Atmospheric Pollution

Lecture 14

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Effects of Pollution on Visibility, Ultraviolet Radiation, and Atmospheric Optics

PROCESSES AFFECTING SOLAR RADIATION IN THE ATMOSPHERE

The solar spectrum is divided into

UV	(0.01 to 0.38 μm),	
visible	(0.38 to 0.75 μm)	
near-infrared (IR)	(0.75 to 4.0 μm)	wavelength ranges

Sir Isaac Newton (1642-1727)

For simplicity, the visible spectrum here is divided into wavelengths of the primary colors:

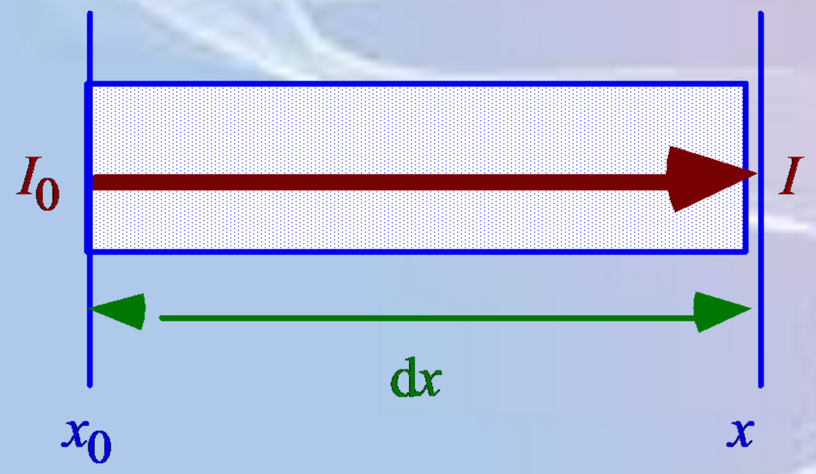
Blue (0.38 to 0.5 m) , Green (0.5 to 0.6 m) , Red (0.6 to 0.75 m)

Table 7.1. Wavelengths of Absorption in the Visible and UV Spectra by Some Atmospheric Gases

Gas Name	Chemical Formula	Absorption Wavelengths (μm)
Visible/Near-UV/Far-UV absorbers		
Ozone	$O_3(g)$	<0.35,0.45–0.75
Nitrate radical	$NO_3(g)$	<0.67
Nitrogen dioxide	$NO_2(g)$	<0.71
Near-UV/Far-UV absorbers		
Formaldehyde	HCHO(g)	<0.36
Nitric acid	$HNO_3(g)$	<0.33
Far-UV absorbers		
Molecular oxygen	$O_2(g)$	<0.245
Carbon dioxide	$CO_2(g)$	<0.21
Water	$H_2O(g)$	<0.21
Molecular nitrogen	$N_2(g)$	<0.1

Attenuation of Light Passing Through Gas

The determination of visibility depends on all processes that attenuate or enhance radiation. In this subsection, attenuation by *gas absorption* is briefly discussed.



The product of the number concentration and absorption cross section of a gas is called an absorption extinction coefficient.

An extinction coefficient measures the loss of electromagnetic radiation due to a specific process per unit distance.

Extinction coefficients, symbolized σ with , have units of inverse distance

$$(\mathrm{cm}^{-1}, \mathrm{m}^{-1}, \text{or } \mathrm{km}^{-1})$$

and vary with wavelength

The absorption extinction coefficient (cm^{-1}) of *gas q is*

$$\sigma_{a,g,q} = N_q b_{a,g,q}$$

The *gas* absorption extinction coefficient due to the sum of all *gases* $\sigma(a,g)$ this equation over all absorbing *gases*.

The greater the absorption extinction coefficient of a *gas* in the visible spectrum, the more the *gas* reduces visibility.

Extinction Coefficient of Nitrogen Dioxide and Ozone

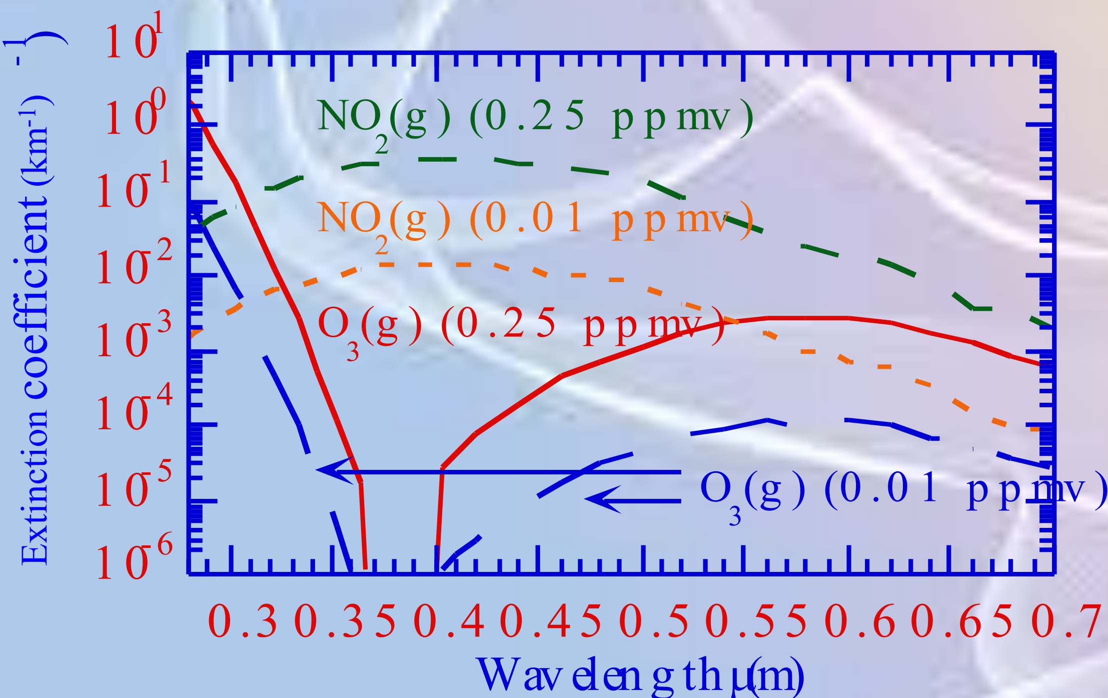


Figure shows absorption extinction coefficients of both $NO_2(g)$ and $O_3(g)$, at two mixing ratios.

The figure indicates that nitrogen dioxide affects extinction (and therefore visibility)

The reduction in radiation intensity (where I denotes intensity) at a given wave-length with distance through an absorbing gas can now be defined as:

Attentuation of light intensity

$$I=I_0e^{-\sigma_{a,g,q}(x-x_0)}=I_0e^{-N_q b_{a,g,q}(x-x_0)}$$

σ = gas absorption cross section

N_q = gas concentration

EXAMPLE

Find the fraction of incident radiation intensity (the transmission) passing through a uniform gas column of length 1 km when the number concentration of the gas is Nq = 10^{12} molecules cm^2 and the absorption cross section of a gas molecule is $b_{a,g,q}=10^{-19}$ cm^2 per molecule.

the extinction coefficient through the gas is

$$\sigma_{a,g,q} = N_q b_{a,g,q} \quad = 10^{-7}\ \text{cm}^{-1}.$$

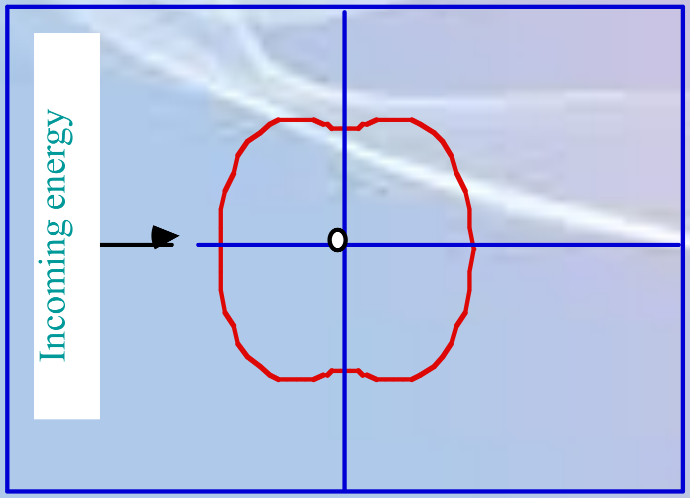
$$I = I_0 e^{-\sigma_{a,g,q}(x-x_0)} = I_0 e^{-N_q b_{a,g,q}(x-x_0)}$$

the transmission is $I/I_0 = e^{-10^{-7} \times 10^{5}} = 0.99$.

