AOSC400-2015
October 6, Lecture # 10

- o Refractive Index; Snell Law-*(refresher)*
- o Rayleigh scattering – continued

Aerosols:

- o Composition,
- o size distribution,
- o optical properties
  - ❖ optical depth,
  - ❖ single scattering albedo,
  - ❖ asymmetry parameter
  - ❖

Refractive index- *(refresher)*

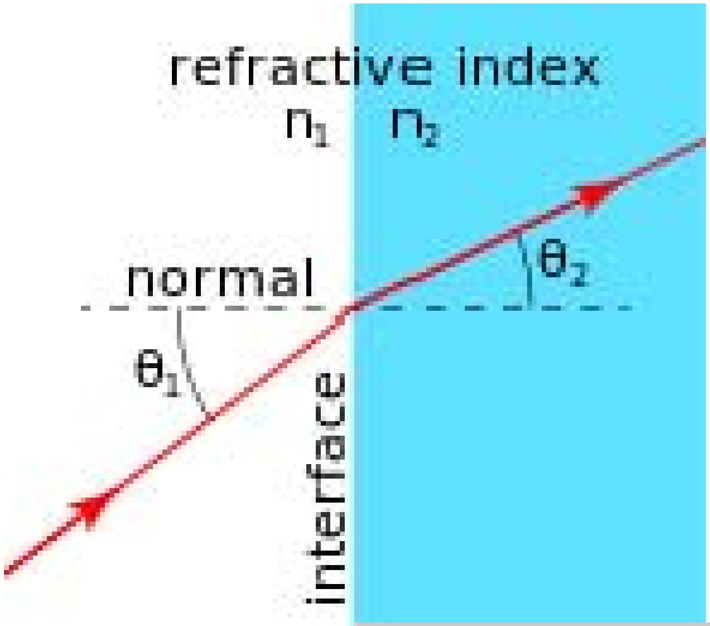
Light changes speed as it passes from one medium to another. This is called refraction.

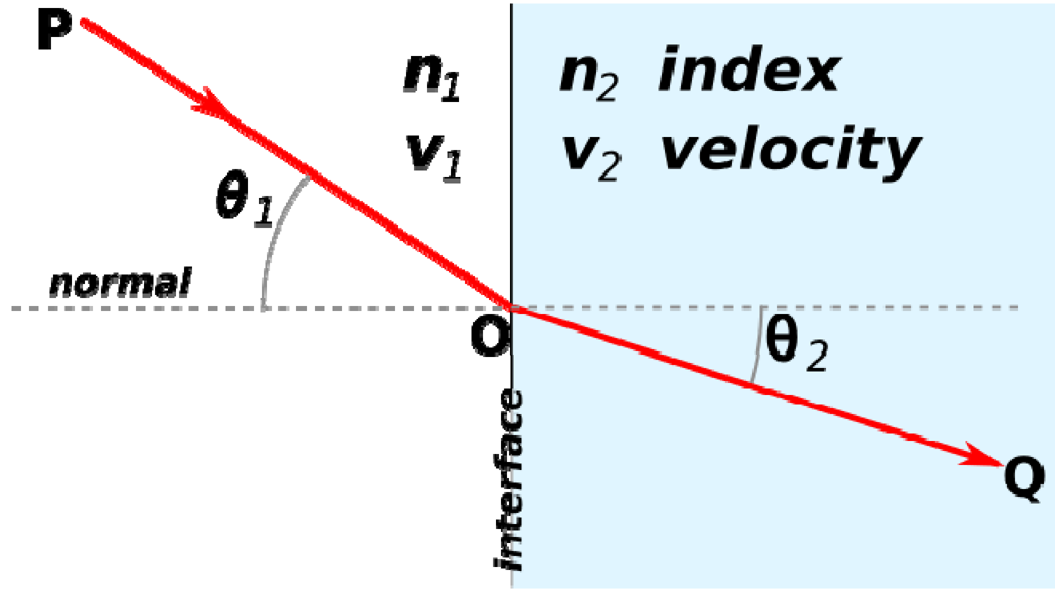
$$n = c/v$$

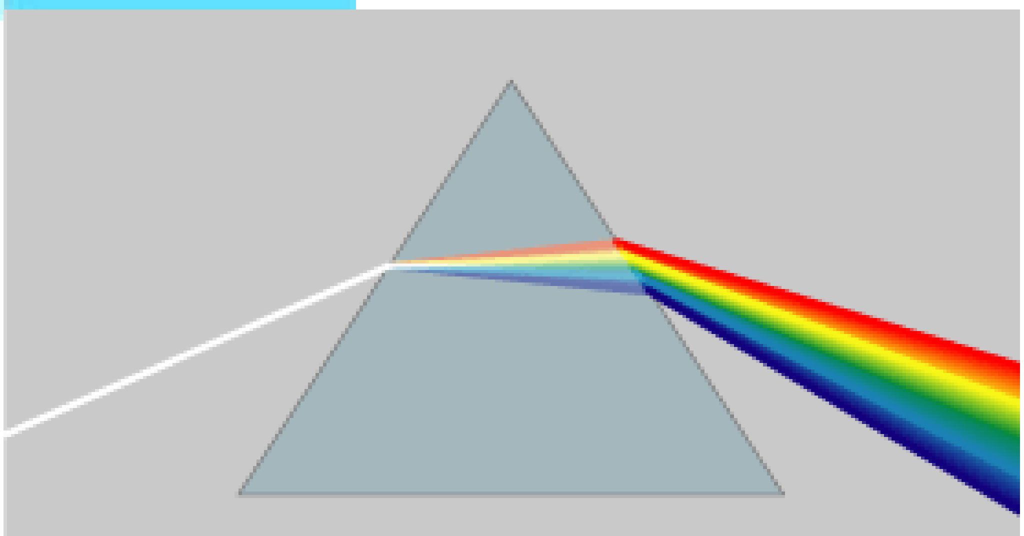
c is the speed of light in vacuum equal to 299 792 458 m/s and v is the phase velocity of the light in the medium.

The phase velocity is the speed at which the peak or the phase of the wave moves (which may be different from the group velocity, the speed at which the pulse of light or the envelope of the wave moves).

Refractive index of a material is a measure of the change in speed of light as it passes from a vacuum (or air as an approximation) into the material.







