BASIC OPTICAL PROPERTIES OF MIRRORS, PRISMS, AND LENSES (OPTICAL DISK)

OBJECT: To study the basic optical properties of mirrors, prisms, and lenses by the use of an optical disk.

METHOD: A light source sends parallel rays of light to an optical disk. The paths of the rays are observed after they strike various optical devices, such as mirrors, prisms, and lenses, which are mounted on the disk. From these observations the fundamental principles that govern the reflection and refraction of light are studied.

THEORY: A beam of light can be represented by a single line, a ray, parallel to the direction in which the light is propagated. When a beam of light strikes a surface of a different medium some of the light may be reflected, some may be transmitted, and the remainder is absorbed. The light which is reflected from a smooth surface and that which is transmitted through the medium obey certain elementary laws. Those laws will be studied in this experiment.

A. Reflection of Light. The angle between an incident ray and the normal to the surface is called the *angle of incidence i*. The angle between the reflected ray and the normal is called the *angle of reflection r*. By the law of reflection the

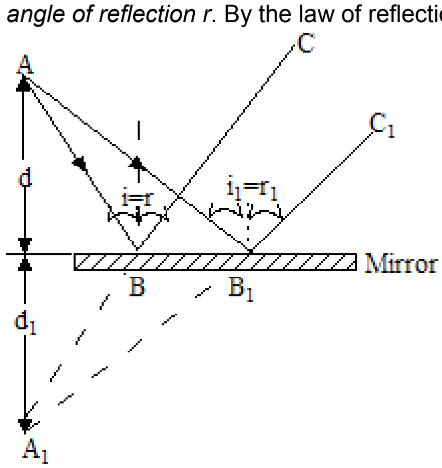

Fig. 1. Reflection of light by plane mirror.

angle of incidence is equal to the angle of reflection, as shown in Fig. 1. When the reflected beam, formed by the diverging rays *BC* and B_1C_1, is viewed by the eye of an observer, it seems to converge at the point A_1, and this *virtual image* appears to the observer as if it were the source of the light.

The position of the image of an extended object formed by a plane mirror may be readily located by a ray diagram, following the law of reflection, Fig. 2. The image is virtual, as far behind the mirror as the object is in front of the mirror, and the same size as the object. A plane mirror does not change the curvature of the wave front of the light beam incident upon it.

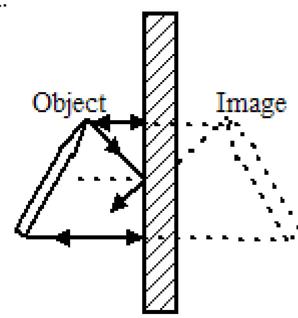

Fig. 2. Image of an extended source formed by a plane mirror.

If the reflecting surface is curved, the same law of reflection holds at each point as for a plane mirror, but the size and position of the image are quite different. Spherical mirrors are classified as *concave* or *convex* when the reflecting surface is on the inside or outside, respectively, of the spherical shell, Fig. 3. The *center of curvature C* is at the

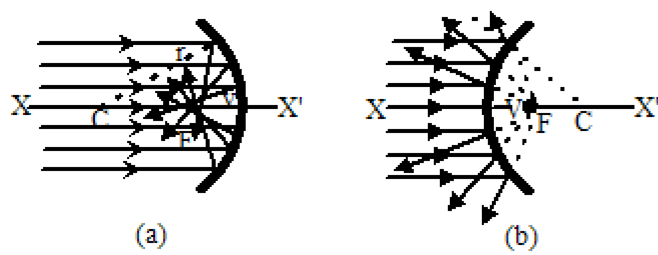

Fig. 3. Reflection of parallel rays:
(a) from concave mirror and
(b) from convex mirror.

center of the sphere. The *radius of curvature r* is the radius of the sphere. A line connecting the vertex *V* and the center of curvature *C* is called the *principal axis*. In Fig. 3 there are also shown incident light rays parallel to the principal axis of the mirrors. From the law of reflection it follows that these rays will converge through a common point *F* after reflection from a concave mirror, or will diverge after reflection from a convex mirror, as though they originated from a common point *F* behind the mirror. Such a point is called the principal focus of the mirror. The distance of the principal focus from the mirror vertex is called the focal length f. It can be shown that $r = 2f$.

