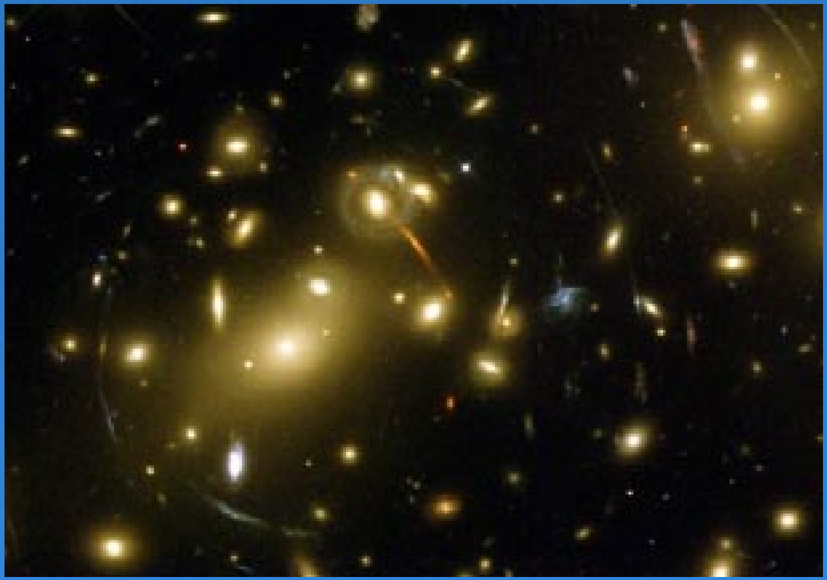


Astronomy 80 B: Light

Lecture 8: Refraction, dispersion, rainbows, mirrors

24 April 2003

Jerry Nelson

Topics for Today

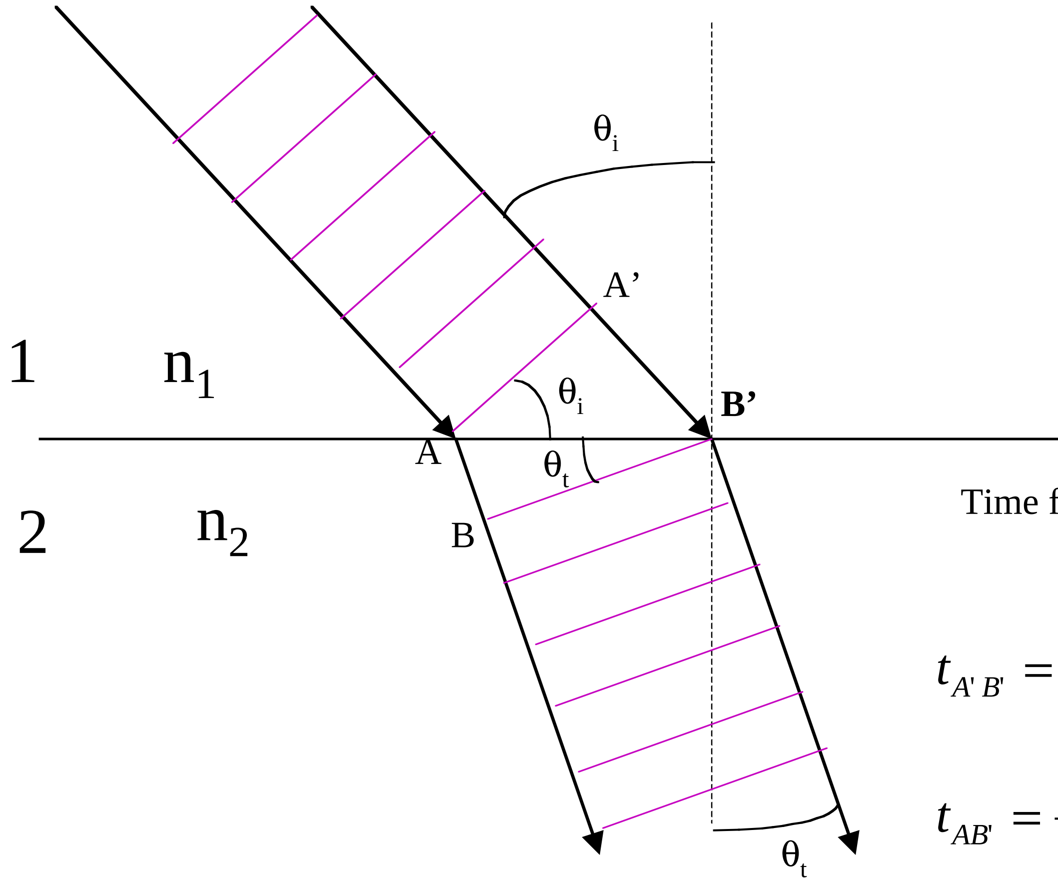
- Optical illusion
- Index of refraction of materials
- Review of mirages
- Light curving in atmosphere
- Rainbows
- Sundogs
- Halos
- Virtual images, kaleidoscopes
- Reflections from curved mirrors

Iridescent Clouds

- **What is this?**

The figure represented in these fragments generally is not immediately perceived. Recognition is accompanied by altered form and depth perception.

Derivation of Snell's law from wavefront continuity



n=c/v

Time for light to go from A' to B'

$$t_{A'B'} = \frac{d}{v_1} = \frac{A'B'}{c/n_1} = \frac{n_1}{c} AB' \sin\theta_i$$

$$t_{AB'} = \frac{d}{v_2} = \frac{AB}{c/n_2} = \frac{n_2}{c} AB' \sin\theta_t$$

so $t_{A'B'} = t_{AB}$

Which yields $n_1 \sin\theta_i = n_2 \sin\theta_t$

Prisms and color

- A prism separates white light into its constituent colors
- These colors cannot be separated any more
- These colors can be recombined into "white" light

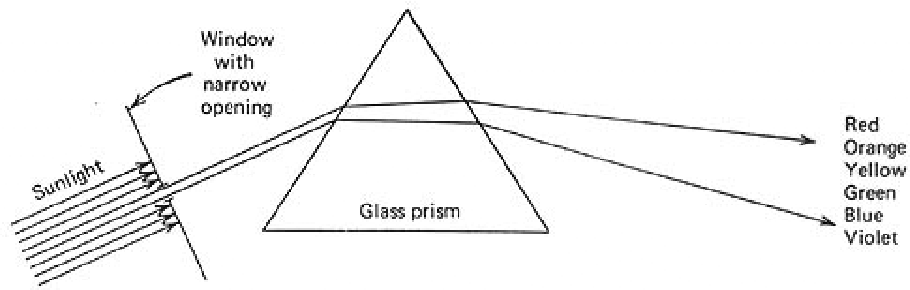


Figure 1.2 A prism separating the white light of the sun into the spectrum of colors.

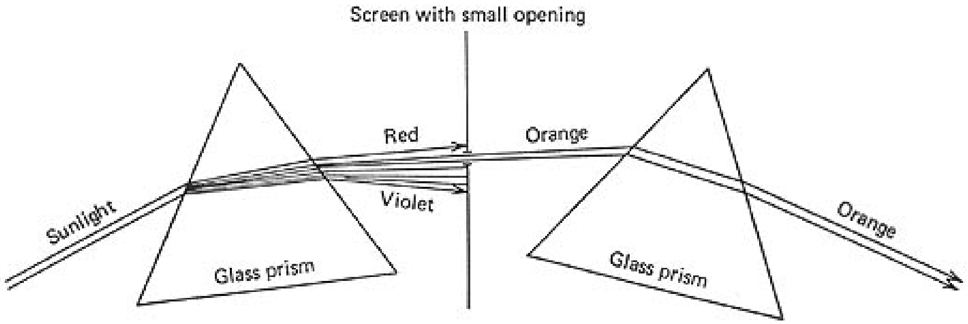


Figure 1.3 A second prism has no effect on the pure orange light.

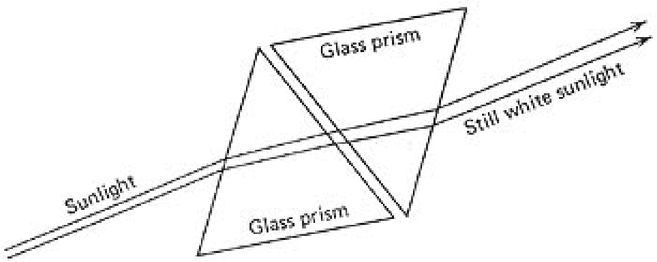


Figure 1.4 Inverted second prism puts the colors back together again, resulting in white light.

Common Indices of Refraction

Material	Index
Vacuum	1.0
Air	1.0003
Ice	1.31
Water	1.33
Alcohol (ethyl)	1.37
Plastics	~ 1.5
Glass	1.5
Cubic Zirconia	2.15
Diamond	2.4

Diamonds

- **Diamonds take advantage of their extremely high index of refraction to produce very bright gems- thanks to total internal reflection**

$$\theta_c = \sin^{-1}\left(\frac{1}{n}\right)$$

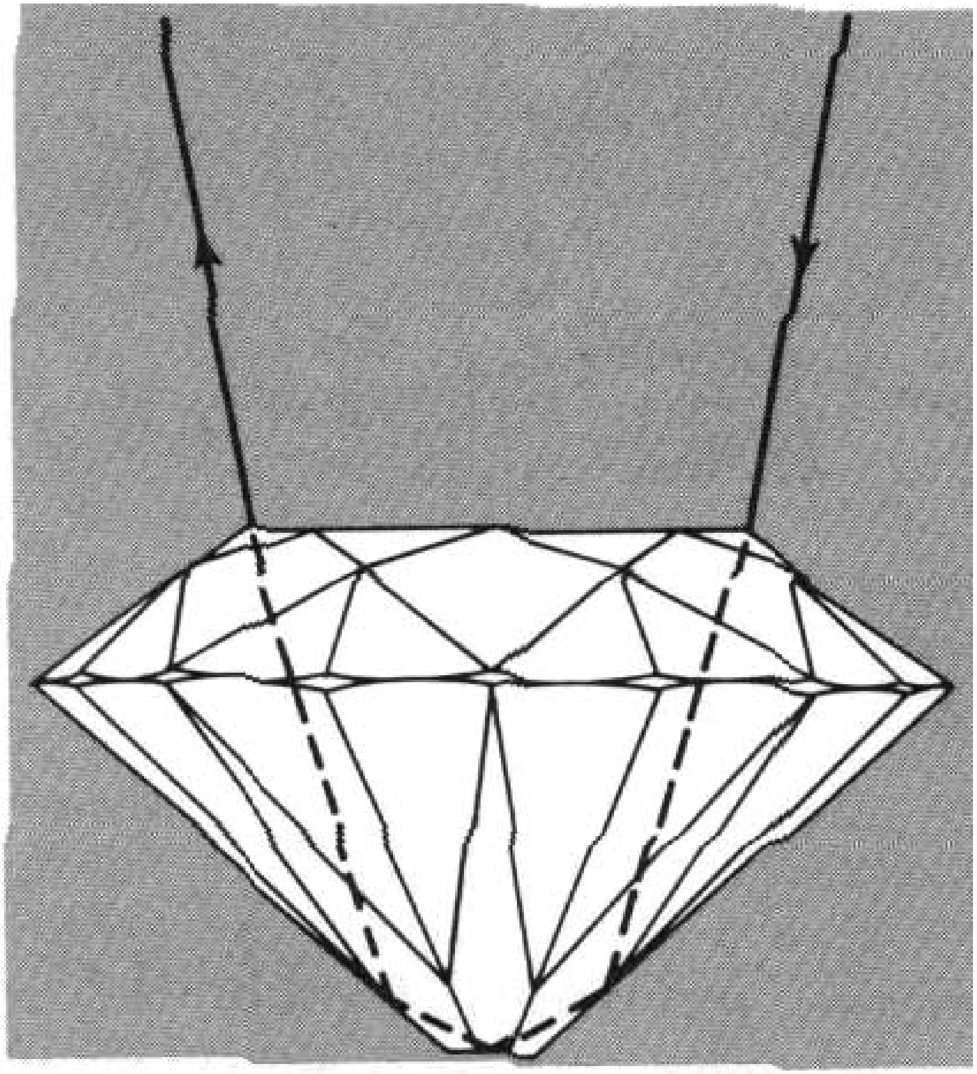


FIGURE 2.66

Most of the light entering a diamond is eventually reflected back out the front.