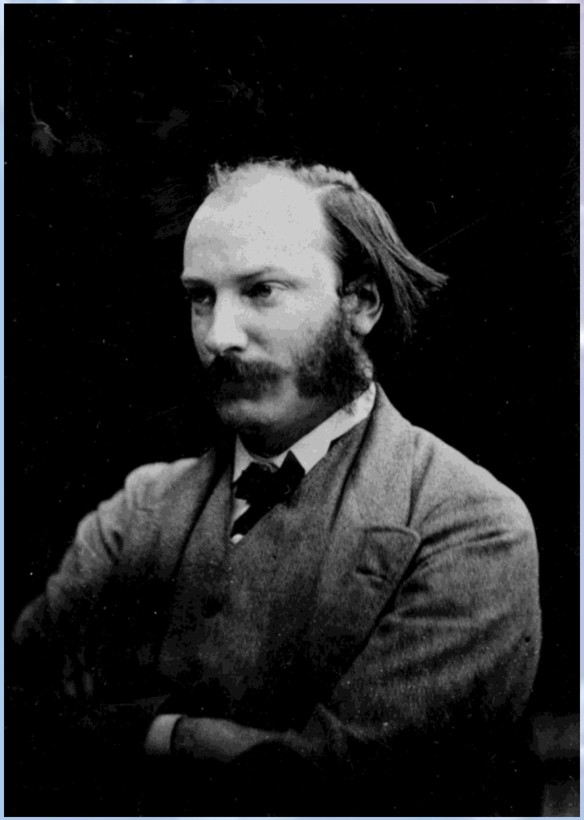
Thus 99 percent of incident radiation trav- eling through this column reaches the other side.

Gas Scattering

Probability Distribution For Gas Scattering



Lord Baron Rayleigh (John William Strutt) (1842-1919)



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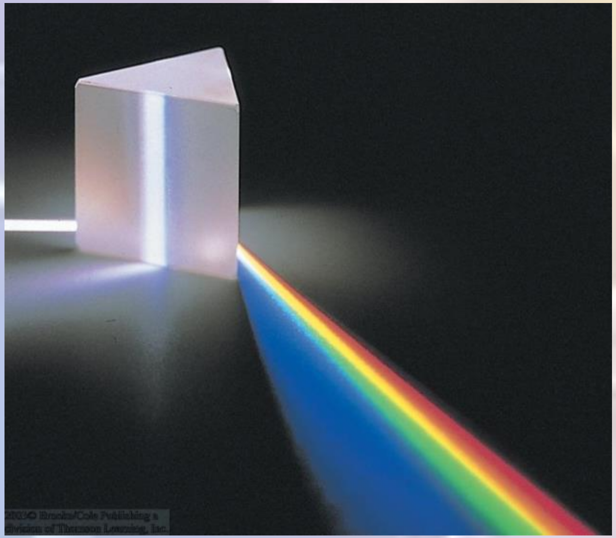
Color

- The human eye is sensitive to the visible part of the electromagnetic spectrum (λ=0.4-0.7 μm):
  - Intensity - light or dark;
  - Wavelength – color.
  - We see the objects because they emit and/or interact with light (reflection, transmission, absorption, refraction, scattering, diffraction)



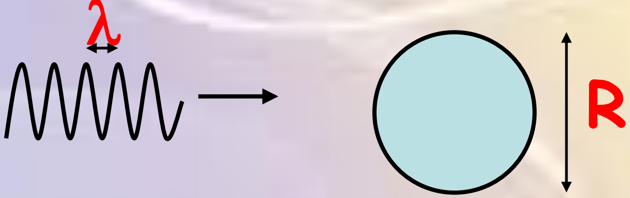
- Perception of color:
  - Each color corresponds to a particular wavelength.
  - White: all wavelengths are present with equal intensity;
  - Black: no light is emitted and/or reflected from the object.

- Color of emitted light and temperature:
  - The sun appears white.
  - Colder stars look redder (λ_{max} is longer than λ_{max} of the sun).
  - Hotter stars look bluer (λ_{max} is shorter than λ_{max} of the sun).

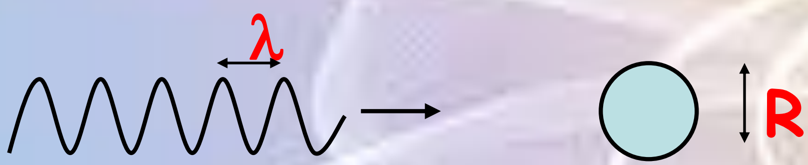
Scattering of light

- The scattering of light in the atmosphere depends on the size of the scattering particles, **R**, and on the wavelength, **λ**, of the scattered light.

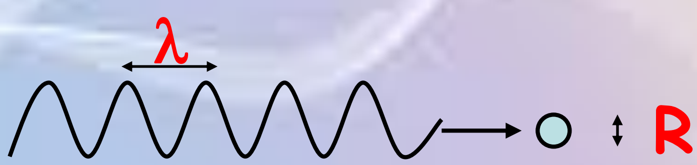
- Geometric scattering: R>>λ
  - Rain drops (R~10-100 μm)
  - All wavelengths equally scattered
  - Optical effects: white clouds



- Mie scattering: R~λ
  - Aerosols (R~0.01-1 μm)
  - Red scattered better than blue
  - Blue moon, blue sun



- Rayleigh scattering: R<<λ
  - Air molecules (R~0.0001-0.001 mm)
  - Blues scattered better than red
  - Blue sky, blue mountains, red sunsets



• TABLE 19.1

The Various Types of Scattering of Visible Light			
TYPE OF PARTICLE	PARTICLE DIAMETER (MICROMETERS, μm)	TYPE OF SCATTERING	PHENOMENA
Air molecules	0.0001 to 0.001	Rayleigh	Blue sky, red sunsets
Aerosols (pollutants)	0.01 to 1.0	Mie	Brownish smog
Cloud droplets	10 to 100	Geometric	White clouds

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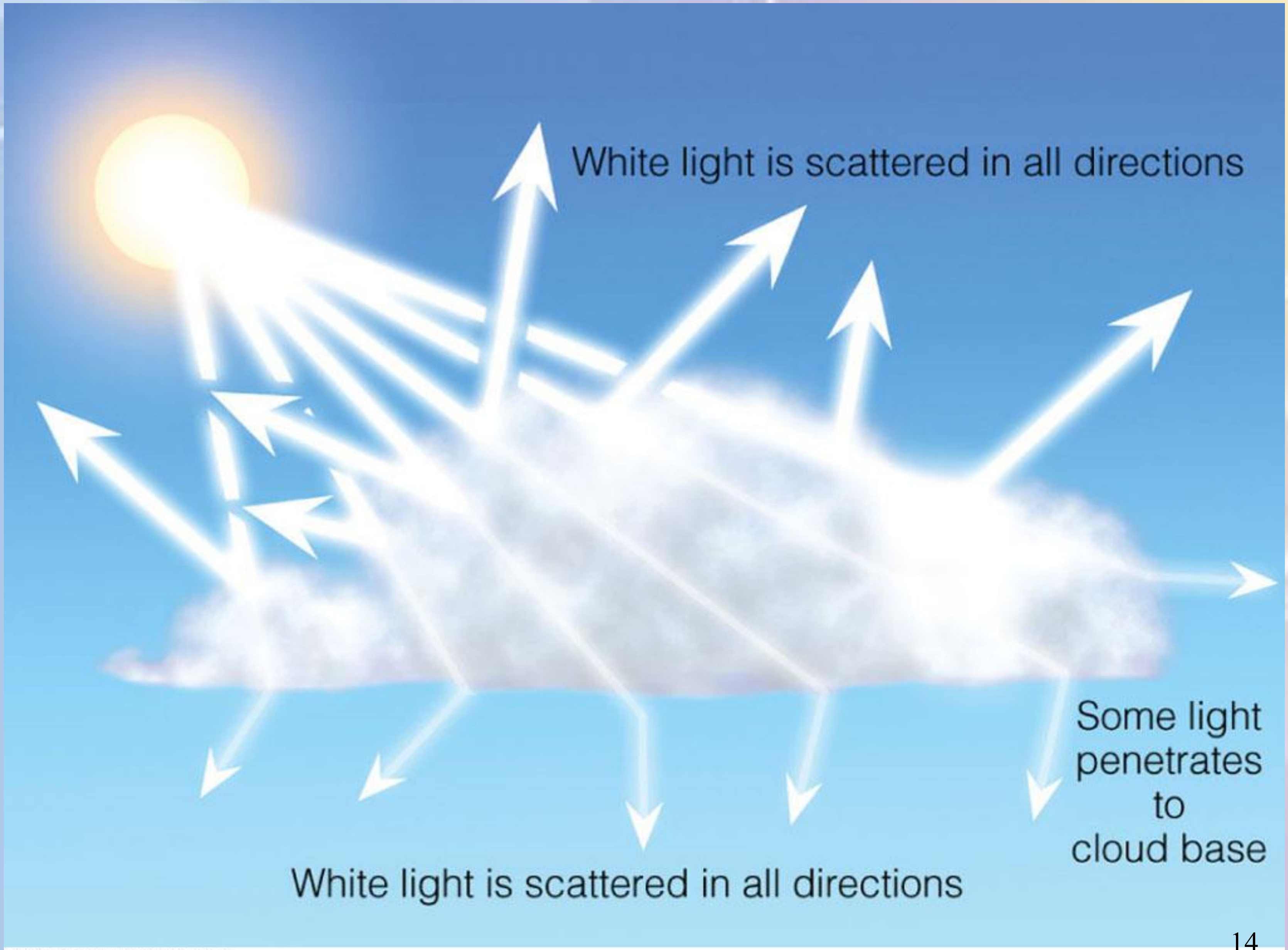