Simple geometrical constructions are available for locating images formed by spherical mirrors, as shown in Fig. 4.

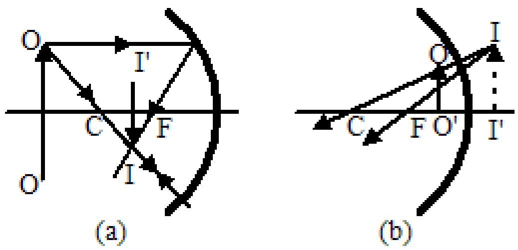

Fig. 4. Location of images formed by concave mirror.

Two rays from any point *O*, whose directions after reflection can readily be predicted, are drawn: first, the ray parallel to the principal axis, which after reflection passes through *F*; and second, a ray from *O* in the direction *OC* through the center of curvature, which strikes the mirror normally and is reflected back upon itself. The intersection of these two rays at *I* locates the image of *O*. Another similar pair of rays could be drawn from *O*' to locate *I'*. The image depicted in Fig. 4a is *real*, since it is formed by converging rays that could form an image on a screen at *II'*. In Fig. 3b the reflected rays are diverging, as if they came from *II'*; such an image is said to be *virtual.* The image of any real object formed by a convex mirror (Fig. 5) is always virtual, erect, and diminished.

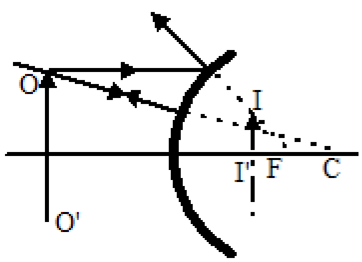

Fig. 5. Location of image formed by convex mirror.

There is a simple relation between the distance p of an object from the mirror, the distance *q* of the image from the mirror, and the focal length f; this relationship makes it easy to locate images in spherical mirrors. This *mirror equation* is

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \qquad (1)$$

This equation can be used for both concave and convex mirrors if the following convention with regard to the algebraic signs of the quantities in Eq. (1) is used: *f* is positive for concave mirrors, negative for convex mirrors; *p* is positive for real objects arid negative for virtual objects; *q* is positive for real images and negative for virtual images.

Only the rays which are parallel to the principal axis and which are close to the axis are focused at the principal focus. The extreme rays farther from the axis in a mirror of large aperture (Fig. 6) cross the axis closer to the mirror than do the rays reflected nearer the center. This imperfection of

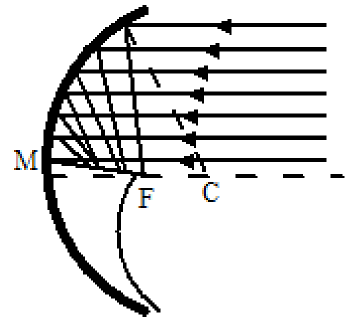

Fig. 6. Spherical aberration.

spherical mirrors is called *spherical aberration*. It results in a blurring of the image. The trace of the surface formed by the intersecting rays is called the *caustic curve* of the mirror. Spherical aberration can be minimized by using a diaphragm in front of the mirror to block off the rays far from the axis.

B. Refraction of Light. When light passes obliquely from one medium into a second medium, it undergoes an abrupt change in direction if the speed of light in the second medium differs from the speed in the first medium. This bending of the light path is called *refraction*. If the speed of light in the second medium is less than the speed in the first medium, the second medium is said to have a greater *optical density* and the ray is bent *toward* the normal. When light travels from an optically more dense medium into one of lesser optical density, the ray is bent *away from* the normal. The angle between the refracted ray and the normal to the surface is called the *angle of refraction r*.

