Description of radiation field

Qualitatively, we know that characterization should involve

- energy/time
- frequency
- direction

all functions of $x, t$.

We also know that radiation is not altered by passing through empty space.

Flux of energy varies in empty space and therefore cannot be the fundamental quantity.

Ex.

$$ F : \frac{L \text{ energy/time}}{4\pi r^2} \leftarrow \frac{1}{r} $$

Energy per solid angle works.
Assume solar surface emits uniformly.

Each unit of area on Sun emits

$$ \text{flux} \propto \frac{1}{r^2} $$

Fixed solid angle receives emission from area $\propto r^2$

$$ \Rightarrow \frac{\text{energy flux}}{\text{solid angle time}} \propto \frac{1}{r^2} $$

independent of $r$. 
Intensity or radiance

\[ I_\lambda(x,t, \hat{n}) = \lim_{\Delta s \to 0} \frac{\Delta E}{\Delta t \, \Delta \lambda \, \Delta A \, \Delta \Omega} \]

where
\[ t = \text{time} \]
\[ \lambda = \text{wavelength} \]
\[ A = \text{area} \quad \perp \hat{n} \]
\[ \Omega = \text{solid angle} \]

With I defined this way, radiative transfer in empty space reduces to:

\[ \frac{dI_\lambda}{ds} = 0, \quad s = \text{distance in } \hat{n} \text{ direction} \]

(along beam)

Energy flux In direction \( \hat{n} \), monochromatic flux is

\[ F_{\lambda \hat{n}} = \int_{4\pi} I_\lambda(\hat{n}') \, \hat{n}' \cdot \hat{n} \, d\Omega' \]

Total flux

\[ F_{\hat{n}} = \int_0^\infty F_{\lambda \hat{n}} \, d\lambda \]

Comments:

* Notice that if \( I(\hat{n}') = I(-\hat{n}') \) then \( F_{\hat{n}} = 0 \).
* \( I(\hat{n}') \hat{n}' \) is a vector and \( F_{\hat{n}} \) is a vector sum of vector components.
\[
\vec{F} = F_{\hat{e}_1} \hat{e}_1 + F_{\hat{e}_2} \hat{e}_2 + F_{\hat{e}_3} \hat{e}_3 \quad \text{is vector energy flux.} \]
Isotropic radiation

\[ I(\mathbf{x}, t, \hat{n}) \rightarrow I(\mathbf{x}, t) \]

No net flux by symmetry.
Flux in one direction across surface is of interest.

\[ F^+ = \int \frac{I(\mathbf{r}) \hat{n}^+ \cdot \hat{n} \ d\Omega(\hat{n})}{2\pi} \]

\[ = \int \int_{0}^{2\pi} \cos \theta \ d(\cos \theta) \ d\phi = \pi I \]

Notice \( \pi I < 2\pi I \) (whole hemisphere).

This result is of special interest because thermal emission from a surface or isotropic scattering from a surface give this geometry.

Interaction with matter

Absorption

A medium can absorb, emit or scatter radiation. Under absorption alone one expects

Energy loss along beam distance \( \Delta s \) = Beam intensity \( I \) \( \times \) absorption \( \sigma \) \( \times \) \( n \) \( \times \) \( \Delta s \)

Since \( n \Delta s = \text{protons} \text{ } \text{per } \text{area } \text{per } \text{particle} \), need absorption strength in area per particle

\[ \Delta I = -I \cdot \hat{n} \cdot \nabla_a \ q \Delta s \]
Thus
\[
\frac{dI}{ds} = -\frac{\sigma_a}{\lambda} n \cdot I
\]
\[= -\beta_n \cdot I, \quad \text{Units } \beta = \text{length}^{-1}
\]

The factor $\beta$ is the absorption coefficient. This attenuation equation is called Lambert's law. Its integral is
\[
\frac{dI}{I} = -\beta \, ds
\]
\[\ln I = -\int_0^s \beta \, ds' + \text{const.}
\]
\[
I_s = I_s(0) \exp\left(-\int_0^s \beta_n \, ds'\right)
\]

