

CHAPTER 4

REFLECTED LIGHT OPTICS

4.1 INTRODUCTION

Light is a form of *electromagnetic radiation*, which may be emitted by matter that is in a suitably “energized” (excited) state (e.g., the tungsten filament of a microscope lamp emits light when “energized” by the passage of an electric current). One of the interesting consequences of the developments in physics in the early part of the twentieth century was the realization that light and other forms of electromagnetic radiation can be described both as waves and as a stream of particles (*photons*). These are not conflicting theories but rather complementary ways of describing light; in different circumstances, either one may be the more appropriate. For most aspects of microscope optics, the “classical” approach of describing light as waves is more applicable. However, particularly (as outlined in Chapter 5) when the relationship between the reflecting process and the structure and composition of a solid is considered, it is useful to regard light as photons.

The electromagnetic radiation detected by the human eye is actually only a very small part of the complete electromagnetic spectrum, which can be regarded as a continuum from the very low energies and long wavelengths characteristic of radio waves to the very high energies (and short wavelengths) of gamma rays and cosmic rays. As shown in Figure 4.1, the more familiar regions of the infrared, visible light, ultraviolet, and X-rays fall between these extremes of energy and wavelength. Points in the electromagnetic spectrum can be specified using a variety of energy or wavelength units. The most common energy unit employed by physicists is the electron volt¹ (eV), whereas

¹One electron volt is the energy acquired by an electron accelerated through a potential difference of one volt.

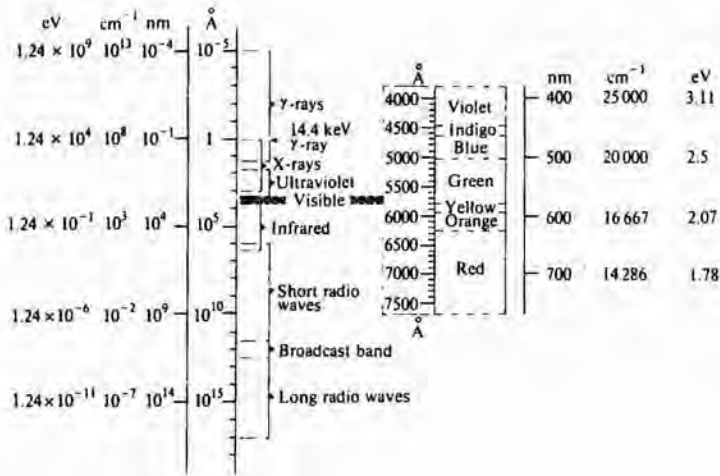


FIGURE 4.1 The electromagnetic spectrum between 10^{-5} and 10^{15} Å. Energies within this range are also shown as wave numbers (cm^{-1}) and electron volts (eV). Energies of the visible light range are shown on an expanded scale. (Reproduced from *Mineral Chemistry of Metal Sulfides* by D. J. Vaughan and J. R. Craig, copyright © 1978, Cambridge University Press, with the publisher's permission).

wavelengths may be expressed in terms of *Angström units* (Å, where $1 \text{ Å} = 10^{-8} \text{ cm}$) or *nanometers* (nm, where $1 \text{ nm} = 10^{-7} \text{ cm} = 10 \text{ Å}$). Another unit employed in the literature of physics and chemistry is the wavenumber, or reciprocal centimeter (cm^{-1}), which, unlike the wavelength units, varies linearly with energy. The nanometer is most commonly used in mineralogical literature and will be used in this book. In Figure 4.1, the relationships between these units are indicated for different regions of the spectrum. Shown in detail is the visible light region, which extends between approximately 390 and 770 nm; particular wavelength regions within this range are characterized by the eye as different colors. Seven primary colors were recognized by Sir Isaac Newton (the “colors of the rainbow”), and their wavelength limits are shown in Figure 4.1. *White light* from the sun or an artificial light source is comprised of contributions from all of these wavelengths. Light of a very limited range of wavelengths, such as the characteristic yellow light from a sodium vapor lamp that consists chiefly of wavelengths 589.0 and 589.6 nm, is described as *monochromatic*.