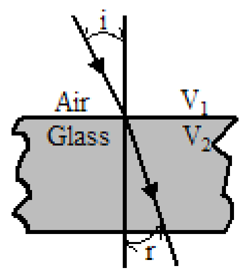

Fig. 7. Refraction at a plane surface.

In Fig. 7 a ray of light is shown passing from air to glass. The angle of refraction *r* is less than the angle of incidence *i*. There is an experimental relationship between these two angles known as *Snell's law of refraction,* namely: The ratio of sin *i* to sin *r* is a constant (for a given wave length of light and pair of substances). This constant is known as the index of refraction n of the second medium relative to the first. Expressed in equation form

$$\frac{\sin i}{\sin r} = n \qquad (2)$$

It may also be shown that

$$n = v_1 / v_2 \qquad (3)$$

where v_1 and v_2 are the speeds of the light in the first and second mediums, respectively.

When light passes from an optically dense medium, such as glass, into a medium of lesser optical density, such as air (Fig. 8), the angle of refraction *r* is greater than the angle of

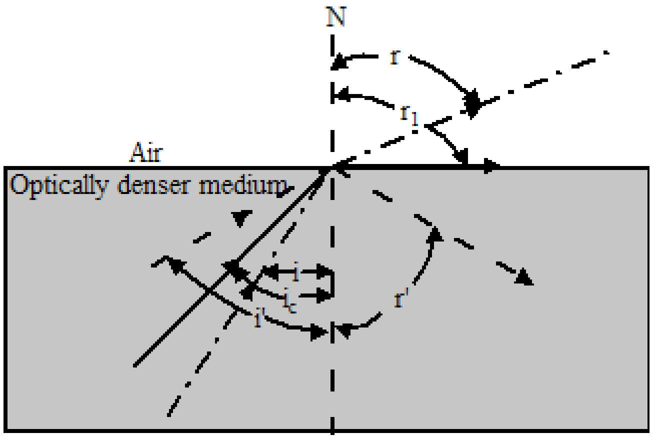

Fig. 8. Total internal reflection.

incidence *i*, and *r* increases more rapidly than does *i*. The value of *r* approaches the limiting value of 90°, beyond which no light is refracted into the air. The angle of incidence in the denser medium, for which the angle of refraction is 90°, is called the *critical angle of incidence* i_c. From Snell's law of refraction it follows that, when the medium of lesser optical density is air,

$$\sin i_c = 1/n \tag{4}$$

When the angle of incidence is increased beyond its critical value, the light is totally reflected, making the angle of reflection *r'* equal to the angle of incidence *i*. Total reflection can take place only when the light in the optically denser medium is incident on the surface separating it from the medium of lesser optical density, and the angle of incidence is greater than the critical angle.

C. Dispersion. The index of refraction of light depends in a non-linear manner upon the wavelength of the light and the nature of the refracting substance. Blue-producing light is refracted more than red-producing light. The separation of complex light into its differently colored rays is called *dispersion*.

D. Prisms. A transparent body bounded by two plane faces which are not parallel is called a *prism*. It often is desirable to use prisms for the deviation or the dispersion of light. In a triangular prism the angle of deviation is determined by the angle of the prism, its index of refraction and the angle of incidence of the entering ray. When light passes through a glass prism in air the ray is bent toward the thicker part of the prism.

E. Lenses. A transparent body with regularly curved surfaces ordinarily produces changes in the path of light; such a body is called a *lens*. The most common forms of lenses are those in which at least one surface is a part of a sphere. As shown in Fig. 9a, rays parallel to the principal axis, after passing through a convex (converging) lens, will converge to the principal focus *F*; rays parallel to the principal axis, after passing through a concave (diverging) lens, diverge from the principal focus, at which a virtual image is formed, Fig. 9b. As in the case of spherical mirrors, rays not near the principal axis are focused closer to the lens than are the central rays. This *spherical aberration* is minimized by use of a diaphragm to decrease the aperture of the lens. This small aperture produces a sharper image but reduces its brightness.