Refraction: angle of transmission

TABLE 2.5 Angle of transmission, θ_t, for various angles of incidence, θ_i, and various media

From	To	θ_i = 15°	30°	45°	60°	75°	89°
Air	Water	11°	22°	32°	41°	47°	49°
Air	Glass	10°	19°	28°	35°	40°	42°
Air	Diamond	6°	12°	16°	20°	23°	24°
Glass	Water	17°	34°	53°	78°	—	—
Glass	Air	23°	49°	—	—	—	—

See Sec. 2.5A for a discussion of the blank entries.

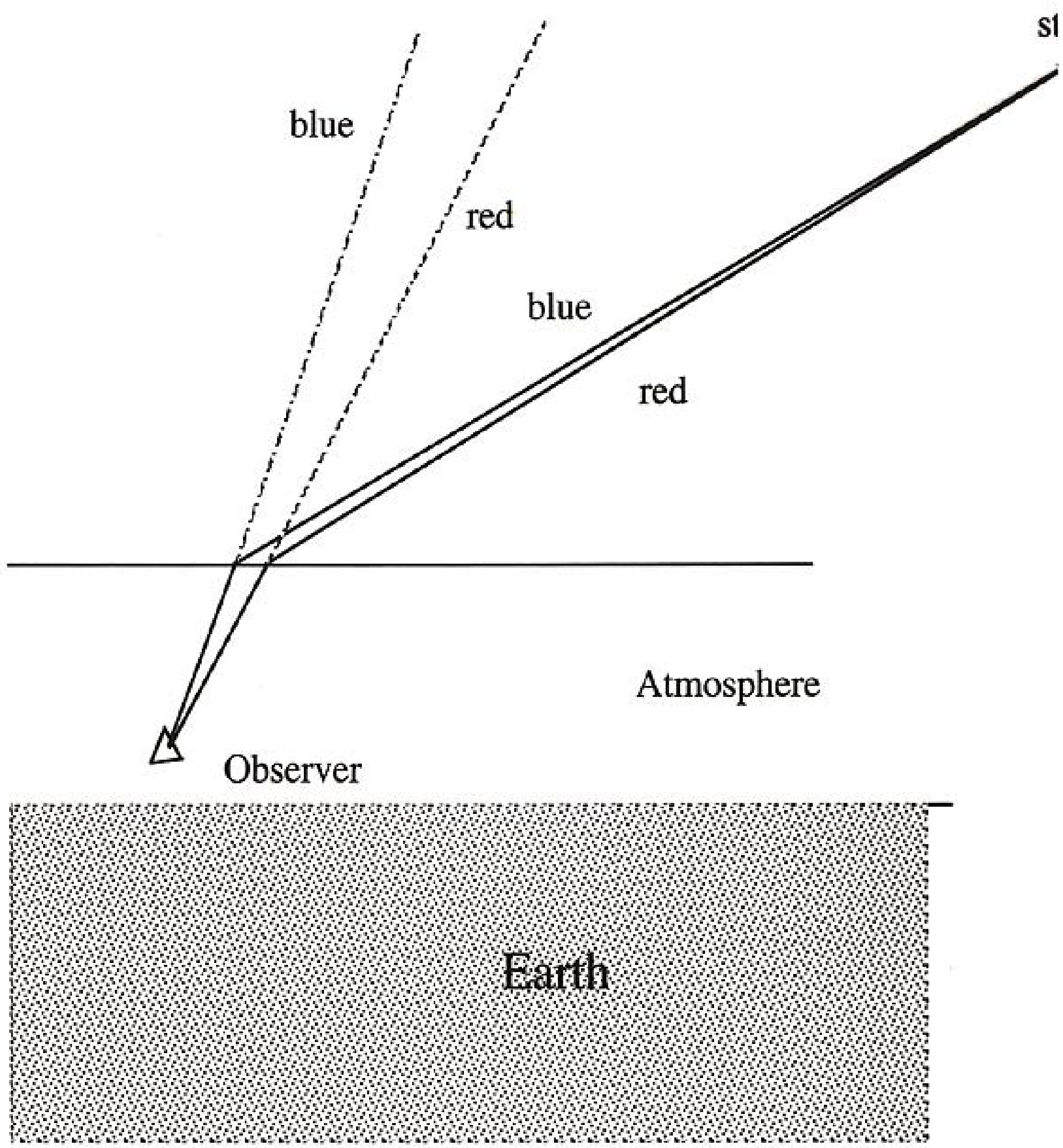
Index of refraction and dispersion

- **Table shows the variation in index of refraction of a few materials with the wavelength.**
- **This is called dispersion**

TABLE 2.6 *Index of refraction for various media*

Frequency (hertz)	*Wave-length (nm)*	*Color*	*Index of refraction*			
			Glass zinc crown	*Glass light flint*	*Diamond*	*Water*
4.57×10^{14}	656	Red	1.514	1.571	2.410	1.331
5.09×10^{14}	589	Yellow	1.517	1.575	2.418	1.333
6.91×10^{14}	434	Deep blue	1.528	1.594	2.450	1.340

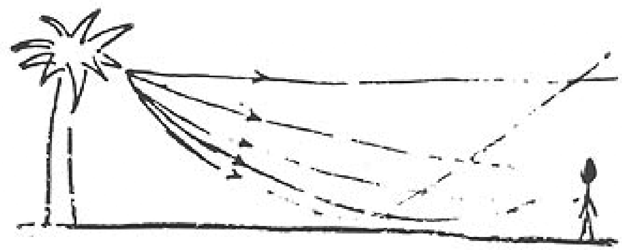
Dispersion in the Atmosphere



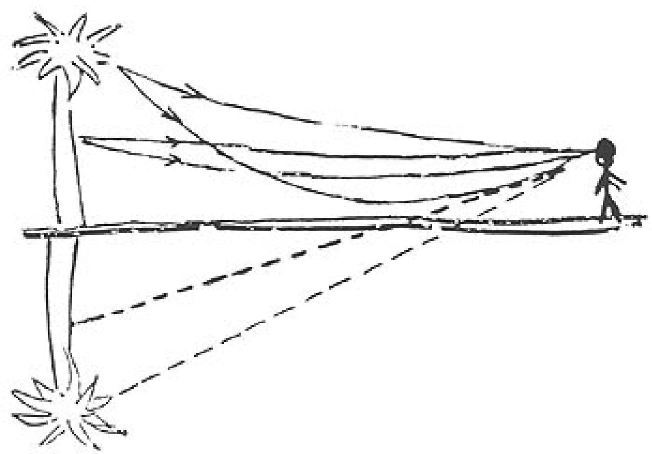
Desert Mirage

TY6

2 different light rays, emitted in very different directions, will make it into the observer's eye.

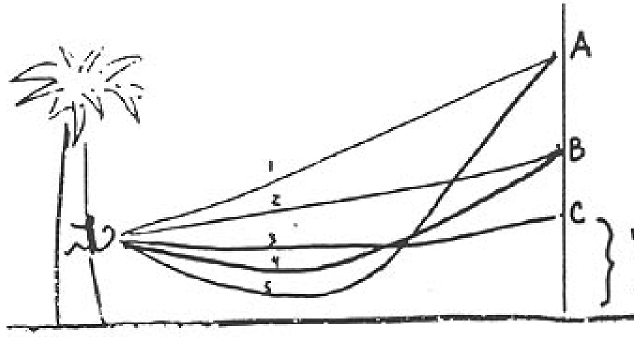


Origin of the inverted image



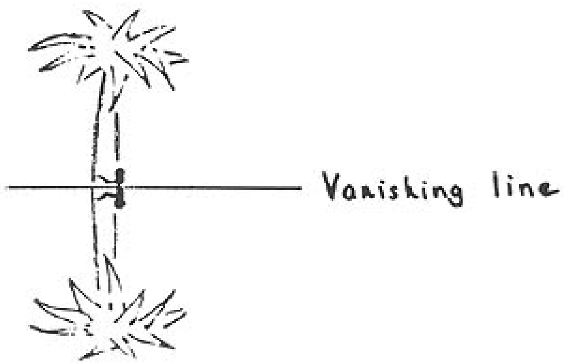
Upper and lower image can be compressed or stretched vertically depending on the details of the temperature variation with height.

The Vanishing Line in a Desert Mirage



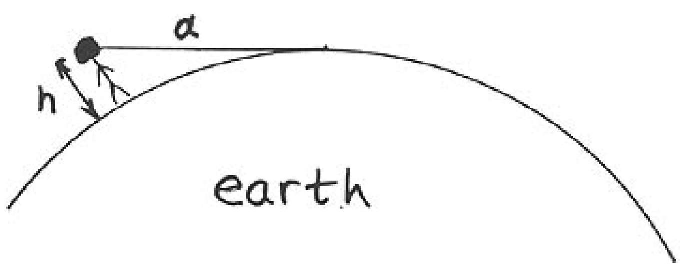
no light ray from monkey can reach this area. Therefore someone below C cannot see monkey. Likewise, someone at C cannot see anything below the monkey.

View from C:



As the observer goes further from the tree, the vanishing line rises until the tree disappears completely.

The Geometric Horizon



h height of observer	d distance from observer to geometric horizon	
5 feet	2.7 miles	
50 feet	8.7 miles	
500 feet	27 miles	
1200 feet	43 miles	
29,000 feet	210 miles	← approximately distance from Iceland to Greenland

- **Elevation angle increase of apparent sun vs real sun**
- **Approximation is that atmosphere is plane parallel (actually curved)**

Calculating the elevation increase of the apparent sun

$\theta 1$ is the zenith angle of the true sun (above atmosphere)
$n1$ is the index of refraction of a vacuum
$\theta 2$ is the zenith angle of the apparent sun (seen on earth)\
$n2$ is the index of refraction of air at sea level

Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

$n1 = 1.000$
$n2 = 1.0003$

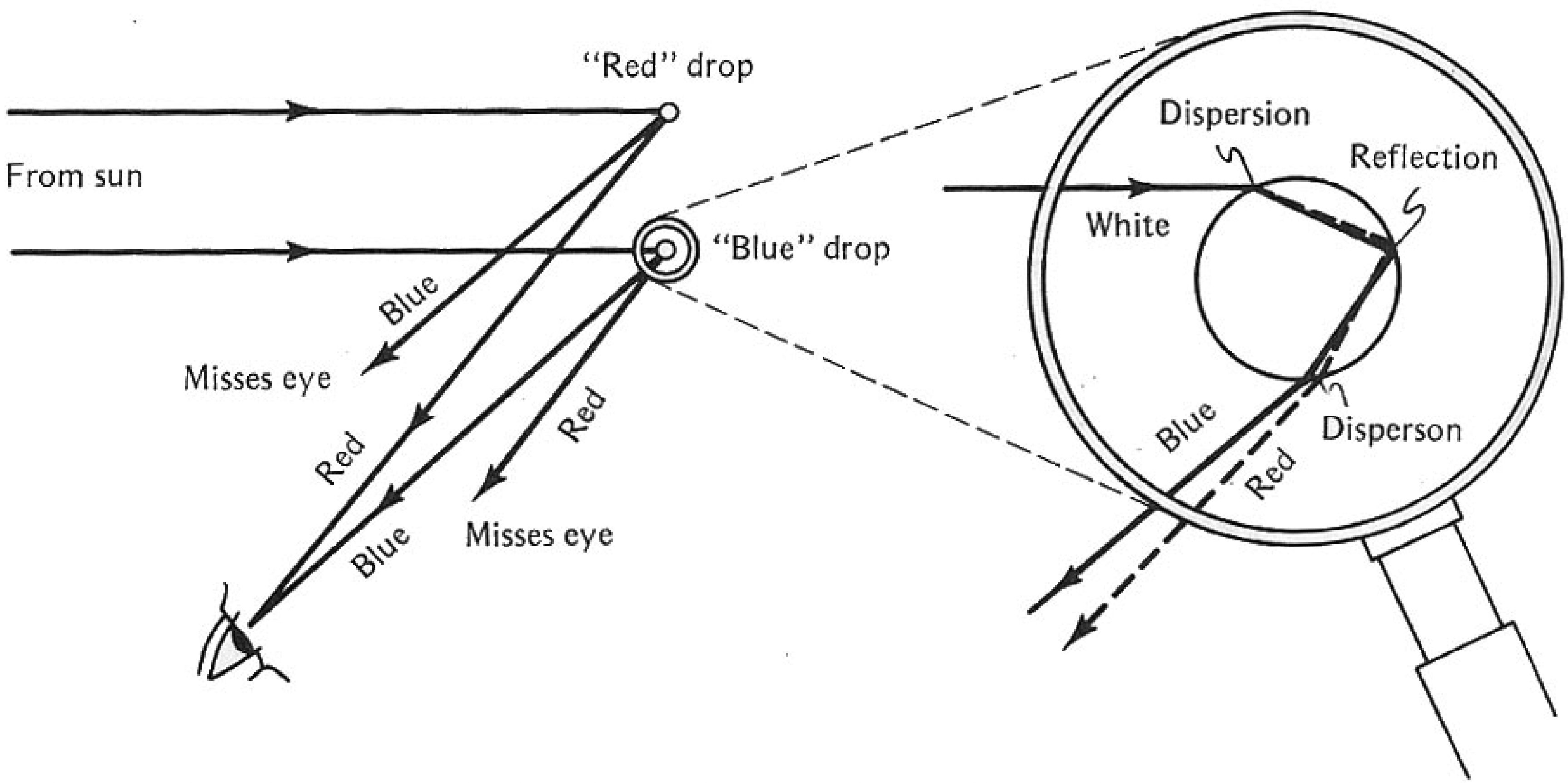
so $\theta 2 = \arcsin\left(\frac{n1}{n2}\sin\theta 1\right)$

$\theta 1$	$\sin\theta 1$	$\frac{n1}{n2}\sin\theta 1$	$\arcsin\left(\frac{n1}{n2}\sin\theta 1\right)$
80°	0.9848	0.9845	79.90°
82°	0.9903	0.9900	81.87°
84°	0.9945	0.9942	83.84°
86°	0.9976	0.9973	85.76°
88°	0.9994	0.9991	87.56
90°	1.0000	0.9997	88.60°

Rainbows-1

FIGURE 2.67

A light beam is dispersed twice and reflected once by a raindrop, letting the eye see a rainbow. (The dispersion is exaggerated here.)



Rainbows-2

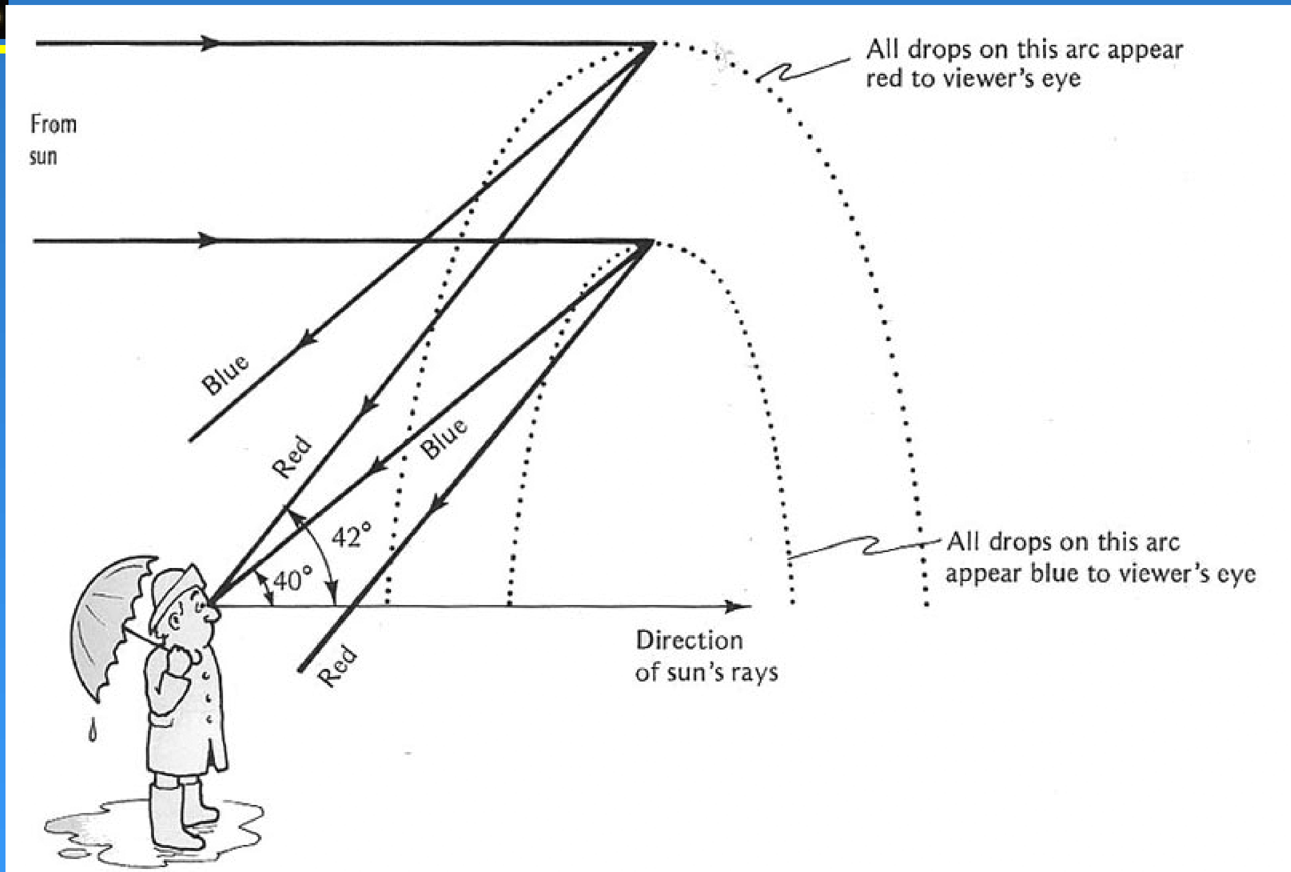
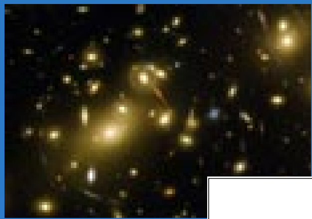
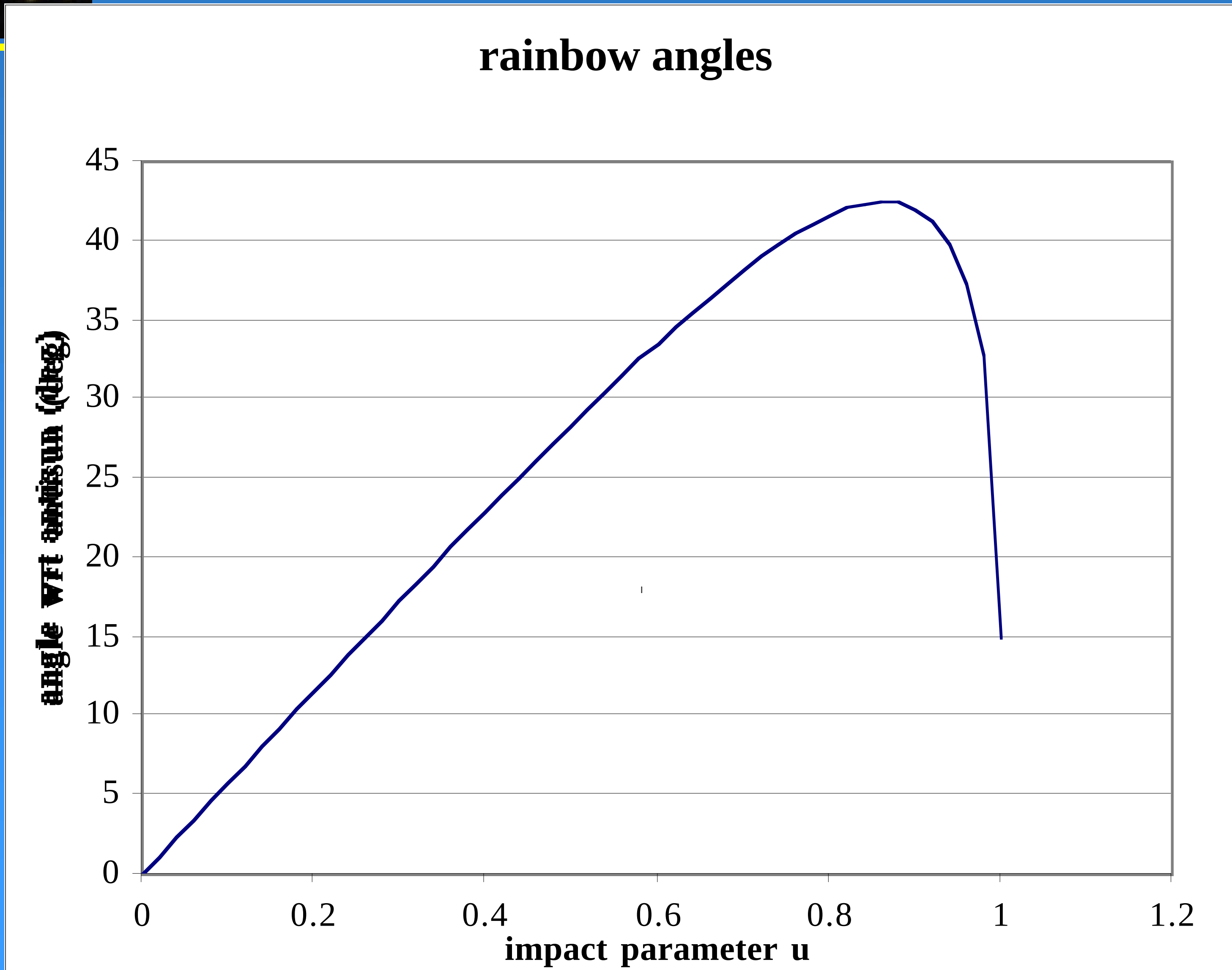


FIGURE 2.68

Only the drops along the rainbow's arc send light to a particular eye. All the drops on the upper arc appear red—the blue light they send out misses the eye. Similarly, all the drops on the lower arc appear blue.



