

Atmospheric Visibility

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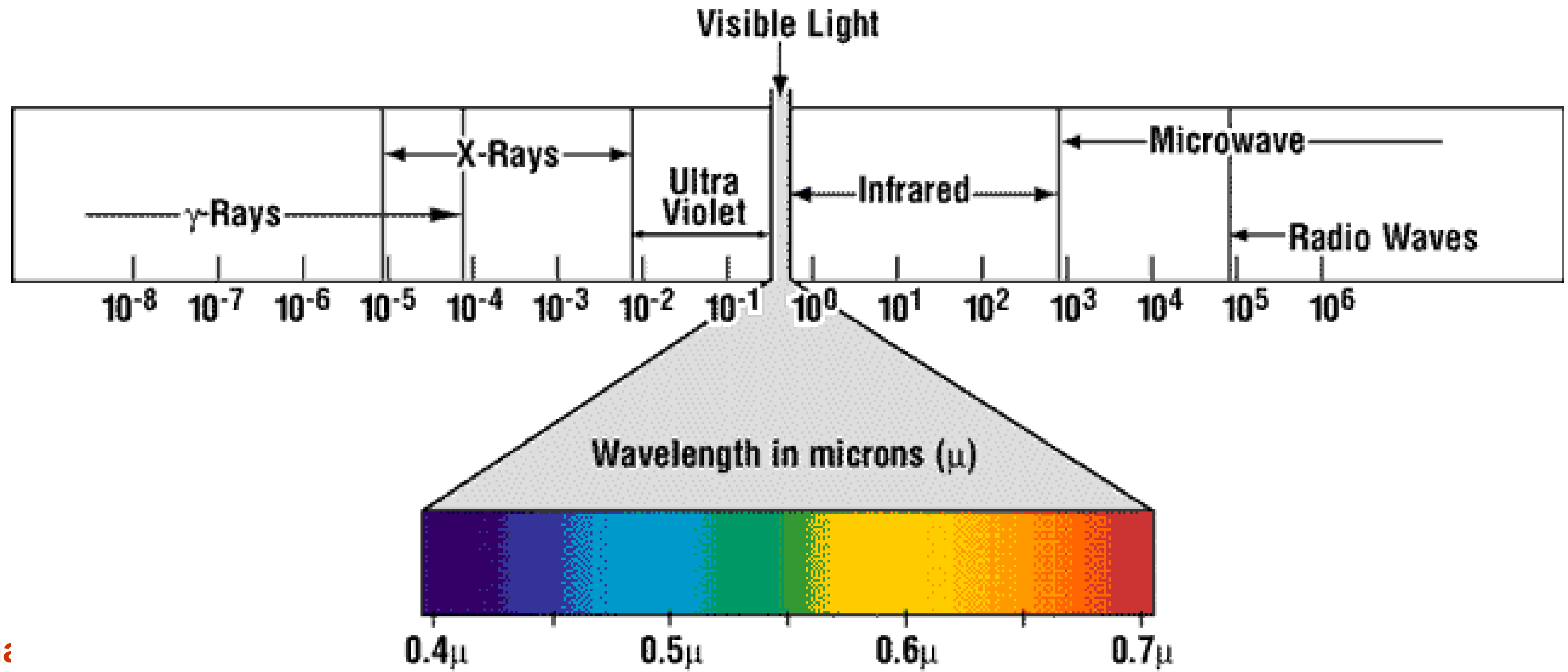
Nature of Light

Light can be thought of as waves. Electric and magnetic fields transmit energy in waves that are called electromagnetic radiation. Ordinary light is a form of electromagnetic radiation, as are x-rays, ultraviolet, infrared, radar, and radio waves. The various forms of electromagnetic radiation differ from one only in wavelength, and therefore in the energy they can transmit.

Figure below is a representation of the electromagnetic spectrum with the visible portion shown in color to emphasize the portion of the spectrum to which the human eye is sensitive. The visible spectrum is white light separated into its component wavelengths or colors. The wavelength of light, typically measured in terms of millionths of a meter (microns), extends from about 0.4 to 0.7 micron.



The Properties of Light

- Linear Propagation
- Refraction
- Reflection
- Diffraction
- Polarization

THE WAVE MODEL OF LIGHT

- Waves and light have two big similarities

1. Both are forms of energy
2. Both travel out in all directions

The Wave Model:

- Different colours of light have different wavelengths
- Waves with shorter wavelengths have higher energy than those with longer wavelengths

Scattering

Scattering, Absorption and Extinction

Extinction of radiation in the earth's atmosphere results from two processes, scattering and absorption; both of which remove energy from the direct radiation.

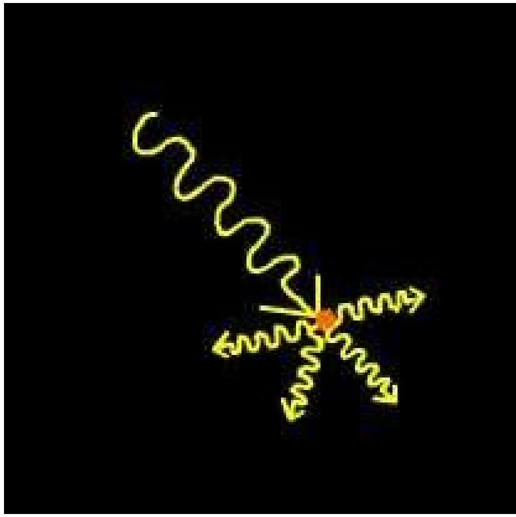
Extinction = Scattering + Absorption

Both scattering and absorption depend on the wavelength of the incident radiation and the property of the intervening medium. But the similarity ends here only.

In absorption, a portion of the incident wave energy is absorbed by the medium, which in turn is utilized to change its internal energy, leading to re-emission at other wavelengths or as thermal energy.

Scattering Effects

Scattering is the process by which any matter (scatterer) in the path of an electromagnetic radiation continuously abstracts energy from the incident wave and re-radiates this energy into the total solid angle (4π) centered at the particle. Scattering of light occurs when a beam of light is broken into several smaller, less intense beams of light by gases, aerosols, or particulates in the atmosphere.