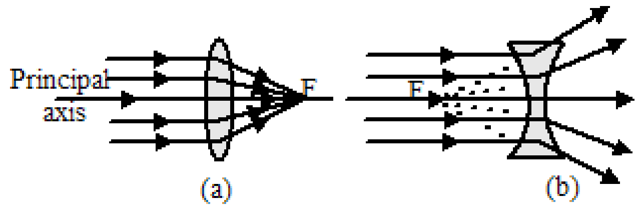

Fig. 9. Focusing of light:
(a) by a conversion lens and
(b) by a diverging lens

APPARATUS: Hartl optical disk, with accessories, Figs. 10 and 11; illuminator, Fig. 12; ruler; protractor, compass; cross- ruled paper.

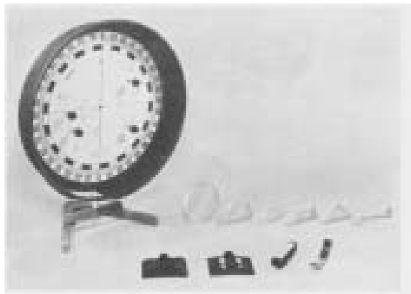

Fig. 10 Hartl optical disk.

The optical disk consists of an aluminum disk surrounded by a sheet metal screen. These two parts turn independently upon the same horizontal axis. The disk is etched in degrees

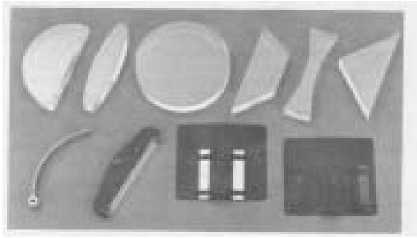

Fig. 11. Accessories for optical disk.

marked on a circular scale around the circumference and two diameters are marked upon it. The screen has as its center a square opening over which slotted plates can be attached. The optical accessories, Fig. 11, consist of a set of four concave and convex lenses, two prisms and a plane, a concave and a convex mirror. Any one of the mirrors may be attached to the face of the disc by means of thumbscrews. The lenses and prisms are frosted on one side so that the path of the light in the glass may be seen just as it is seen on the face of the disc. So that lenses and mirrors may be placed in the proper position for use, their outlines are marked upon the disc. These outlines are so positioned that the necessary angles, such as the angles of incidence, reflection, refraction, etc., may be obtained from the graduated circle.

A steady, intense beam of parallel rays of light may be obtained either from a carbon arc illuminator or from a concentrated filament incandescent lamp illuminator, Fig. 12.

Fig. 12. Concentrated filament illuminator.

PROCEDURE: I. Preliminary Adjustments.

1. Place the disk so that a beam of parallel rays from the illuminator strikes the edge of the disk. Turn the screen so that it is between the illuminator and the disk. Adjust the illuminator until the beam covers most of the opening in the screen and traces its path across the face of the disk. Put the three-slot plate in place and cover the two slots on each side of the central slot. Adjust the disk and screen until the beam of light crosses along the zero axis of the disk. The angle of incidence of this beam upon any optical device fastened to the disk may be varied at will by leaving the screen stationary and rotating the disk.

II. Plane Mirrors.

2. Fasten the plane mirror to the disk so that the face of the mirror coincides with the 90-90 diameter of the disk (see Fig. 10). Arrange the screen so that the beam passes along the 0-0 axis of the disk (Fig. 10) and strikes the mirror exactly at the center of the disk, Fig. 13. Turn the disk so that several angles of incidence and reflection can be observed and recorded. Do these data obey the law of reflection?