Rainbow scattering angles

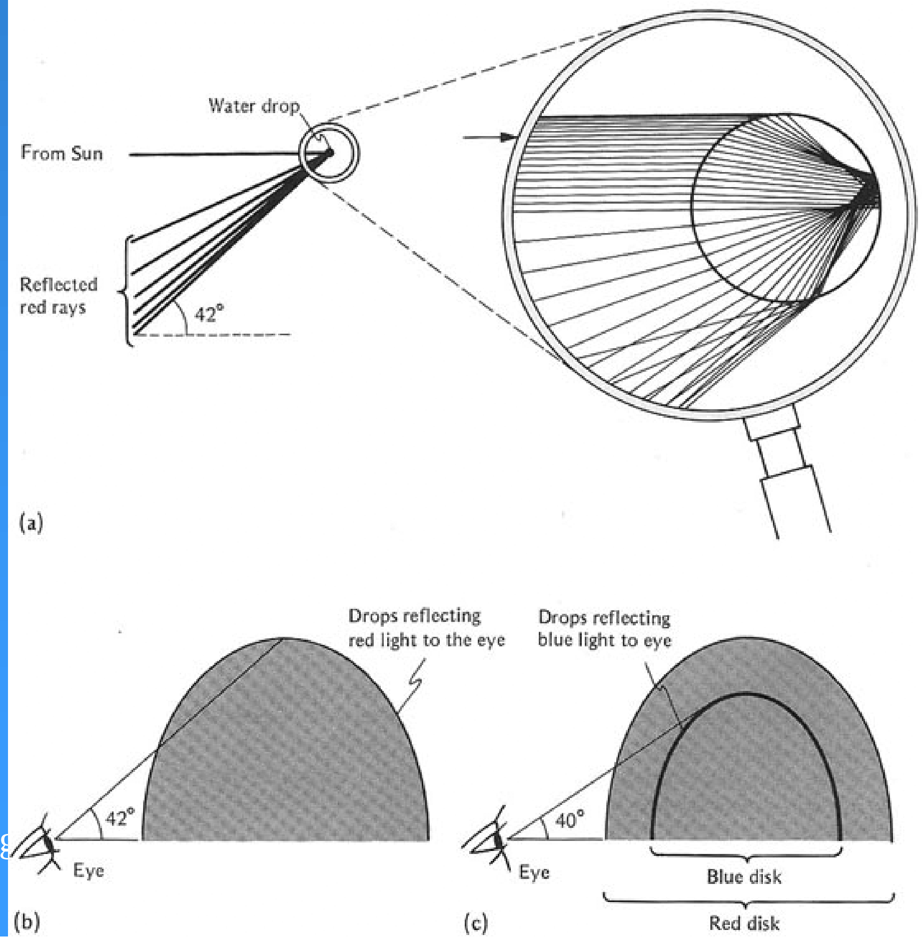


Rainbows-4

- **For a given color, there is a maximum angle that the light takes. At the maximum there is a brightening because many incident rays are scattered at about the same maximum angle**

FIGURE 2.70

(a) Light from the sun falls on the raindrop at all levels. Most but not all of the red rays from this light are returned by the raindrop at about 42°. In the magnified view, the arrow indicates the special ray that is returned *at* 42°. **(b)** The eye sees a red disk, brightest at the rim. **(c)** Superimposed on the red disk is a smaller blue disk (as well as disks of intermediate colors).



- **Secondary bow**

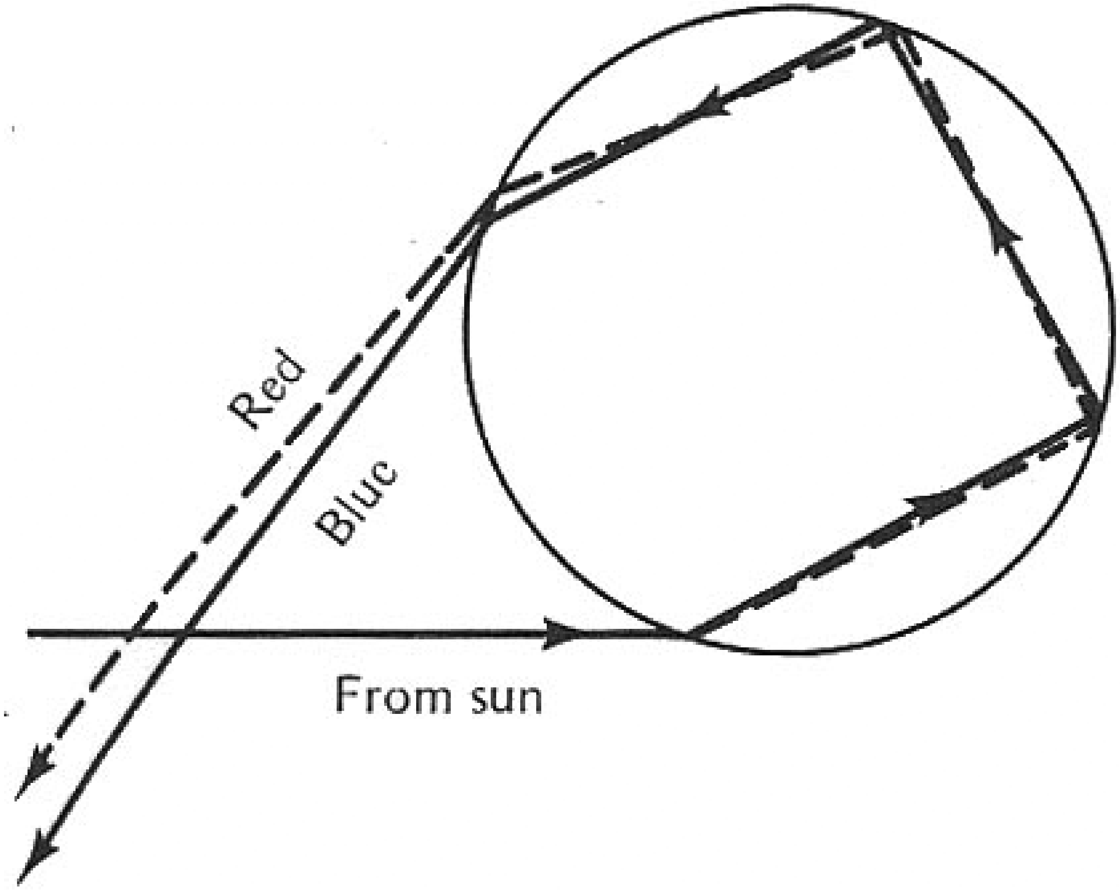
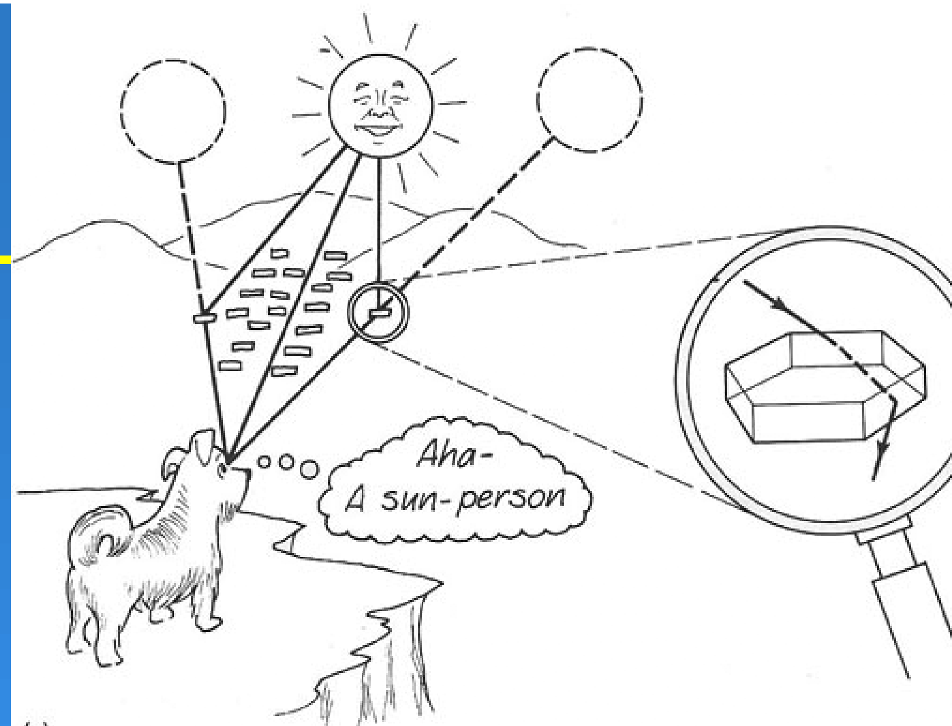


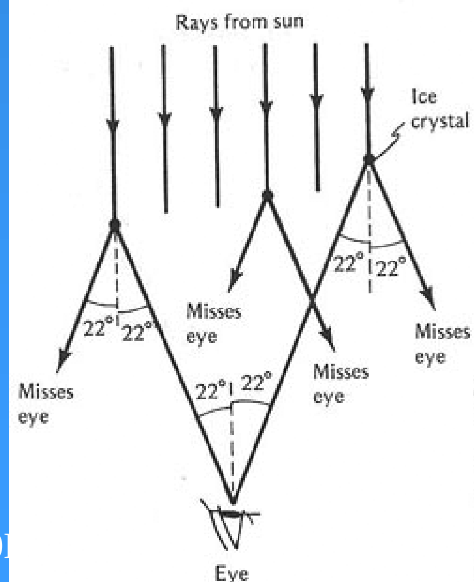
FIGURE 2.69

The secondary rainbow is caused by two reflections and two refractions in each raindrop. The extra reflection reverses the order of the colors.

- **Sundogs**



(a)



(b)

FIGURE 2.72

A sun dog is caused by refraction in hexagonal ice crystals. **(a)** As seen by an observer. **(b)** The path of a light ray through a crystal, as seen from above. Only those crystals that are at 22° from the eye send light to it. Light from all the other crystals misses this particular eye.

Sun dogs

- Sundogs are at 22° from sun and are caused by refraction through hexagonal ice crystals

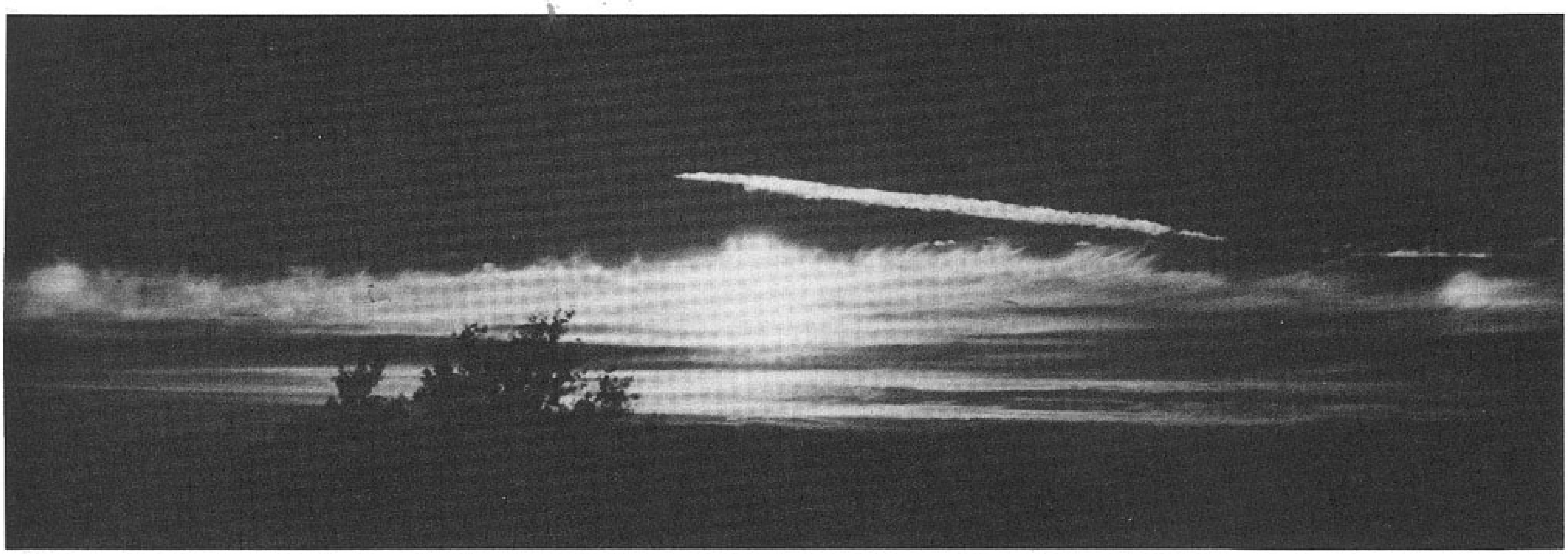
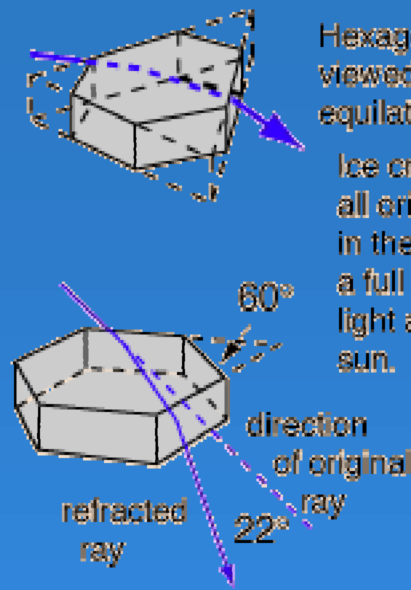


FIGURE 2.73

Photograph of the sun flanked by sun dogs on each side.