Snell's law

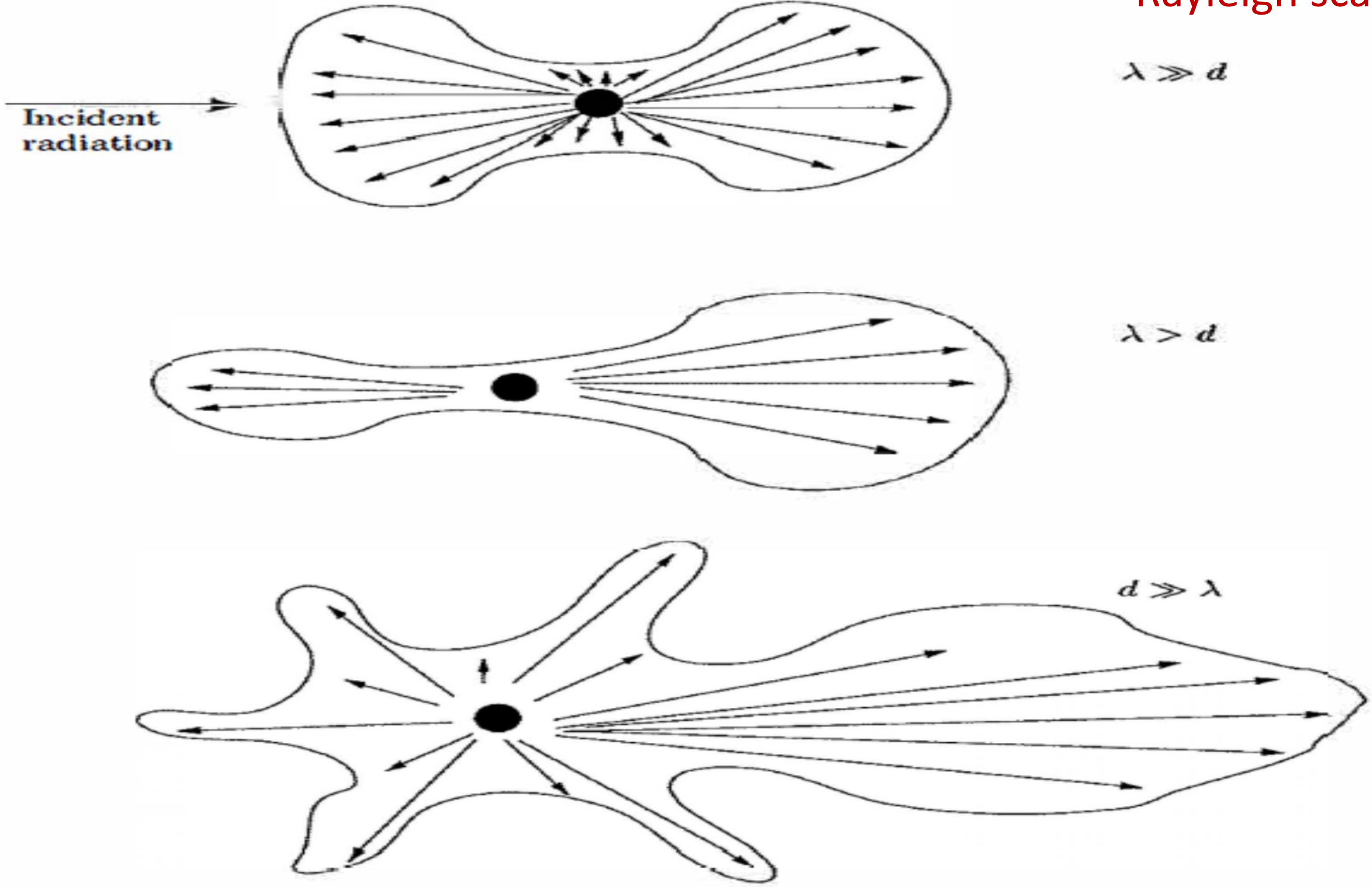
$$n_1 \sin \theta_1 = n_2 \sin \theta_2.$$

Selected refractive indices at λ=589 nm

Vacuum	1
Gases at 0 °C and 1 atm	
Air	1.000293
Helium	1.000036
Hydrogen	1.000132
Carbon dioxide	1.00045
Liquids at 20 °C	
Water	1.333
Ethanol	1.36
Olive oil	1.47
Solids	
Ice	1.309
Soda-lime glass	1.46
PMMA (Plexiglas)	1.49
Crown glass (typical)	1.52