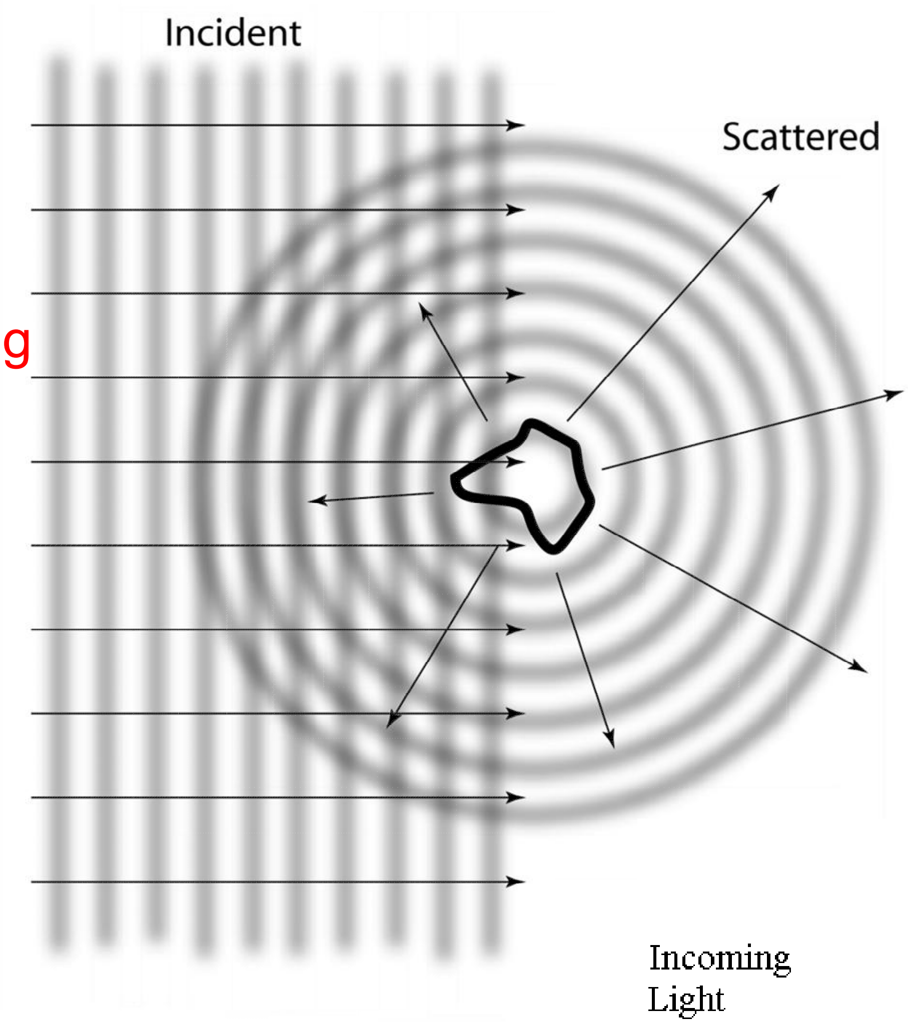
Lunar sky looks black because there is no atmosphere to scatter light!

Scattering fundamentals

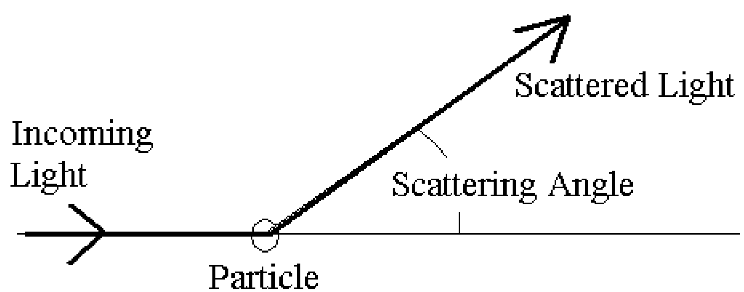
- Scattering can be broadly defined as the *redirection of radiation out of the original direction of propagation*, usually due to interactions with molecules and particles
- Reflection, refraction, diffraction etc. are actually all just forms of scattering
- Matter is composed of discrete electrical charges (atoms and molecules – dipoles)
- Light is an oscillating electromagnetic (EM) field – excites charges, which radiate EM waves
- These radiated EM waves are *scattered waves*, excited by a source external to the scatterer

Scattering geometry

Backward scattering (backscattering)



Forward scattering



When does scattering matter?

- Scattering can be ignored whenever gains in intensity due to scattering along a line of sight are negligible compared to:
    - Losses due to extinction
    - Gains due to thermal emission
- Usually satisfied in the thermal IR band and for microwave radiation when no precipitation (rain, snow etc.) is present
- Also can be ignored when considering direct radiation from a point source, such as the sun
- In the UV, visible and near-IR bands, scattering is the dominant source of radiation along any line of sight, other than that looking directly at the sun

Types of scattering

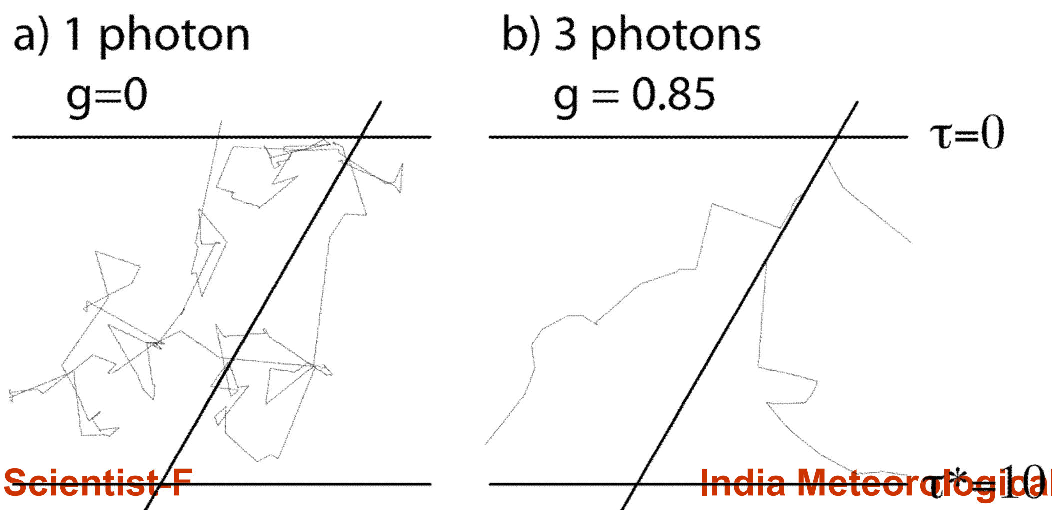
- Elastic scattering – the wavelength (frequency) of the scattered light is the same as the incident light (*Rayleigh and Mie scattering*)