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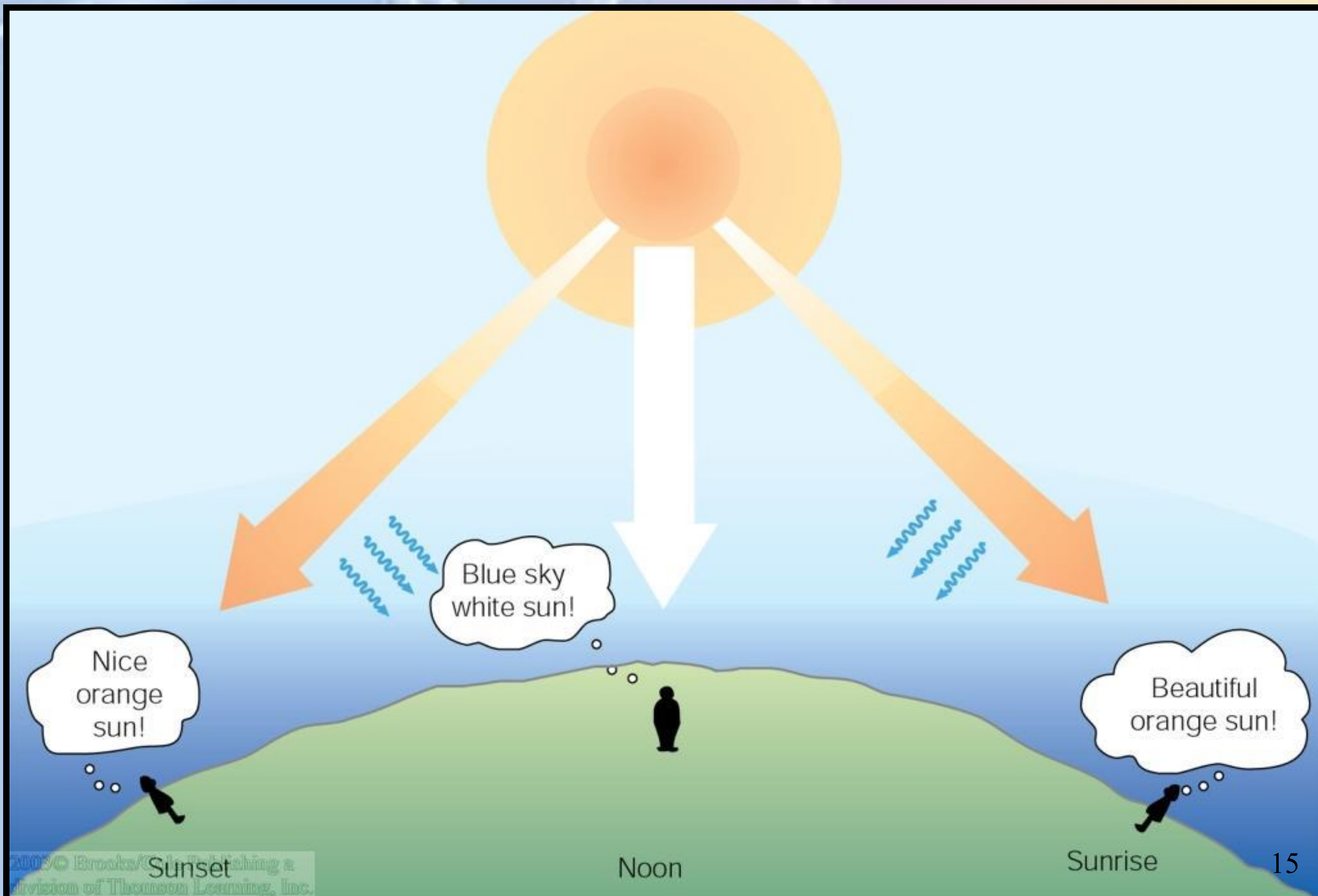
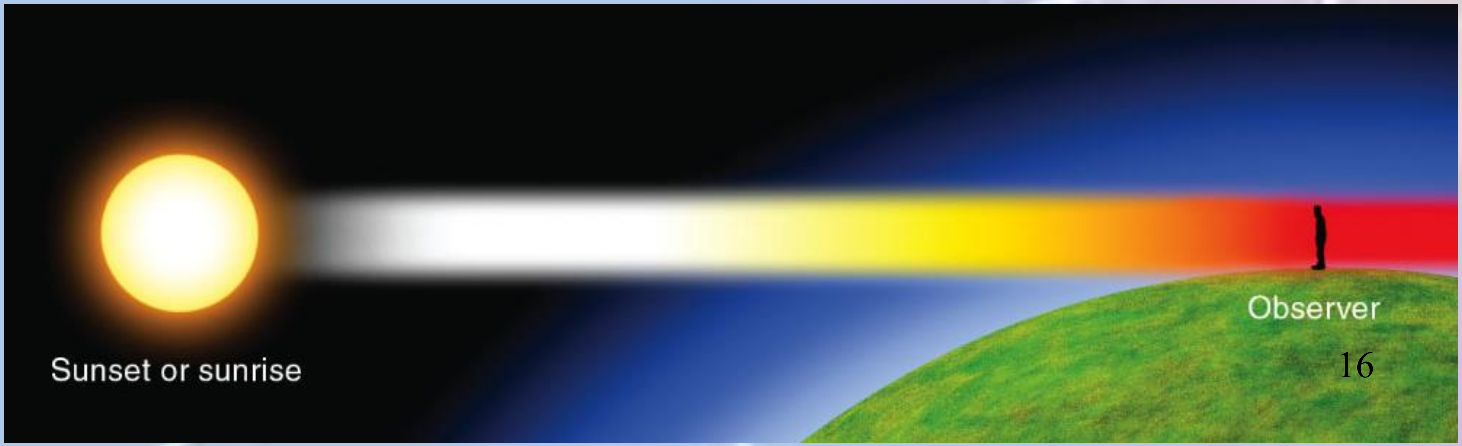
The Color of the Sun



The Color of The Sun

- Description: at sunrise and sunset the sun is yellow, orange or red
- Physical process: Rayleigh scattering by air molecules and fine dust particles.
- Explanation: on clear days only the blue light is scattered away, on hazy days the yellow and the orange wavelengths are also scattered and only the red remains in the direct solar light.
- Conclusion: Red sunsets suggest that there is dust in the air (pollution, haze over the ocean, volcanic activity, dust storms).