The "optical path" or "optical depth"
\[
u_n(2) = \int_0^s \beta_n \, ds'
\]
has no units.
\[
\frac{I_s(2)}{I_s(0)} = e^{-\nu} = \int_0^2 \nu(2) \text{ Transmissivity}
\]

Comment: Absorption strength is expressed in a variety of units. Fundamental combination is $\nu$.
\[
\frac{dI}{I} = -\beta \, ds = -d\nu = -\frac{\sigma_n}{\lambda} \cdot n \, ds
\]
$\nu$ is always (strength measure) $\times$ (gas amount along path)

Strength might be area, area per particle, mass, km-amagats. Be careful.
Planck intensity spectrum

A radiation field inside a container with walls at uniform temperature comes into thermodynamic equilibrium.

(It is assumed that the walls have a continuous spectrum of energy transitions that can happen.)

This spectrum is the Planck function

\[ B_\lambda = \frac{2hc^2}{\lambda^5 \left[ \exp \left( \frac{hc}{k_B \lambda T} \right) - 1 \right]} \]

This is energy per unit wavelength. To evaluate \( B_\nu \), energy per unit frequency, use

\[ \Delta E = B_\lambda \Delta \lambda = B_\nu \Delta \nu \]

\[ \therefore \ B_\nu = B_\lambda \left| \frac{d\lambda}{d\nu} \right|, \quad \lambda \nu = c \]

\[ \rightarrow \ B_\nu = \frac{2hc^3}{c^2 \left[ \exp \left( \frac{hc}{k_B \nu} \right) - 1 \right]} \]

In practice, the first and second radiation constants are used to numerically evaluate \( B \). For example

\[ B_\lambda = \frac{C_1 \lambda^{-5}}{\pi \left[ \exp \left( \frac{C_2}{\lambda T} \right) - 1 \right]} \]

\[ C_1 = 3.749 \times 10^{-16} \, \text{W m}^2 \]

\[ C_2 = 1.4388 \times 10^{-2} \, \text{m K} \]

Max of \( B_\lambda \) is at \( \lambda T = 0.29 \) cm K.

Max of \( B_\nu \) is at \( \lambda T = 0.51 \) cm K.
Fig. 6.2.5 Emission spectrum from a cloudy area (Hanel et al., 1972c).

Fig. 6.2.6 Emission spectra from a desert area showing the effect of low emissivity between 1100 and 1250 cm\(^{-1}\) caused by residual rays in quartz sand. The comparison spectrum from an area covered by vegetation shows nearly the same brightness temperature on both sides of the ozone band at 1042 cm\(^{-1}\) (Hanel et al., 1972c).
Figure 1. Planetary emission spectra. The uppermost spectrum was recorded by Nimbus 4 in 1970 over the mid-Atlantic Ocean. The second spectrum is of mid-latitudes of Mars recorded in 1972 by Mariner 9. The spectra of Jupiter, Saturn and Titan have been taken by Voyager 1 in 1979 and 1980 respectively.

IRIS THERMAL EMISSION SPECTRA
SUMMER POLE, MARS AND EARTH
Brightness temperature

Thermal emission spectra are often presented in units of brightness temperature.

Observe \( I_\lambda (\lambda) \) radiance units.

Set \( I_\lambda \) equal to the Planck function at unknown \( T_b (\lambda) \)

\[ B_\lambda (T_b, \lambda) = I_\lambda \]

Invert, solve for \( T_b (\lambda) \).

\( T_b (\lambda) \) gives the temperature, at each wavelength, that a black surface would need to have in order to emit the observed intensity.
**Stefan–Boltzmann Law**

Many surfaces emit approximately the same way that a point in a black cavity would emit.

\[ I_\lambda = B_\lambda(T, \lambda) \quad \text{independent of direction} \]

\[ \therefore F_\lambda = \pi B_\lambda \]

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

\[ \sigma = 5.67 \times 10^{-8} \, \text{W m}^{-2} \text{K}^{-4} \]