In further developing the wave description of light, transmission can be considered to occur by a transverse wave motion in which the vibrations are perpendicular to the direction of travel of the energy. A wave resulting from this type of (simple harmonic) motion is shown in Figure 4.2a and has the shape of a sine curve. For such a wave,

$$c = \nu\lambda \quad (4.1)$$

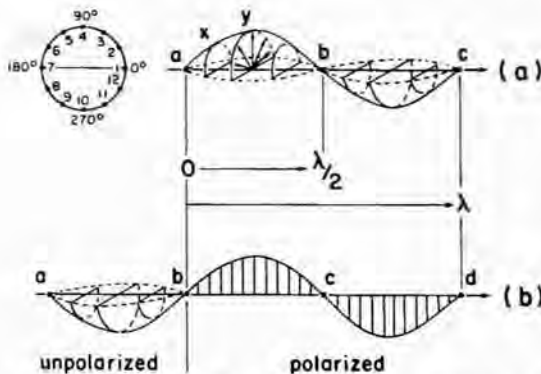


FIGURE 4.2 The wave motion of light showing (a) unpolarized light with the wave motion represented along the propagation direction and normal to it (on the left); (b) unpolarized light in contrast to light that is linearly polarized.

where c = velocity of the wave, ν = frequency of the wave, λ = wavelength. As Figure 4.2a shows, the ray's vibration directions within any plane perpendicular to its path may be represented by a semicircle of radius equal to the vibration of the wave within that plane, except at points a , b , or c , where the vibration is nil. In addition to this, a single wave of this type has a kind of spiraling motion that can best be explained by describing the behavior of a single point on the wave that on progressing from $a \rightarrow b$ changes its direction of vibration with reference to the circular section normal to the line abc . At point a , it can be considered as being at point 1 on the circular section in Figure 4.2; by point X , it will be at 2, point Y at 4, and so on. The position of this single point on the wave is termed its *phase*. Finally, the *amplitude* of the wave is the maximum vibrational displacement (i.e., the radius of the semicircular section at point y in Figure 4.2).

It is possible to restrict the vibration of the light wave illustrated in Figure 4.2a to a single plane, in which case the light is said to be *plane polarized*, although the more correct term *linearly polarized* is less confusing in a discussion of reflected-light optics and will be used in this text. The plane of vibration of this polarized light is that plane parallel to both the path of the ray and the vibration direction.

4.1.1 Interaction of Light with Transparent Media

The velocity of a light wave (c) or other electromagnetic wave is constant in a vacuum (299,793 km/sec) but changes if the wave passes into another transmitting medium, a change expressed by the concept of the *refractive index* of that medium:

$$n = \frac{c}{c_m} \quad (4.2)$$

where n is the refractive index of the medium and c and c_m represent the velocity of light in a vacuum and in the medium, respectively. Since c_m is always less than c , n is always greater than 1.0, although for air $n = 1.0003 (\approx 1)$. Since the refractive index is a ratio of two velocities, it is a dimensionless number.

Those materials through which monochromatic light travels at the same speed, regardless of the direction of light vibration relative to the medium, are optically *isotropic*. A vacuum, all gases, most liquids, glasses, and cubic (isometric) crystalline substances are isotropic; other materials (chiefly non-isometric crystals) are optically anisotropic, and light rays may travel through them at different speeds, depending on the direction of light vibration within them. The *optical indicatrix* shows how the refractive index of a transparent material varies with the vibration direction of the (monochromatic) light wave in the material. If an infinite number of vectors are imagined radiating in all directions from one point within the substance and if each vector has a length that is proportional to the refractive index for light vibrating parallel to that vector direction, then the indicatrix is the surface connecting the tips of these vectors. For an isotropic substance, therefore, the indicatrix is a sphere of radius n (Figure 4.3a). However, it should be noted that the value of n does still vary as a function of wavelength of light. For anisotropic crystals, the refractive index varies with vibration direction in the crystal, even for monochromatic light, so that the indicatrix is not a sphere but an ellipsoid.

The optical indicatrix for crystalline substances with hexagonal (used here as including the trigonal system) or tetragonal crystal symmetry is such that one cross section through the ellipsoid is circular and all other sections are elliptical. The indicatrix is termed *uniaxial*, and the direction normal to this unique circular section is the *optic axis* and is parallel to the c axis of the crystal. The value of the refractive index in this circular section through the ellipsoid (termed the *ordinary* vibration direction and often symbolized as ω or o) may be either the maximum or the minimum value of the refractive index, so that the indicatrix may be either prolate or oblate, as shown in Figures 4.3b and 4.3c. Conversely, the value of the refractive index of the crystal for the vibration along the direction of the optic axis (crystal c axis) and termed the *extraordinary* vibration direction (often symbolized ϵ or e) must also be either a maximum or a minimum value. Materials in which the value ($e-o$) is positive (a prolate indicatrix) are termed *uniaxial positive*; those with ($e-o$) negative (an oblate indicatrix) are termed *uniaxial negative* in their optic signs.

