## Lecture 4* <br> Inherent optical properties, part I

What properties of a medium affect the radiance field as it propagate through it?

1. Sinks of photons (absorbers)
2. Sources of photons (internal sources)
3. Redirectors of photons (scatterers)
*based, in part, on a lecture prepared by $C$. Roesler


Loss due to absorption



## Beam Attenuation Measurement Theory



Recap: two processes cause attenuation (loss of light):
a-absorption.
b-scattering (re-direction).
$\rightarrow c=a+b$


$$
L_{t}=L_{0} \exp (-c \cdot x)
$$

Beer(1852), Lambert(1729), Bouguer (before 1729)

## Important characteristics:

Absorption and scattering feature similarly.
$c$ is Linear with concentration or added substances.

Assumes no internal sources.

Class demo: BLB law with food coloring or maalox

BLB's law and statistics (e.g. Bohren and Clothiaux, 2006).
Define an optical 'cross-section' of a single particle as the 'area' of energy removed from that of a monochromatic plane wave:


## What is absorption:

Photons 'disappear' due to interaction with matter.


Feom: http://www.haverford.edu/chem/Scarrow/GenChem/quantum/BohrAtom.gif
Following absorption energy could be reemitted (or not) at the same or different wavelength (e.g. scattering, fluorescence, thermal emission).

Absorption due to molecular:
Translational, rotational, vibrational and electronic modes (+combinations).

Observation include also spontaneous emmison.

Explained by quantum mechanics.


## Absorption lines broadened

 by:Doppler (motion of molecules and source of photons) $\propto T$

Self broadening (consequence of intermolecular forces) $\propto T$

Foreign broadening (interactions with other molecules) $\propto$ pressure, $T$
$\rightarrow$ Expect absorption spectra to vary with height and $T$ in the atmosphere.

Angular scattering:


Figure 2.19: Line-by-line calculations of water vapor absorption at two pressure altitudes. The dashed curve shows a calculation from which continuum absorption is omitted. At 10 mb , omission of the continuum results in a curve indistinguishable from that shown.

Bohren and Clothaux, 2006.
Note: wavenumber $=1 /$ wavelength $=v / c$

## Absorption broadening:




## What is scattering:

Matter is composed of diecrete electric charges which are excited by an oscillating EM field (light). When excited they emit EM waves. Elastic (coherent) scattering-same frequency as the source.

Scattering refers also to the redirection of energy of an 'infinite' 'planeparallel' electro-magnetic wave due to interaction with matter. By interaction we mean that the wave travels at different speed at different location within the medium due to inhomogeneities within the medium. Such inhomogeneities may be caused by particles of different optical properties within the medium or fluctuations, regions within the medium that have slightly different concentrations of molecules.

The 'relative' index of refraction $\left(n_{r}\right)$ of a particle relative to the medium in which it is embedded, is the ratio of the speeds of lights: $n_{p}=c_{\text {medium }} / c_{p}$.

For a given size and shape of a particle in a medium, the more different the index of refraction is from 1 the more pronounce is the scattering.

## What is scattering:

Scattering is the 'sum' of:

1. Reflection: at a boundary of a particle with different $n$ than the medium in which it is embedded, a certain amount of radiation is reflected back.
2. Refraction: at a boundary of a particle with different $n$ than the medium in which it is embedded, a certain amount of radiation penetrates into the particle, usually at a different angle than the angle of incidence (Snell).
3. Diffraction: the light propagating along the boundary of the particle responds to the boundary causing a change in direction.


From: http://www.cs.ucl.ac.uk/staff//S.Bhatti/D51-notes/img229.gif
refraction, reflection and diffraction:


Large particles: scattering is dominated by diffraction, since light going through the particles is likely to be absorbed.
$\rightarrow$ Geometric optics. Response is proportional to particle's cross-sectional area (sensitive to shape).

Small particles: scattering is dominated by refraction and reflection, Rayleigh scattering. Response is proportional to particle's volume (insensitive to shape).

In between (for sphere): Mie scattering. Analytical solutions exist for idealized shapes.

## Dependence of IOP on properties of particles:

The output of Mie scattering codes for a particles with a given $D / \lambda$ and $n$ is:
Cross sections ( $\sigma,\left[m^{2}\right]$ ) or efficiency factors ( $Q$, $[\phi]$ ) for absorption, scattering and attenuation as well as the phase function (multiply by $\sigma$ to get angular scattering cross-section).

Example: the attenuation cross-section, $\sigma_{\text {ext }}$, is the attenuation due to a single particle in a $\mathrm{m}^{3}$ of medium:
$c=\sigma_{e x t} \cdot 1=Q_{e x t} \cdot \pi r^{2} \cdot 1$
Since the mass increase with size, it is instructive to study how the mass normalized optical properties vary as function of size and index of refraction.
$(c, a, b) / V=\left(\sigma_{e x t}, \sigma_{a}, \sigma_{b}\right) /\left\{0.75 \pi r^{2}\right\}$

## Another way to look at it:

Define an optical 'cross-section' of a single particle as the 'area' of energy removed from that of a monochromatic plane wave:
$W(\lambda)=\sigma(\lambda)_{a} E(\lambda), \quad$ (efficiency factors: $\left.\mathrm{Q}(\lambda)_{a} \equiv \sigma(\lambda)_{a, b \text { or } c} / G\right)$
Assuming no overlap in
Thin: absorbed radiant flux per unit volume $(1 / A \Delta x) \propto k$


## Angular dependence of scattering on size:




Size distributions: summing up contribution of all bins.