- Inelastic scattering – the emitted radiation has a wavelength different from that of the incident radiation (*Raman scattering, fluorescence*)

- Quasi-elastic scattering – the wavelength (frequency) of the scattered light shifts (e.g., in moving matter due to Doppler effects)

More types of scattering

- Single scattering: photons scattered only once
  - Prevails in optically thin media ($\tau << 1$), since photons have a high probability of exiting the medium (e.g., a thin cloud) before being scattered again
  - Also favored in strongly absorbing media ($\omega << 1$)
- Multiple scattering: prevails in optically thick, strongly scattering and non-absorbing media
  - Photons may be scattered hundreds of times before emerging



Parameters governing scattering

- (1) The wavelength (λ) of the incident radiation

- (2) The size of the scattering particle, usually expressed as the non-dimensional size parameter, x:

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

- **r** is the radius of a spherical particle, **λ** is wavelength

- (3) The particle optical properties relative to the surrounding medium: the complex refractive index

- Scattering regimes:

  - **x << 1** : Rayleigh scattering
  - **x ~ 1** : Mie scattering
  - **x >>1** : Geometric scattering

Atmospheric particles

Type	Size	Number concentration
Gas molecule	~10^{-4} μm	< 3×10^{19} cm^{-3}
Aerosol, Aitken	< 0.1μm	~10^4 cm^{-3}
Aerosol, Large	0.1-1 μm	~10^2 cm^{-3}
Aerosol, Giant	> 1 μm	~10^{-1} cm^{-3}
Cloud droplet	5-50 μm	10^2-10^3 cm^{-3}
Drizzle drop	~100 μm	~10^3 m^{-3}
Ice crystal	10-10^2 μm	10^3-10^5 m^{-3}
Rain drop	0.1-3 mm	10-10^3 m^{-3}
Graupel	0.1-3 mm	1-10^2 m^{-3}
Hailstone	~1 cm	10^{-2}-1 m^{-3}
Insect	~1 cm	<1 m^{-3}
Bird	~10 cm	<10^{-4} m^{-3}
Airplane	~10-100 m	<1 km^{-3}

Refractive indices of substances

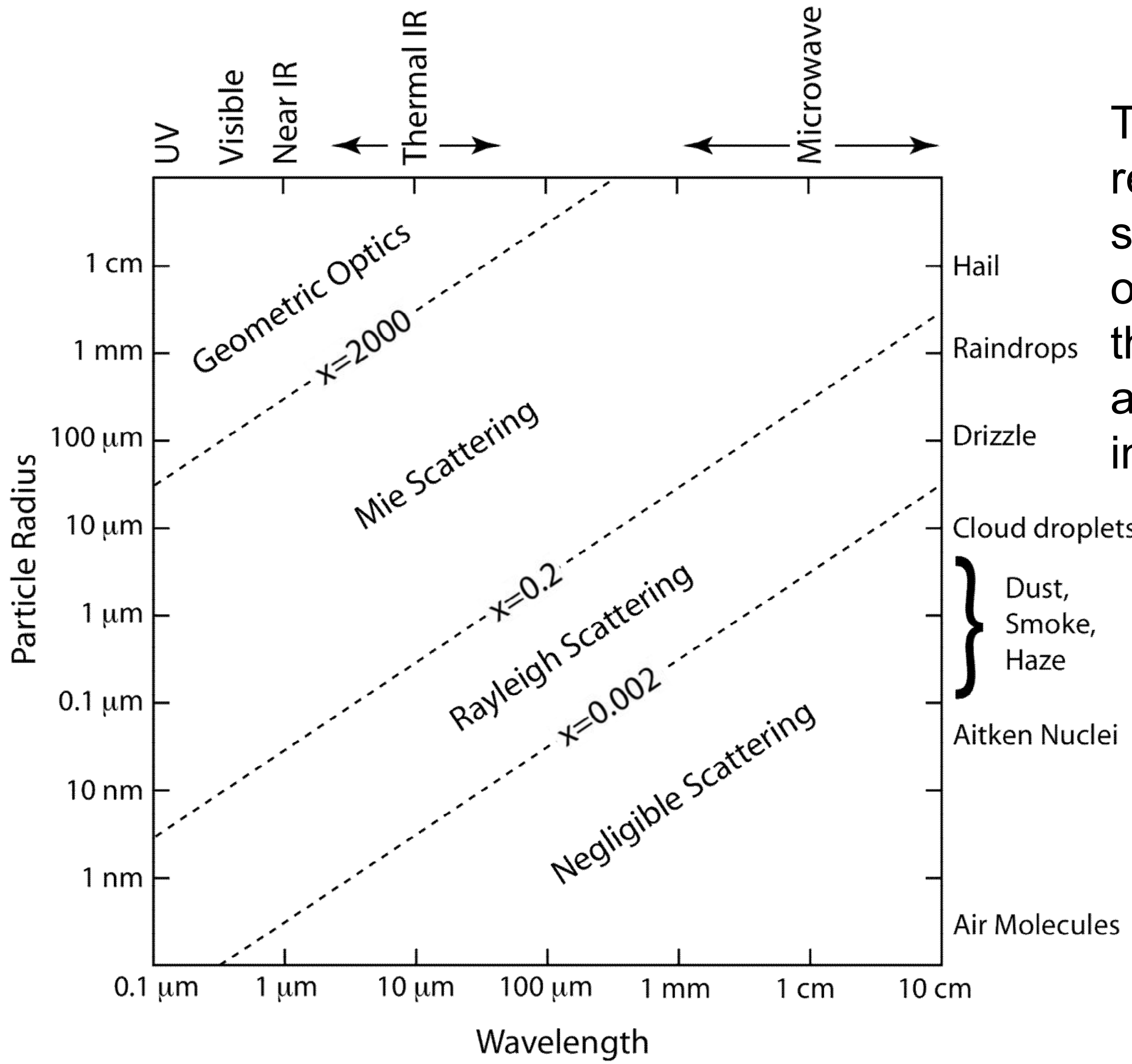
(λ = 589 nm unless indicated)

Substance	$\mathbf{n_r}$	$\mathbf{n_i}$	**($n = n_r + i\, n_i$)**
Water	1.333	0	
Water (ice)	1.309	0	
NaCl (salt)	1.544	0	
H_2SO_4	1.426	0	
$(NH_4)_2SO_4$	1.521	0	
SiO_2	1.55	0	(λ = 550 nm)
Carbon	1.95	-0.79	(λ = 550 nm)
Mineral dust	1.56	-0.006	(λ = 550 nm)

The most significant absorbing component of atmospheric particles is *elemental carbon (soot)*; reflected in the large value of the imaginary part of the refractive index.