© Joe Orman



Hexagonal ice crystals can be viewed as part of an equilateral 60° prism.

Ice crystals at all orientations in the sky give a full circle of light around the sun.

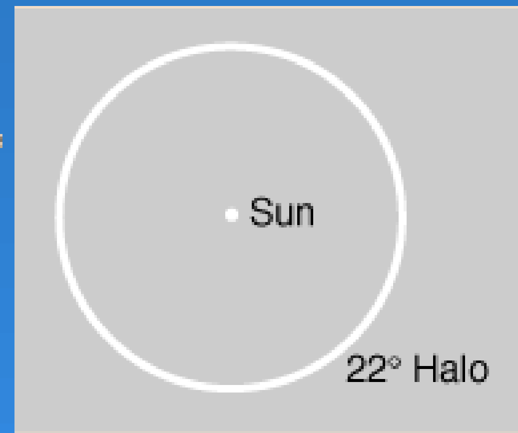
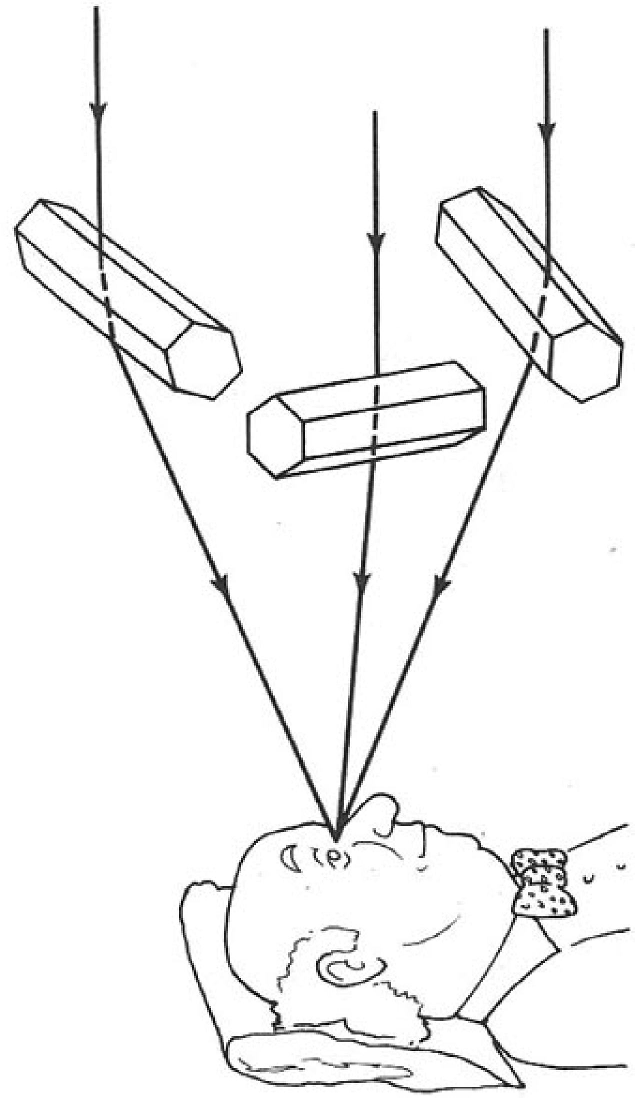


FIGURE 2.74

The 22° halo, caused by tiny pencil-shaped ice crystals. As in Figure 2.72b, only those crystals that are at 22° from the eye send light to it.



Solar halo at Manresa beach April 2003

- **Halo and sub halo**

- **22° halo around the moon**

- **22° Halo around the sun Note the sun is blocked to see the halo better**

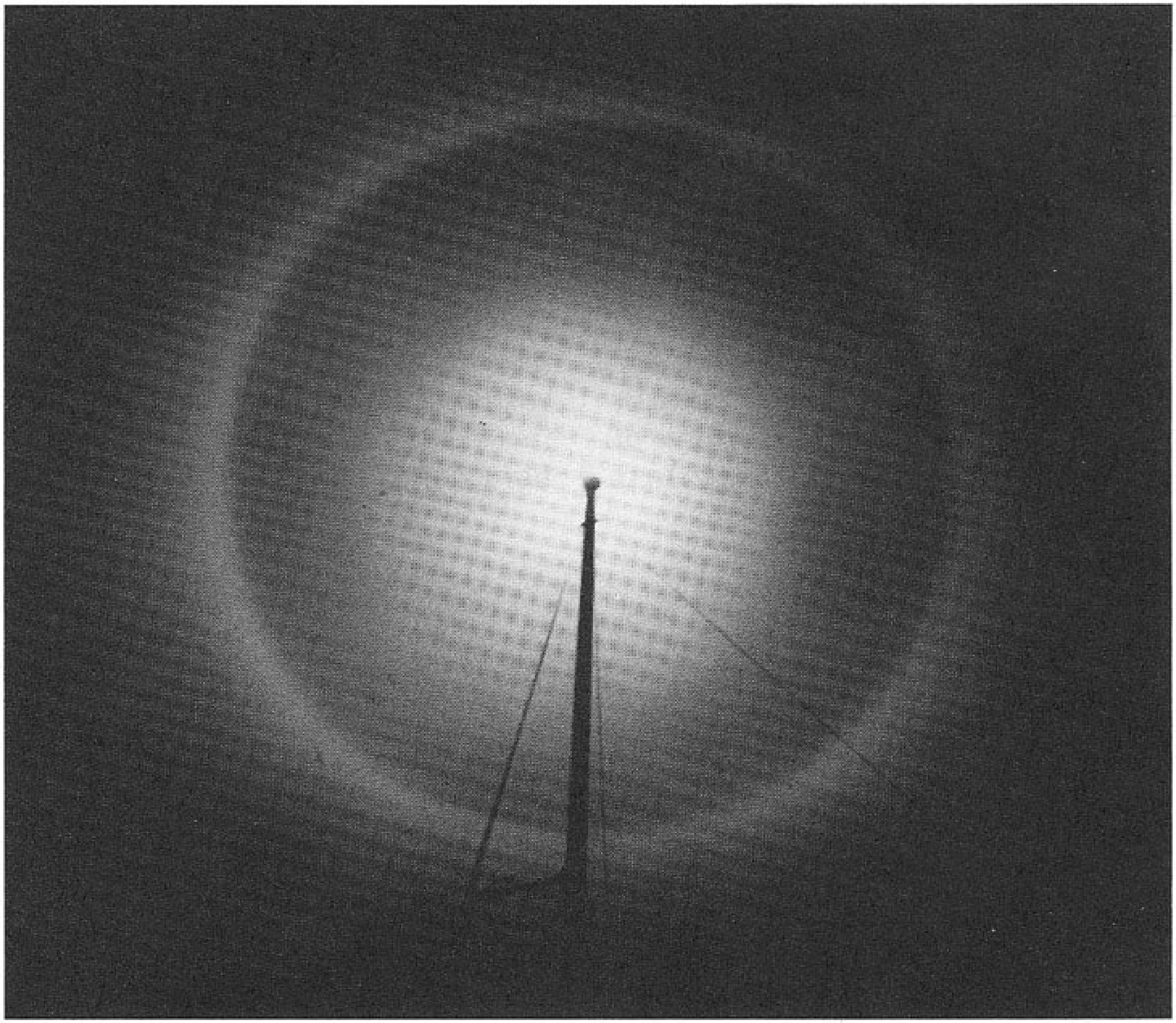
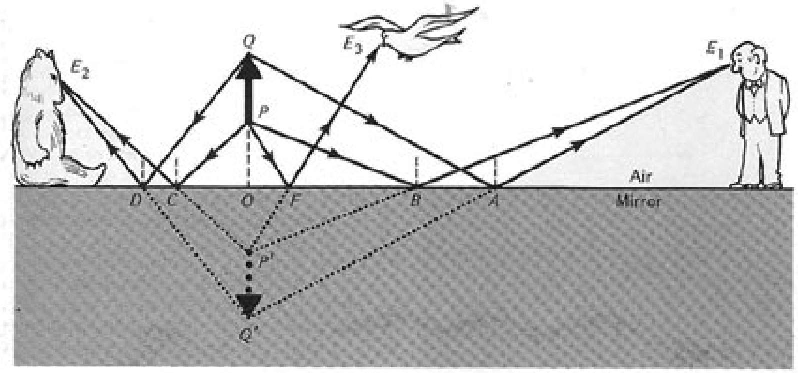
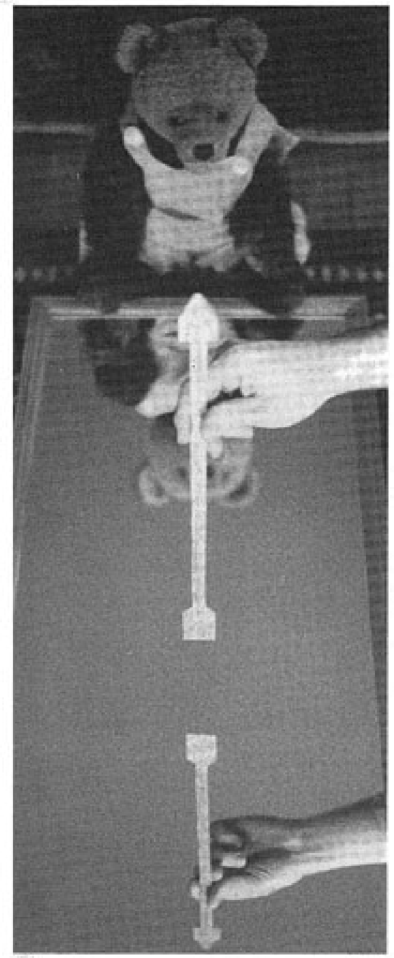


FIGURE 2.75

Photograph of a 22° halo.



(a)



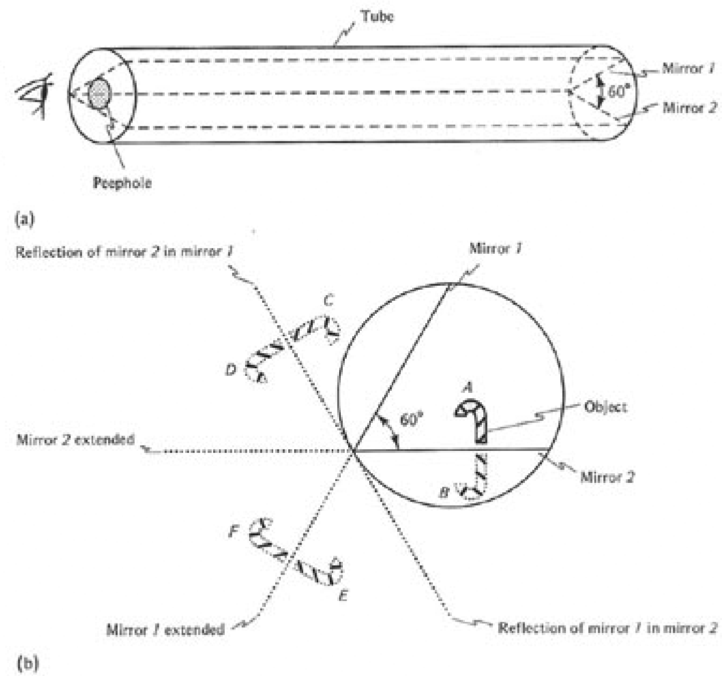
(b)

FIGURE 3.2

(a) Rays from an object that reach three different eyes can be used to locate the image. **(b)** Photograph taken from the position of eye E_3.