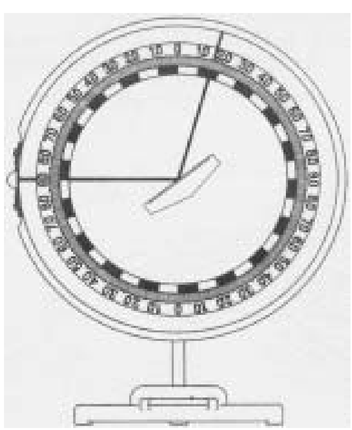

Fig. 13. Reflection of a beam of light from a plane mirror.

3. Substitute the seven-slot plate and check to see if parallel rays are still parallel after reflection from a plane mirror (Fig. 14).

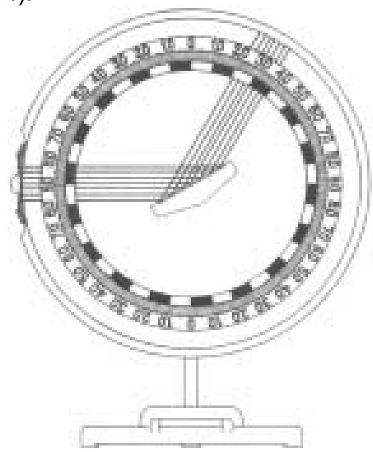

Fig. 14. Reflection of parallel rays from a plane mirror.

III. Spherical Mirrors.

4. Arrange the slot covers to obtain only a single beam of light. Fasten the concave mirror to the center of the disk. (It is sometimes desirable to put a piece of paper under the back edge of the mirror to tip it slightly forward.) Rotate the disk until the single light ray crosses the center of the disk in the axis of the mirror. Leave the disk stationary and rotate the screen slightly backward and forward to move the ray parallel to itself across the face of the mirror. The reflected ray will be seen always to pass through one point on the axis of the disk. Mark this point. What is it called?

5. Attach a piece of cross-ruled paper to the disk with masking tape and sketch the mirror, rays, principal axis, and principal focus. Measure *f* and compare it with the radius of curvature of the mirror as determined by a compass and ruler.

6. Adjust the screen and disk so that the ray passes through the center of curvature of the mirror. Record the way in which this ray is reflected.

7. Use the seven-slot plate to check the location of the principal focus of the mirror (Fig. 15).

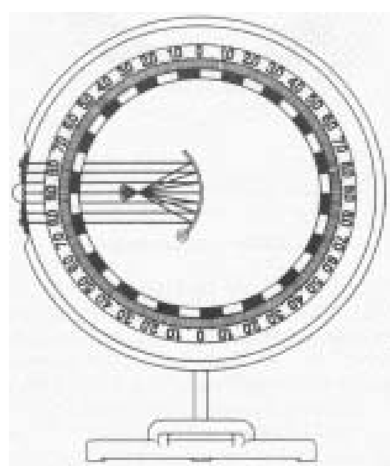

Fig. 15. Principal focus of a concave mirror.

8. Remove the slotted plate and use the full opening. Note the spherical aberration and the caustic curve.

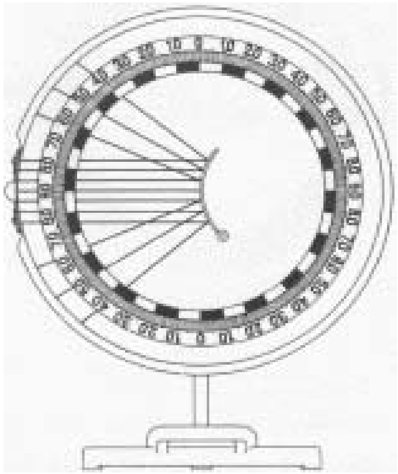

Fig. 16. Principal focus of a convex mirror.

9. Turn the disk so that the convex side of the mirror faces the opening, and repeat the appropriate observations as in Step 4. Use the seven-slot plate to trace with dotted lines the reflected rays back to the virtual principal focus (Fig. 16).

