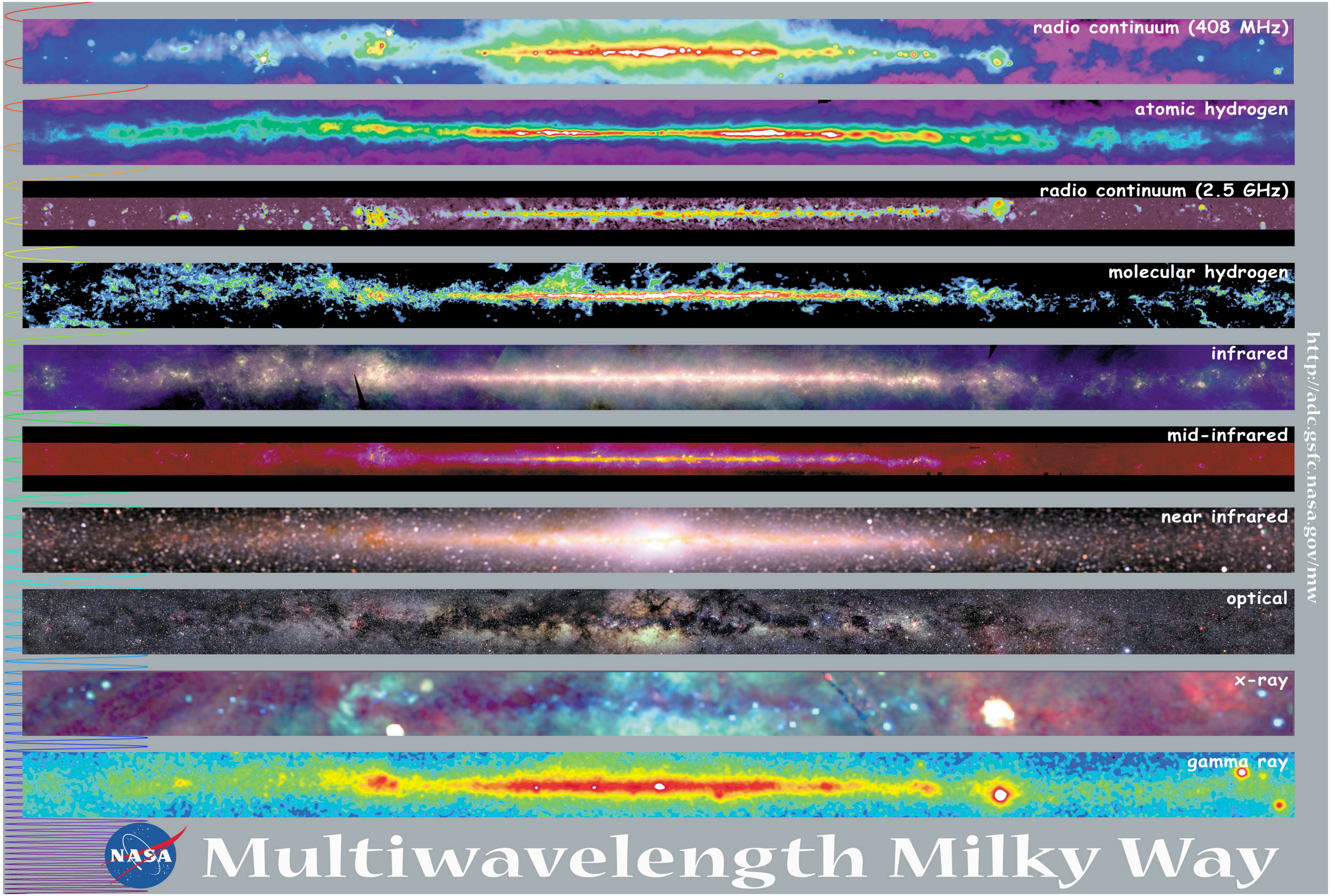

radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

PHY3145 Topics in Theoretical Physics

Astrophysical Radiation Processes

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Textbooks

Main texts

- Rybicki & Lightman *Radiative Processes in Astrophysics* (Wiley-Interscience) – unsurpassed introduction to basics, rigorous analysis, in places going further than Longair. CGS units. UL 523.01 RYB
- Longair *High Energy Astrophysics,* Vols. I and II (Cambridge University Press) – covers high energy processes only, chatty style. SI units. UL 523.01 LON

