# Chapter 14

# Radiation III. Light Scattering by Particles

## Short Summary

The interaction of electromagnetic radiation with particles (aerosols and clouds) is important both aesthetically and practically in the atmosphere. The interaction of visible light with molecules and particulate matter is responsible for much of the beauty we see in the sky—white clouds, blue skies, red sunsets, rainbows, halos. By the same token, the interaction of light with particles can also lead to a degradation of visibility in polluted air loaded with human-made particulates. The way in which radiation in the visible and infrared interacts with aerosols and clouds can also lead to a cooling effect on the atmosphere, which may partly counteract the atmospheric warming induced by the greenhouse effect. The study of such light processes in the atmosphere is therefore of paramount importance.

## What you should know by the end of this lecture

1. The ways in which electromagnetic radiation interacts with solid and liquid objects (reflection, refraction, diffraction, dispersion)

2. The meaning of scattering, absorption, and extinction of light.

3. The properties of a particle that control the scattering of light.

4. The meaning of geometric, Mie, and Rayleigh scattering, and examples of each type of scattering in the atmosphere.

## 14.1 Basic light processes

The **propagation** of light can be described in terms of **wavefronts** or in terms of **rays** (see Figure 14.1).

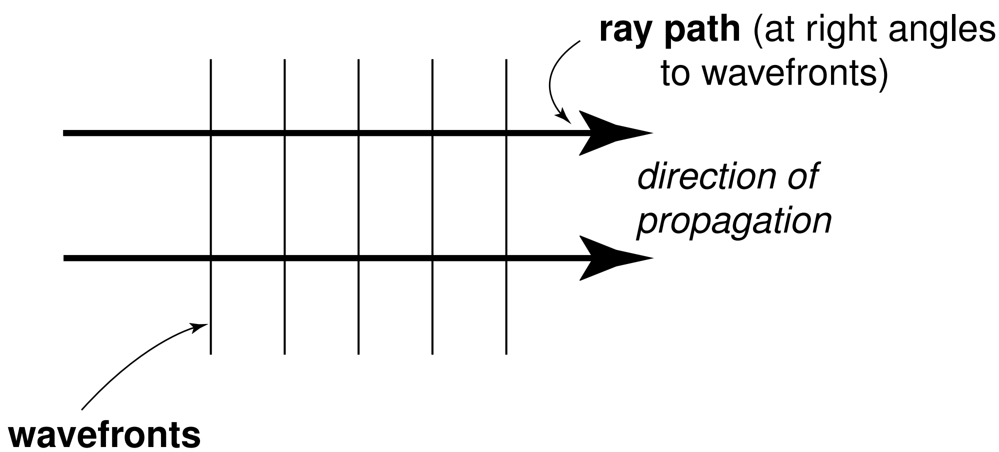


Figure 14.1: Ray paths and wavefronts.

**Reflection** occurs when light is absorbed by a material and re-emitted with an angle equal to the angle of incidence. The **reflectivity** is the fraction of **incident light** energy reflected and the **absorptivity** is the fraction absorbed (Reflectivity = 1 - absorptivity).

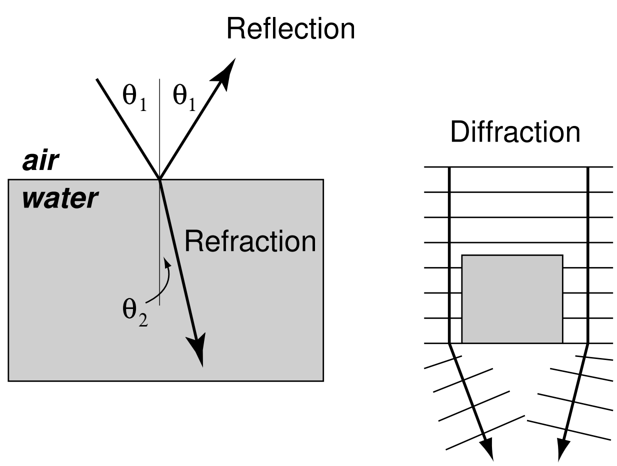


Figure 14.2: Different ways in which light can interact with solids and liquids.