Other common atmospheric particles are purely scattering.

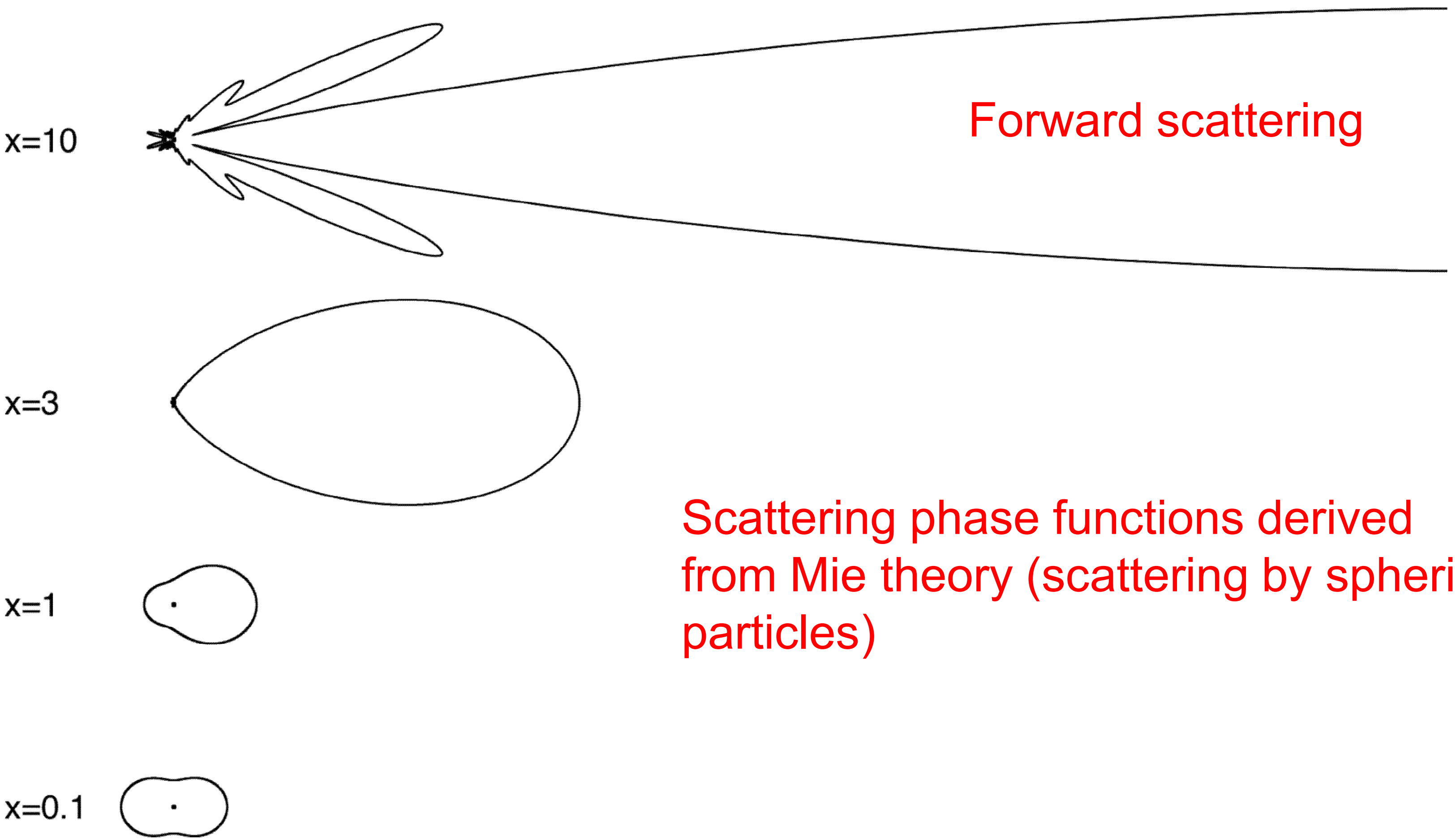
Light scattering regimes



There are many regimes of particle scattering, depending on the particle size, the light wave-length, and the refractive index.

This plot considers only single scattering by spheres. Multiple scattering and scattering by non-spherical objects can get really complex!

Scattering phase functions



Forward scattering

Scattering phase functions derived from Mie theory (scattering by spherical particles)

The scattering phase function, or phase function, gives the angular distribution of light intensity scattered by a particle at a given wavelength

Rayleigh scattering

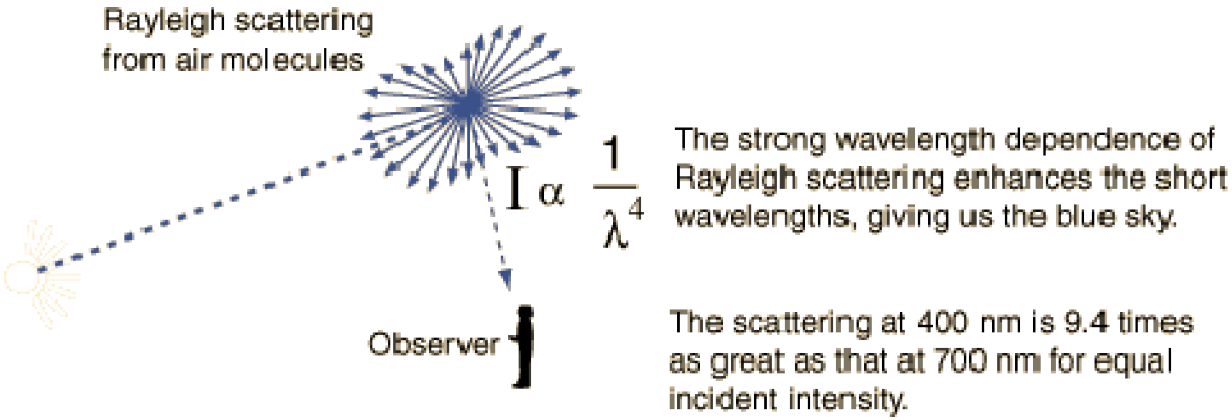
Atmospheric composition: N_2 (78%), O_2 (21%), Ar (1%)

