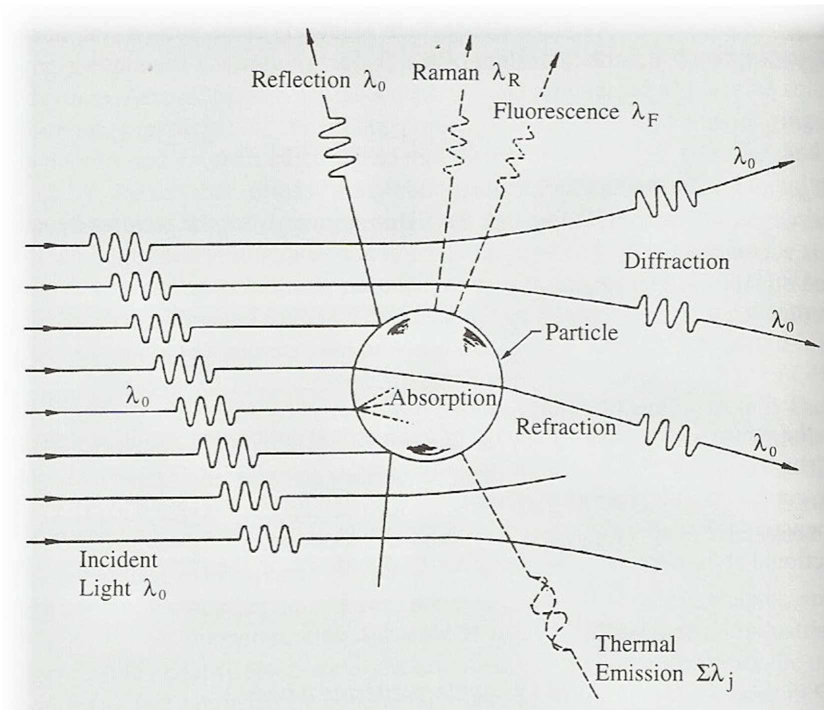
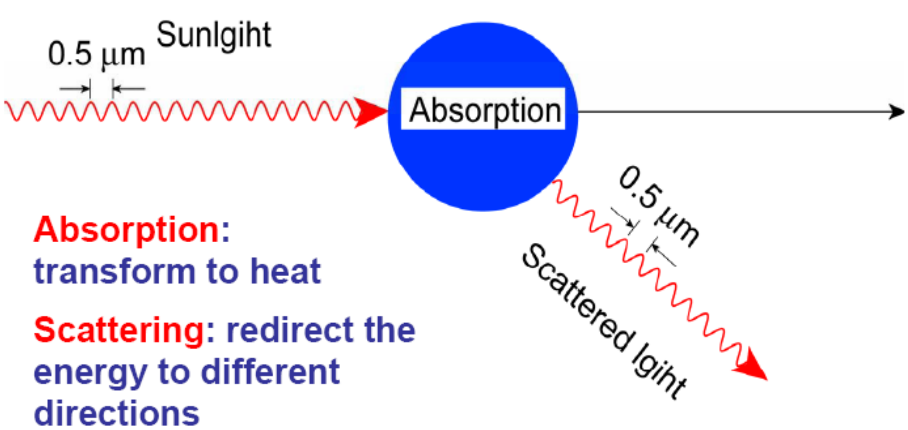
Lecture 3. Optical properties

1. <u>Attenuation of atmospheric radiation by particulates.</u>



Aerosol particles can scatter or/and absorb electromagnetic radiation at different wavelengths.



NOTE: aerosol particles also can emit thermal radiation.

Scattering is a process, which conserves the total amount of energy, but the direction in which the radiation propagates may be altered.

Absorption is a process that removes energy from the electromagnetic radiation field, and converts it to another form.

Extinction (or attenuation) is the sum of scattering and absorption, so it represents total effect of medium on radiation passing the medium.

- In the atmosphere: aerosol particles can scatter and absorb solar and infrared radiation altering air temperature and the rates of photochemical reactions.