**Refraction** occurs when light passing through a medium of a given density enters a second medium of different density. The speed of light in the two mediums is different, leading to a deviation in the path of the light (see Figure 14.2). The angle of refraction depends on the angle of incidence and the **refractive index** in each medium

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}. \tag{14.1}$$

This is **Snel's law**. In this equation, the indices 1 and 2 refer to the incident and refracted light respectively, $n$ is the **real index of refraction** (dimensionless), and *theta* is the angle of incidence and refraction (as in Figure

| Wavelength ($\mu$m) | $n_{air}$ | $n_{water}$ |
|---|---|---|
| 0.2 | 1.000324 | 1.396 |
| 0.3 | 1.000292 | 1.349 |
| 0.4 (blue) | 1.000283 | 1.339 |
| 0.5 | 1.000279 | 1.335 |
| 0.6 | 1.000277 | 1.332 |
| 0.7 (red) | 1.000276 | 1.331 |
| 1.0 | 1.000274 | 1.327 |
| 4.0 | 1.000273 | 1.351 |
| 7.0 | 1.000273 | 1.317 |
| 10.0 | 1.000273 | 1.218 |
| 20.0 | 1.000273 | 1.480 |

Table 14.1: Real indices of refraction for air and liquid water versus wavelength.

14.2).

The real index of refraction is the ratio of the speed of light in air ($c$) to that in the medium

$$n_1 = \frac{c}{c_1}. \tag{14.2}$$

Because light cannot travel faster than its speed in vacuum, $n$ is always greater than 1. The real index of refraction depends on the density of the medium and on wavelength. Table 14.1 gives some values for air and water.

**Diffraction** is the process by which light bends around an obstruction. Diffraction can be explained by **Huygen's principle**, which states that each point of an advancing wavefront may be considered as the new source of a series of secondary wavefronts.

**Dispersion** is the separation of white light into colours (often called the spectrum). Dispersion results from refraction and occurs because the refractive index is dependent on wavelength, with blue light having a higher refractive index than red light. Blue light is therefore refracted to a greater degree than red. There is, of course, a continuous separation of different wavelengths from blue ($n \approx 1.339$) to red ($n \approx 1.332$) although the human eye perceives there to be seven distinct colours (red, orange, yellow, green, blue, indigo, violet). The best method to demonstrate dispersion is with a prism (see Figure 14.3)

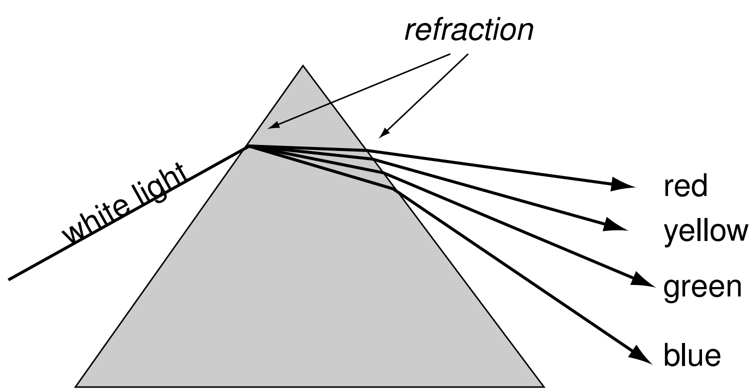


Figure 14.3: Dispersion caused by refraction in a prism.

## 14.2 Scattering by particles

Particles scatter light by reflection, refraction and diffraction. Scattering results in an initially parallel incident light beam being **scattered** in all directions. When scattering occurs, the total energy of the scattered light (**transmitted** light) is equal to the energy of the incident beam. Some particles (such as black carbon) can **absorb** light energy, which is converted into heat and therefore lost from the scattered light.

Light that is lost from the initial **direct beam** is said to be **extinguished**. Both scattering and absorption can lead to the **extinction** of light from the direct beam; absorption actually removes light, while scattering simply redirects the light.