FIGURE 3.3

(a) Construction of a kaleidoscope. (b) A kaleidoscope view. An object, *A*, is placed between the two mirrors. You see the object directly. The object is also reflected in mirror *2*, so you also see a virtual image at *B*. As this is an image, the light appears to come from *B* just as if there were an object there. Hence both the object, *A*, and the image, *B*, are reflected in mirror *1* and their virtual images are located at *C* and *D*. (*D* is an image of an image.) Thus, looking in the peephole between the mirrors, you see what appear to be objects at *C* and *D* (outside the actual tube). Again, these are reflected in mirror *2*, and the new virtual images occur at *E* and *F*. The final pattern observed is then the object, *A*, and the five virtual images, *B* to *F*, arrayed in the threefold symmetric pattern shown. (c) Photograph of object reflected in two mirrors: (1) mirrors at 60°, (2) mirrors at 45°, (3) mirrors at 36°, and (4) mirrors at 50°, a nonintegral fraction of 360°.



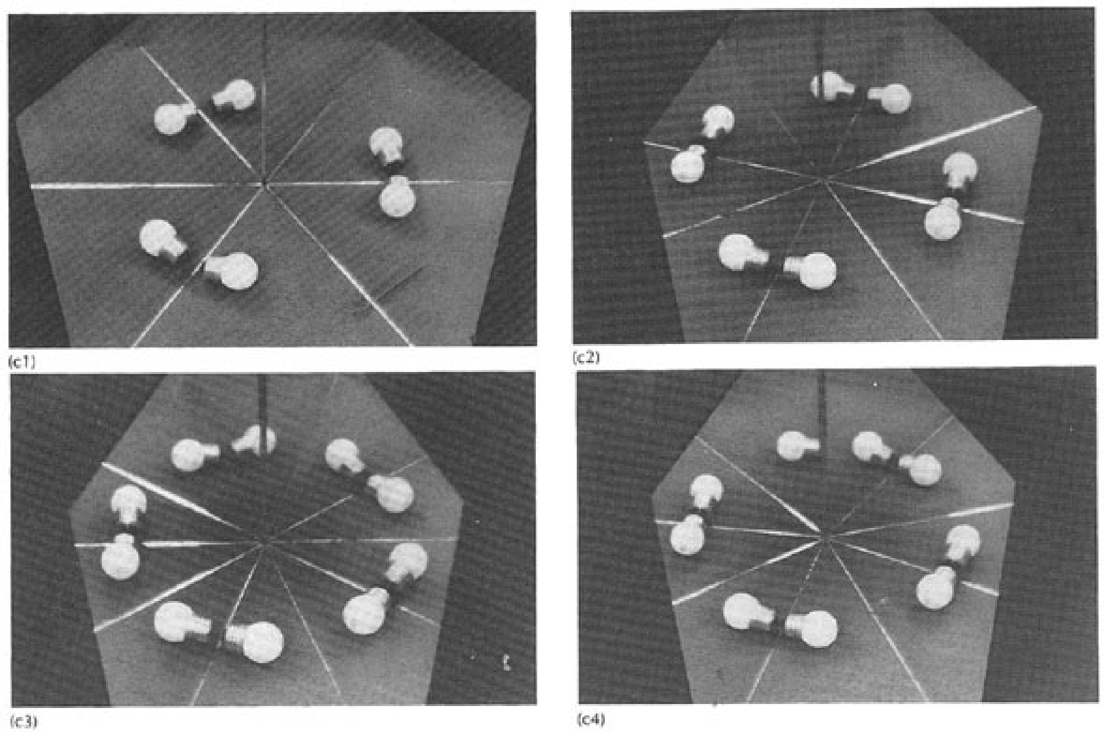
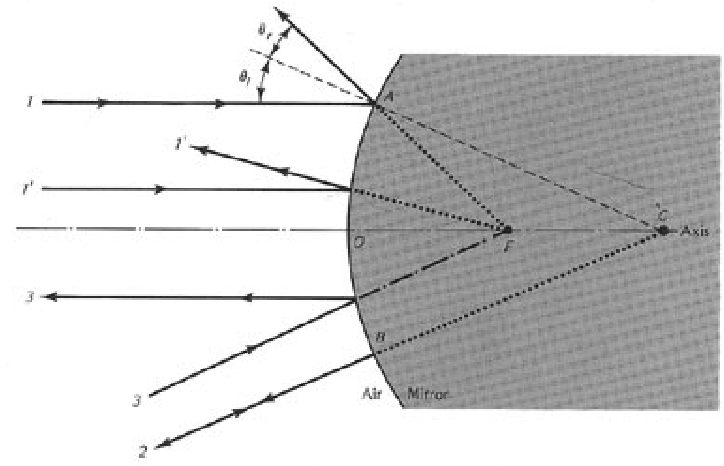
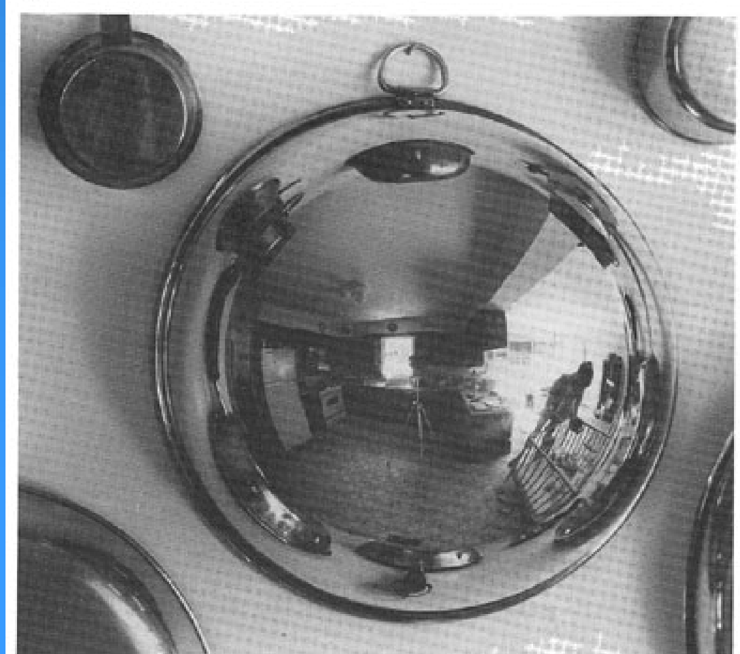


FIGURE 3.5

(a) Light rays illustrating the three rules, incident on a convex spherical mirror. Note direction of the rays—they are *not* all incident parallel to the axis! In this two-dimensional diagram and throughout the rest of the book, the three-dimensional spherical mirror appears as a part of a circle. **(b)** A shiny copper bowl makes a fine convex spherical mirror.



(a)



(b)

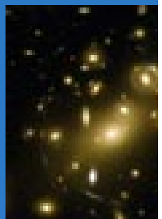
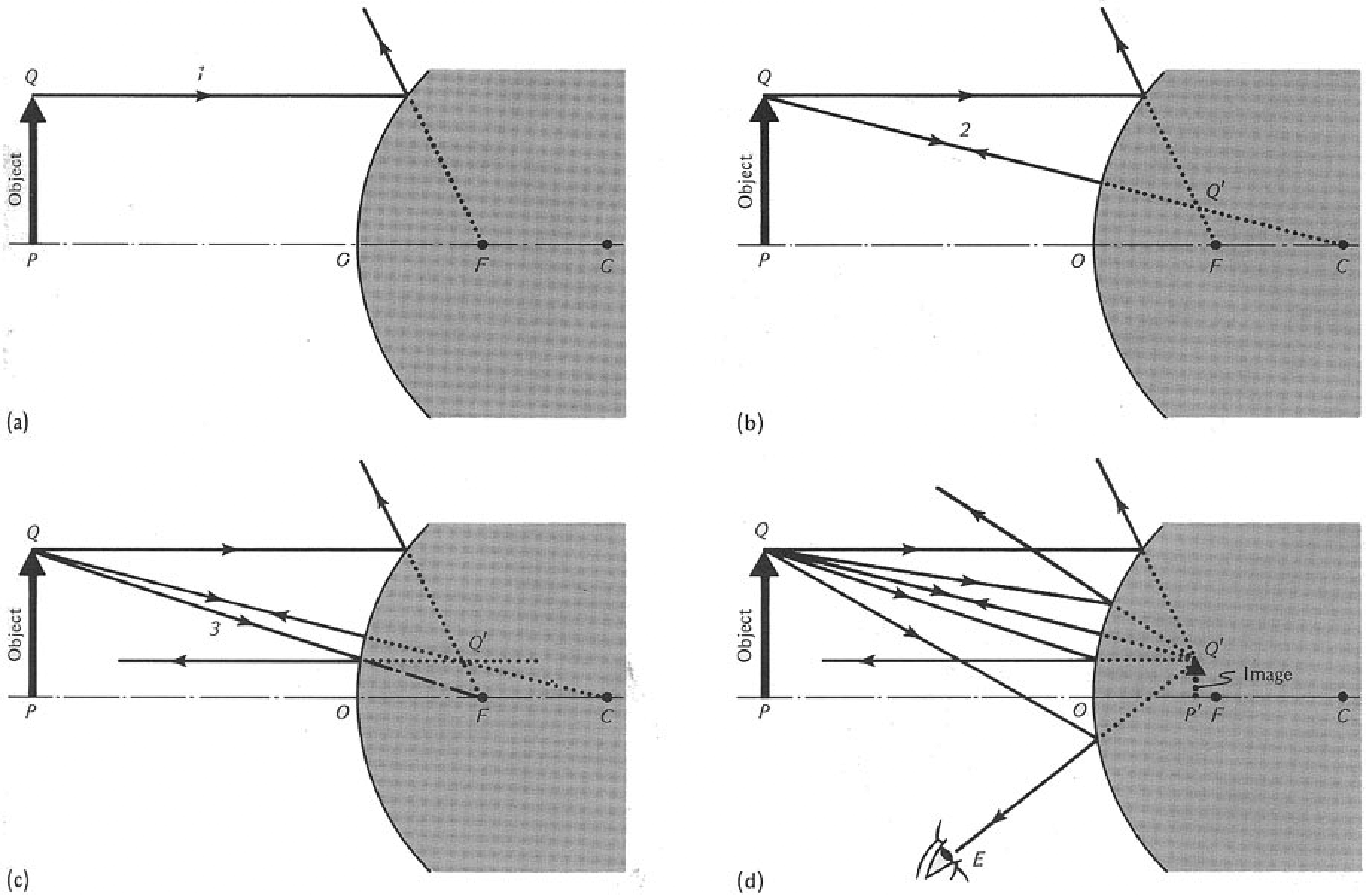