Key parameters that govern the scattering and absorption of radiation by a particle:

i. the wavelength

   λ of the incident radiation;

ii. the size of the particles, expressed as a dimensional size parameter x:

   $x \frac{\pi D}{\lambda}$ (where D is the particle diameter);

iii. complex refractive index (or optical constant) of a particle:

   m = n + i k where **n** is the real part of the refractive index, **k** is the imaginary part of the refractive index. Both **n** and **k** depend on the wavelength.

Important to remember:

- complex refractive index of a particle is defined by its chemical composition;
- **real part , n**

, is responsible for scattering.

- **imaginary part, k,**

  is responsible for absorption. If k is equal to 0 at a given wavelength thus a particle does not absorb radiation at this wavelength.

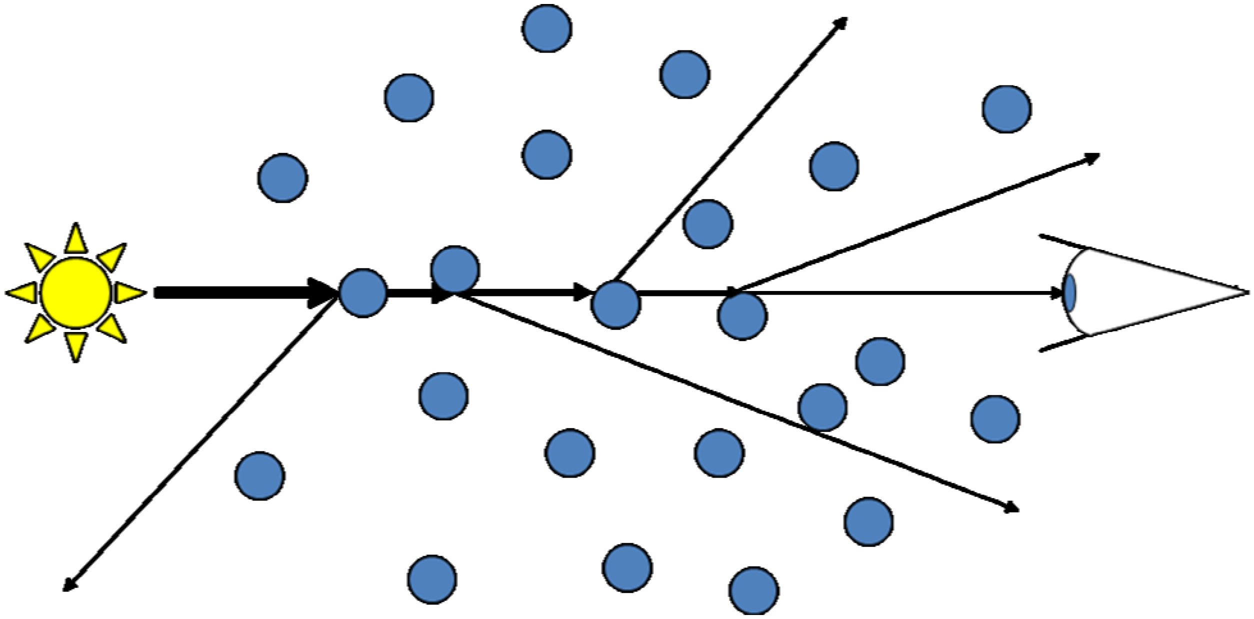
Table 3.1 **Some refractive indices of atmospheric aerosol substances at $\lambda = 0.5\ \mu m$.**

Substance	**n**	**k**
Water	**1.333**	**0**
Hematite	**2.6**	**1.0**
Elemental carbon	**1.75**	**0.44**
Organic carbon	**1.53**	**0.05**
NaCl(s)	**1.544**	**0**
H_2SO_4(aq)	**1.53**	**0**
$(NH_4)_2SO_4$(s)	**1.52**	**0**
SiO_2	**1.55**	**0**

NOTE: hematite is a mineral that is a main light absorbing components of mineral dust.

Mie theory **is the basis for calculation of the scattering and absorption coefficients of a spherical particle having a given diameter and refractive index.**

How it works:



For a particle with diameter D and refractive index m we can calculate the scattering efficiency Q_{sc}, absorption efficiency Q_{abs}, and extinction efficiency Q_{ext} at a given wavelength using Mie theory.

NOTE: $Q_{ext} = Q_{sc} + Q_{abs}$, and they are dimensionless.