Size of N_2 molecule: 0.31 nm

Size of O_2 molecule: 0.29 nm

Size of Ar molecule: 0.3 nm

Visible wavelengths ~400-700 nm



- Scattering of light off air molecules is called Rayleigh Scattering
- Involves particles much smaller than the wavelength of incident light
- Responsible for the blue color of clear sky

Rayleigh scattering phase function

- **E** is the orientation of the electric field vector in the incident wave

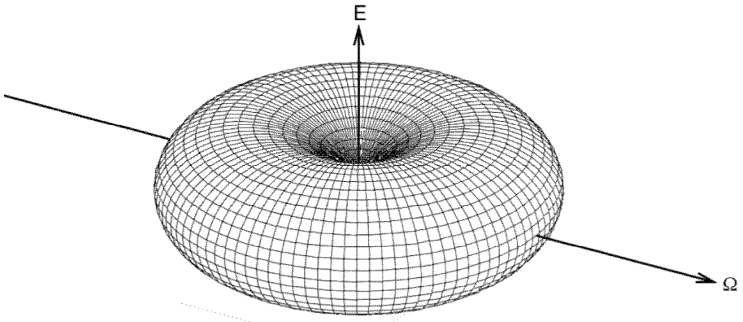
$$I = I_0 \frac{8\pi^4 N\alpha^2}{\lambda^4 R^2}(1 + \cos^2\theta)$$

Scattering at right angles is half the forward intensity for Rayleigh scattering

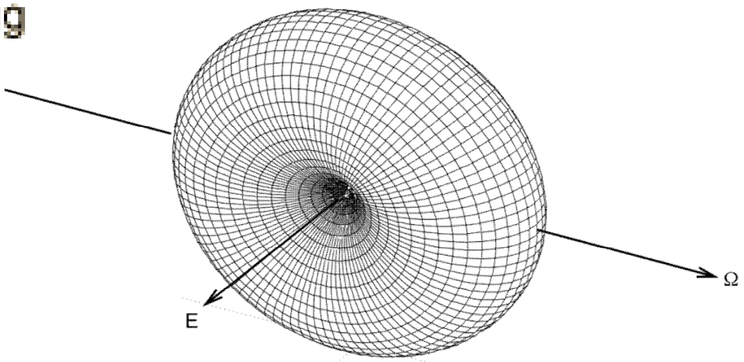
N = # of scatterers

α = polarizability

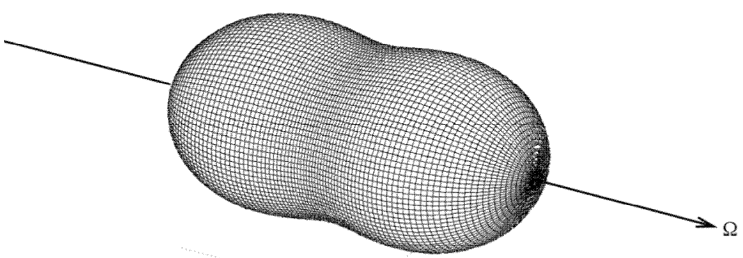
R = distance from scatterer



Vertically polarized



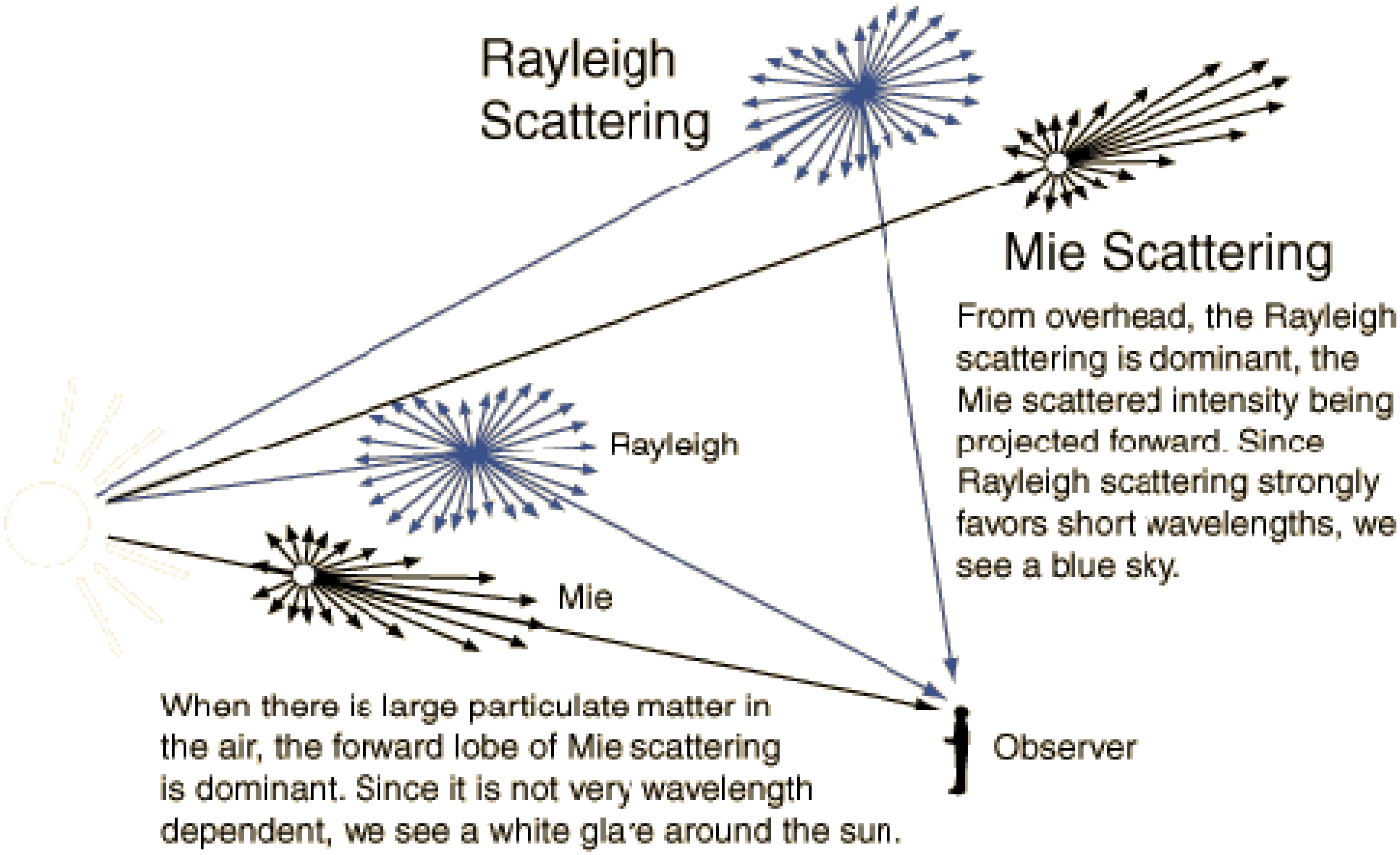
Horizontally polarized



Unpolarized

- Recall that scattered skylight is 100% polarized when viewing the sky at a 90º angle from the sun
- Polarizability: ease with which electrons and nuclei can be displaced from their average positions