Scattering

Rayleigh scattering



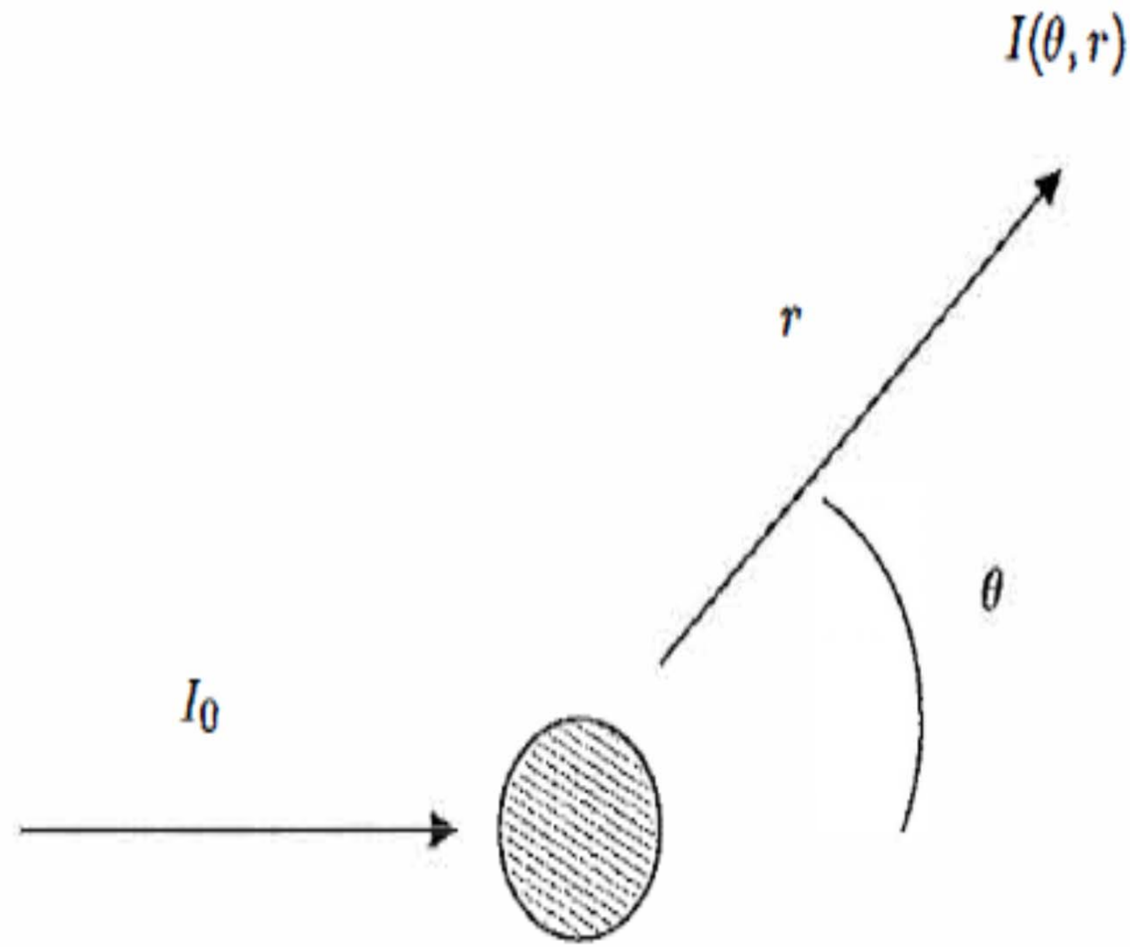


Fig. 2.7 Scattering of an incident radiation (I_0)

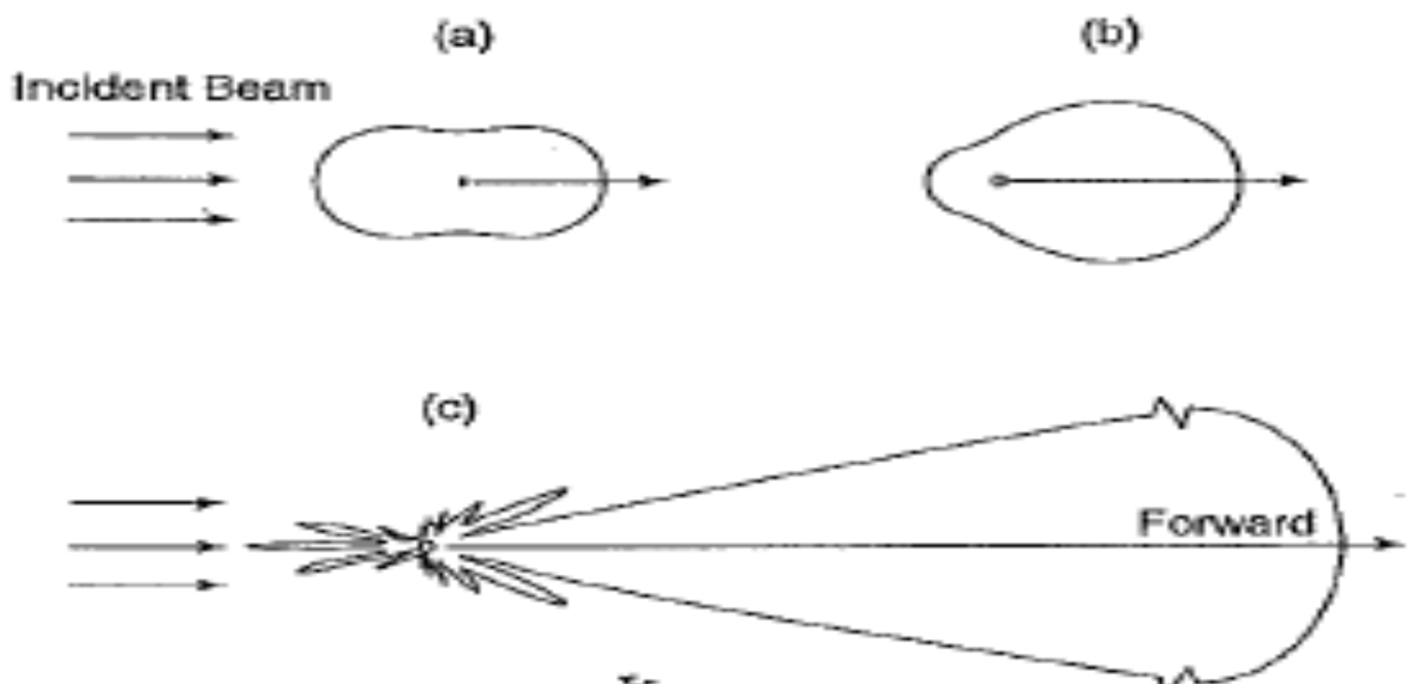
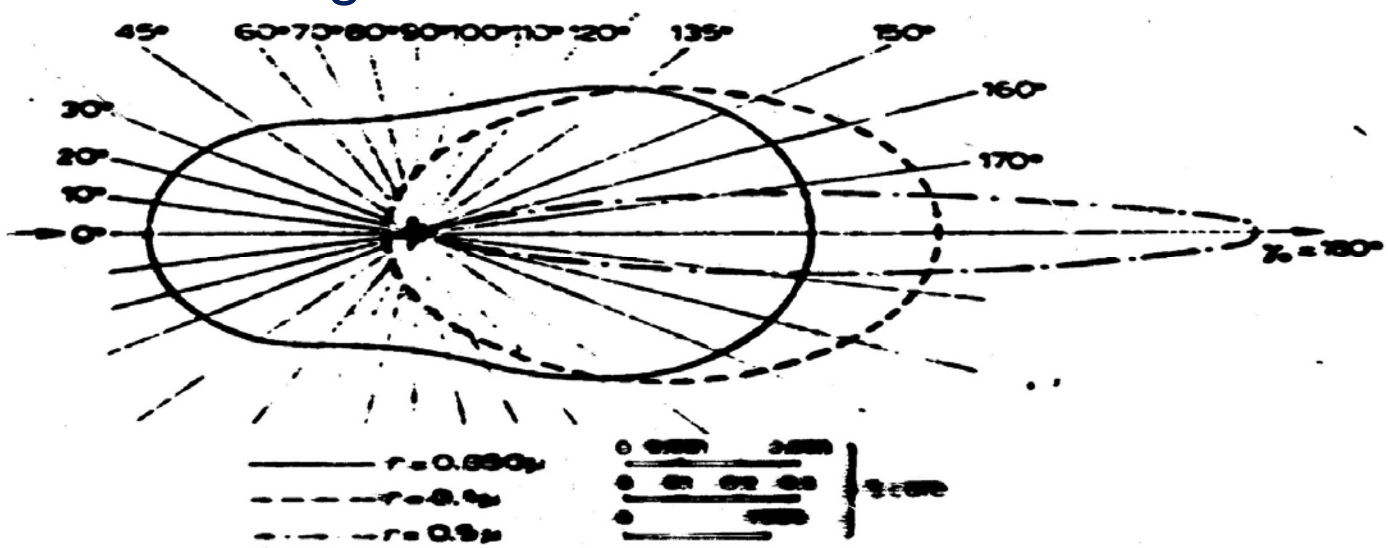