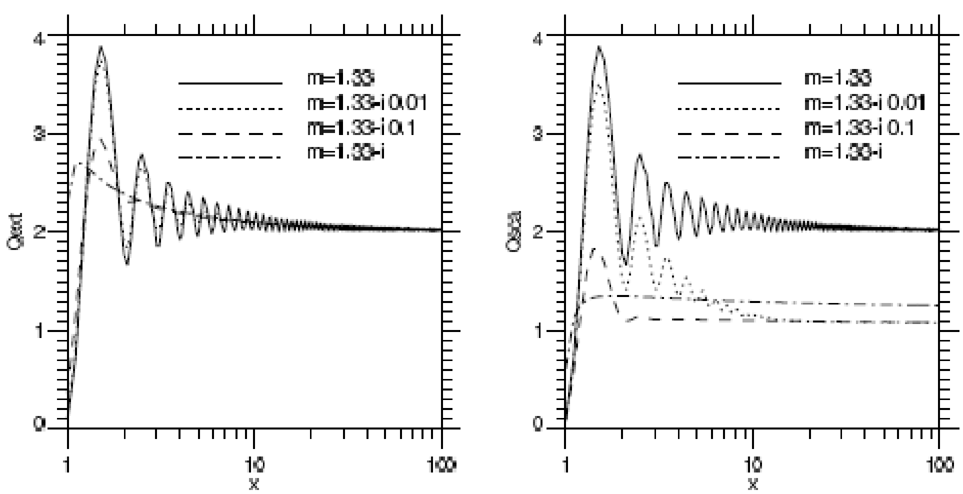


Figure 21. Extinction (upper panel) and Scattering (lower panel) efficiencies from a dielectric sphere having real component of refractive index n=1.33 for several imaginary components k, as a function of the dimensionless size parameter $x = \frac{2\pi r}{\lambda}$.

Then we calculate cross sections as

$\sigma_{sc} = (\pi D^2/4)\, Q_{sc}$

$\sigma_{abs} = (\pi D^2/4)\, Q_{abs}$

$\sigma_{ext} = (\pi D^2/4)\, Q_{ext}$

NOTE: $\sigma_{ext} = \sigma_{sc} + \sigma_{abs}$, and they have the units of area.

And then we calculate scattering, absorption and extinction coefficients as

$\varepsilon_{sc} = N\,\sigma_{sc} = N\,(\pi D^2/4)\, Q_{sc}$

$\varepsilon_{abs} = N\,\sigma_{abs} = N\,(\pi D^2/4)\, Q_{abs}$

$\varepsilon_{ext} = N\,\sigma_{ext} = N\,(\pi D^2/4)\, Q_{ext}$

where N is the number concentration of the particles with diameter D.

Optical properties for size distribution

NOTE: $\varepsilon_{ext} = \varepsilon_{sc} + \varepsilon_{abs}$ **, and they have the units of inverse length.**

Knowing the particle density we can calculate the mass extinction coefficient $\alpha_{ext}=\varepsilon_{ext}/\rho_p$

Where ρ_p is the mass density [kg/m3]

Important to remember:

- **Mie theory is used when size parameter x is about 1 (particle about the same size as the wavelength).**
- **If x << 1 (particles small compared with the wavelength) we use Rayleigh regime, in which scattering and extinction coefficient are given by approximate expressions.**

Rayleigh regime: $Q_{scat} \approx \lambda^{-4} \quad and \quad Q_{abs} = \lambda^{-1}$

- **If x >> 1 (particles large compared with the wavelength) we use Geometric regime. If size parameter increases the extinction efficiency approaches 2.**

In general, if we want to know how radiation will be attenuated in the atmosphere by aerosols, gases and/or clouds we need to solve a radiation transfer equation, which requires information on optical properties of the gases and particulates (such as extinction coefficients, single scattering albedo, scattering phase function, etc.).