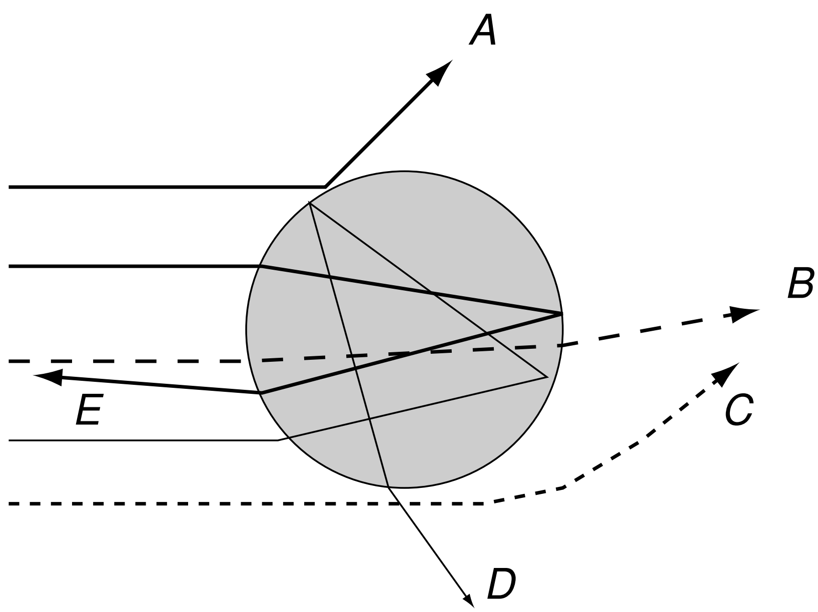


Figure 14.4: Scattering of light by a single droplet. Ray A is reflected; B is refracted twice; C is diffracted, D is refracted, reflected twice, then refracted again; E is refracted, reflected, then refracted again. Rays A, B, C, and D scatter in the forward or sideward direction. E scatters in the backward direction.

The way in which light is scattered by a particle depends in a complex way on several parameters:

1. The size of the particle
2. The wavelength of the light
3. The real refractive index of the particle
4. The shape of the particle

The method of determining the scattering of light by a single particle depends on the ratio of the particle size to the wavelength of the light. This ratio is normally expressed as the **size parameter**, $\alpha$, which is given by

$$\alpha = \frac{2\pi r}{\lambda} \tag{14.3}$$

There are three **scattering regimes**:

1. **Geometric scattering** ($\alpha \gg 1$, particles large compared with the wavelength)

2. **Mie scattering** ($\alpha \sim 1$, particles about the same size as the wavelength)
3. **Rayleigh scattering** ($\alpha \ll 1$, particles much smaller than the wavelength)

There are two important scattering quantities that we want to calculate. These are:

1. The fraction of light that is scattered. Not all the light that is incident on a particle is scattered. This probably goes against our gut feeling: surely light that impinges a droplet must be either refracted or reflected? This is actually only the case in the geometric regime, which we are most familiar with. The fraction of incident light that is scattered is expressed in terms of the **scattering efficiency**, $Q_{scat}$ (dimensionless).
2. How the scattered light is distributed in space. By this we mean in which direction the light is distributed. Does it reflect back to us or scatter off to the sides? This will be important for determining the ability of aerosols to reduce the intensity of light in the direct beam (which affects visibility). The distribution of scattered light around a sphere surrounding the particle is called the **phase function**.

### 14.2.1 Geometric scattering

Particles for which the radius is much greater than the wavelength of light fall into the so-called geometric scattering regime. In this case, the scattering can be determined from geometrical optics of reflection, refraction and diffraction. Geometric optics means that the scattering of light can be determined by **ray tracing**, which is also used to determine the optical effects of lenses and prisms, etc.

A good example of the application of geometric optics to particle scattering is the formation of a rainbow. Figure 14.5 shows the ray paths in a single droplet that contribute to the formation of a primary rainbow. Light

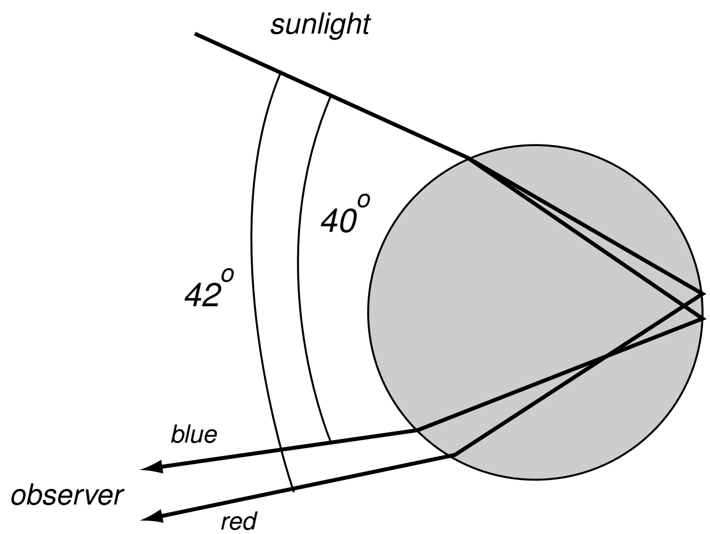


Figure 14.5: Ray paths inside a droplet that lead to the formation of a rainbow.

beams entering a droplet are first refracted (leading to dispersion), reflected off the back of the droplet and refracted again on leaving the droplet. Independent of the size of the droplet (provided $\alpha \gg 1$) the angle between the incident beam and the return beam is 42° for red light and 40.6° for the blue light. Note that not all the light that impinges the droplet goes into forming the rainbow. Much of it is simply reflected off the surface or is refracted and then exits the droplet in the forward direction (see Figure 14.4). Note also that only one wavelength from a single droplet impinges upon the viewer's eye. A rainbow appears when waves from many droplets hit the eye.