**Example: Estimate the temperature of a planet.**

Power received from \( \theta = \pi a^2 \cdot \frac{L_0}{4\pi r^2} \cdot (1-A) \)

\[ = \pi a^2 \cdot F_s \cdot (1-A) \quad F_s \approx 1368 \, \text{W m}^{-2} \quad A \approx 0.31 \]

Power emitted by planet = \( 4\pi a^2 \cdot \sigma T^4 \)

\[ \therefore \sigma T^4 = \frac{1-A}{4} F_s \approx 236 \, \text{W m}^{-2} \]

\[ T = 254 \, \text{K} \]
Equation of transfer

Thermal emission

In the presence of absorption and emission,

\[ \frac{dI_v}{da} = -\beta_v I_v + S_v \]

where \( S_v \) is a source term due to emission by the medium.

In a region many optical depths across, the exterior boundaries will become unimportant. Then if the region is isothermal the radiation field will be in thermodynamic equilibrium, with \( I_v = B_v \).

Then \( \frac{dI_v}{da} = 0 \), and \(-\beta_v I_v + S_v = 0 \)

\[ \therefore S_v = \beta_v B_v \]

\[ \frac{dI_v}{da} = -\beta_v (I_v - B_v) \]

Emission coefficient = absorption coefficient is Kirchoff's law.
Emission and scattering

Denote $\beta_{\nu}$ = extinction coefficient. In general,

$$\beta_{\nu} = \sum \sigma_{\nu i} n_i,$$

$\sigma_{\nu i}$ = monochromatic cross section \((\text{length})^2\),  
$n_i$ = number density of constituent \(i\).

Let $\omega_{\nu}$ be fraction of extinction that scatters into a new direction and is not absorbed.  
$\omega_{\nu}$ = single scattering albedo.  
Governing equation

$$\frac{dI_{\nu}}{ds} = \beta_{\nu} (-I_{\nu} + J_{\nu}),$$

$$J_{\nu}^{(scat)}(\hat{n}) = \omega_{\nu} \int P(\hat{n}, \hat{n}') I_{\nu} (\hat{n}') \frac{d\Omega'}{4\pi}.$$  

By $\omega_{\nu}$ definition

$$\int_{4\pi} P(\hat{n}, \hat{n}') d\Omega' = 1.$$  

Ex. Forward scattering

What is $J_{\nu}^{(emission)}$? Expect $CB_{\nu}$, cf. LTE.

$$\frac{dI_{\nu}}{ds} = \beta_{\nu} \left[ -I_{\nu} + \omega_{\nu} \int P(\hat{n}, \hat{n}') I_{\nu} (\hat{n}') \frac{d\Omega'}{4\pi} + CB_{\nu} \right].$$

Deep inside homogeneous region $I_{\nu} \rightarrow B_{\nu}$ (isotropic) and $\frac{dI_{\nu}}{ds} = 0$. Thus

$$-B_{\nu} + \omega_{\nu} B_{\nu} \int P(\hat{n}, \hat{n}') d\Omega' + CB_{\nu} = 0.$$

12
Summary:

\[ \frac{1}{\beta_{\nu}} \frac{dI_\nu}{d\nu} = -I_\nu + (1 - \omega_{\nu}) \beta_\nu + \omega_{\nu} \int \frac{P(\hat{n}, \hat{n}')}{4\pi} I_\nu(\hat{n}') d\Omega' \]

Intensity    Extinction    Emission    Scattering
change

Formal integral in absence of scattering

Let \( \beta_{\nu} d\nu = -dX_\nu \) optical thickness

\[ \begin{align*}
    x_\nu & \quad \rightarrow \quad \rightarrow \quad \leftarrow \quad \rightarrow \quad \rightarrow \quad \rightarrow \\
    \nu & \quad \rightarrow \\
    \frac{dI_\nu}{dX_\nu} & = I_\nu - \beta_\nu (\nu) \quad \text{(no scattering)}
\end{align*} \]

\[ e^{\chi_\nu} \frac{d}{dX_\nu} \left( e^{-\chi_\nu} I_\nu \right) = -\beta_\nu \]