Scattering phase function describes the angle-dependent scattering of light incident on a particle. For an aerosol particle without preferential emerging direction, the phase function depends only on the relative angle θ between the incident and emerging beams, and is given by

$$P(\theta) = \frac{4\pi}{\sigma_{scat}} \frac{d\sigma_{scat}}{d\theta}$$

Asymmetry parameter g is defined as the intensity-weighted average of the cosine of the scattering angle:

$$g = <\cos\theta> = \frac{1}{2}\int_0^{\pi} \sin(\theta)\cos(\theta)P(\theta)d\theta$$

Single scattering albedo, ω_0, is defined as

$$\omega = \frac{\varepsilon_{scat}}{\varepsilon_{scat} + \varepsilon_{abs}}$$

which is fraction of total extinction that is due to scattering.

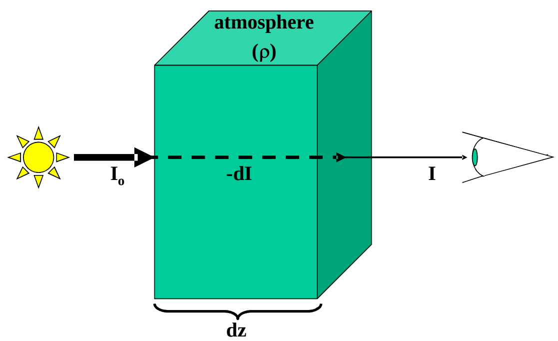
NOTE: single scattering albedo is a key aerosol optical characteristic in assessment the radiative effects due to aerosols (will be discussed in Lectures 39-41).

- **There are many computational and analytical techniques to solve the radiation transfer equation accounting for multiple scattering, absorption and emission by atmospheric particulates and gases.**

Under single scattering approximation we can employ the Beer-Lambert law to calculate the light intensity I at any distance z attenuated by the atmospheric aerosols with extinction ε_{ext} as

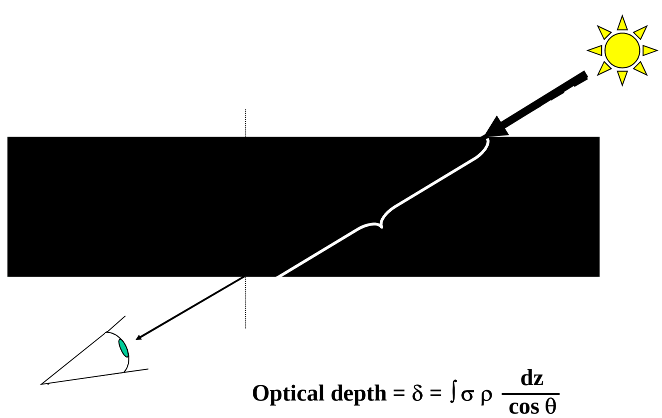
$$\frac{I}{I_0} = \exp(-\varepsilon_{ext} z) = \exp(-\tau)$$

where $\tau = \varepsilon_{ext} z$ is the aerosol optical depth, and $\mathbf{I_0}$ is the incident intensity.