Rayleigh and Mie scattering



- Scattering determines the brightness and color of the sky

Variation in sky brightness

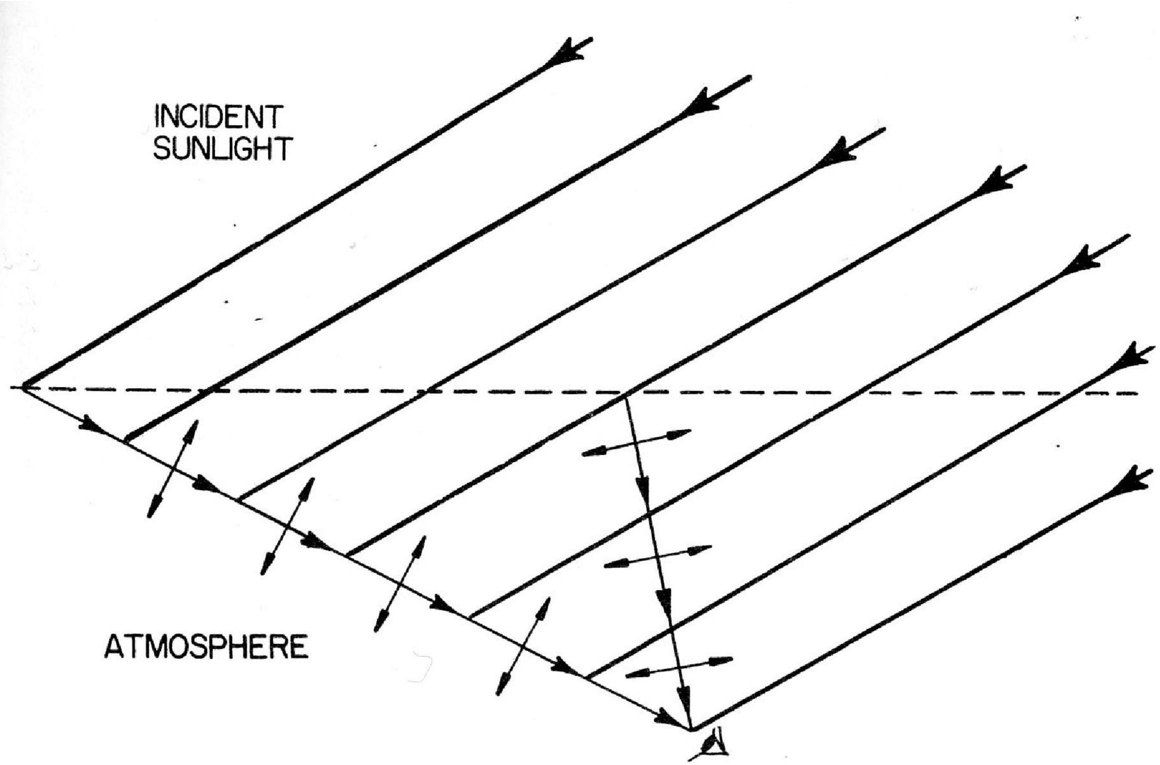


Figure 20.3 Path lengths in the atmosphere. An observer receives light scattered by all the molecules and particles along the line of sight. Paths near the horizon are longer than those near the zenith, hence the horizon sky is brighter. From *The Physics Teacher*, C. F. Bohren and A. B. Fraser, May 1985.

- The horizon sky is usually brighter than the zenith sky
- This is a result of single scattering (zenith) vs. multiple scattering (horizon)

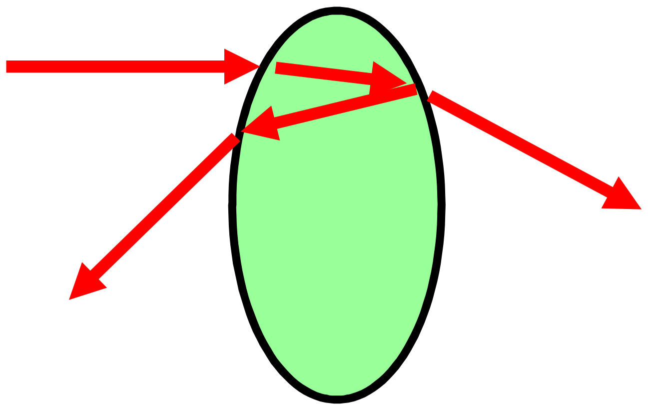
Scattering from particles is much stronger than that from molecules.

They're bigger, so they scatter more.

For large particles, we must first consider the fine-scale scattering from the surface microstructure and then integrate over the larger scale structure.

If the surface isn't smooth, the scattering is incoherent.

If the surfaces are smooth, then we use Snell's Law and angle-of-incidence-equals-angle-of-reflection.



Then we add up all the waves resulting from all the input waves, taking into account their coherence, too (Mie theory)

Scattering by a dipole array

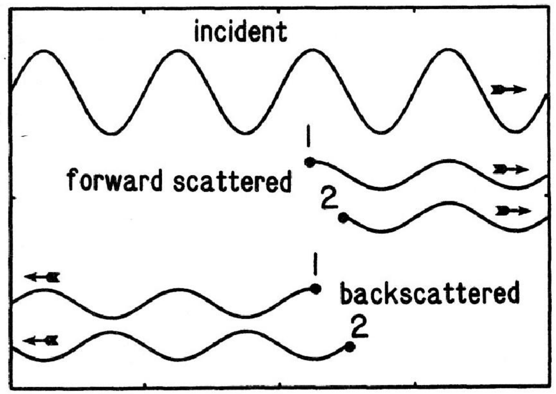


Figure 18.3 Excited by an incident wave, two dipoles scatter waves in all directions. When these two waves are added together, the resultant wave depends not only on the separation of the dipoles, but on the direction of scattering as well. In the forward direction, the two waves are exactly in phase, regardless of the separation of the dipoles. This is not true for any other direction. For the example chosen here (two dipoles one-quarter wavelength apart), the scattered waves are exactly out of phase in the backward direction. Figure courtesy of Roger Johnston.