The optical indicatrix for crystalline substances with orthorhombic, monoclinic, or triclinic crystal symmetry, although ellipsoidal (being geometrically termed the "general ellipsoid"), is such that there are two cross sections that are circular, all others being ellipsoidal. Again, the two directions normal to these sections are optic axes, so that the indicatrix is termed *biaxial* (Figure 4.3e). The biaxial crystal has three principal refractive indices that are commonly symbolized α , β , γ , with α and γ being the smallest and largest, respectively. The vector directions corresponding to the α and γ refractive indices are unique directions termed *principal vibration axes* and are symbolized X and Z , re-

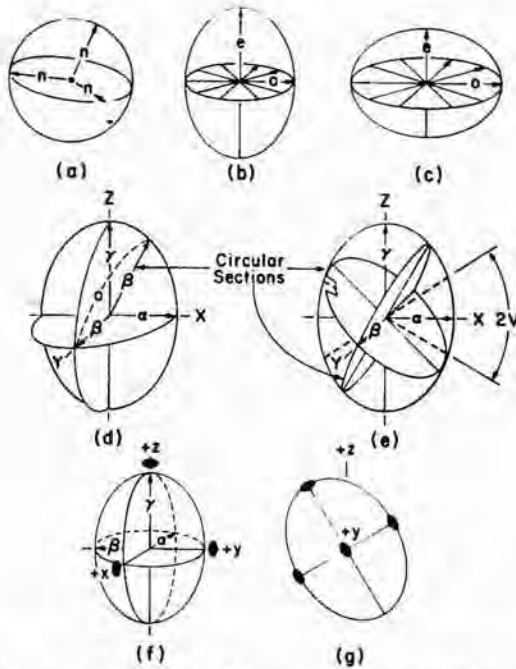


FIGURE 4.3 The optical indicatrix for (a) an isotropic substance, (b, c) a uniaxial positive and negative crystal, (d, e) a biaxial crystal showing principal vibration axes and optic axes, (f, g) crystallographic orientation of the biaxial indicatrix in orthorhombic and monoclinic crystals.

spectively, as shown in Figure 4.3d. These are always orthogonal axes of maximum and minimum length, respectively, and the principal vibration axis (Y), corresponding to the vector direction of the β refractive index, is also always normal to the X and Z axes. However, since the value of β is intermediate between α and γ , there must be an equivalent vector in the arc between the Z and X vibration axes, as shown in Figure 4.3d. There must, in fact, be a complete series of vectors of length β between these two that give a circular section through the indicatrix. Examination of the figure will show that two such circular sections must exist intersecting along the Y axis, as shown in Figure 4.3e; as in the uniaxial indicatrix, the normals to these circular sections define the optic axes (hence *biaxial*), which must always lie in the plane XZ (*optic axial plane*). The angle between these planes of circular section, and hence between the optic axes, varies depending on the relative values of α , β , and γ , and by convention the acute angle between the optic axes is the *optic axial angle* (or $2V$). When Z (γ) is the acute bisectrix, the crystal is *biaxial positive* in optic sign, and when X (α) is the acute bisectrix, it is *biaxial negative*. The special case when $2V = 90^\circ$ is optically signless.²

²Some problems arising with regard to the determination of optic sign have been discussed by Galopin and Henry (1972, p. 277).

Although in uniaxial crystals the optic axis always coincides with the crystallographic c -axis direction, in biaxial crystals the relationship between the orientation of the indicatrix and the crystallographic axes is not so straightforward. For orthorhombic crystals, the X , Y , and Z (principal vibration) axes of the indicatrix all coincide with the a , b , and c crystallographic axes, but, although the relationship $a = X, b = Y, c = Z$ is possible (see Figure 4.3f), any one of the five other combinations ($a = Y, a = Z$, etc.) is also possible. In monoclinic crystals, a principal axis X, Y , or Z coincides with the single twofold axis normally selected as the b axis. The two other principal axes then lie in the plane perpendicular to this twofold axis (see Figure 4.3g). Finally, in the triclinic crystal, none of the X, Y , or Z axes coincides with a crystallographic axis unless by chance.

It is important to note that, as the value of $2V$ approaches zero in a biaxial negative crystal, it approaches a uniaxial negative indicatrix; in a similar way, a biaxial positive crystal approaches a uniaxial positive when $2V$ approaches zero. Also, as e and o approach the same value, the uniaxial anisotropic crystal approaches the isotropic. For anisotropic materials, the difference between their two most divergent refractive indices ($e - o$ for uniaxial, $\gamma - \alpha$ for biaxial) at a particular wavelength is known as *birefringence*.

4.1.2 Interaction of Light with Opaque Media

The refractive index of an opaque substance is a complex number defined as follows:

$$N = n + ik \quad (4.3)$$

where N is the *complex refractive index*, n is the *refractive index* (or ratio of the velocities of light in the two adjoining media), k is the *absorption coefficient*, and i is the complex conjugate (Jenkins and White, 1976).