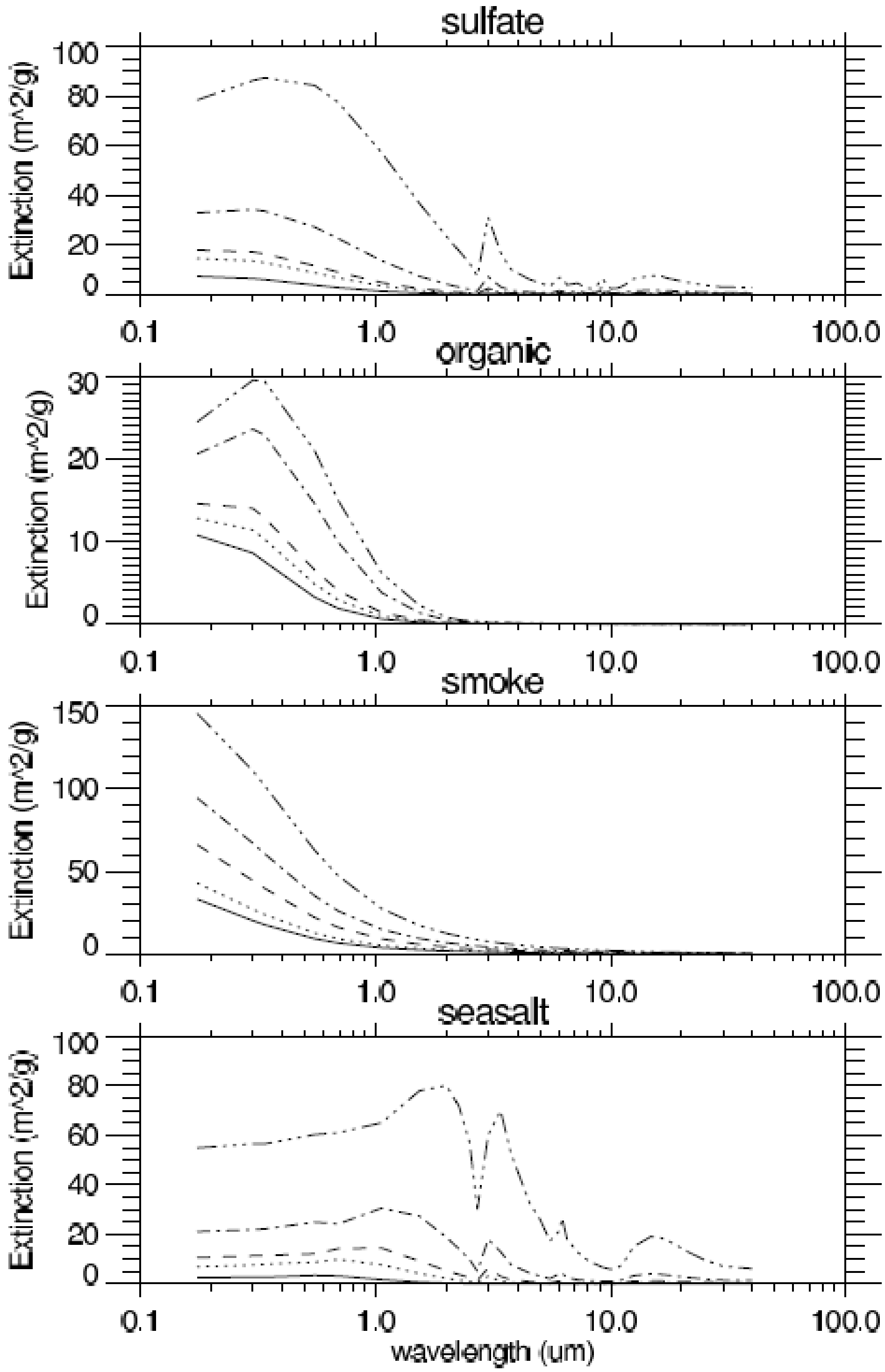


Plane parallel atmosphere approximation:

