiation
- Black body radiation
  - Rayleigh-Jeans
- Power-Temperature correspondence
- Non-Blackbody radiation
  - T_B, brightness temperature
  - T_{AP}, apparent temperature
  - T_A, antenna temperature
- More realistic Antenna
  - Effect of the beam shape
  - Effect of the losses of the antenna



Thermal Radiation



- **All matter** (at T>0K) **radiates electromagnetic energy!**
- **Atoms radiates at discrete frequencies given by the specific transitions between atomic energy levels.** (*Quantum theory*)
  - ***Incident energy on atom can be absorbed by it to move an e- to a higher level, given that the frequency satisfies the Bohr's equation.***
  - $f = (\mathcal{E}_1 - \mathcal{E}_2)/h$

where,
h = Planck's constant = 6.63×10^{-34} *J*

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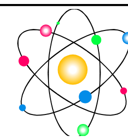
Thermal Radiation



- ***absorption* =>** e- moves to higher level
- ***emission* =>** e- moves to lower level

(collisions cause emission)

Absortion Spectra = Emission Spectra

- ***atomic gases*** **have (discrete)** **line spectra according to the allowable transition energy levels.**

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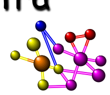
Molecular Radiation Spectra



- **Molecules consist of several atoms.**
- **They are associated to a set of vibrational and rotational motion *modes.***
- **Each *mode* is related to an allowable energy level.**
- **Spectra is due to contributions from; vibrations, rotation and electronic transitions.**
- **Molecular Spectra = many lines clustered together; not discrete but *continuous*.**

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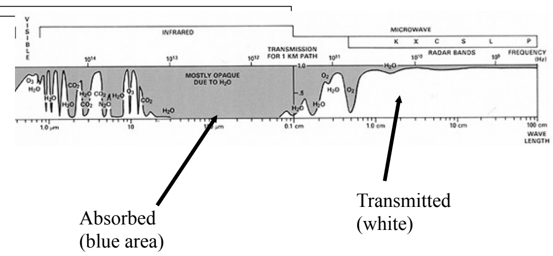
Atmospheric Windows



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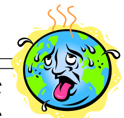
Radiation by bodies (liquids - solids)

- ***Liquids and solids*** **consist of many molecules which make radiation spectrum very complex, continuous; all frequencies radiate.**
- **Radiation spectra depends on how hot is the object as given by Planck's radiation law.**

CommonTemperature -conversion



- *90ºF = 305K = 32ºC*
- *80ºF = 300K = 27ºC*

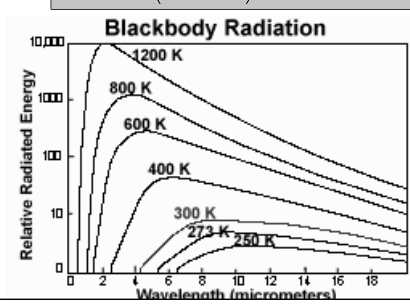
- *70ºF = 294K = 21ºC*

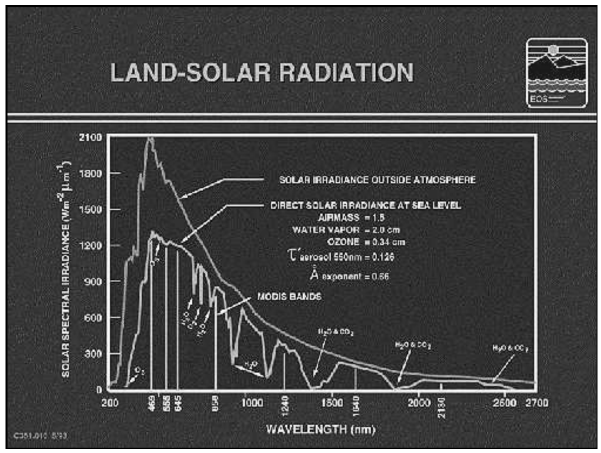
- *32ºF = 273K=0ºC*

- *0ºF = 255K = -18ºC*
- *-280ºF = 100K = -173ºC*

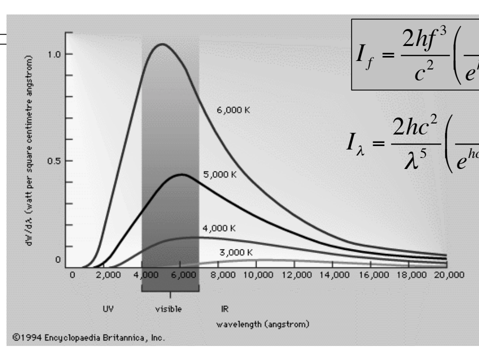
Spectral brightness intensity I_f [Planck's Law]

$$I_f = \frac{2hf^3}{c^2}\left(\frac{1}{e^{hf/kT}-1}\right) \quad [\mathrm{W/m^2\,sr\,Hz}]$$