IV. Refraction of Light.

10. Attach the semi cylindrical glass plate to the disk so that the straight edge coincides with the 90-90 diameter (Fig. 17). Adjust the screen so that the single ray touches the flat edge at the 0-0 axis.

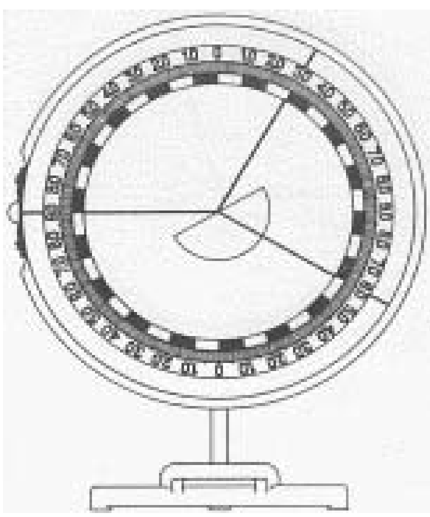

Fig. 17. Reflected and refracted rays, air to glass surface.

Sketch the reflected and refracted rays. Compare the angle of incidence with the angle of reflection and the angle of refraction. Read the angles of refraction for several angles of incidence, such as 30°, 40°, and 55°. Compute the corresponding values of the index of refraction and comment on the results.

11. Rotate the disk through 180° and send the light through the glass in a direction opposite to that of Step 10 (Fig. 18). Note the reflected and refracted rays. Compare the angle of incidence with the angle of reflection; with the angle of refraction. What difference is seen as compared with Step 10? Note the new angles of refraction when the same angles of incidence are used as were observed in Step 10. Do the observations indicate that the light paths are reversible?

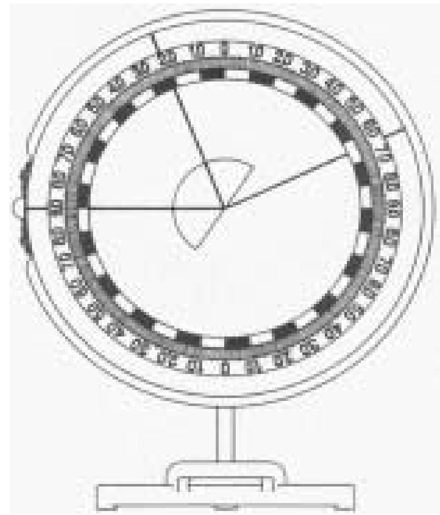

Fig. 18. Reflected and refracted rays, glass to air surface.

V. Total Internal Reflection.

12. Vary angle *i* and note that as *i* is increased, the intensity of the refracted ray is decreased. Turn the disk carefully near an angle of incidence of about 41.5° and note the value of the critical angle for which the refracted ray is parallel to the surface (Fig. 19). Measure the critical angle for white, red, and blue light, obtained by covering the slit with colored glass. Comment on the values of the index of refraction.

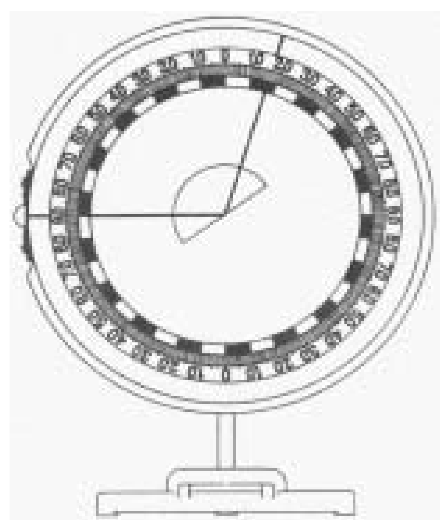

Fig. 19. Total internal reflection.