FIGURE 3.6

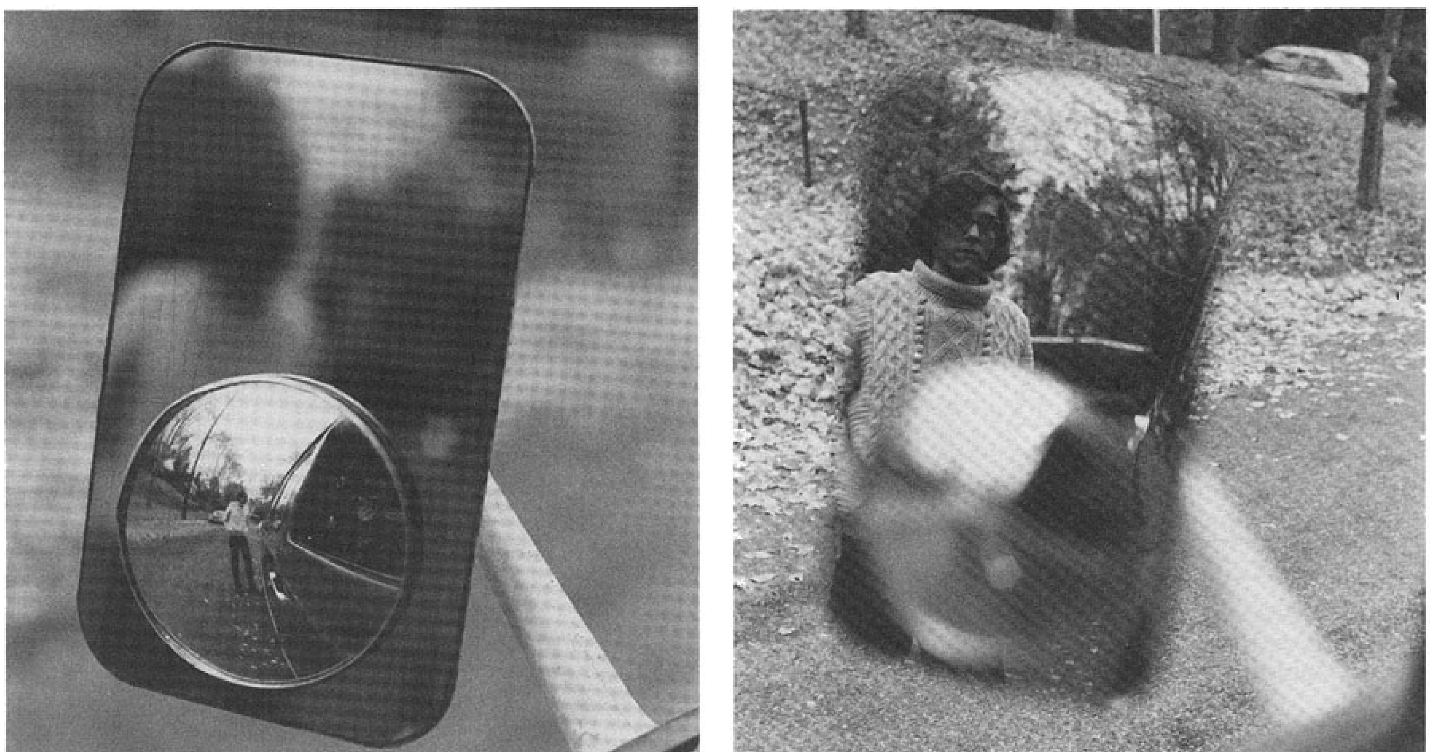
Construction of the image in a convex mirror: **(a)**, **(b)**, and **(c)** show the use of ray *1*, ray *2*, and ray *3* rules respectively; **(d)** shows how you can mass produce other rays—for example, one going to eye *E*—once you have found the image.



Images from convex mirror

FIGURE 3.7

Photograph of a convex mirror used to give a wide-angle view. The plane mirror on which it is mounted shows the normal view. **(a)** The camera is focused on the image in the convex mirror, just behind the mirror (see Fig. 3.6). **(b)** The camera is focused on the image in the plane mirror, as far behind the mirror as the object is in front. From a distance, your eye can focus on both images simultaneously.



(a) (b)

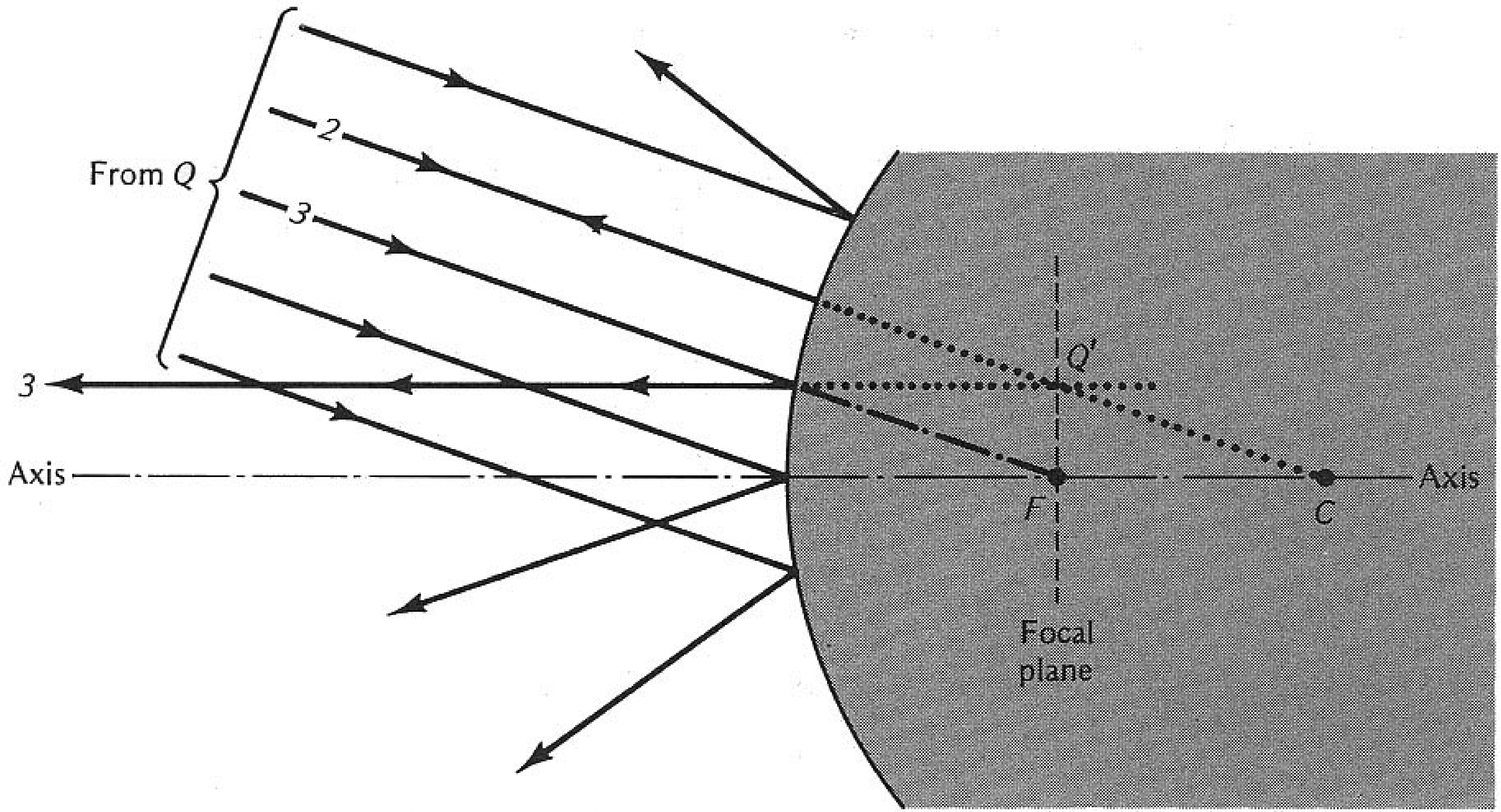


FIGURE 3.8

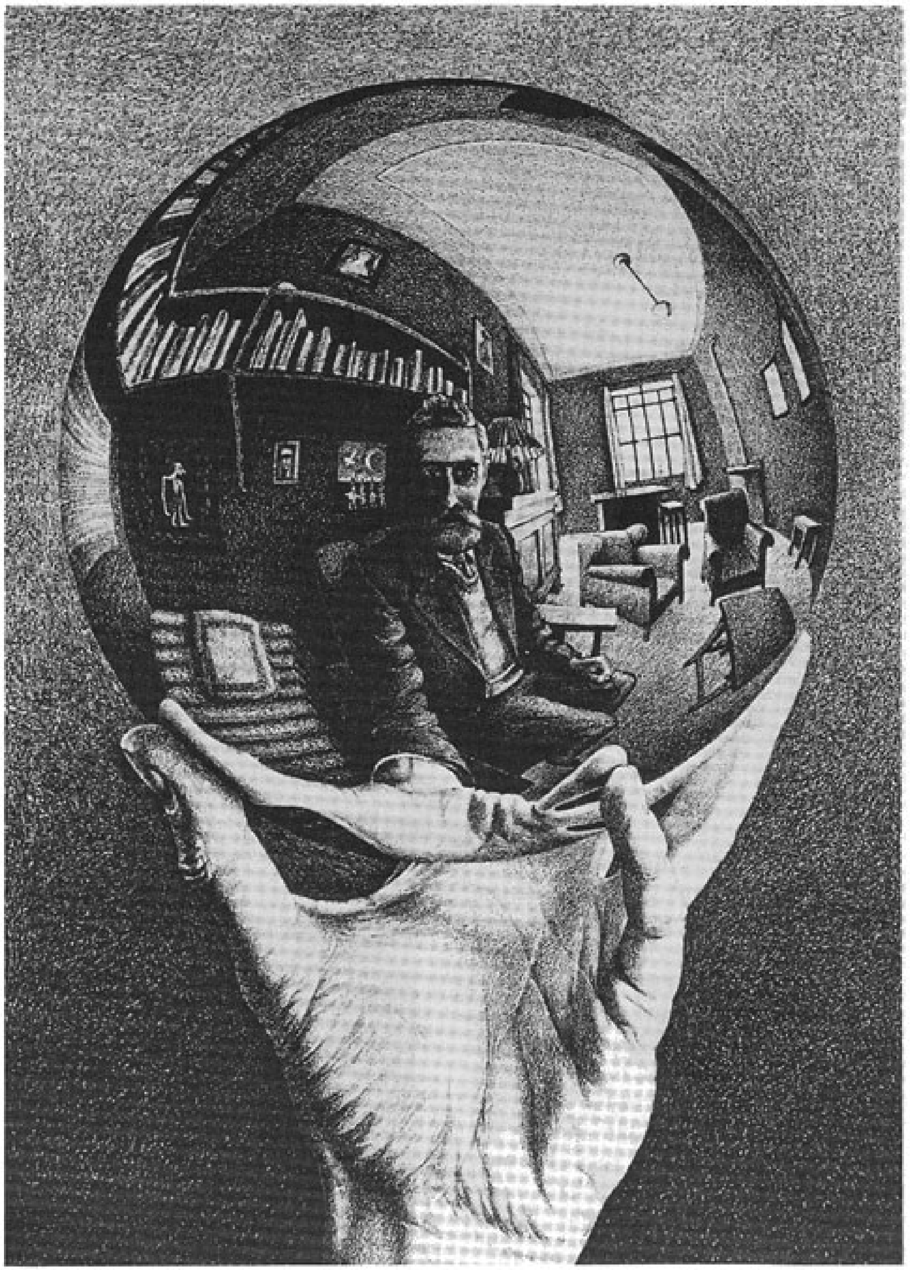
An object Q, too distant to be shown, sends parallel rays to a convex mirror. Its image, Q', lies in the mirror's focal plane.