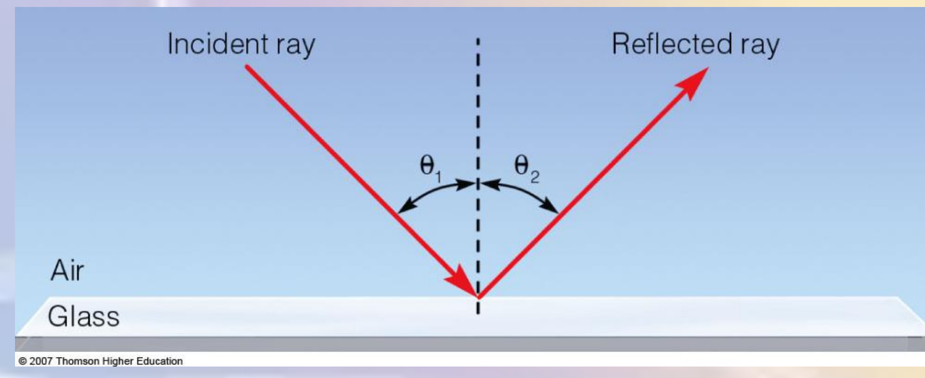


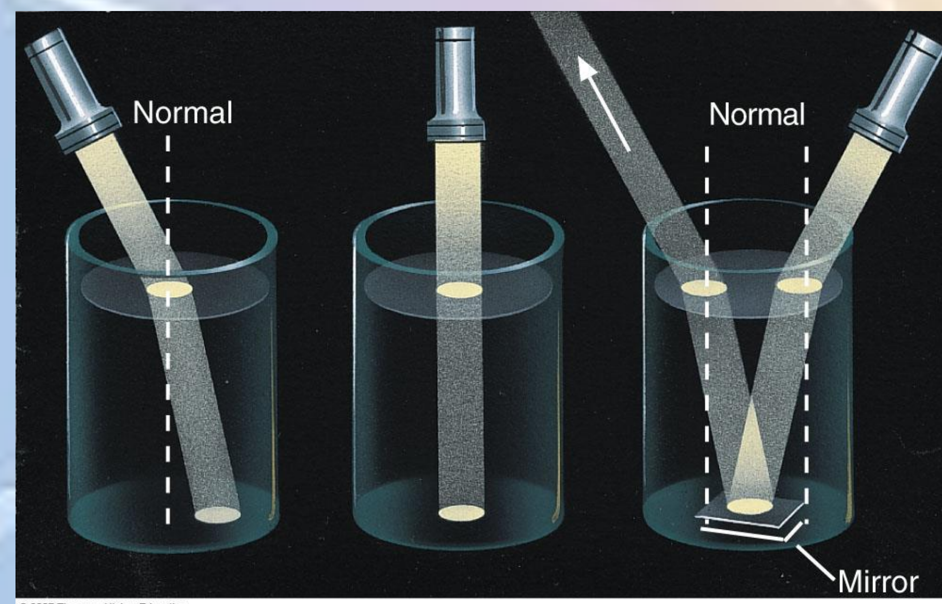
Blue Moon

- Description: the moon appears blue.
- Physical process: Mie scattering by dust particles.
- Explanation: When the size of the dust particles is approximately equal to the visible wavelengths the red light is scattered better than the blue light.
- Conclusion: one can guess what is the size of the particles in the air.

Reflection and Refraction of Light

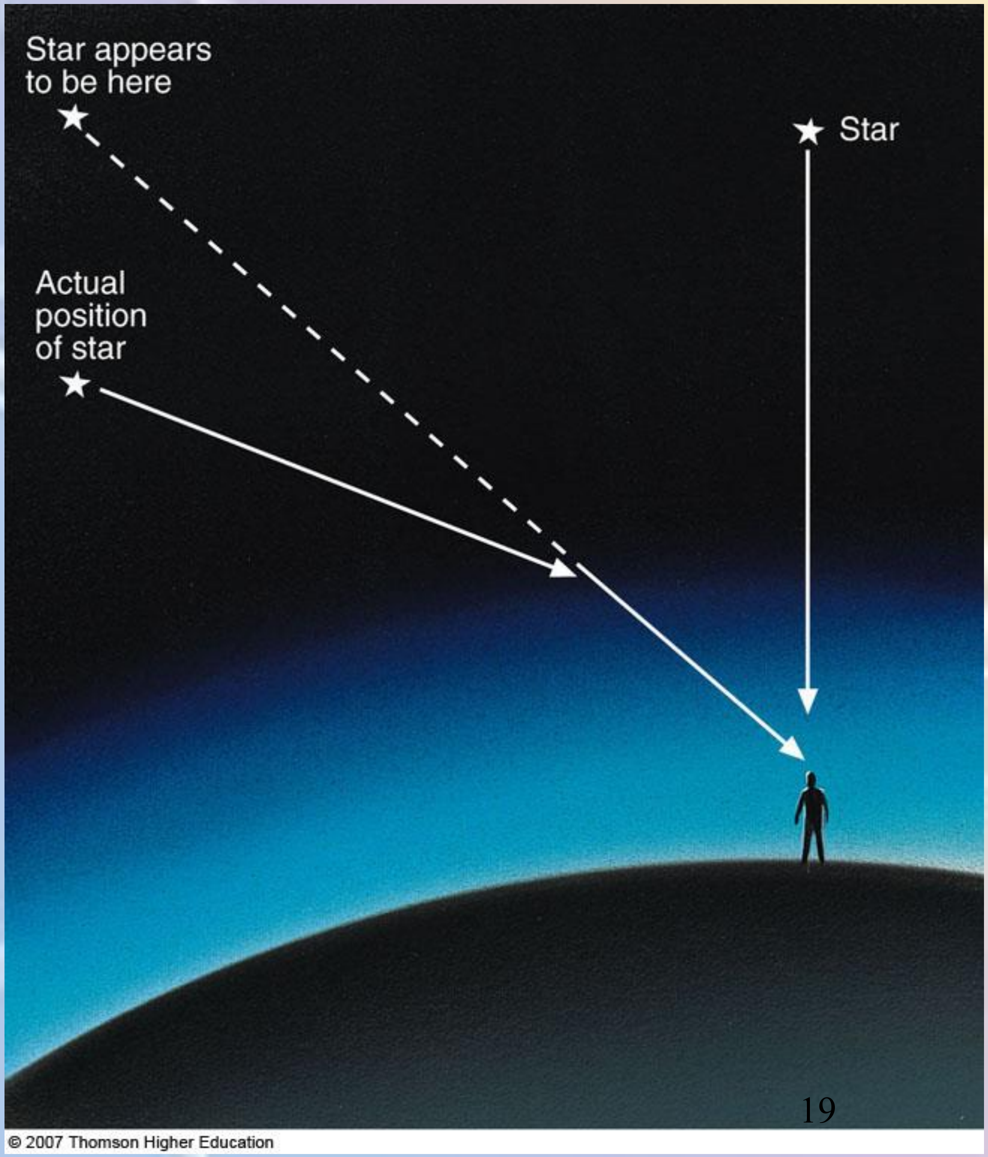
- The speed of light in vacuum is c=300,000 km/s
- Snell's law: The angle of incidence is equal to the angle of reflection.
- Light that enters a more-dense medium slows down and bends toward the normal.
- Light that exits a more-dense medium speeds up and bends away from the normal.



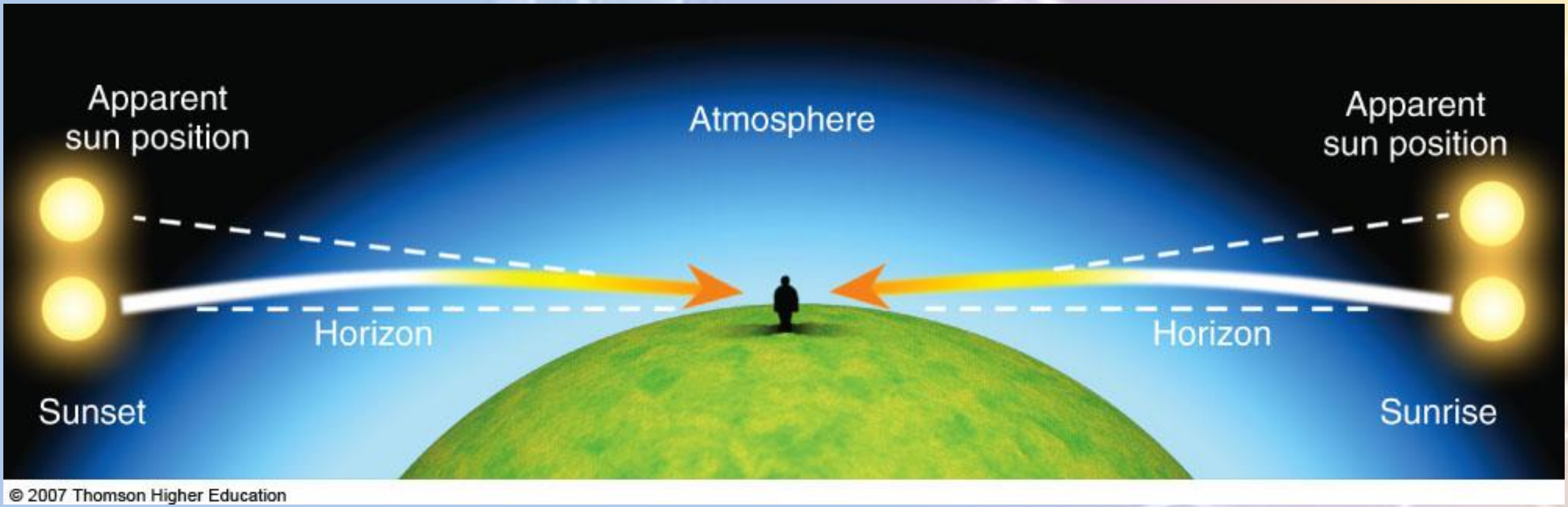


True and apparent position of objects

- Due to the refraction of light the objects on the sky appear higher than they actually are.
  - Star location and scintillations;
  - Timing of the sunset and the sunrise;
  - The sun on the horizon looks flattened;
  - Twilight.