Solar Radiation T_{sun}= 5,800 K



$$I_f = \frac{2hf^3}{c^2}\left(\frac{1}{e^{hf/kT}-1}\right)$$

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

Properties of Planck's Law

- **f_m = frequency at which the maximum radiation occurs**

$\boxed{f_m = 5.87 \times 10^{10}\, T}$ ***[Hz]***

where *T* is in Kelvins

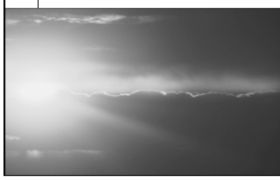
- **Maximum spectral Brightness $B_f(f_m)$**

$\boxed{I_f(f_m) = c_1\, T^3}$

where c_1 = 1.37 x 10^{-19} [W/(m^{2}srHzK^3)]

Problem 4.1

- Solar emission is characterized by a blackbody temperature of 5800 K. Of the total brightness radiated by such a body, what percentage is radiated over the frequency band between $f_m/2$ and $2 f_m$, where f_m is the frequency at which the spectral brightness B_f is maximum?



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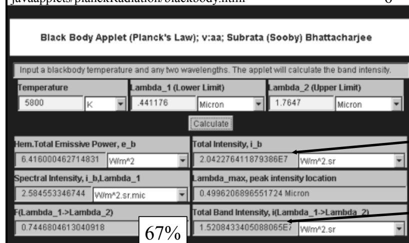
Stefan-Boltzmann
Total brightness of body at *T*

- Total brightness is $I = \int_0^\infty I_f \, df = \frac{\sigma T^4}{\pi}$

http://energy.sdsu.edu/testcenter/testhome/javaapplets/planckRadiation/blackbody.html



where the Stefan-Boltzmann constant is
σ= 5.67x10^{-8} W/m^{2}K^{4}sr

20M W/m^2 sr

13M W/m^2 sr

Solar power

- How much solar power could ideally be captured per square meter for each Steradian?

$$I = \left(20\text{MW/m}^2\text{sr}\right)\left(.35 sr\right)$$
$$= 7M\,\text{W/m}^2$$

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Blackbody Radiation - given by Planck's Law

- Measure spectral brightness I_f [Planck]

$$I_f = \frac{2hf^3}{c^2}\left(\frac{1}{e^{hf/kT}-1}\right) \quad [\text{W/m}^2\text{sr Hz}]$$

- For microwaves, Rayleigh-Jeans Law, condition $hf/kT<<1$ (low f), then e^x-1≅x

$$I_f = \frac{2f^2kT}{c^2} = \frac{2\text{kT}}{\lambda^2} \quad [\text{W/m}^2\text{sr Hz}]$$

At T<300K, the error < 1% for f<117GHz), and error< 3% for f<300GHz)

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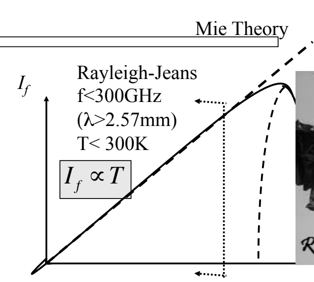
Rayleigh-Jeans Approximation



$Boltzmann's$

$k = 1.38\times10^{-23} J/K$

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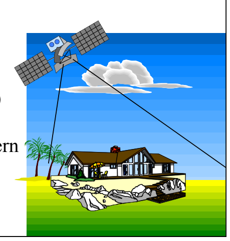
Total power measured due to objects Brightness, I_f

$$P_{bb} = \frac{1}{2} A_r \int_f^{f+\Delta f} \iint_{4\pi} I_f\left(\theta,\varphi,f\right) F_n\left(\theta,\varphi\right) d\Omega\, df$$

I=Brightness=radiance [W/m^2 sr]
I_f= spectral brightness (B per unit Hz)
I_λ = spectral brightness (B per unit cm)

F_n= normalized antenna radiation pattern
Ω= solid angle [steradians]
A_r=antenna aperture on receiver