\[ e^{-\chi_\nu} I_\nu \bigg|^{\chi_\nu}_{0} = - \int_{0}^{\chi_\nu} \beta_\nu (\chi'_\nu) d\chi'_\nu \]

\[ e^{-\chi_\nu} I_\nu - I_\nu (\chi_\nu = 0) = - \int_{0}^{\chi_\nu} e^{-\chi'_\nu} \beta_\nu (\chi'_\nu) d\chi'_\nu \]

\[ \therefore I_\nu (\chi_\nu = 0) = I_\nu (\chi_\nu) e^{-\chi_\nu} + \int_{0}^{\chi_\nu} e^{-\chi'_\nu} \beta_\nu (\chi'_\nu) d\chi'_\nu \]

Intensity    Attenuated    Incident    Accumulated
emergncy    intensity    emission    along
path
Absorption spectrum

Transitions

In planetary atmospheres transitions between discrete energy levels are of most importance. In stars free-free or bound-free transitions give continuum absorption.

\[ \cdot \text{ absorption lines dominate, } h\nu = \Delta E \]

Exception: UV and EUV absorption in upper atmosphere.

Transitions are:

- electronic
- vibrational
- rotational

\[ \text{for IR} \]

\[ \text{Visible} \]

\[ \text{IR} \}

\text{combination}

Examples of spectra are shown in Salby and in viewgraphs.

Units

Spectroscopists usually work in frequency units expressed in wavenumbers,

\[ h\nu = c \]

\[ V = \frac{c}{\lambda} \quad (\text{s}^{-1}) \]

\[ \tilde{V} = \frac{h\nu}{c} = \frac{1}{\lambda} \quad \text{(length, usually cm}^{-1}) \]

wavenumber

Handy identity:

\[ \lambda \text{ (microns)} = \frac{10,000}{V \text{(cm}^{-1})} \]
Lorentz line profile

In the lower atmosphere, collisional broadening is the most important factor producing frequency dispersion of absorption.

Phase coherence of emitted photon is destroyed by collisions.

$\sim t$  \hspace{1cm} \text{time between collision}

$\leftarrow t \rightarrow$

Spectrum is broadened by $\alpha \approx \frac{1}{t} \ \ (\frac{1}{c} \ \text{time units})$

To estimate $\alpha$,

$\ell_m \cdot A \cdot n = 1$

$\frac{1}{t} = \frac{v}{\ell_m} = v An$

$A \sim \pi \ (4a_0^2), \ a_0 = \text{Bohr radius} \sim 0.5 \ A$

$\rightarrow 10^{-19} \ m^2$

$n \sim 2.69 \times 10^{25} \ m^{-3} \ \text{Loschmidt's #}$

$v \sim 300 \ m \ s^{-1} \ \text{(sound speed)}$

$\alpha \sim \frac{1}{t} \frac{1}{c} \sim \frac{v An}{c} \sim \frac{3 \times 10^{-19} \times 2.7 \times 10^{25}}{3 \times 10^8} \sim 3 \ m^{-1}$

$= 0.03 \ cm^{-1}$

Typical IR frequency $\lambda = 10 \ \text{microns} \Rightarrow \bar{\nu} = 1000 \ cm^{-1}$

Narrow.

Since $\alpha \propto n$,

width of pressure.
The shape is the Lorentz profile

$$f_L = \frac{\alpha_L}{\pi (\tilde{v} - \tilde{v}_0)^2 + \alpha_L^2}, \quad \int_{\tilde{v} < \tilde{v}_0} f_L \, d\tilde{v} = 1$$

The cross section is

$$\sigma = S \int f_L(\tilde{v}) \, d\tilde{v}, \quad S \equiv \text{line strength}.$$  

The strength is a function of temperature $S(T)$, and $\alpha_L$ is usually taken to be

$$\alpha_L = \alpha_{\infty} \frac{p}{p_0} \left( \frac{T_0}{T} \right)^n,$$

where $p_0, T_0$ are STP, and $n \approx \frac{1}{2}$ and $\alpha_{\infty}$ are tabulated in line atlases.