The Timing of the Sunset & Sunrise



We see the sun before it actually rises above the horizon and after it sets below the horizon.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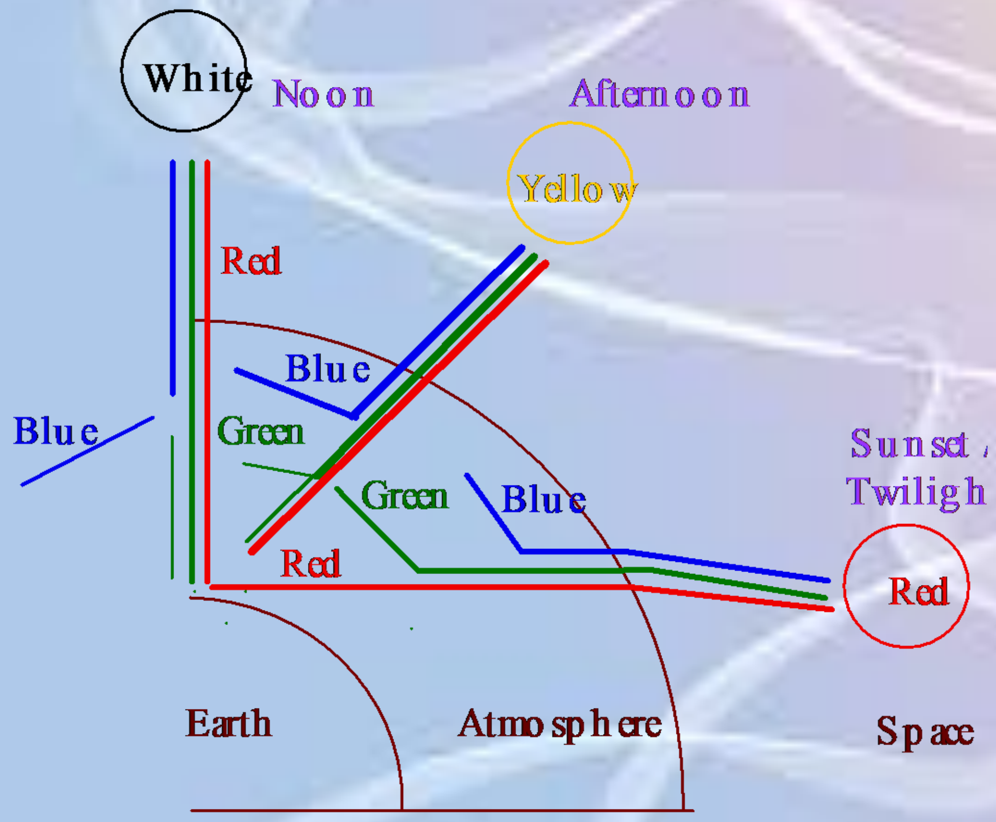
Color of the Sun During the Day



Yellow Sun Over the South Pacific

Mark Z. Jacobson

Red Horizon Over Clouds During Sunset

Mark Z. Jacobson

Attenuation of Light Passing Through Single Particle

Attentuation of light intensity

- $I = I_0 e^{-4\pi\kappa(x-x_0)/\lambda}$ (7.4)

κ = imaginary refractive index

λ = wavelength

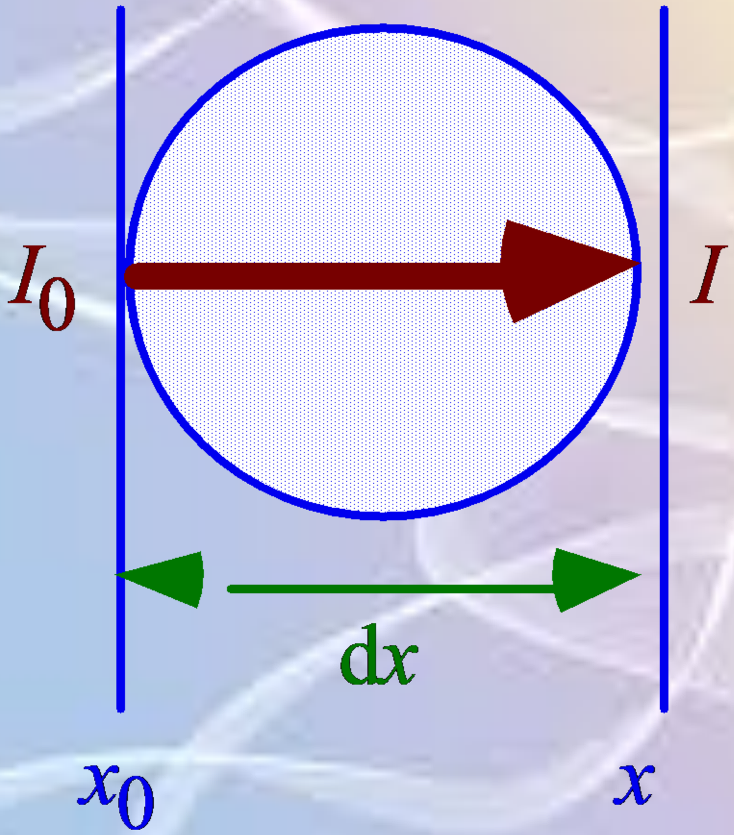


Figure 7.9

Refractive Indices of Some Substances

	0.5 µm		10 µm	
	Real (n)	Imaginary (κ)	Real (n)	Imaginary (κ)
H_2O (aq)	1.34	1.0×		
Black Carbon (s)	1.82	0.74	2.40	1.0
Organic Matter (s)	1.45	0.001	1.77	0.12
H_2SO_4 (aq)	1.43	1.0×		

Table 7.2

Transmission of Light Through Black Carbon and Water

	Transmission (I/I_0)	
Particle Diameter (µm)	Black carbon (κ=0.74)	Water ($\kappa=10^{-9}$)
0.1	0.16	0.999999997
1.0	8.0×10^{-9}	0.99999997
10.0	0	0.9999997