Power-Temperature correspondence

$$P_{bb} = \frac{1}{2} A_r \int_f^{f+\Delta f} \iint_{4\pi} \left[\frac{2\mathrm{kT}}{\lambda^2}\right] F_n(\theta,\varphi)\, d\Omega\, df$$

if B_f is approximately constant over Δf

$$P_{bb} = \frac{1}{2}\frac{2\mathrm{kT}}{\lambda^2}\Delta f\, A_r \iint_{4\pi} F_n(\theta,\varphi) d\Omega$$

but the pattern solid angle is $\Omega_p = \dfrac{\lambda^2}{A_r}$

$$P_{bb} = kT\Delta f = kTB$$

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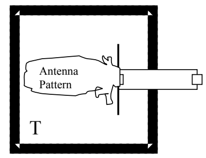
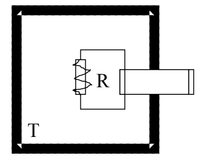
Analogy with a resistor noise

Direct linear relation power and temperature



$P_{bb} = kTB$

Analogous to Nyquist; noise power from R



$P_n = kTB$

*The blackbody can be at any distance from the antenna.

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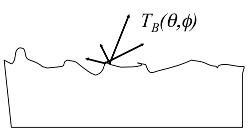
Non-blackbody radiation



Isothermal medium at physical temperature T

For Blackbody,

$$I_{bb} = I_f B = \frac{2\mathrm{kT}}{\lambda^2} B$$

But in nature, we find variations with direction, $I(\theta,\phi)$

=>So, define a radiometric temperature (bb equivalent) T_B

$$\boxed{I(\theta,\varphi) = e(\theta,\varphi) I_{bb} = \frac{2kT_B(\theta,\varphi)}{\lambda^2}B} \qquad I_{bb} = _{Ulaby} = \frac{\mathrm{kT}}{\lambda^2}B$$

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Emissivity, e

- **The brightness temperature of a material relative to that of a blackbody at the same temperature *T*. (it's always "cooler")**

$$e(\theta,\varphi) = \frac{I(\theta,\varphi)}{I_{bb}} = \frac{\mathrm{T_B}(\theta,\varphi)}{T}$$

where $0 \le e \le 1$

T_B is related to the self-emitted radiation from the observed object(s).

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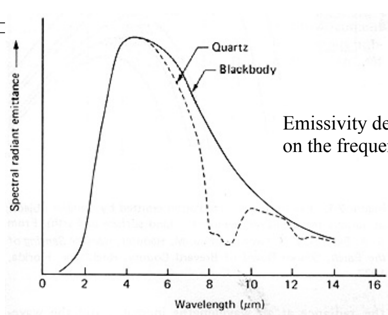
Quartz versus BB at same T



Emissivity depends also on the frequency.

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Ocean (color) visible radiation

- **Pure Water is turquoise blue**
- **The ocean is blue because it absorbs all the other colors. The only color left to reflect out of the ocean is blue.**

"Sunlight shines on the ocean, and all the colors of the rainbow go into the water. Red, yellow, green, and blue all go into the sea. Then, the sea absorbs the red, yellow, and green light, leaving the blue light. Some of the blue light scatters off water molecules, and the scattered blue light comes back out of the sea. This is the blue you see."

Robert Stewart, Professor

Department of Oceanography, Texas A&M University

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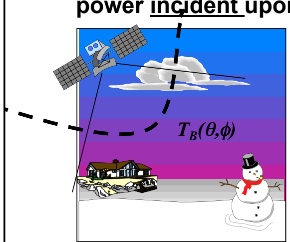
Apparent Temperature, T_{AP}

Is the equivalent T in connection with the power incident upon the antenna



$$T_B = T_{UP} + \Upsilon_a (T_{SE} + T_{SS})$$

$$I_{inc}(\theta,\varphi) = \frac{2kT_B(\theta,\varphi)}{\lambda^2}\Delta f$$

$$P = \frac{1}{2}\frac{2k}{\lambda^2} B A_r \iint_{4\pi} T_B(\theta,\varphi) F_n(\theta,\varphi) d\Omega$$

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Antenna Temperature, T_A

$$P = \frac{1}{2}\frac{2kBA_r}{\lambda^2} \iint_{4\pi} T_B(\theta,\varphi) F_n(\theta,\varphi) d\Omega$$

$$P_n = kT_A B$$

Noise power received at antenna terminals.

$$T_A = \frac{A_r}{\lambda^2} \iint_{4\pi} T_B(\theta,\varphi) F_n(\theta,\varphi) d\Omega$$

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Antenna Temperature (cont…)

- Using $\frac{A_r}{\lambda^2} = \Omega_A$ we can rewrite as

$$T'_A = \frac{\iint_{4\pi} T_B(\theta,\varphi) F_n(\theta,\varphi) d\Omega}{\iint_{4\pi} F_n(\theta,\varphi) d\Omega}$$

- for discrete source such as the Sun.

$$T_A = \frac{\Omega_{sun}}{\Omega_A} T_{sun}$$

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Antenna Beam Efficiency, η_M