For geometric scattering by a sphere

$$Q_{scat} = 2 \tag{14.4}$$

This means that a sphere with radius much greater than the wavelength of light scatters twice as much energy as it intercepts. This is because light is not only redirected by refraction and reflection (for rays that *enter* the droplet) but also diffracted about the sphere. Thus a droplet can 'intercept' light waves that would otherwise pass by.

### 14.2.2 Mie scattering

Geometric optics breaks down when the wavelength of light approaches the dimension of the scattering droplet (i.e., as $\alpha \to 1$). For this case, the scattering must be calculated by solving Maxwell's equations for the electromagnetic field about a dielectric sphere (a dielectric sphere is one capable of sustaining an electric field without conducting, such as a water droplet).

Gustav Mie in 1908 was the first to solve these equations. Often, the size parameter is termed the **Mie parameter** since the solution of the equations results in a series expansion in terms of $2\pi a/\lambda$.

The scattering efficiency depends on the size parameter as shown in Figure 14.6.

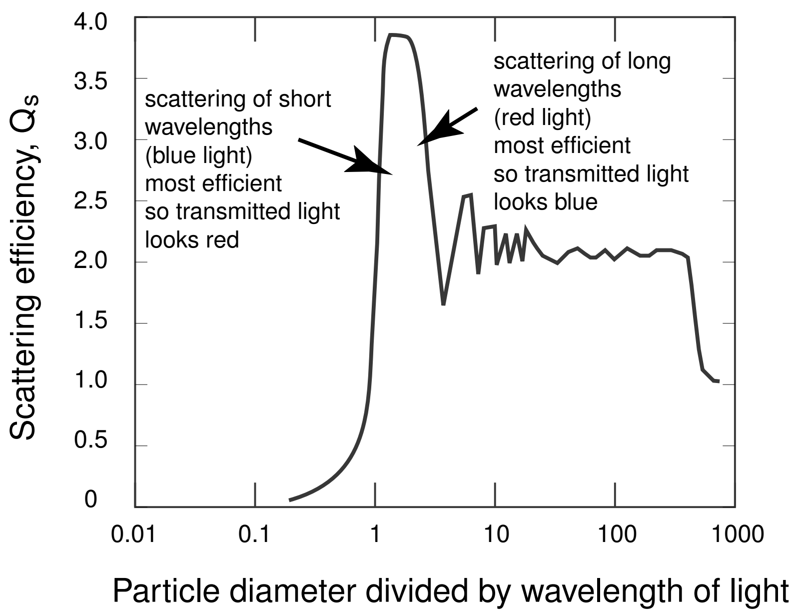


Figure 14.6: $Q_{scat}$ versus the ratio of the particle diameter to the wavelength of the light, illustrating Mie scattering

Some observations:

1. $Q_{scat}$ falls below 1 for $a/\lambda$ less than about 0.3. This means that particles smaller than this become inefficient scatterers and scatter less light than is incident upon them.

2. $Q_{scat}$ reaches a maximum of about 4 for $a \approx \lambda$. This means that such a particle scatters 4 times as much light as is incident on its surface.

3. For $a \gg \lambda$ $Q_{scat} \to 2$. This is the geometric scattering regime.

4. Between the maximum and the geometric regime the scattering efficiency passes through a series of oscillations. This is caused by the interference of light that is diffracted around the particle and that which is refracted through it.

5. Mie scattering is relevant for calculating the optical effects of aerosol particles with a size of approximately the wavelength of light—that is, about 0.1 to 1 $\mu$m.

Note that if $\lambda \gg a$, scattering is very weak. This means that *visible* light can be strongly scattered by atmospheric aerosols, while *infrared* radiation, which has a wavelength much greater than the size of aerosols, will be only weakly scattered.