Imaginary Refractive Indices of Some Liquid Organics

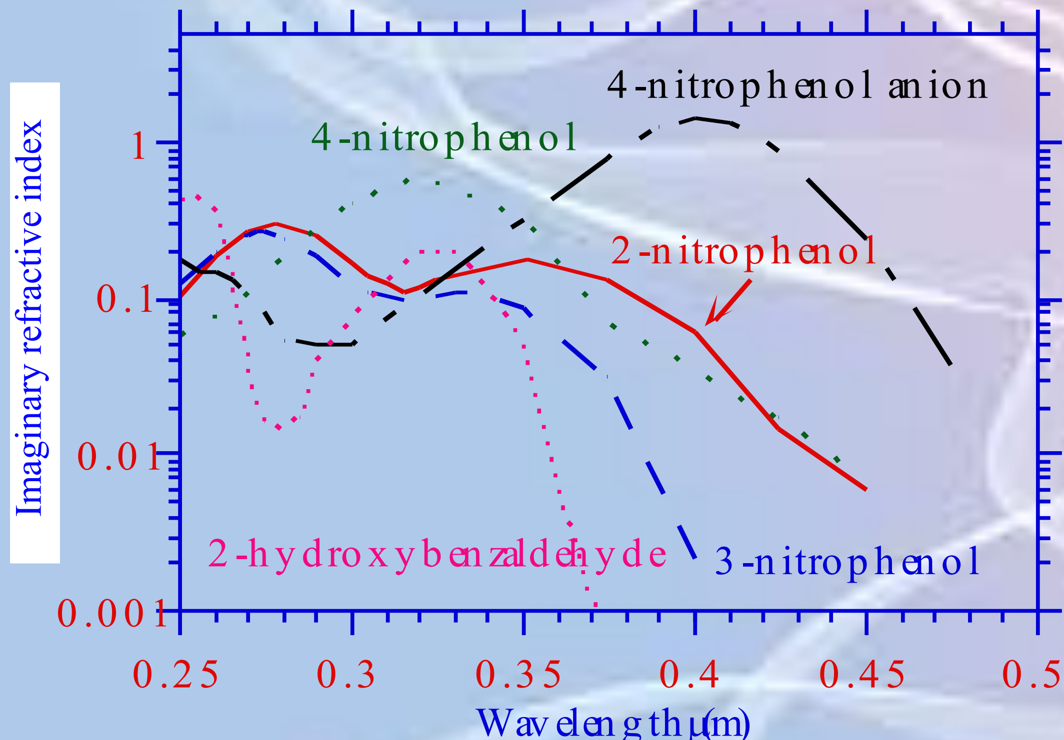


Figure 7.10

Effects of Pollution on UV Radiation

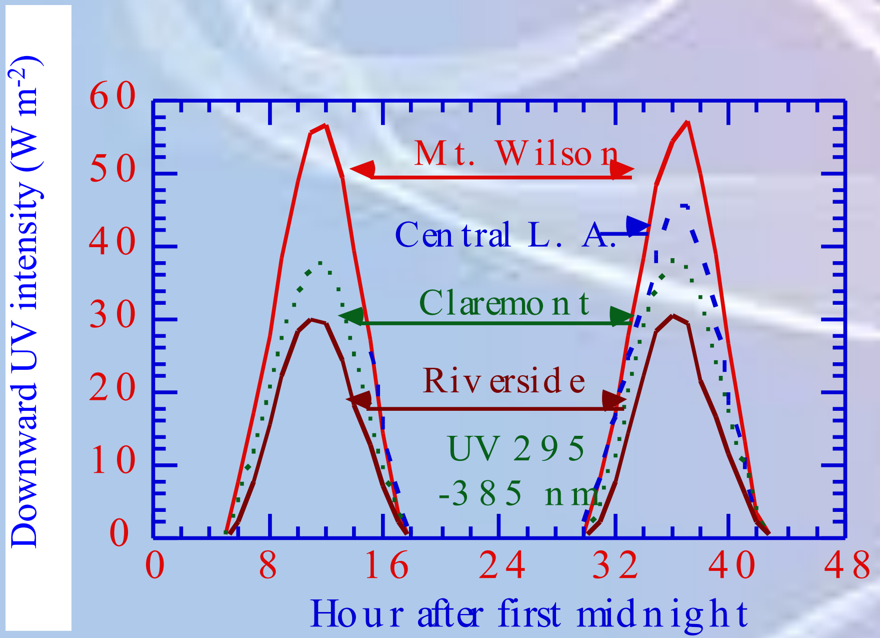


Figure 7.11

Reflection and Refraction

Snell's Law

- $n_2/n_1 = \sin\theta_1/\sin\theta_2$ (7.5)

Real part of refractive index

- $n_1 = c/c_1$ (7.6)

c = speed of light in vacuum

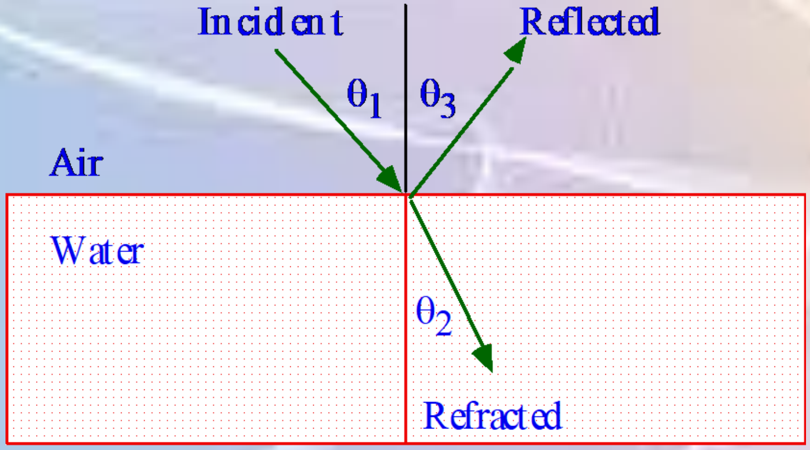


Figure 7.12

Refraction of Starlight

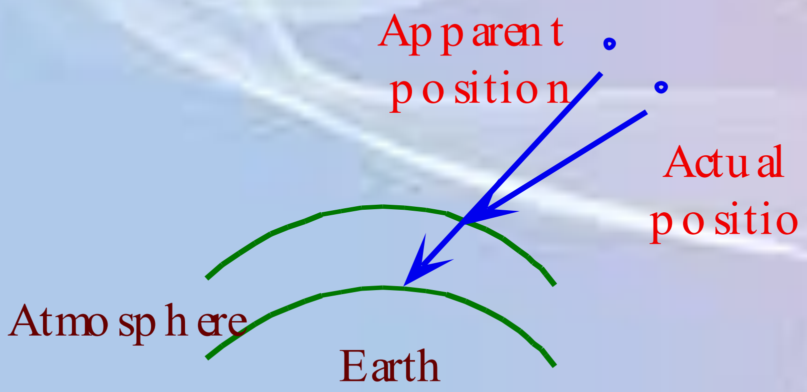


Figure 7.13

Diffraction of Light Around A Particle

Huygens' principle

Each point of an advancing wavefront may be considered the source of a new series of secondary waves