Fig. 4.12 Schematic showing the angular distribution of the radiation at visible (0.5 µm) wavelength scattered by spherical particles with radii of(a) 10^{-4} µm, (b) 0.1 µm, and (c) 1 µm. The forward scattering for the 1-µm aerosol is extremely large and is scaled for presentation purposes. (Adapted from K. N. Liou, An Introduction to Atmospheric Radiation, Academic Press, p. 7, Copyright (2002}, with permission from Elsevier.]

Mie scattering:

For large particle to wavelength ratio. The larger the particle, the more forward scattering is.



Rayleigh scattering is symmetrical with respect to the direction of incidence; the angular scattering by Mie particles - the amount of light scattered in the forward is much larger than in the backward direction .

A more explicit formulation: the intensity *I* of light scattered by a single small particle from a beam of un-polarized light of wavelength *λ* and intensity I_0 is given by:

$$I = I_0 \frac{1+\cos^2\theta}{2R^2}\left(\frac{2\pi}{\lambda}\right)^4\left(\frac{n^2-1}{n^2+2}\right)^2\left(\frac{d}{2}\right)^6$$

where *R* is the distance to the particle, *ϑ* is the scattering angle, *n* is the refractive index of the particle, and *d* is the diameter of the particle.

For the whole atmosphere

the vertical optical depth $\tau_{R\lambda}$, is given by:

$$\tau_{R\lambda} = \int_0^\infty \kappa_{R\lambda} \rho dz = \int_0^\infty \beta_{R\lambda} dz$$

where

$\kappa_{R\lambda}$ = Rayleigh mass scattering coefficient

$\beta_{R\lambda}$ = volume scattering coefficient

$$\kappa_{R\lambda} \rho = \beta_{R\lambda}$$

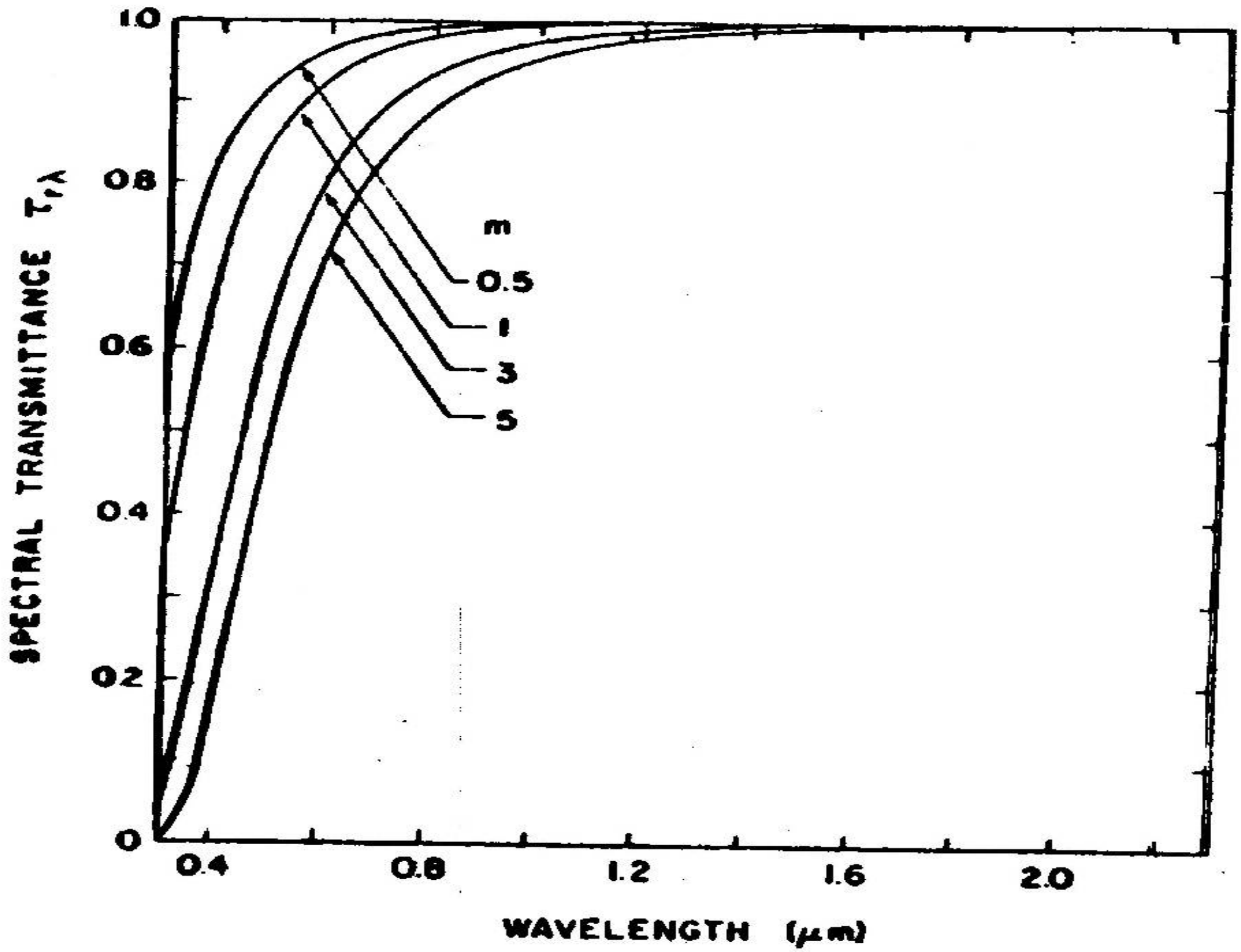
To a good approximation:

$$\tau_{R\lambda} = 0.00888\, \lambda^{-4.05}$$

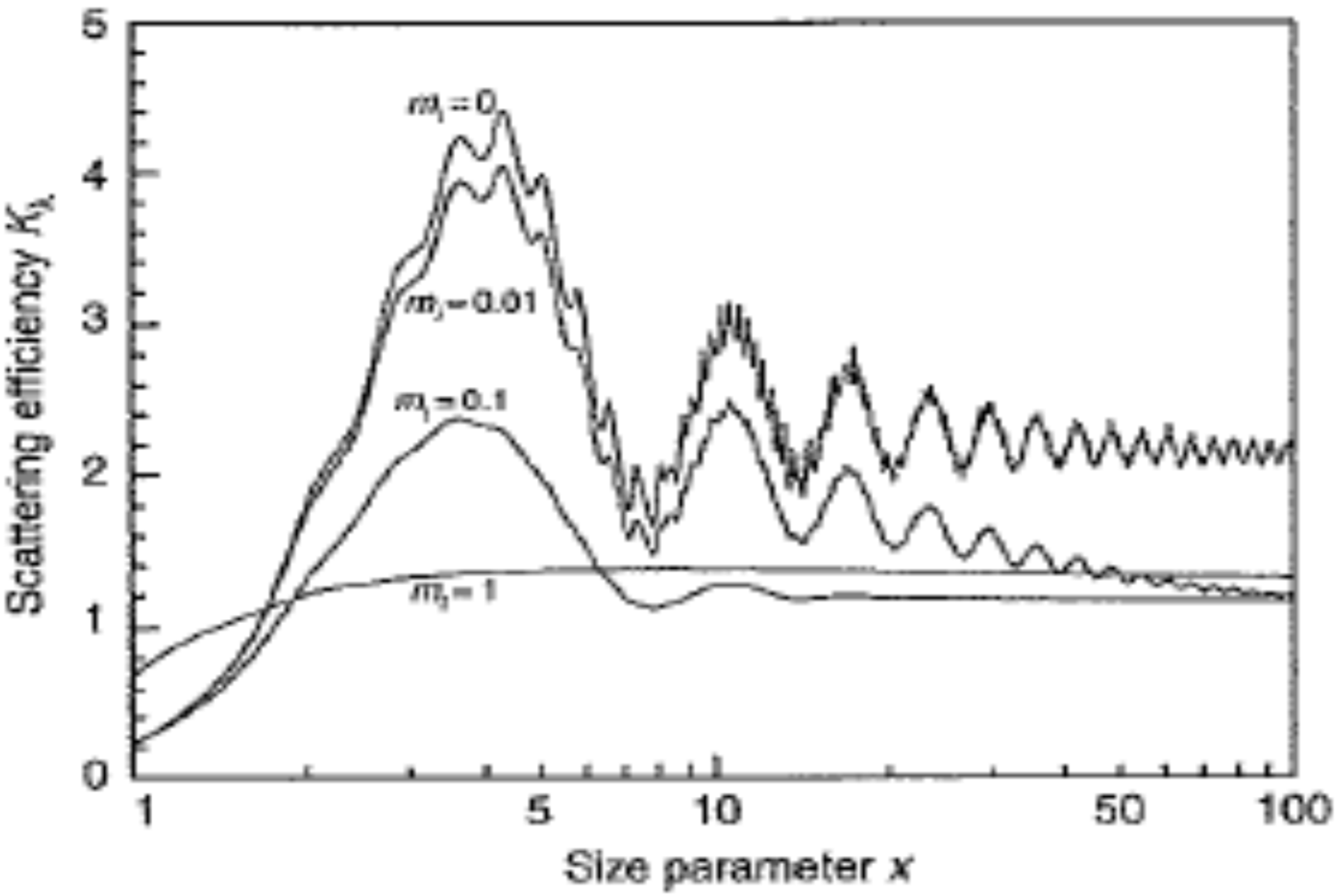
Table 6.1

m_r	$\bar{\tau}_R(m_r)$	I (mW cm^{-2})
0.5	0.105	128.6
1.0	0.099	122.8
1.5	0.094	117.7
2.0	0.089	113.5
3.0	0.082	106.0
4.0	0.076	100.0
6.0	0.067	90.7
8.0	0.060	83.9
10.0	0.055	78.2

Rayleigh scatter "mean optical depth" and corresponding direct beam irradiance as a function of relative air mass



Rayleigh spectral transmittance as a function of air mass



$$x = \frac{2\pi r}{\lambda} \tag{4.19}$$

Fig. 4.13 Scattering efficiency K_λ as a function of size parameter x, plotted on a logarithmic scale for four different **refractive indices** with m = 1.5 and m ranging from O to 1, as indicated. (From K. N. Liou, An Introduction to Atmospheric Radiation, Academic Press, p. 191, Copyright (2002), with permission from Elsevier.]

In Lecture # 9 we have discussed:

Other information one can derive from the solar direct beam

Solar direct beam:

$$I = \int_0^\infty I_{o\lambda} \exp\left(-\tau_{e\lambda} \sec\theta\right) d\lambda$$

$\sec\theta \approx m_r$ (relative optical mass)

$\tau_{e\lambda}$ = sum of extinctions due to scatter and absorption

$$I = \int_0^\infty I_{0\lambda} \exp\left[-\left(\tau_{R\lambda} + \tau_{oz\,\lambda} + \tau_{wv\,\lambda} + \tau_{D\lambda}\right) m_r\right] d\lambda$$

where

$\tau_{R\lambda}$ is due to Rayleigh scattering

$\tau_{oz\lambda}$ is due to ozone absorption

$\tau_{wv\lambda}$ is due to water vapor absorption

$\tau_{D\lambda}$ is due to aerosol extinction

Assuming 3 out of the 4 terms

$$\left(\tau_{R\lambda} + \tau_{oz\,\lambda} + \tau_{wv\,\lambda} + \tau_{D\,\lambda}\right)$$

are known, the 4^{th} can be estimated.

Most commonly, assumed that the first 3 terms are known and the 4^{th} (aerosol extinction) needs to be estimated.