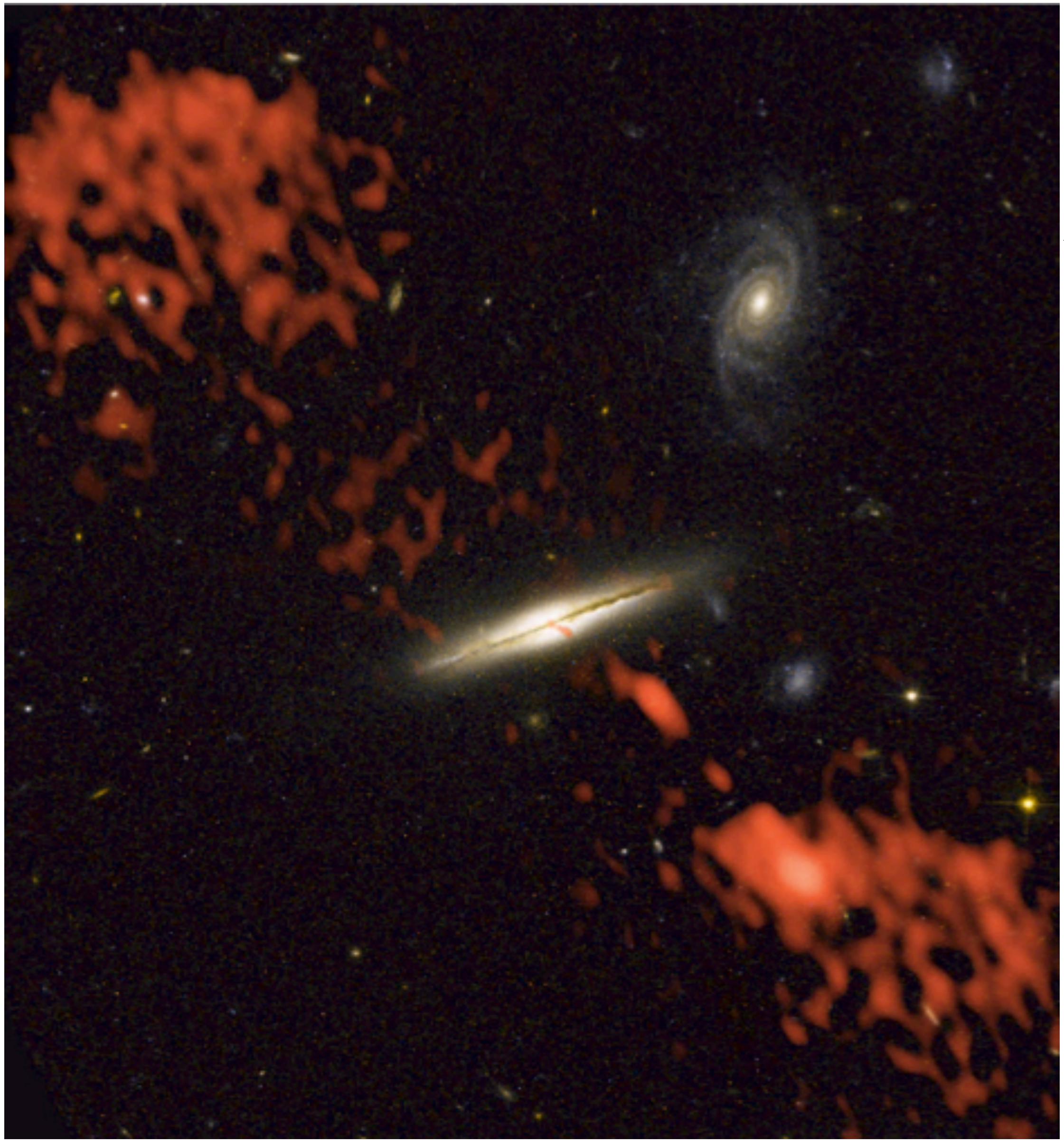
Supporting texts

- Griffiths, *Introduction to Electrodynamics* (Prentice Hall) - basic introduction to relativistic electrodynamics - UL 537 GRI
- Feynman, Leighton, Sands *Lectures on Physics*, vol. II (Addison-Wesley) - imaginative introduction to relativistic motion of charged particles - UL 530 FEY/X
- Spitzer *Physical processes in the Interstellar Medium* (Wiley Classics) - old-fashioned but a classic. Physics library. CGS units.