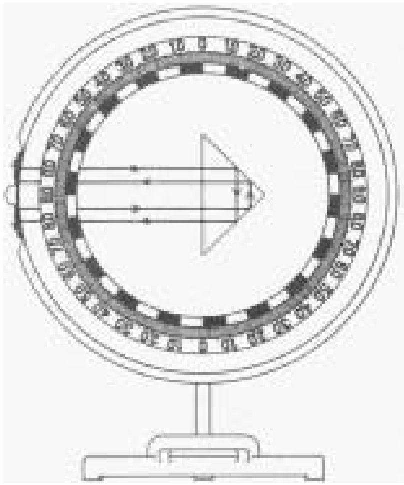

Fig. 20. Totally reflecting prism.

13. Insert the 90° prism so that the long face is on the vertical 90-90 axis, with the apex of the prism toward the right (Fig. 20). Use two differently colored rays to show the paths of the rays that are totally internally reflected. Turn the disk through 45° so that the rays fall perpendicularly on one leg face and trace the totally internal-reflected rays. This is an example of the use of such a prism in modern field glasses.

VI. Refraction Through a Parallel Plate.

14. Arrange the trapezoidal glass plate on the disk in such a position that a ray enters one of the parallel surfaces and emerges at the other (Fig. 21). Note the relative directions of the incident and emergent beams. Repeat for several angles of incidence and comment on the results.

VII. Refraction by a Prism.

15. Rearrange the trapezoidal prism so that first the 45° and then the 60° angle can be bisected by the 90-90 diameter (Fig. 22). Use a colored glass over the slit to obtain a monochromatic beam and, thus, avoid dispersion.

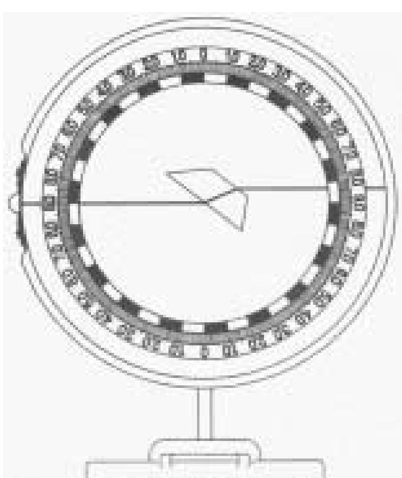

Fig. 21. Refraction by a parallel plate.

Let the single beam fall on the edge of the glass so that half the beam passes through the glass and the other half passes by the edge undeviated. Read the deflection caused by the glass. Record the deviation both for the 45° angle and the 60° angle. Comment on the variation of the deviation with the refracting angle of the prism.

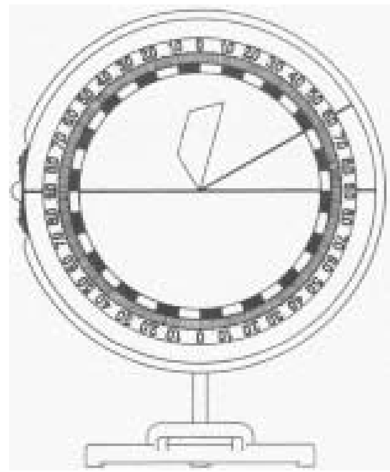

Fig. 22. Refraction by a prism.

16. With the single beam of white light, hold a prism against the disk behind the square opening of the screen. Note the dispersion of the white light into a prismatic spectrum. Record the colors in their order of deviation.

VIII. Refraction by Lenses.

17. Fasten the convex lens to the disk parallel to the 90-90 diameter (Fig. 23). Send a single beam along the 0-0 axis passing through the center of the lens. Rotate the disk through a small angle on either side of the initial position and observe the incident and emergent rays. When such a ray passes through the optical center of a lens, how does it emerge?