Reflection from sphere

- **Escher drawing of images from convex sphere**

FIGURE 3.9

M. C. Escher, "Hand with Reflecting Globe."



- **Anamorphic mirror and image**

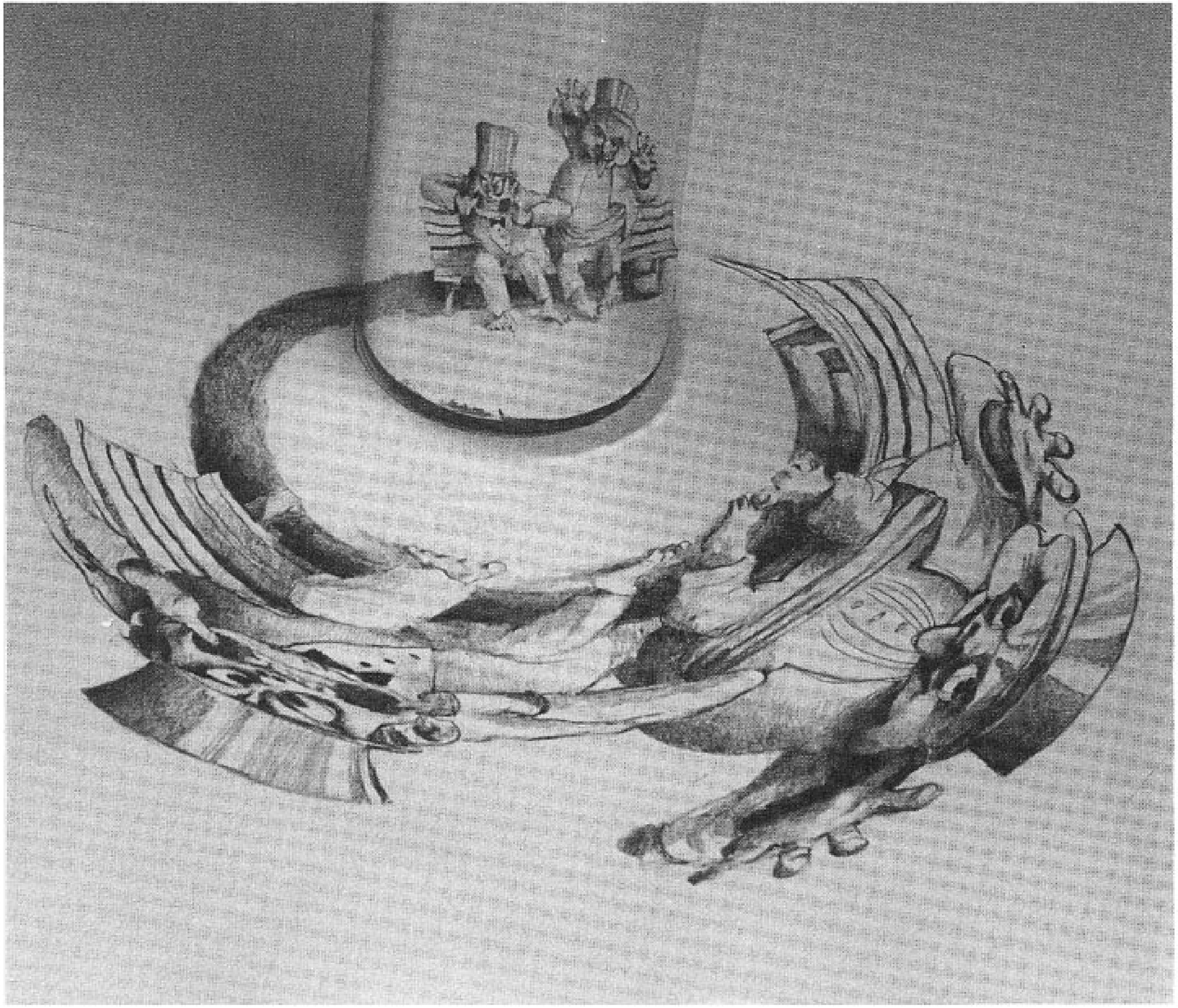


FIGURE 3.10

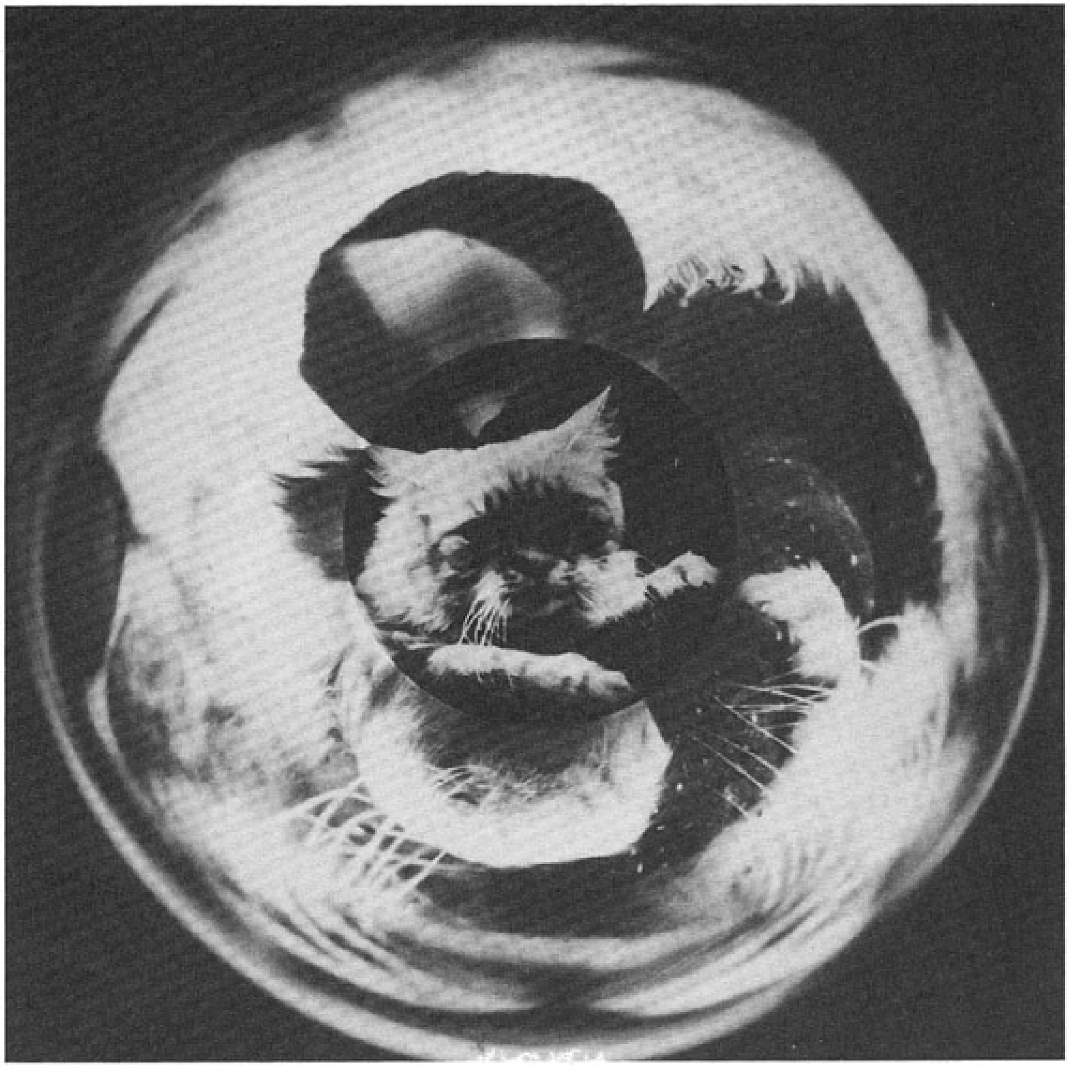
Cylindrical anamorph, with mirror that reconstructs the image.

- **Anamorphic mirror (conical)**

2003 April 24

FIGURE 3.11

A conical anamorphic photograph, made by the method of the TRY IT. The conical mirror in the center reconstructs the undistorted image from the anamorph surrounding it, so you see the cat's head in the central circle surrounded by the deformed image.



- **The artist Hans Holbein made anamorphic paintings**

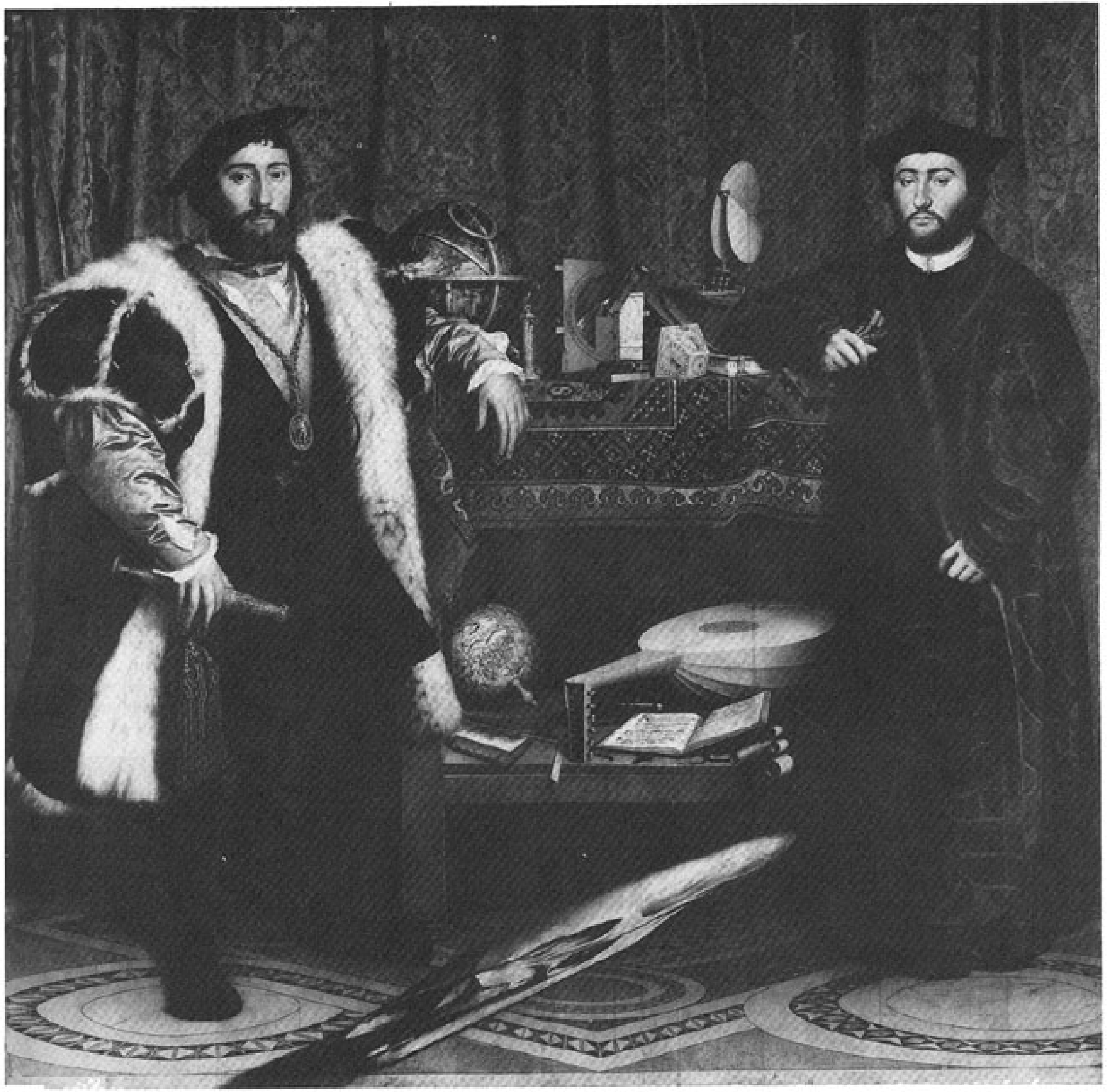


FIGURE 3.12

Hans Holbein's "The Ambassadors." View the streak across the foreground of the picture from the upper right. (Reproduced by courtesy of the Trustees, The National Gallery, London.)