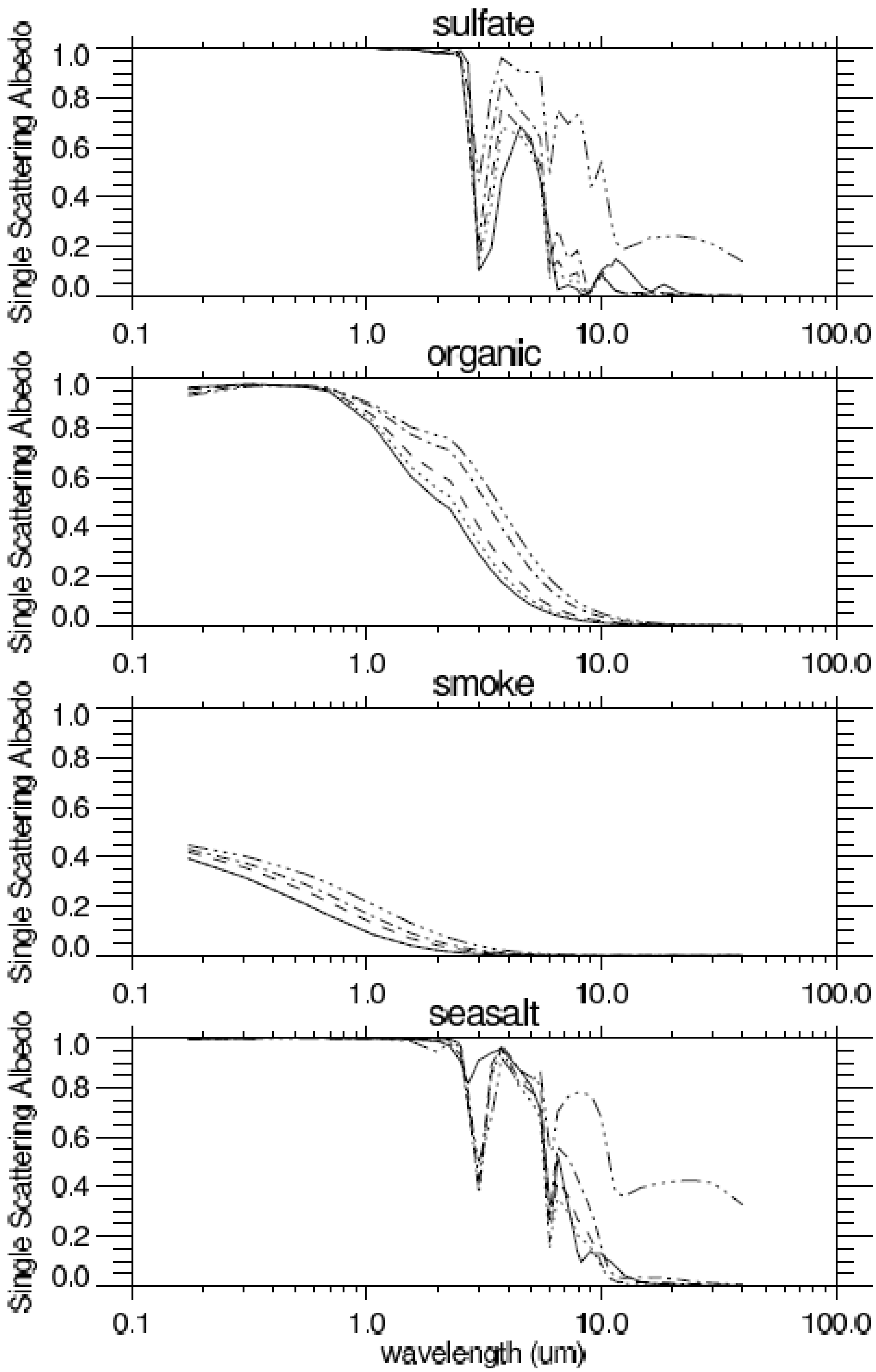
- Horizontally uniform atmosphere
- Vertically uniform layer