### 14.2.3 Rayleigh scattering

Lord Rayleigh was the first to explain (in 1871) why the sky is blue (Lord Rayleigh, *"On the light from the sky, its polarization and colour", Philosophical Magazine, 41, 107-120, 1871*). He deduced a relationship between the intensity of light scattered by air molecules and the wavelength of the incident light.

The essence of Rayleigh scattering is that the intensity of scattered radiation is inversely proportional to the fourth power of the wavelength, that is

$$I \propto \frac{1}{\lambda^4} \tag{14.5}$$

This steep variation with wavelength is shown in Figure 14.6—the Rayleigh regime pops naturally out of the full Mie solution to Maxwell's equations!

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An aside: Note that the reason blue light scatters more strongly is due to the way the light interacts with the molecules. The oscillating electric field of the light induces an oscillating electric dipole in the molecules (essentially causing the negative electrons and positive nuclei to oscillate towards and away from each other). This induced oscillating dipole emits its own electromagnetic field with the same wavelength as the incident light. The electric field strength emitted by an oscillating dipole is proportional to the second derivative of the dipole moment with time. This makes the electric field strength proportional to $1/\lambda^2$. The intensity of the light is the square of the electric field strength, giving the $1/\lambda^4$ dependence.

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Figure 14.7 shows schematically what happens as light of two different wavelengths passes through air. The long and short wavelengths used in the example could be red and blue light, respectively. With the shorter wavelength blue light, the interaction of the electromagnetic radiation with the molecules is strong each time the light impinges a molecule. Each interaction removes light energy from the direct beam and scatters it in all directions. Thus, energy is slowly lost from the direct beam (it is *extinguished*) and the intensity of the blue light at B is weaker than it was at A. The interaction of red light with the molecules is weaker than for blue light. Consequently, less energy is removed from the direct beam, leaving the red light intensity less diminished at B.

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Example 14 *How much more does blue light scatter compared with red in the Rayleigh regime?*

*Blue light has a wavelength of about 0.4 $\mu$m and red light has a wavelength of about 0.65 $\mu$m. The intensity of the scattered blue light, according to Equation 14.5, is therefore approximately a factor* $(1/0.4^4)/(1/0.65^4) = 7$ *greater than that of scattered red light.*

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The consequences of Rayleigh scattering in the atmosphere depend on your viewing angle with respect to the direct beam.

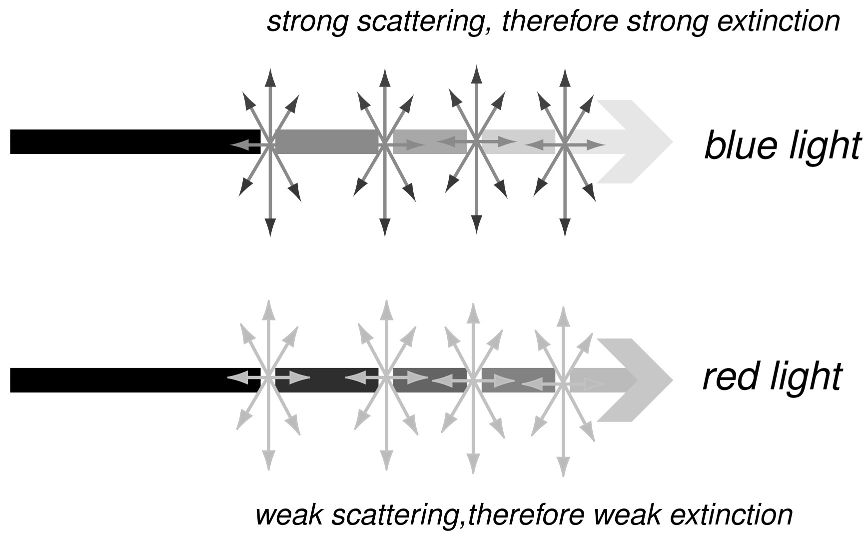


Figure 14.7: Schematic of Rayleigh scattering along light beams of red and blue light

## Questions for understanding

1. Using what you know about Rayleigh scattering, explain what controls the colour of the sun as (a) you look directly at it at mid day; (b) you look away from the sun at midday; (c) the sun sets.
2. Which size of particles are likely to cause the greatest scattering in the Mie regime?
3. List the properties of an atmospheric particle that influence the way in which light is scattered.
4. Blue light is incident on a flat water surface at an angle of incidence of 10° (angle $\theta_1$ in Figure 14.2). Calculate the angle of refraction.