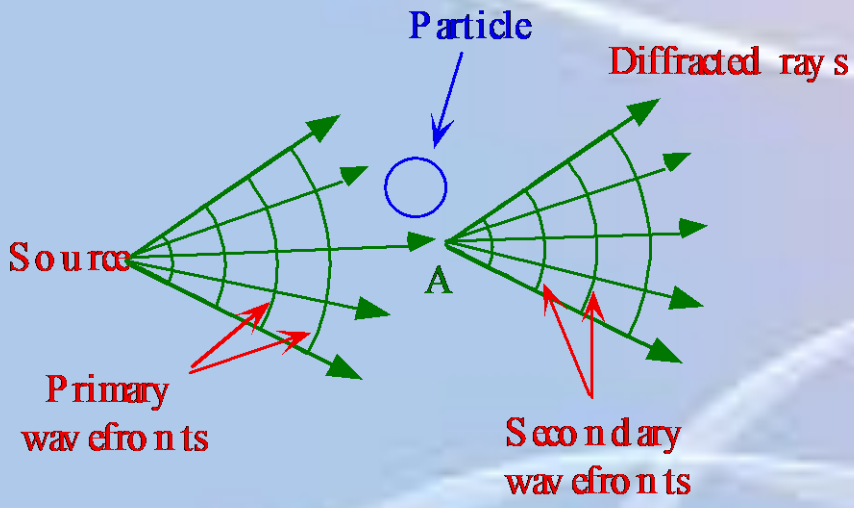


Figure 7.14

Radiation Scattering by a Sphere

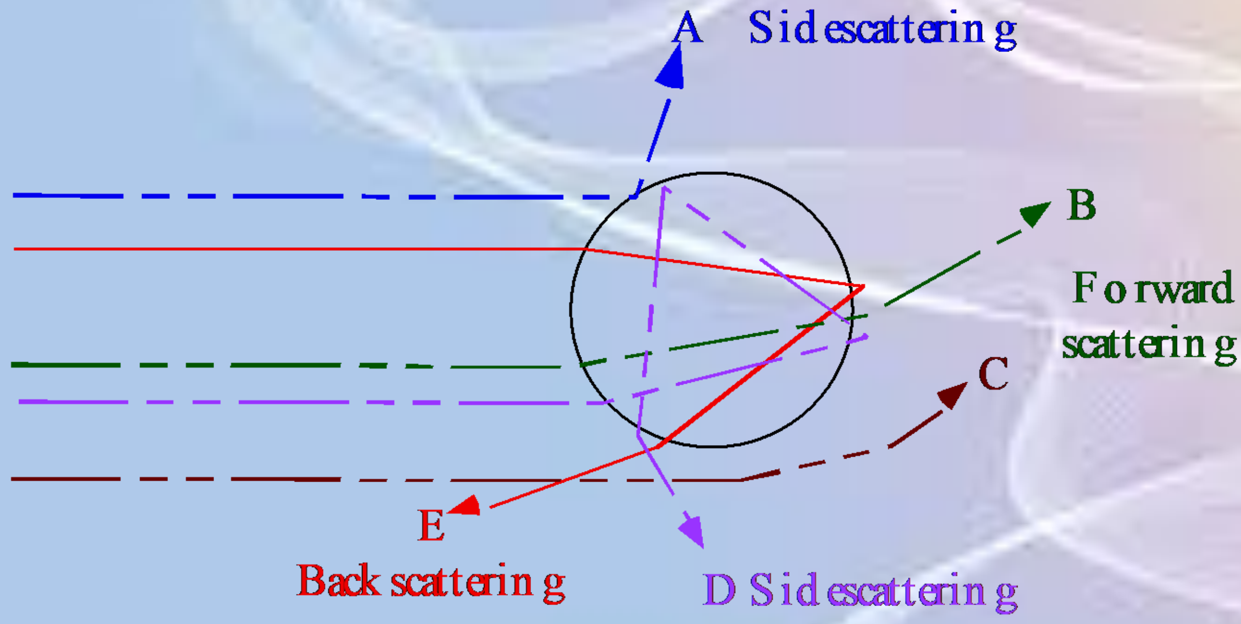


Figure 7.15

Forward Scattering of Sunlight

Mark Z. Jacobson

Figure 7.16

Primary Rainbow

Figure 7.17

Geometry of a Primary Rainbow

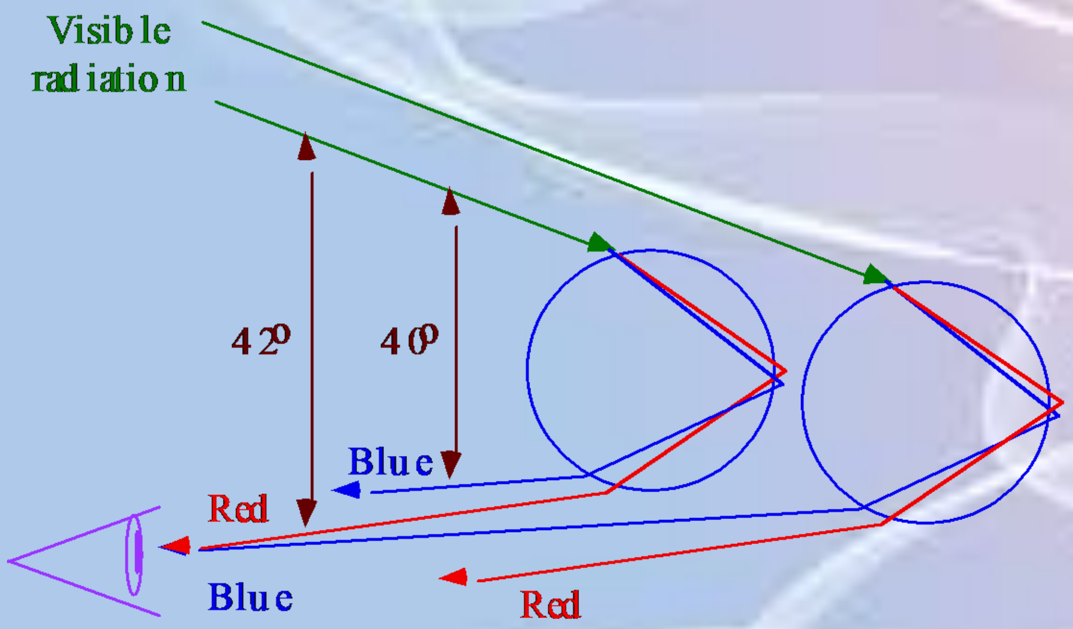
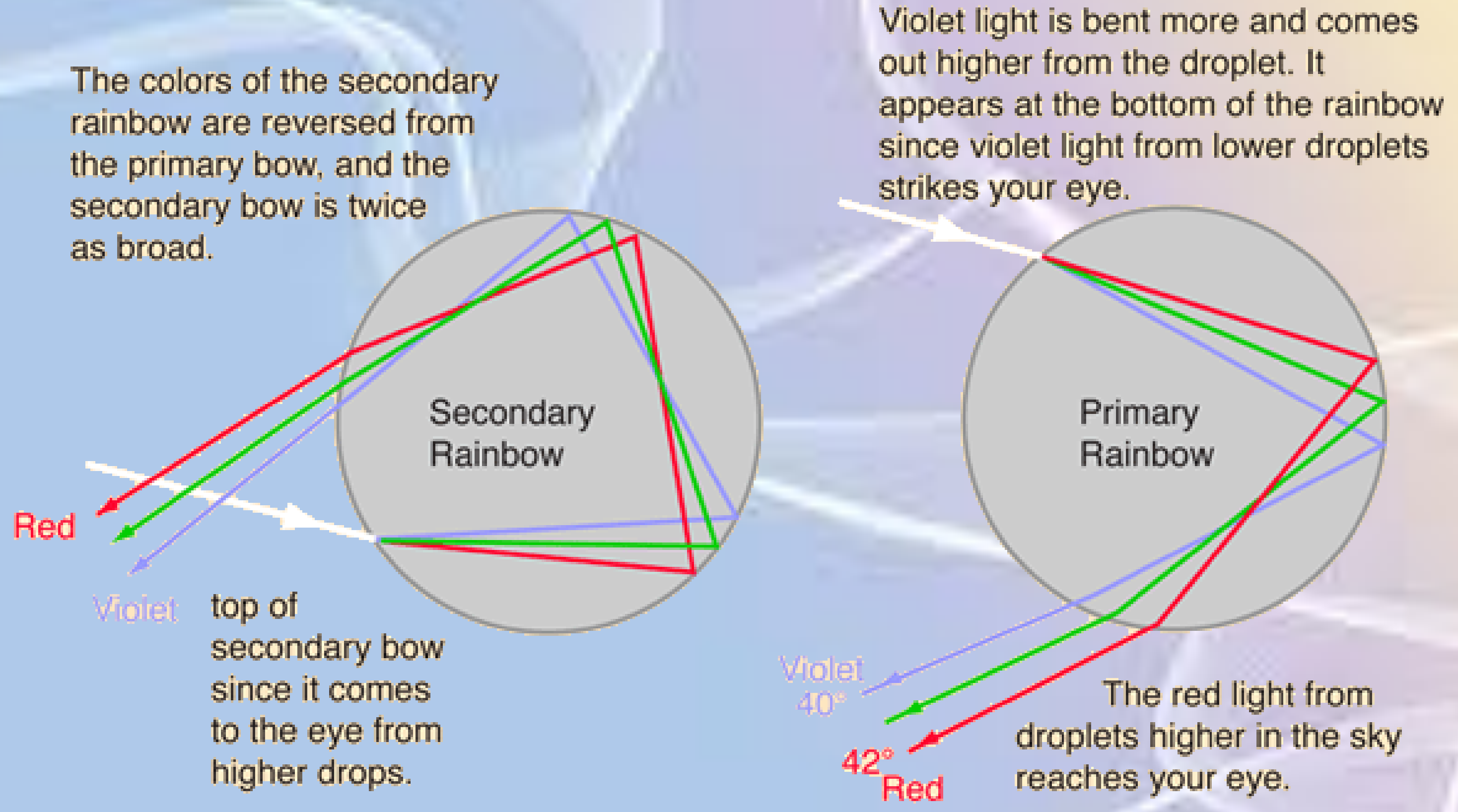
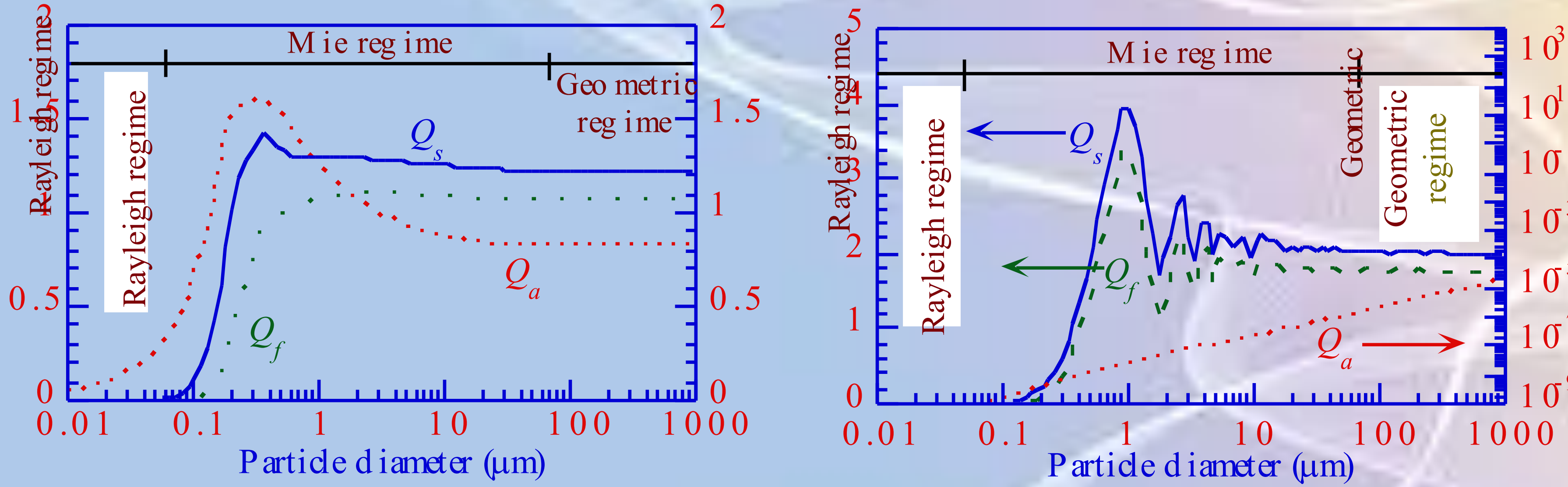