- Accounts for sidelobes & pattern shape

$$T_A = \frac{\iint_{ML} T_B(\theta,\varphi) F_n(\theta,\varphi) d\Omega}{\iint_{4\pi} F_n(\theta,\varphi) d\Omega} + \frac{\iint_{ml} T_B(\theta,\varphi) F_n(\theta,\varphi) d\Omega}{\iint_{4\pi} F_n(\theta,\varphi) d\Omega}$$

$$T_A = \left[\frac{\iint_{ML} T_B(\theta,\varphi) F_n(\theta,\varphi) d\Omega}{\iint_{ML} F_n(\theta,\varphi) d\Omega}\right]\left(\frac{\iint_{ML} F_n(\theta,\varphi) d\Omega}{\iint_{4\pi} F_n(\theta,\varphi) d\Omega}\right) + \left[\frac{\iint_{ml} T_B(\theta,\varphi) F_n(\theta,\varphi) d\Omega}{\iint_{ml} F_n(\theta,\varphi) d\Omega}\right]\left(\frac{\iint_{ml} F_n(\theta,\varphi) d\Omega}{\iint_{4\pi} F_n(\theta,\varphi) d\Omega}\right)$$

$$T_A = \eta_b T_{ML} + (1-\eta_b) T_{SL}$$

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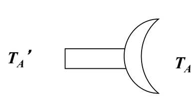
Radiation Efficiency, η_l

Heat loss on the antenna structure produces a noise power proportional to the physical temperature of the antenna, given as

$T_N = (1-\xi)T_o$

The η_l accounts for losses in a real antenna

$T_A{}' = \xi T_A + (1-\xi)T_o$



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Combining both effects

- ***Combining both effects***

$T_A{}' = \xi\, \eta_b T_{ML} + \xi\,(1-\eta_b)T_{SL} + (1-\xi)T_o$

$T_{ML} = 1/(\xi\, \eta_{b)}\, T_{A'} + [(1-\eta_M)/\eta_{b}]T_{SL} + (1-\xi)T_{o/}\,\xi\eta_{\mathcal{B}}$

$T_{ML} = aT_A + b$

**where, $T_A{}'$ = measured,*
T_{ML} = to be estimated
a= scaling factor
b= bias term

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Ej. Microwave Radiometer

- **K-band radiometer measures blackbody radiation from object at 200K. The receiver has a bandwidth of 1GHz. What's the maximum power incident on the radiometer antenna?**

$$\begin{aligned} &Answer: \\ &P_{bb} = P_{\max} = kTB \\ &= (1.38\times10^{-23})(200K)(10^9) \\ &= 2.8\times10^{-12} \\ &= -115.6\text{ dBW} \end{aligned}$$

Ej. The Arecibo Observatory…

…measured an antenna temperature of 245K when looking at planet Venus which subtends a planar angle of 0.003º. The Arecibo antenna used has an effective diameter is 290m, its physical temperature is 300K, its radiation efficiency is 0.9 and it's operating at 300GHz (λ=1cm).

- what is the apparent temperature of the antenna?

  T_A=239K

- what is the apparent temperature of Venus?

  T_{Venus}= 130K

- If we assumed lossless, what's the error?

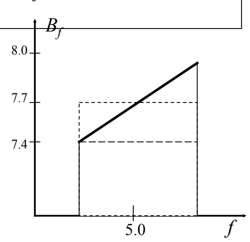
  T_{Venus}= 136K (4% error)

$$\begin{aligned} &Answer: \\ &T_A' = \eta_l T_A + (1-\eta_l)T_o \\ &\Omega_A = \lambda^2 / A_r \\ &\Omega_{venus} = (.003)^2 (\rightarrow steradians) \end{aligned}$$

Demo of Rayleigh-Jeans

- Let's assume T=300K, f=5GHz, Δf=200MHz

$$\begin{aligned} &I_{bb}^{TOT} = I_f B \\ &I_f = \frac{2kT}{\lambda^2} = \frac{2(1.38\times10^{-23})(300)f^2}{c^2} \\ &I_f(f = 4.9GHz) = 7.4\times10^{-21}[W/m^2 sr] \\ &I_f(f = 5.0GHz) = 7.7\times10^{-21}[W/m^2 sr] \\ &I_f(f = 5.1GHz) = 8\times10^{-21}[W/m^2 sr] \end{aligned}$$



$$\begin{aligned} &I_{bb}^{TOT} = Area = (200)(7.4) + \frac{1}{2}200M(8-7.4) = 1.54\times10^{-12} \\ &I_{bb}^{TOT} \cong Area = (200)(7.7) = 1.54\times10^{-12} \end{aligned}$$