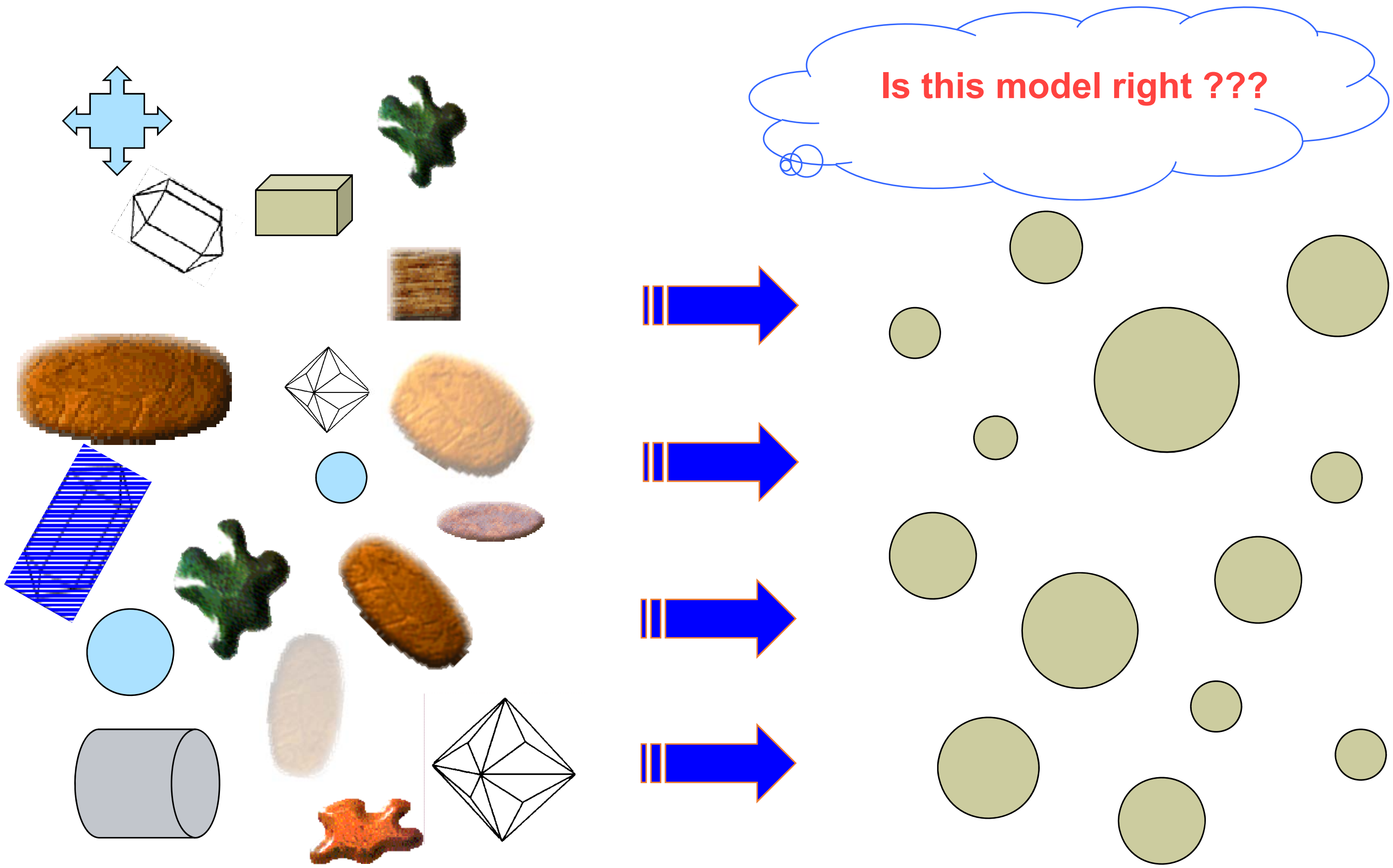
What are aerosols

Aerosols are fine solid particles or liquid droplets, in air or another gas.

Examples of aerosols include haze, dust, particulate air pollutants and smoke.

The liquid or solid particles have diameter mostly smaller than 1 μm or so.

Optical model of aerosol



Aerosol Optical Depth (AOD)

- AOD is a measure of the integrated columnar aerosol load and is an important parameter for evaluating aerosol-radiation interactions.
- Better satellite sensors and ground-based sun-photometer networks, along with improved retrieval methods and methodological inter-comparisons allow assessment of regional AOD trends since about 1995.
- AOD sun photometer measurements starting in 1986 at two stations in northern Germany corroborate the long-term decline of AOD in Europe.

Basic Concepts

Mass concentration (M)

An aerosol is characterized by its mass concentration (M) which is the mass of particulate matter per unit volume. It is given in g m^{-3} for atmospheric aerosols and is frequently called as total suspended particulates (TSP)

.

Shape

Shape controls the particle's optical properties. Particles formed by condensation of vapor molecules are generally spherical in shape; those formed by breaking larger particles are non-spherical.

Classification of aerosols

Atmospheric aerosols can be classified according to size and shape.

Size

Aerosols are often grouped into three size ranges:

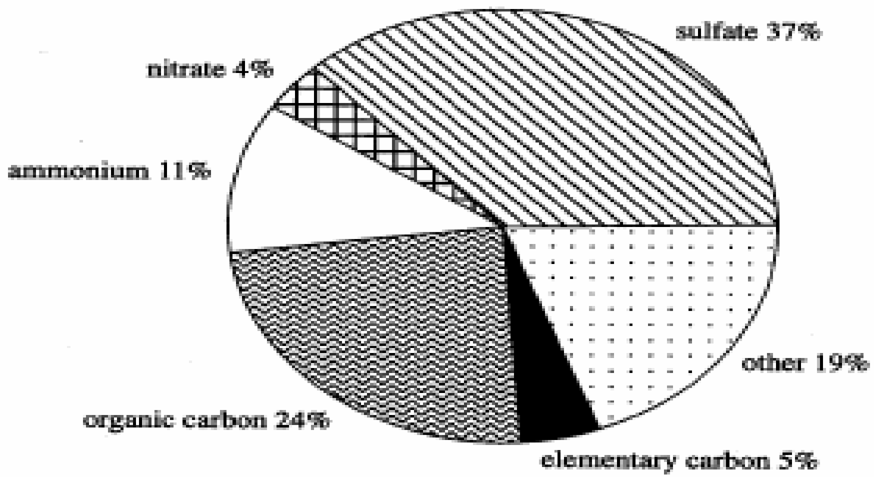
1) < 0.1 micron radius: Aitken particles, which comprise the majority of aerosols. The peak in the number distribution that occurs here is often referred to as the 'accumulation mode' because it's due to the tendency of small particles to collide via Brownian motion and clump together
electrostatically. Most Aitken particles are due to the ionic products of atmospheric chemistry.

2) 0.1-1 micron radius: Large particles, dominated by dust and sea spray (which depend on wind speed), and combustion. Sedimentation provides an upper limit for the size of large particles that remain in the atmosphere.