Figure 7.18



The colors of the secondary rainbow are reversed from the primary bow, and the secondary bow is twice as broad.
Secondary Rainbow
Red
Violet
top of secondary bow since it comes to the eye from higher drops.
Violet light is bent more and comes out higher from the droplet. It appears at the bottom of the rainbow since violet light from lower droplets strikes your eye.
Primary Rainbow
Violet
40°
42°
Red
The red light from droplets higher in the sky reaches your eye.

Single Particle Absorption, Scattering, Forward Scattering Efficiencies of Soot and Water



Figures 17.19 and 17.20

Visibility Definitions

Meteorological range

Distance from an ideal dark object at which the object has a 0.02 liminal contrast ratio against a white background

Liminal contrast ratio

Lowest visually perceptible brightness contrast a person can see

Visual range

Actual distance at which a person can discern an ideal dark object against the horizon sky

Prevailing visibility

Greatest visual range a person can see along 50 percent or more of the horizon circle (360°), but not necessarily in continuous sectors around the circle.

Meteorological Range

Contrast ratio

- $C_{ratio} = (I_B - I) / I_B$ (7.8)

Change in object intensity

- $dI/dx = \sigma_t (I_B - I)$ (7.9)

Total extinction coefficient

- $\sigma_t = \sigma_{a,g} + \sigma_{s,g} + \sigma_{a,p} + \sigma_{s,p}$ (7.10)

Integrate Equation 7.9

- $C_{ratio} = (I_B - I)/I_B = e^{-\sigma_t x}$ (7.11)

Solve for meteorological range

- $x = 3.912 / \sigma_t$ (7.12)

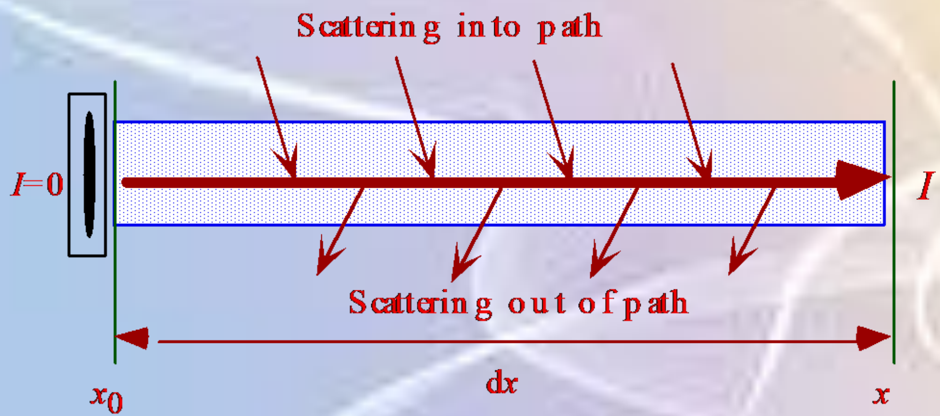


Figure 7.21

Meteorological Range Due to Gas Scattering and Absorption vs. Wavelength

		NO_2(g) absorption	
λ	Rayleigh Scattering	0.01 ppmv	0.25 ppmv
(μm)	(km)	(km)	(km)
0.42	112	296	11.8
0.50	227	641	25.6
0.55	334	1,590	63.6
0.65	664	13,000	520

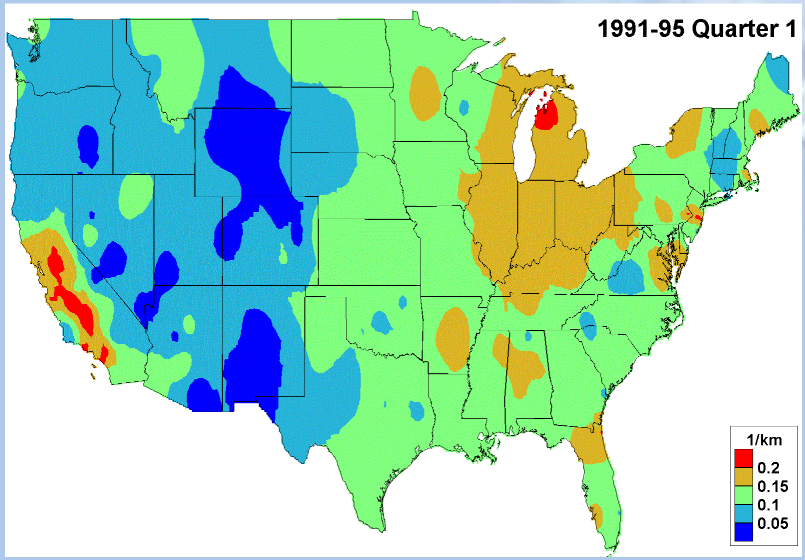
Table 7.3

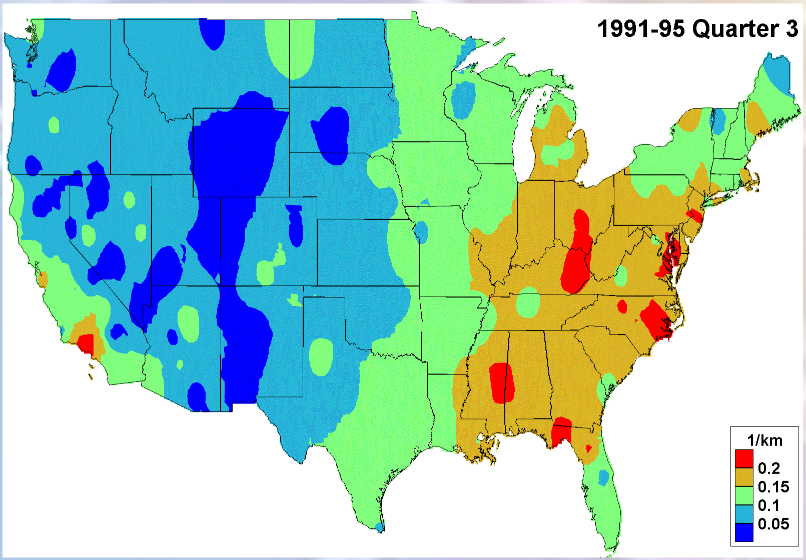
Meteorological Range on Polluted and Less-Polluted Day in Los Angeles

	Meteorological Range (km)				
	Gas scattering	Gas absorption	Particle scattering	Particle absorption	All
Polluted day	366	130	9.59	49.7	7.42
Less-polluted day	352	326	151	421	67.1

Table 7.4, Larson et al. (1984)

Winter and Summer Maps of Light Extinction





Schichtel et al. (2001)

Haze Over Los Angeles (May, 1972)

Gene Daniels, U.S. EPA, May, 1972, Still Pictures Branch, U.S. National Archives

Haze and Fog Over Los Angeles (May, 1972)

Gene Daniels, U.S. EPA, May, 1972, Still Pictures Branch, U.S. National Archives

Reddish and Brown Colors in Los Angeles Smog (December 19, 2000)

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Red Sky Due to Smog (Salton Sea, California, May, 1972)

Charles O'Rear, U.S. EPA, May, 1972, Still Pictures Branch, U.S. National Archives

Purple Sunset (Palos Verdes, California, 1982)