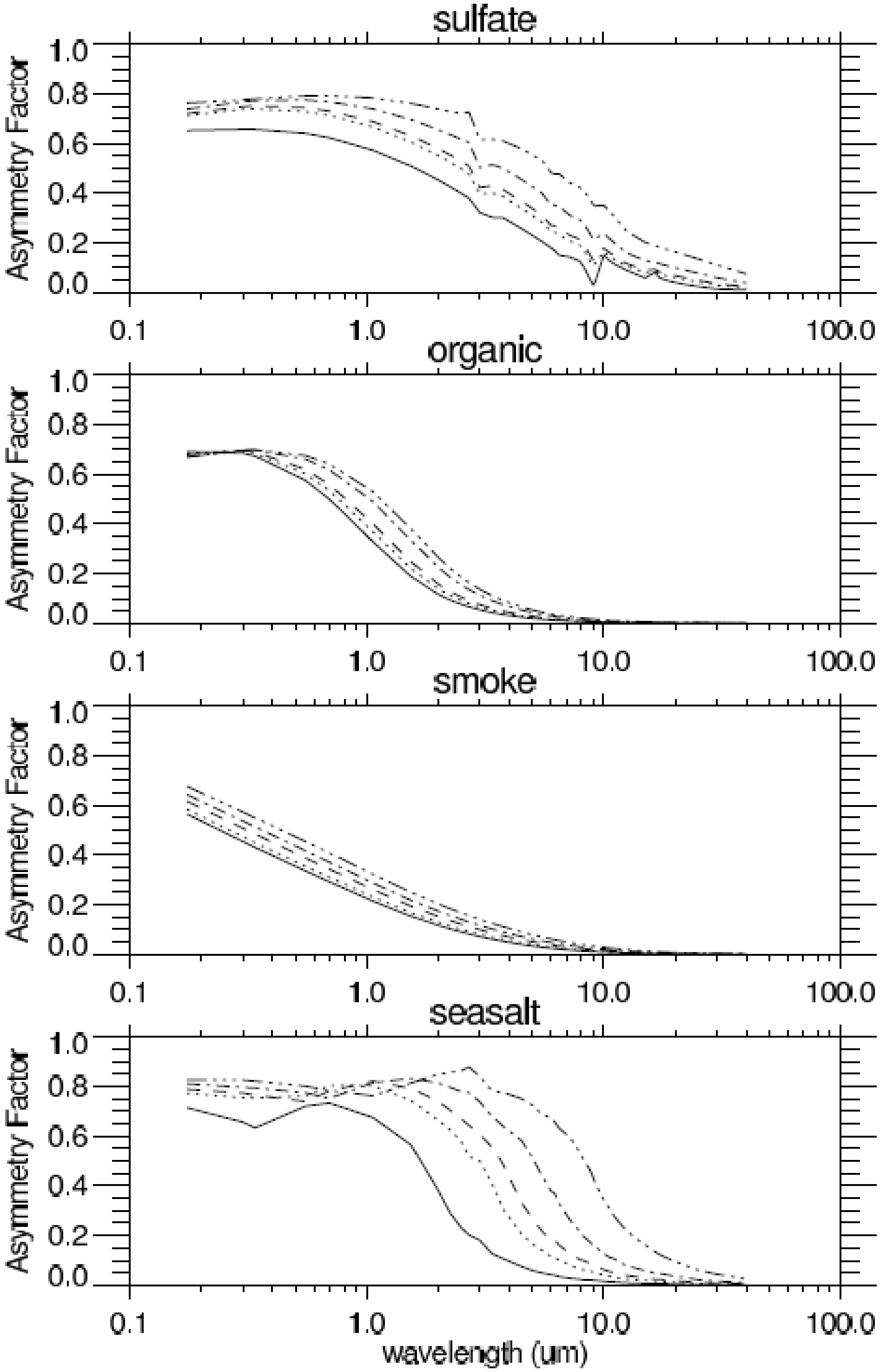
Mass extinction of lognormal distribution of sulfate, organic, black carbons, and sea-salt



Single Scattering Albedo of log-normal distribution of Sulfate, Organic, Black carbons, and sea-salt