Radiation Processes Summary

- **Bremsstrahlung**: radiation from unbound charges accelerated by Coulomb interactions
- **Gyrotron/Cyclotron/Synchrotron:** radiation from charges accelerated in a magnetic field.
  - Gyrotron: non-relativistic
  - Cyclotron: mildly relativistic
  - Synchrotron: fully relativistic
- **Thomson/Compton/Inverse Compton:** scattering of radiation from charges
  - Thomson: classical scattering, non-relativistic, low-energy photons
  - Compton: high-energy photon scattering with wavelength shift due to loss of momentum
  - Inverse Compton: photons gain energy due to upscattering from hot electrons

Radio galaxies Quasars



← Radio jet from galaxy 0313-192

Red: VLA 20cm

White: HST optical

Quasar radio spectra

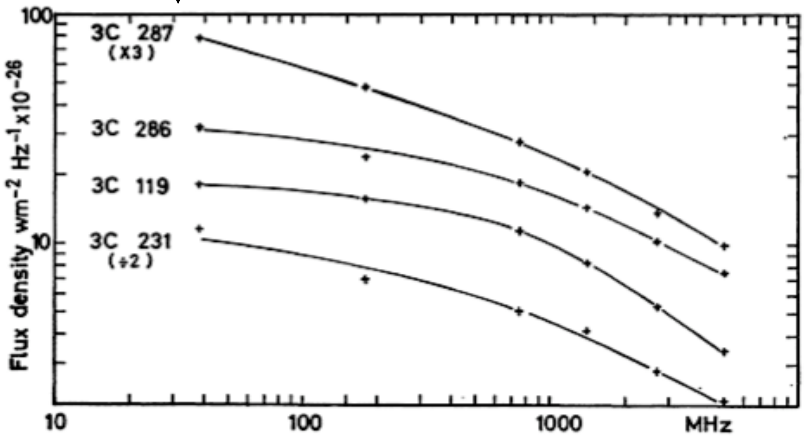


Image: Keel, Ledlow & Owen (2006 AJ 132 2233) / STSci, NRAO/AUI/NSF, NASA; Spectra: Scheuer & Williams 1968 ARAA

Course objectives

- Explain the mechanisms behind important astrophysical radiation processes:
  - Bremsstrahlung
  - Gyrotron/cyclotron/synchrotron
  - Thomson scattering/Compton scattering/Inverse Compton
- Relate emission and absorption through the equation of radiative transfer (Sect. 1)
- Calculate the power emitted by accelerated charges in a range of situations (Sect. 2)
- Show how relativistic velocities affect the radiation seen by an observer (Sect. 3 & 4)
- Understand how your toolkit of basic physics can be applied in steps to tackle complex, research-level problems (Sect. 5).

If an equation is in a coloured box, you should be able to reproduce it in the exam!

Course structure

1. **Radiation basics**. Radiative transfer.
2. **Accelerated charges produce radiation**. Larmor formula. Acceleration in electric and magnetic fields – non-relativistic bremsstrahlung and gyrotron radiation.
3. **Relativistic modifications I**. Doppler shift and photon momentum. Thomson, Compton and inverse Compton scattering.
4. **Relativisitic modifications II**. Emission and arrival times. Superluminal motion and relativistic beaming. Gyrotron, cyclotron and synchrotron beaming. Acceleration in particle rest frame.
5. **Bremsstrahlung and synchrotron spectra.**