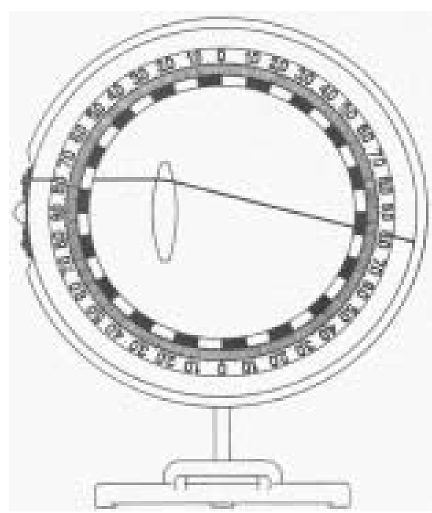

Fig. 23. Refraction by a convex lens.

18. Turn the disk so that the 0-0 diameter (axis of lens) is parallel to the incident ray. Rotate the screen about its horizontal axis and note that the refracted ray turns about one point on the disk. What is this point called? Record this location of the principal focus *F* of the lens. Show the location of *F* by using the plate with seven slits (Fig. 24). Remove the slotted plate and shine the light through the square opening. Is the light sharply focused? Sketch the caustic curve.

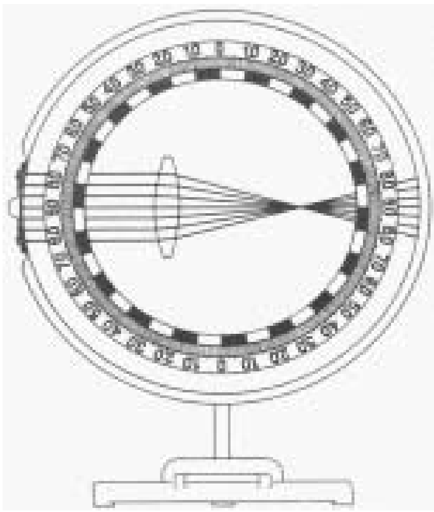

Fig. 24. Principal focus of convex lens.

19. Attach the concave lens in place of the convex lens. Use the seven parallel rays to trace the paths of the diverging rays and to locate the virtual principal focus of the lens (Fig. 25). Is this focus sharply identified? Explain?

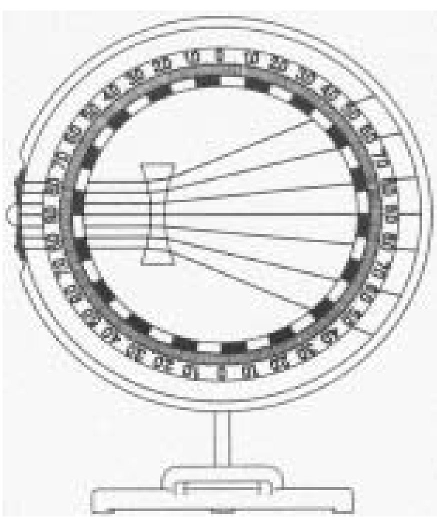

Fig. 25. Principal focus of concave lens.

QUESTIONS: 1. Show geometrically that the image of an object formed by a plane mirror is as far behind the mirror as the object is in front of the mirror. Use the spherical-mirror equation to justify this same fact.

2. If light waves are to converge to a point after reflection from a plane mirror, what must be their form before reflection? Explain by a sketch.

3. Justify geometrically the fact that when a plane mirror is rotated, the beam of light reflected from it rotates through twice the angle turned by the mirror.

4. Is it truthful to say that the image seen in a plane mirror is located behind the mirror?

5. An observer moves toward a mirror at a speed of 5mi/hr. At what speed does his image move toward him?

6. Mention a number of practical uses of (a) concave and (b) convex mirrors.

7. What effect is produced on the curvature of a plane wave by a plane mirror? By a concave mirror? By a convex mirror? By a concave lens?

8. Mention several conditions under which a double convex glass lens will produce diverging rays.

9. A glass concave lens (n = 1.52) has a focal length of 15 cm in air. How would this focal length be affected if the lens were placed in water (n = 1.33)? In carbon disulfide (n = 1.64)?

10. A glass prism is placed first in air and then in water. Trace the paths of a beam of light for these two cases. Repeat for an "air prism," that is, a hollow prism made from plane glass sides.