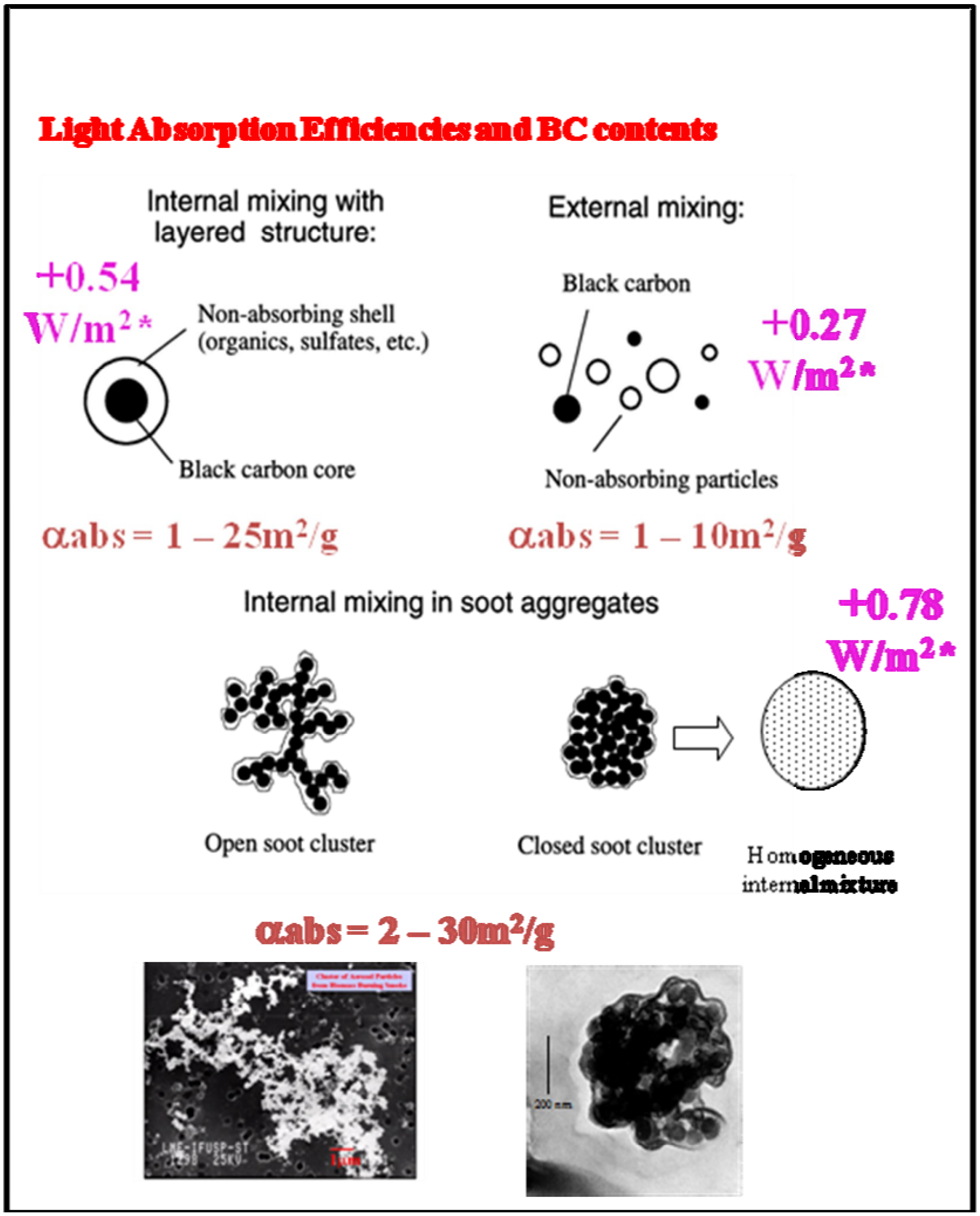


Asymmetry factor for lognormal distribution of sulfate, organic, black carbons and sea-salt



Mixture of aerosols: External/Internal mixture

If a particle is made of a mixture of substances an effective refractive index must be calculated. The particles can be treated as external or internal mixture



2. Haze and Visibility.

Clean (background) atmospheric conditions: light is scattered and absorbed by natural gases and particulates (background aerosol).

Polluted atmospheric conditions: air pollutants (gases and particles) cause additional attenuation of light.

Haze is a form of air pollution consisting of small particles of dust, soot, sulfates, and other material.

- Haze has natural and anthropogenic sources.

Total suspended particulate (TSP) refers to the total mass concentration of aerosol particles present in the air.

- In heavily polluted cities, average TSP abundance is about 50-100 $\mu m/m^3$, with upper limits of about 1000 $\mu m/m^3$.

Two major problems caused by haze:

1. visibility reduction;
2. health effects

Visibility is generally used synonymously with "visual range", meaning the farthest distance at which one can see a large, black object against the sky at the horizon.

Some factors determining how far one can see through the atmosphere:

i. optical properties of the atmosphere;
ii. amount and distribution of light;
iii. characteristics of the objects observed;
iv. properties of the human eye.

- Visibility is reduced by the absorption and scattering of light by both gases and particles. However, light scattering by particles is the most important phenomenon responsible for visibility degradation.

Clean (background) atmospheric conditions: one can see over distances up to several hundred kilometers.

Polluted atmospheric conditions: visibility is up to 10 km.

Koschmieder equation:

relates visual range (visibility), $\mathbf{x_v}$, and extinction coefficient ,$\boldsymbol{\varepsilon_{ext}}$, as

$$\mathbf{x_v = 3.912/\boldsymbol{\varepsilon}_{ext}}$$

NOTE: in Koschmieder equation the extinction coefficient is sum of extinction coefficients of all gases and particles, which attenuate light.

NOTE: in Koschmieder equation the extinction coefficient is averaged over visible wavelengths, however it is often taken at about 550-nm wavelength