according to the Fresnel relations. The overall intensity in a particular direction is proportional to the intensity of the individual rays times the density of rays per increment of Θ.

Although the trend initially is toward ever-smaller Θ, there comes a point where Θ reaches a minimum, which we'll call Θ_0, and starts increasing again. For water, which has an index of refraction of approximately 1.33 in the visible band, $\Theta_0 \approx 137^\circ$.

Because the reversal is gradual, there is a fairly significant range of x for which the scattered rays all bunch up rather close to Θ_0. It is this "focusing" of energy on a narrow range of Θ that gives rise to the bright ring that we call a rainbow. Of course, a rainbow is only visible when a rainshower is illuminated by a directional source of bright light — e.g., sunlight.

The precise value of Θ_0 depends of course on the index of refraction: increasing n_r has the effect of increasing Θ_0. A rainbow exhibits the characteristic separation of colors for which it is best known because n_r for water increases slightly from the red end to the violet end of the visible spectrum (Fig. 4.1).

As already mentioned, a similar process is behind the much weaker secondary rainbow, which arises from two internal reflections. The scattering angle for the second rainbow is approximately 130°, which puts it about 7° outside the primary rainbow, when you are viewing it with the sun at your back.

Halos and Related Optical Phenomena

Ray tracing can also be used to explain optical features like *halos* , which are bright rings that appear around the sun in conjunction with a thin cirrostratus cloud layer, and *parhelia* (or sundogs), which are bright iridescent spots positioned on either side of the sun, usually in connection with cirrus clouds, when the sun is fairly low in the sky. In both cases, the most common angle separating the halo or parhelion from the sun is 22°. This scattering angle is associated with refraction (without internal reflection) through two faces of a hexagonal ice crystal whose extensions form a 60° angle.

In contrast to the case for the rainbow, ray tracing analysis of various optical phenomena associated with ice crystals is complicated by the fact that they are not spherical. Therefore, results for all pos-