3) 1-10 micron radius: Giant particles – large dust and combustion products. Though comprising the greatest mass of atmospheric aerosol, these tend to have a short dwell time due to sedimentation. A peak in the distribution between 5 and 10 microns radius is often referred to as the 'coarse mode' and is due to nearby sources of dust and combustion.

Ultrafine aerosols – nucleation mode (10^{-3}-10^{-2} μm)

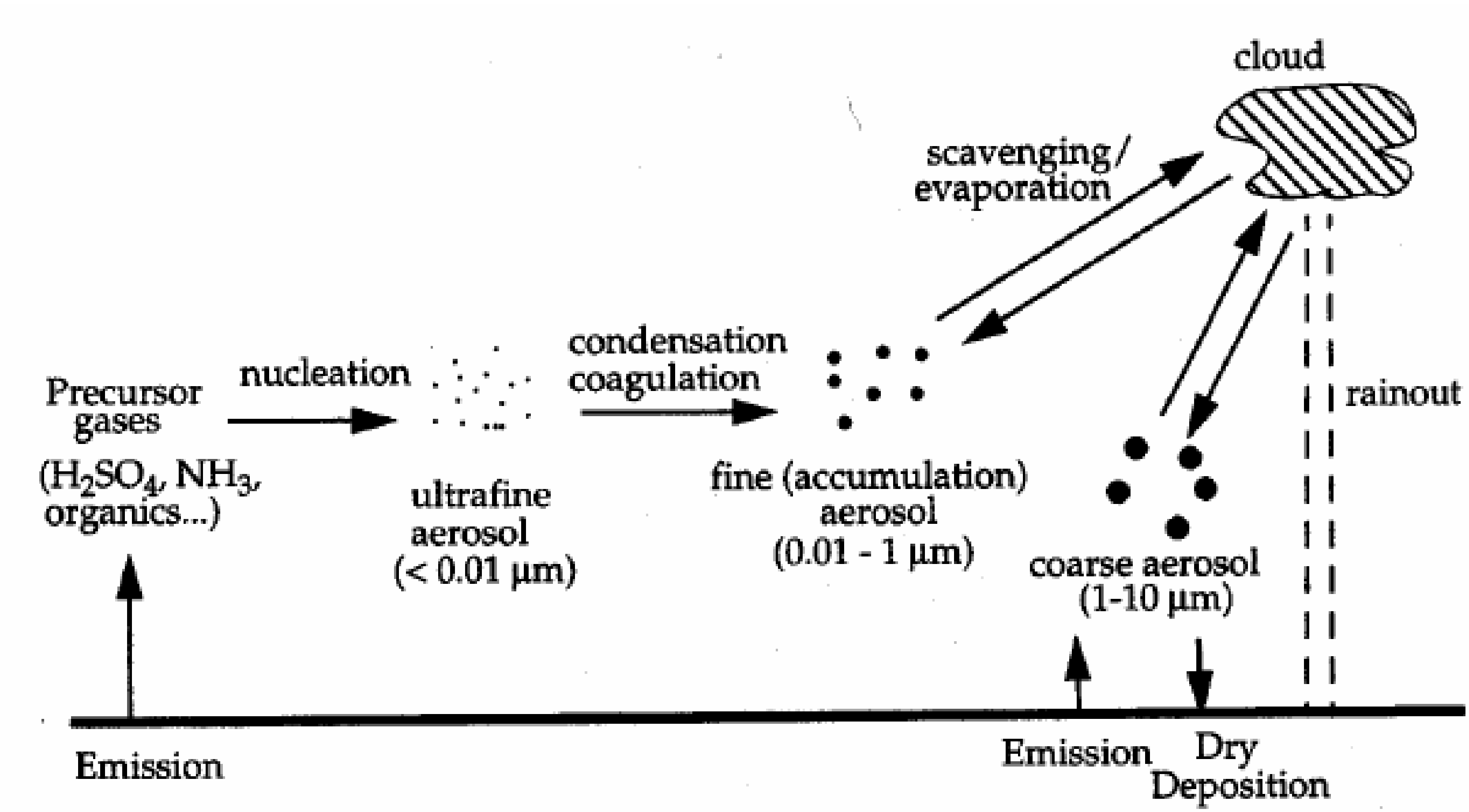
Fine aerosols – condensation and coagulation (0.01-1 μm)

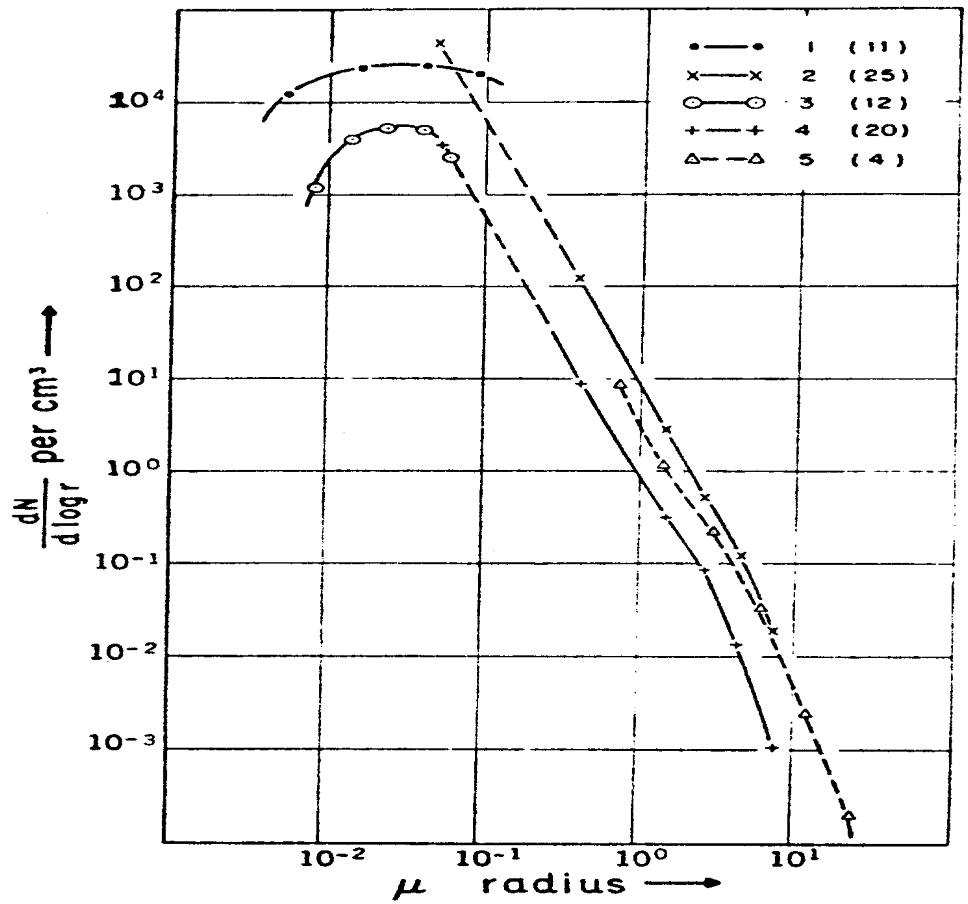


Accumulation mode:
Too small to sediment and are lost mainly by scavenging by cloud droplets

Coarse mode – form by wind erosion (land, sea, vegetation).