**Doppler line broadening**

$$\Delta \tilde{v} / \tilde{v} \approx \frac{\Delta V}{c} \approx \frac{350 \, \text{m/s}}{3 \times 10^8 \, \text{m/s}} \approx 10^{-6}$$

$$\Delta \tilde{v} \approx 10^{-6} \tilde{v} \approx 10^{-6} \times 10^3 \approx 0.01 \, \text{cm}^{-1}$$

Important in upper atmosphere where $p$ small and Lorentz width is small.

**Doppler shape**

$$\lambda_D = \frac{\lambda_0}{c} \sqrt{\frac{2k_\text{B}T}{m}}$$

$$f_D = \frac{1}{\lambda_D \alpha D} \exp \left[-\left(\frac{\tilde{v} - \tilde{v}_0}{\alpha D} \right)^2\right]$$
Voigt line profile
Convolve Doppler + Lorentz broadening

\[ f_v (v-v_0) = \int_{-\infty}^{\infty} f_L (v'-v_0) f_D (v-v') dv' \]

There are efficient algorithms to evaluate it. See Grudic & Yung.

Line atlases

See the description of the HITRAN, GEISA atlases.

Line strength \( S(T) \) involves lower state energy. This is because of state population dependence on \( T \). From Lomon,

\[ S_i(T) \approx S_i(T_0) \left( \frac{T}{T_0} \right)^n \exp \left[ - \frac{\hbar c E_i}{k_0} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right] \]

- \( n = 2 \) linear molecule
- \( n = 5/2 \) nonlinear molecule
- \( E_i \) = lower state energy for line \( i \)
- \( T_0 = 296 \text{ K} = \text{reference } T \).
Fig. 2.3  Lorentz, Doppler, and Voigt profiles corresponding to a pressure and temperature at 30 km for infrared lines centered at 1587 cm$^{-1}$ (H$_2$O), 1043 cm$^{-1}$ (O$_3$), and 667 cm$^{-1}$ (CO$_2$) (after Kuhn and London, 1969).
The 1997 spectroscopic GEISA databank


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THE HITRAN MOLECULAR SPECTROSCOPIC DATABASE
AND HAWKS (HITRAN ATMOSPHERIC WORKSTATION):
1996 EDITION

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(Received 13 March 1998)

Abstract—Since its first publication in 1973, the HITRAN molecular spectroscopic database has been recognized as the international standard for providing the necessary fundamental spectroscopic parameters for diverse atmospheric and laboratory transmission and radiance calculations. There have been periodic editions of HITRAN over the past decades as the database has been expanded and improved with respect to the molecular species and spectral range covered, the number of parameters included, and the accuracy of this information. The 1996 edition not only includes the customary line-by-line transition parameters familiar to HITRAN users, but also cross-section data, aerosol indices of refraction, software to filter and manipulate the data, and documentation. This paper describes the data and features that have been added or replaced since the previous edition of HITRAN. We also cite instances of critical data that are forthcoming. Published by Elsevier Science Ltd.

1. INTRODUCTION

A new edition of the HITRAN (HIgh-resolution TRANsmission) database was released on CD-ROM in 1996. This line-by-line compilation of spectroscopic parameters is a widely recognized international standard. It is used for a vast array of applications such as terrestrial atmospheric remote sensing, transmission simulations, fundamental laboratory spectroscopy studies, industrial process monitoring, pollution regulatory studies, etc. HITRAN is now a component of a larger set of spectroscopic data and software called HAWKS (HITRAN Atmospheric Workstation). The goal of HITRAN and HAWKS is to provide a functional and flexible set of software and data in order to accurately model the simulation of transmission and radiance from the microwave through ultraviolet spectral regions. Besides an updated HITRAN high-resolution molecular database of about one million transitions, there are files of aerosol indices of refraction, UV line-by-line and cross-section parameters, supplemental files of gases that have undergone less validation or whose parameters require new definitions, such as ionic species, and extensive IR cross-sections now at different pressures and temperatures. In addition, the compilation contains a moderate-resolution band-model code, MODTRAN3. There is also vastly improved software handling of the data in
Dear colleagues,

This message gives you the instructions for accessing the HITRAN database compilation. The current edition is HITRAN2004, and it is available on an anonymous ftp-site. It can also be accessed via the web.

