- Except at near-grazing and near-normal incidence, the reflectivity for vertical polarization is much lower than that for horizontal polarization. It is this fact that led to the development of polarizing sunglasses, which block the largely horizontally polarized glare from water and other reflecting surfaces while transmitting vertically polarized light from other sources.

- There is a single angle Θ_B, known as the *Brewster angle*, at which the reflectivity for vertically polarized radiation vanishes completely, implying that *only* the horizontally polarized component of incident light survives reflection at that angle. By setting the numerator in (4.16) equal to zero and solving for $\sin\Theta_i$, we find that

$$\boxed{\Theta_B = \arcsin\sqrt{\frac{m^2}{m^2+1}}\ .} \tag{4.22}$$

  For water in the visible band, the $\Theta_B = 53^\circ$.

All of the above features can be found in the reflectivities of most nonconducting materials; i.e., those for which n_i is zero or at least very small. Larger values of the real part of m lead to greater overall reflectivities, larger values for the Brewster angle Θ_B, and smaller values for the critical angle for total internal reflection Θ_0. Diamonds, with their unusually large $N = 2.42$, owe their alluring sparkle to all three properties.

Problem 4.3: For (a) glass with $N = 1.5$ and (b) a diamond with $N = 2.42$, find the values of the reflectivity at normal incidence, and the critical angle for total internal reflection Θ_0. Compare these values with their counterparts for water.

In the case of conducting materials, e.g., metals, as well as liquid water at microwave frequencies (Fig. 4.5b), the imaginary part of m is significantly greater than zero and also contributes to increased reflectivity. However, although the vertically polarized reflectivity still has a minimum at some angle Θ_B, that minimum is no longer zero. Therefore, (4.22) cannot be used to find Θ_B in such cases.

4.3 Applications to Meteorology, Climatology, and Remote Sensing

4.3.1 Rainbows and Halos

Geometric Optics

In the previous section, we tacitly assumed that we were dealing with EM waves incident on a *planar* (flat) boundary between two homogeneous media. However, the above rules for reflection and refraction can be applied not only to planar boundaries, but to any surface whose radius of curvature is much greater than the wavelength of the radiation. In this case, the angles Θ_i, Θ_t, Θ_r, Θ_0, etc., are measured relative to the local normal where the ray intercepts the surface. With this generalization, we have the ability to analyze the scattering and absorption properties of a variety of atmospheric hydrometeors via the straightforward technique of *ray tracing*, also known as *geometric optics*.

Unfortunately, most particles in the atmosphere are not much larger, and may even be smaller, than the wavelength of interest. This is true for air molecules, aerosols and cloud droplets in the visible and infrared bands and even raindrops in the microwave band. Geometric optics cannot be used for these cases; rather, more sophisticated solutions to the wave equation must be derived. These solutions and their interpretation will be outlined in Chapter 12.

Nevertheless, there are a number of interesting cases for which the particle size *is* much larger than the wavelength. This condition applies for example to the scattering of visible sunlight ($\lambda < 0.7\ \mu$m) by large cloud ice particles ($>$50 μm) and raindrops (100 $\mu\text{m} < r < 3$ mm). In fact, a number of common optical phenomena, such as rainbows, halos, and parhelia (sundogs) can be explained by geometric optics, simply by considering how rays of light refract and reflect as they encounter the surface of the particle.

The Rainbow

To a reasonable approximation, a falling raindrop is spherical. If a spherical droplet is uniformly illuminated, then the geometry of the path of each incident ray depends only on $x \equiv r/a$, where r is the

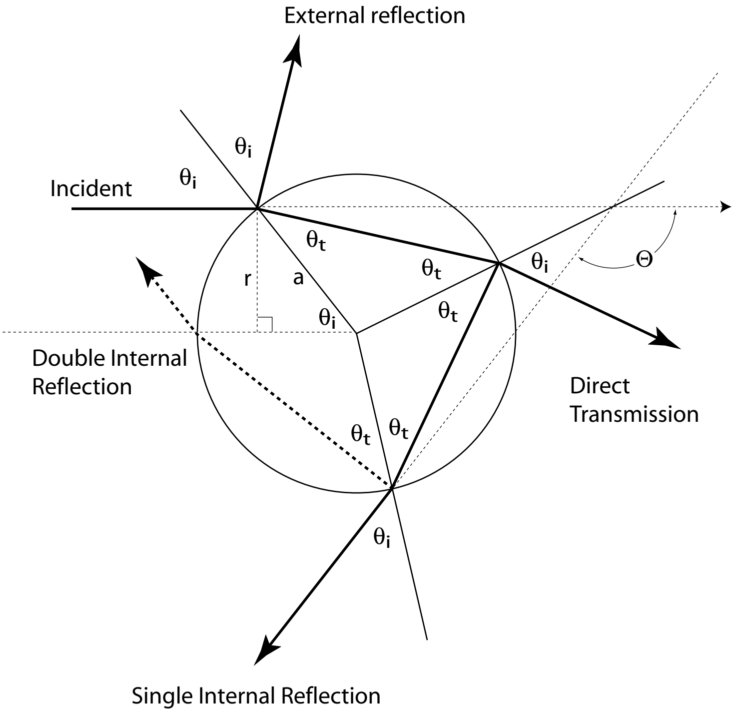

Fig. 4.7: Ray tracing geometry for a spherical water droplet of radius a, for a ray incident at distance r from a parallel line passing through the drop center. θ_i and θ_t denote the incident and transmitted angles relative to the local normal and are related by Snell's law. Θ is the angle of scattering relative to the original direction of the ray, in this case for a ray that has undergone a single internal reflection.

distance of the incident ray from the center axis of the drop, and a is the radius of the drop (Fig. 4.7). So $x = 0$ corresponds to a ray that is incident "dead center," while $x = 1$ corresponds to a ray that barely grazes the edge of the sphere.

Now let's follow the path of a single incident ray after it intercepts the drop:

1. A fraction of the energy in the ray will be reflected upon its first encounter with the surface of the drop. If the incident radiation is unpolarized, then that fraction will be given by the average of the Fresnel relations (4.16) and (4.17), evaluated for the local angle of incidence θ_i. Fig. 4.5 reveals that this fraction is typically only a few percent, except when the ray strikes the