Bohren 2001, chapter 18

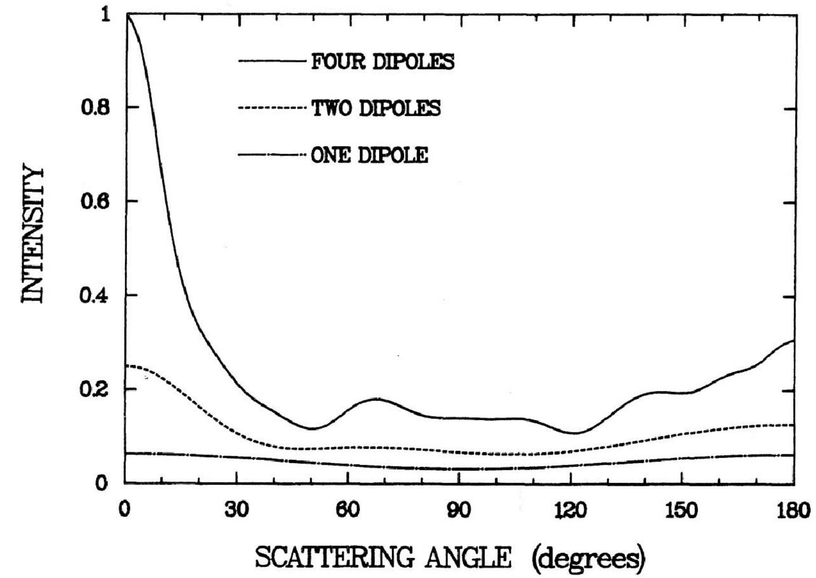


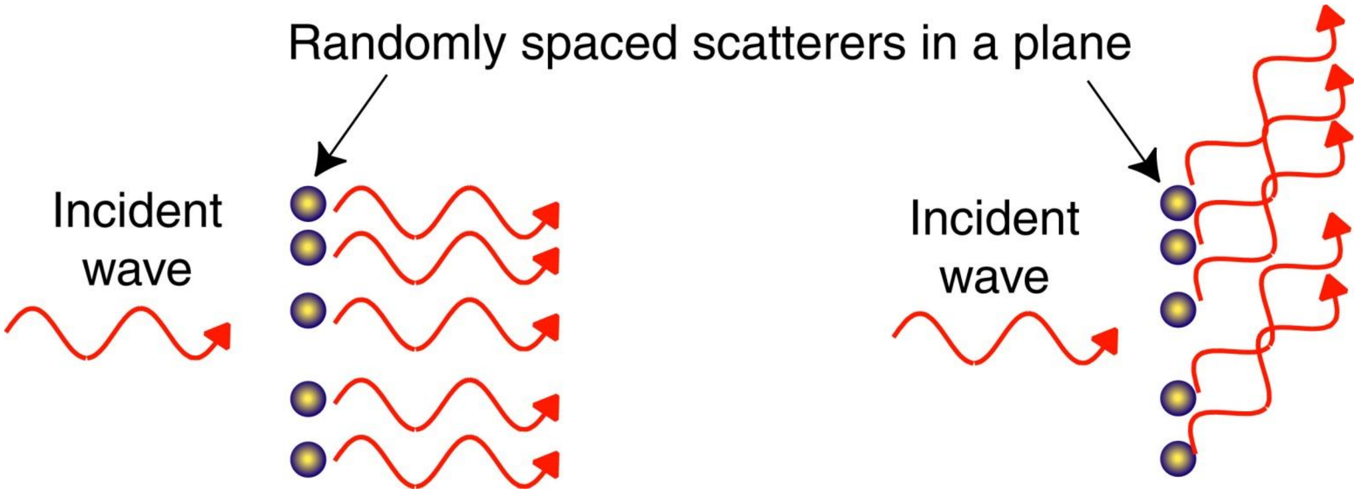
Figure 18.4 The greater the number of dipoles in an array, the more they collectively scatter toward the forward direction. This is evident with only a few dipoles. For the example shown here, all of the dipoles lie on the same line, are separated by one wavelength, and interact with one another. The scattered intensity has been averaged over all orientations of the line of dipoles. Figure courtesy of Shermila Brito Singham.

- Explains forward scattering by particles of similar size or larger than the wavelength of incident light. The larger the particle, the more it scatters in the forward direction relative to the backward direction.
- For particles (or molecules) much smaller than the wavelength, dipole separation is much smaller than wavelength, so phase differences are small, and scattering is roughly the same in all directions.

On-axis vs. off-axis light scattering

Forward (on-axis) light scattering: scattered wavelets have **nonrandom** (equal) relative phases in the forward direction.

Off-axis light scattering: scattered wavelets have **random** relative phases in the direction of interest due to the often random placement of molecular scatterers.



Forward scattering is **coherent** — even if the scatterers are randomly arranged in space.

Off-axis scattering is **incoherent** when the scatterers are randomly arranged in space.

Visibility

VISIBILITY

A formal definition by WMO:

Daytime

Meteorological visibility by day is the greatest distance at which a black object of suitable dimensions located near the ground can be seen and recognized when observed against a scattering background of fog, sky etc.

Nighttime

The greatest distance at which lights in the vicinity of 1000 candelas can be seen and identified against an unlit background.

Visibility

- A general term for light scattered by molecules and particles along a line of sight is airlight
- Airlight initially increases linearly with optical thickness (more scattering), but the increase slows down as *multiple scattering* comes into play
- A threshold contrast of 2% (0.02) corresponds to an optical thickness of ~3.9. This will be lower for a reflective object.
- Mie scattering by aerosol particles comparable in size to visible wavelengths (0.1-1 μm) is responsible for most visibility reduction, and dominates in urban areas
- Scattering by air molecules usually has a minor influence on urban visibility
- Particle absorption is ~5-10% of extinction in remote areas and up to 50% in urban areas (*carbon*)
- **Nitrogen dioxide (NO_2)** is the only light absorbing gas present in significant quantities in the troposphere
- NO_2 is strongly blue-absorbing, and hence colors plumes red, brown or yellow

- Beer's law
  - Describes the attenuation of light

$$B = B_0 \exp\left[-\sigma x\right]$$

- Atmospheric extinction due to hydrometeors (rain, snow, fog) and other particulates (dust, smoke)