Use of the HITRAN database is free. We ask users to please cite the article describing the database when publishing or presenting results based on HITRAN. It is also a good idea in order to indicate to your readers which database, that is which edition, you have employed. The article on the 2004 edition of HITRAN will appear in a Special Issue of the Journal of Quantitative Spectroscopy and Radiative Transfer. A preprint is available in the HITRAN web-site (http://cfa-www.harvard.edu/HITRAN/docs.html).

You have 3 different choices for accessing the HITRAN ftp-site:

1. ---------------
FTP--> cfa-ftp.harvard.edu
User--> anonymous
Password--> your e-mail address
Then change directories--> cd pub/hitran04

2. ---------------
One can also access the data using a web browser. Just type
"ftp://cfa-ftp.harvard.edu/pub/hitran04/*" for the location.
(You may have to configure your browser to send your e-mail
address as anonymous ftp password.)

Alternatively, if you have difficulty using ftp, you can access the site via http by going to the url:
You will then be prompted for:
username --> HITRAN
password --> getdata
(note that some items are case sensitive, such as "hitranda04" and "getdata")

Many of the HITRAN data files are given both in their full ASCII and also compressed in zip format. Some files that have not changed from the previous edition have been compressed using gzip. If you do not presently have this compression program in your system, you can go to the web-site: http://www.gnu.org/software/gzip/gzip.html
where information is available concerning this popular data compression program and how to download the software. It works on
Microsoft Windows, UNIX, and MAC operating systems. The popular program, WinZip, also decompresses these files; this program can be downloaded at the site: http://www.winzip.com

Note that we are still making ongoing improvements to many molecular bands. For example, we are expecting very soon to provide an update for water-vapor parameters in the visible region. There are also some minor problems with the JavaHAWKS software that we are in the process of correcting or improving.

Sincerely,

Laurence Rothman

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There has been some misunderstanding prevalent in the community concerning the units and definitions employed in the HITRAN database. We include in this paper an appendix that summarizes the definitions and usage associated with the compilation.

2. DISCRETE MOLECULAR TRANSITIONS: THE HITRAN DATABASE

The line-by-line portion of the compilation, HITRAN, now contains transitions for 37 molecular species. Table 2 presents a summary of the species that are contained on the compilation. The numbering of the species is simply by chronological entry into the HITRAN database, the last six entries being new species added since the last edition. Furthermore, the final two species, NO* and HOBr, reside in the supplemental directory, not in the main HITRAN database. It should also be noted that one of the new species is in fact an atom (oxygen). The table lists the number of isotopic variants (isotopomers) per molecule represented in HITRAN, as well as the number of vibration-rotation or ro-vibrionic bands. One also notices that certain “heavy” molecules, such as ozone and nitric acid, have a very large number of transitions; this occurs as new bands or more extensive coverage of bands are achieved on new editions. On the other hand, species like water vapor and carbon dioxide remain rather constant in terms of the number of transitions, even though there may be considerable improvement in the quality of the individual parameters.

<table>
<thead>
<tr>
<th>Mol. no.</th>
<th>Molecule</th>
<th>Number of isotopomers</th>
<th>Number of bands</th>
<th>Number of lines</th>
<th>Spectral coverage (cm⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>H₂O</td>
<td>4</td>
<td>137</td>
<td>49 444</td>
<td>0-22 657</td>
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<td>60 802</td>
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**Notes:** FORTRAN Format (E12.1,F12.6,1P2E10.3,0P2F5.4,F10.4,F4.2,F8.6,2I3,2A9,3I1,3I2) corresponding to the following:
- Mol: molecule number
- Iso: isotope number (1 = most abundant, 2 = second most abundant, etc.)
- $v_{ew}$: frequency in cm$^{-1}$
- $S_{ew}$: intensity in cm$^{-1}$ molecule$^{-1}$ cm$^{-2}$ at 296 K
- $K_{ew}$: weighted transition moment squared in Debye$^2$
- $g_{ew}$: air-broadened halflight (HWHM) in cm$^{-1}$ at 296 K
- $g_{ew}$: self-broadened halflight (HWHM) in cm$^{-1}$ at 296 K
- $\delta$: lower state energy in cm$^{-1}$
- $iv'$, $iv''$: upper state global quanta index, lower state global quanta index
- $q'$, $q''$: upper state local quanta, lower state local quanta
- $\text{ierr}$: accuracy indices for frequency, intensity, and air-broadened halflight
- $\text{iref}$: indices for tables of references corresponding to frequency, intensity, and halflight
Plane parallel atmosphere, emission and absorption
Transfer eq. in terms of optical depth