1. Radiation basics

a) Measures of radiation

b) Equation of radiative transfer

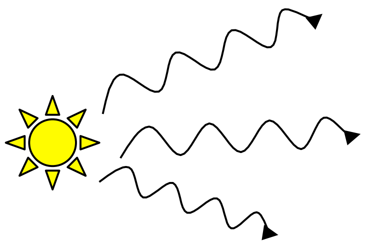
Example: thermal dust emission

c) Kirchoff’s law for thermal emission

Example: Einstein coefficients

Measures of radiation

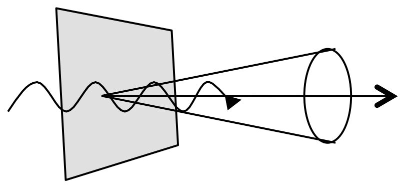
Luminosity



L W

Total power emitted in all directions

Intensity

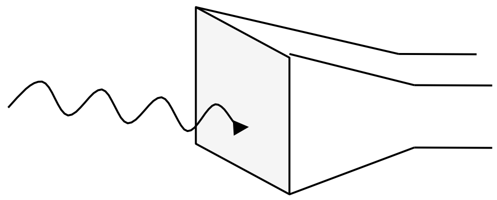


I W m^{-2} sterad^{-1}

I_ν W m^{-2} Hz^{-1} sterad^{-1}

Power per unit area in a particular direction per unit frequency (specific intensity)

Flux



F W m^{-2}

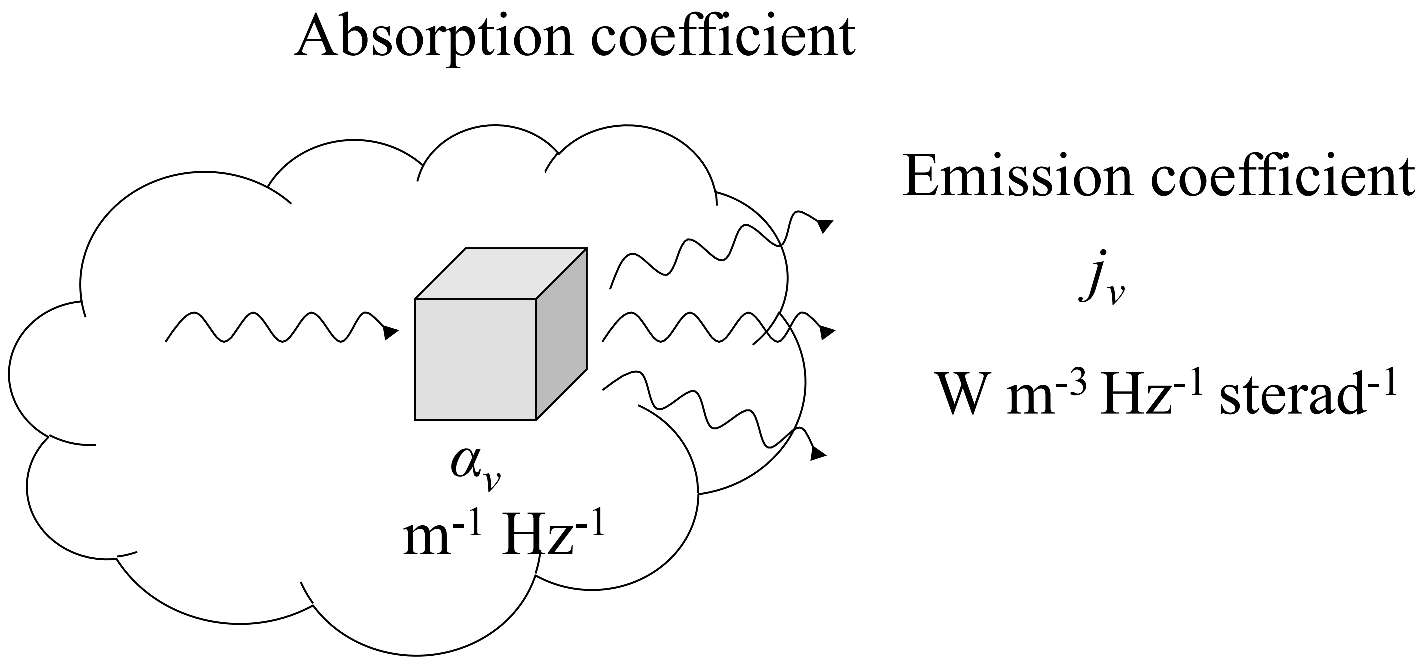
F_ν W m^{-2} Hz^{-1}

Power per unit area per unit frequency (specific flux)