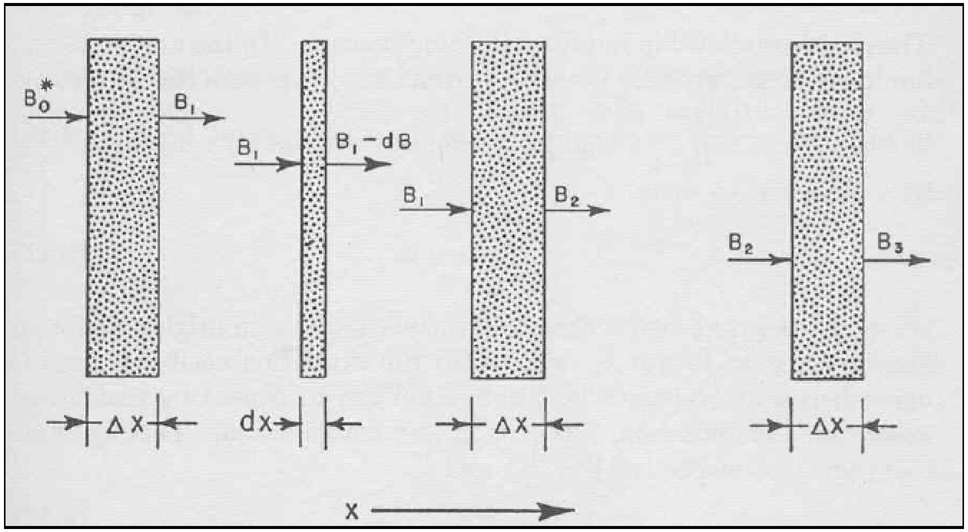
Brightness

The brightness is defined as the intensity of radiant energy per unit area normal to the line of sight. The eye can determine the difference in brightness of two objects down to a point called the threshold of brightness contrast, denoted by '$\in$' and defined as

$$\in = \left| \frac{(B_B - B_O)}{B_B} \right|$$

B_B is the brightness of the background and B_o the brightness of the object under consideration.

The attenuation of radiant energy



•The lowest visually perceptible brightness contrast is called the *threshold contrast*, and is typically about 2% (C(x) = 0.02). Hence, at the threshold contrast: **Vm = 3.912/σ**

Koschmieder equation:
relates visual range (visibility), **Vm**, and extinction coefficient , σ, as
Vm = 3.912/σ

- Daytime visibility factors
  - Observer’s eyesight
  - Amount of scatterers in atmosphere
  - Brightness of object and background
  - Reflective properties of object and background
  - Elevation of the sun
  - Angular separation between the sun and the object
  - Size of the object

- **Nighttime visibility challenges**
  - Scattering of light out of observing path originating from the target
  - Color perception is reduced
- Nighttime visual range is longer than daytime range

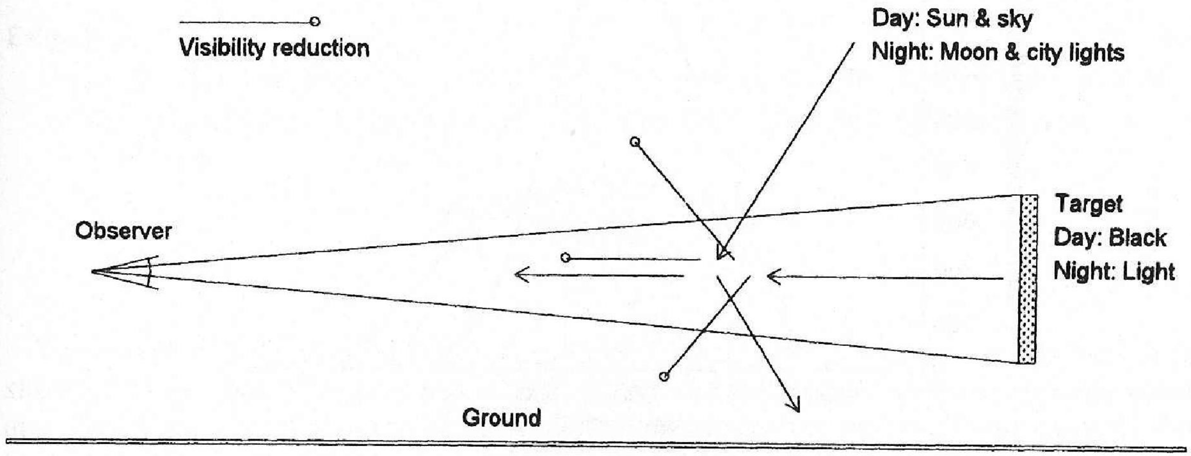


Fig. 11-1 Visibility reduction by scattering.

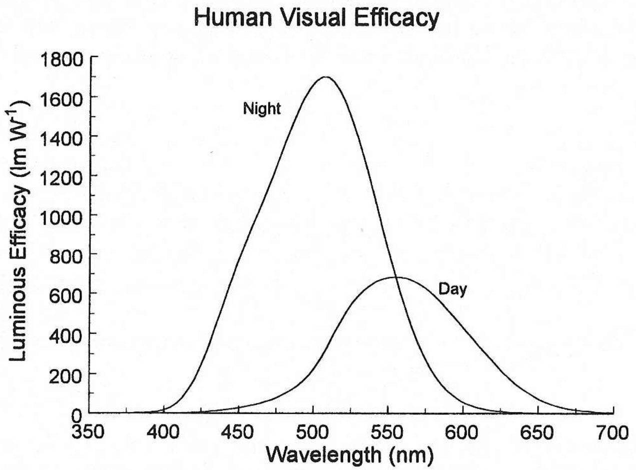


Fig. 11-2 Human visual efficacy by day and by night.

MEASUREMENT

Most visibility sensors actually measure the meteorological optical range. This is the length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp at a color temperature to 5% of its original value.

- Transmissometer
  - A light source with one or two light detectors at fixed distances from the source
  - Detectors are designed to receive light only from the source direction
  - Often located along and parallel to a runway (runway visual range; RVR)
  - Sensitivity of instrument is poor for very short and very long visual ranges
  - Shows the necessity for two receivers and for a long secondary path length

Measurement of visibility

- **Forward Scatter Meters**
  - Detect the amount of light scattered in the forward direction
  - Amount scattered is a function of the ratio of the particle diameter to the wavelength of the light in the beam
  - Light wavelength is constant
  - Particle size (smoke or fog) is *not* constant
  - Xenon flash bulb is source
  - 0.4 to 16 km visibility range
  - Inaccuracy increases with larger visibility ranges
  - Must be calibrated against a transmissometer