\[ \frac{d\tau}{dz} = -\beta_{\nu} \frac{d\tau}{dz} \]

No scattering.

\[ \frac{dI_{\nu}}{dz} = -\beta_{\nu} (I_{\nu} - B_{\nu}) \]

Geometry of ray

\[ d\tau = \frac{dz}{\cos^{2} \theta} = \frac{dz}{\mu} \]

Plane parallel is idealized case \( B_{\nu} = B_{\nu} (z) \). Then \( I_{\nu} = I_{\nu} (z) \).

\[ \frac{1}{\beta_{\nu}} \frac{dI_{\nu}}{dz} = \frac{\mu}{\beta_{\nu}} \frac{dI_{\nu}}{d\tau_{\nu}} = -\mu \frac{dI_{\nu}}{d\tau_{\nu}} \]

\[ \mu \frac{dI_{\nu}}{d\tau_{\nu}} = I_{\nu} - B_{\nu} \]

Solution for upward intensity

\[ I_{\nu} (\tau, \mu) = I_{\nu} (\tau_{0}, \mu) e^{-\frac{\tau_{0} - \tau_{0} (\tau)}{\mu}} \]

\[ + \int_{\tau_{0} (\tau)}^{\tau_{0}} B_{\nu} (\tau_{0}) e^{-\frac{\tau_{0} - \tau_{0} (\tau_{0})}{\mu}} d\tau_{0} \]
Usually \( I_\nu (T_\nu , \mu) \approx B_\nu (T_\nu) \). In some cases, 
\[ I_\nu (T_\nu , \mu) = \epsilon_\nu B_\nu (T_\nu) \]
where the emissivity \( \epsilon_\nu \) varies spectrally but with wide bands rather than narrow lines. Mars surface mineralogy is an example.
For now, assume \( B_\nu (T_\nu) \).

**Average over a band \( \Delta \nu $$

In practice a finite \( \Delta \nu \) is of interest.
* for heating rates can average over spectrum.
* for remote sensing the instrument has spectral resolution limitations.

**Average over \( \Delta \nu $$ small enough so that the Planck function \( \sim $$ constant.

\[
I_\nu (T, \mu) = \frac{1}{\Delta \nu} \int B_\nu (T_\nu) e^{-\frac{\mu}{T_\nu}} d\nu + \frac{1}{\Delta \nu} \int \int B_\nu (T, \mu) e^{-\frac{\mu}{T_\nu}} d\nu d\mu
\]

\[ B_\nu \text{ smooth} \]

\[
B_\nu (T_\nu) \frac{1}{\Delta \nu} \int e^{-\frac{\mu}{T_\nu}} d\nu + \int B_\nu (T', \mu) \frac{1}{\Delta \nu} \int e^{-\frac{\mu}{T_\nu}} d\nu d\mu
\]

\[ = B_\nu \frac{\epsilon_\nu (T, \mu)}{\mu} + \int B_\nu (T', \mu) \frac{d \epsilon_\nu (T', \mu)}{d\mu} d\mu
\]

where
\[
\int \frac{\epsilon_\nu (T', \mu)}{\mu} d\mu = \int \frac{1}{\Delta \nu} \int e^{-\frac{\mu}{T_\nu}} d\nu
\]

N.B. Sign changes from \( \frac{d\tau}{dz} \) and from reversal of integration range.