For a source emitting isotropically

$$F = \frac{L}{4\pi r^2}$$

Emission and absorption coefficients



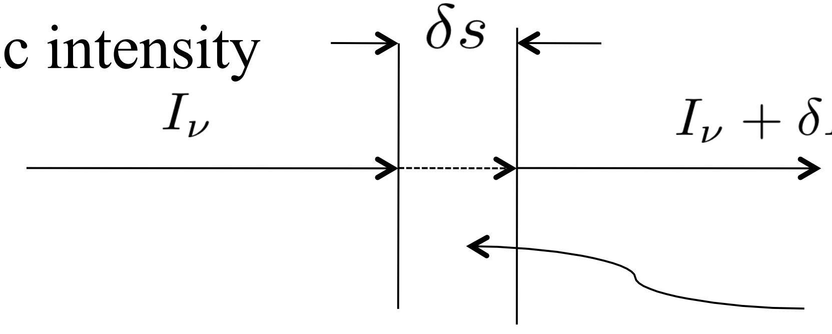
Measures of radiation

Quantity	***Symbol***	***Unit***
Energy	W	J
Power or Luminosity	P L	W
Power per unit solid angle	$\frac{dW}{dt d\Omega}$	W sterad^{-1}
Intensity or surface brightness	I	W m^{-2} sterad^{-1}
Specific intensity eg. black-body intensity	I_ν B_ν	W m^{-2} Hz^{-1} sterad^{-1}
Flux	F or S F_ν	W m^{-2} W m^{-2} Hz^{-1}
Emission coefficient	j_ν	W m^{-3} Hz^{-1} sterad^{-1}
Absorption coefficient	α_ν	m^{-1} Hz^{-1}

Radiative transfer

Macroscopic description of the interaction of radiation with matter.

Specific intensity



Emission coefficient j_ν
Absorption coefficient α_ν

$$\frac{\delta I_\nu}{\delta s} = -\alpha_\nu I_\nu + j_\nu$$

1st order differential equation. Multiply by $e^{\alpha_\nu s}$ and integrate.

$$I_\nu = I_0 e^{-\alpha_\nu S} + \frac{j\nu}{\alpha\nu}(1 - e^{-\alpha_\nu S})$$

SEE LECTURES FOR DERIVATION

Radiative transfer continued…

$$I_\nu = I_0 e^{-\tau_\nu} + \frac{j_\nu}{\alpha_\nu}(1 - e^{-\tau_\nu})$$

Equation of radiative transfer

Optical depth $\tau_\nu = \alpha_\nu S$

$$S_\nu = \frac{j_\nu}{\alpha_\nu}$$ source function

Limiting cases:

Optically thick $\tau > 1, \quad e^{-\tau}$ small

$$I_\nu \simeq S_\nu$$

Optically thin $\tau \ll 1, \quad e^{-\tau} \sim 1 - \tau$

$$I_\nu = I_0(1 - \tau_\nu) + S_\nu \tau_\nu$$

Kirchoff's law for thermal emission

For thermal radiation from an emitter in equilibrium at temperature T **Kirchoff's law** relates emissivity j_ν and absorption coeff. α_ν via Planck black-body function:

$$\frac{j_\nu}{\alpha_\nu} = B_\nu(T)$$

where

$$B_\nu(T,\nu) = \frac{2h\nu^3}{c^2}\frac{1}{(e^{\frac{h\nu}{kT}} - 1)}$$

is the Planck function

So for a **thermal** emitter the equation of radiative transfer becomes

$$I_\nu = I_0 e^{-\tau_\nu} + B_\nu(1 - e^{-\tau_\nu})$$