The life cycle of aerosols





Junge distribution of aerosol sizes.

Power law distributions are often used to model the aerosol populations, but because of the peaks in the accumulation and coarse modes, such models are only useful over limited ranges.

Other observed distributions of aerosols.

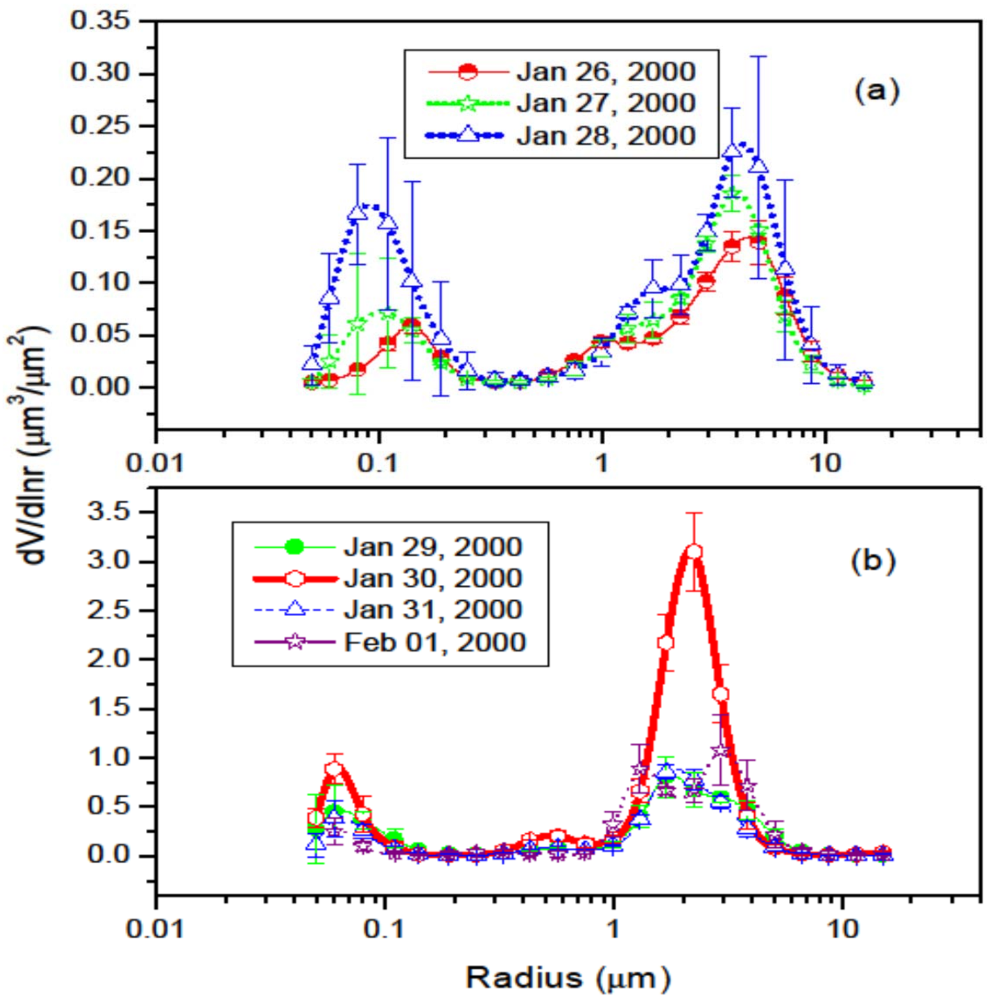
Upper figure:

Normal days

Lower figure:

during

dust outbreak



Bimodal Variability in size distribution during "normal" days and dust outbreak in Africa.

Aerosol Size Distribution

The total aerosol optical depth due to extinction may be written as

$$\tau_{\lambda}^{M} = \int_0^{\infty} \beta_e(\lambda, z)\, dz \qquad (2)$$

Let the height dependent aerosol size distributionbe defined by n(z, a) ($cm^{-3}\mu m^{-1}$)

Then, the extinction coefficient (cm^{-1}) is given as

$$\beta_e(\lambda, z) = \int_0^{\infty} \sigma_e(a, \lambda)\, n(z, a)\, da \qquad (3$$

where σ_e stands for the extinction cross section (cm^2) for an individual particle. For the retrieval purpose, the Junge size distribution can be assumed to a good approximation.

Scattering coefficient σ_s

The scattering coefficient is defined as the fraction of radiant flux lost from a collimated beam per unit thickness of aerosol due to scattering (deflection of light into directions different from the direction of the transmitted beam) and is given in units of reciprocal length.

Absorption coefficient σ_a

The absorption coefficient is defined as the fraction of radiant flux lost from a collimated beam per unit thickness of aerosol due to absorption (transformation of light into other forms of energy) and is also given in units of reciprocal length.

$$\sigma_e = \sigma_s + \sigma_a$$

Single scattering albedo ($\overline{\omega}$)

The ratio of the scattering coefficient to the extinction coefficient is called the single scattering albedo (SSA). It describes the contribution of scattering to extinction.

$$\overline{\omega} = \frac{\sigma_s}{\sigma_e} = 1 - \frac{\sigma_a}{\sigma_e} = (1 - \alpha) \qquad (11)$$

Where the ratio of the absorption coefficient to the extinction coefficient

is termed as the absorption number $\alpha = \frac{\sigma_a}{\sigma_e}$

It is the fraction of scattered light with respect to the total light which interacts with the particles.

Single scattering albedo - ω_0

Ratio of scattering to extinction, describes aerosol absorption.

0.0----------0.5-----------0.8-----------0.9----------0.95---------1.0

black carbon | smoke from fire | urban pollution | sea salt volcanic sulfuric acid

dust in blue

dust in green to NIR