As with transparent crystalline solids, the interaction of light with opaque crystalline materials depends on the physical state of the material. Under the reflected-light microscope, a flat polished surface is subjected to light at normal incidence, a certain percentage of which is reflected directly back as the *specular* component. Such specular reflectance is normally expressed as a percentage of the incident light and relates to the optical constants, n and k , at normal incidence through the Fresnel equation:

$$R = \frac{(n - N)^2 + k^2}{(n + N)^2 + k^2} \quad (4.4)$$

where

n = refractive index of the substance

N = refractive index of the medium (commonly, air or immersion oil)

k = absorption coefficient of the substance

R = reflectance (when $R = 1$ corresponds to 100% reflectance)

When the medium is air, for which $N \sim 1$, the Fresnel equation becomes

$$R = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2} \quad (4.5)$$

Equation 4.5 makes it clear that, when the medium has a refractive index above 1 (e.g., water, $N = 1.33$; index oil, $N = 1.515$), the reflectance is reduced from the value in air.

If an opaque material is crushed to a fine powder, the nature of its optical properties changes, because some light can now pass through particles before being reflected back. Such *diffuse reflectance* is analogous to the *streak* of a mineral and is the color exhibited by the mineral when light is transmitted through it (e.g., in thin or polished thin sections of certain minerals).

The physical nature of the reflecting process and the significance of variations in n and k in substances of different composition will be discussed further in Chapter 5. In the remainder of this chapter, the classical treatment of optics is applied to understanding the behavior of flat polished surfaces of opaque materials when examined under the ore microscope.

4.2 REFLECTION OF LINEARLY (OR "PLANE") POLARIZED LIGHT

4.2.1 Monochromatic Linearly Polarized Light Reflected from an Isotropic Surface

An incident beam of linearly polarized light is unchanged in its polarization when it is reflected from a perfectly flat isotropic surface (whether of a transparent or an opaque mineral). The value of the percentage reflectance ($R\%$) is given in terms of the optical constants by the Fresnel equation (see Equation 4.4). It has been shown for isotropic transparent crystals that the uniform value of refractive index (n) for any orientation of the vibration direction in the crystal is represented by the spherical optical indicatrix (Figure 4.3a). However, the refractive index of an absorbing substance (N) contains a number couple (Equation 4.3) so that this "complex indicatrix" cannot be represented by a three-dimensional surface. It is possible to represent the variation of the component refractive index (n) and absorption coefficient (k) terms as a function of vibration direction in the crystal, and each of these *indicating surfaces*³ is a sphere, as shown in Figure 4.4a. The reflectance is also a real number and can be represented by a single surface that for isotropic materials will, of course, be a sphere (Figure 4.4a). Consequently, isotropic opaque minerals have only

³The term "indicatrix" should be restricted to the application explained in Section 4.1.1.

one reflectance value (R), whatever the orientation. As in transparent materials, all cubic (isometric) crystals, as well as basal sections of hexagonal (including trigonal) and tetragonal crystals, are isotropic. Another useful way of expressing these relationships is in terms of optical symmetry planes. Every plane through an isometric crystal (or straight line on a polished flat surface of that crystal) is a plane (or line) of optical symmetry. The same is true of basal sections of hexagonal and tetragonal crystals, so that linearly polarized light incident on such surfaces is still linearly polarized on reflection.

4.2.2 Monochromatic Linearly Polarized Light Reflected from an Anisotropic Surface

As has been discussed for the simpler case of transparent materials, crystalline opaque substances with hexagonal or tetragonal symmetry are optically *uniaxial*. However, for absorbing uniaxial crystals, the indicating surfaces for n , k , and R depart in shape from the regular ellipsoid that is familiar in transparent materials and are mathematically more complex. This is illustrated in Figures 4.4b and 4.4c and is discussed further in the following section. Nevertheless, as the indicating surfaces for R illustrated in Figures 4.4b and 4.4c show, the figure outlined has a single circular section with a unique direction normal to it (i.e., the optic axis). As in transparent materials, the vibration direction parallel to this axis is the (principal) *extraordinary* vibration direction, whereas that in the circular section is the *ordinary* vibration direction. Reflectance values measured for light that is vibrating parallel to these directions are consequently labeled R_e and R_o , and each one is generally either the maximum or the minimum value. However, as in transparent crystals, either $R_e > R_o$, resulting in the prolate figure of *uniaxial positive* crystals, or $R_o > R_e$, resulting in the oblate figure characteristic of *uniaxial negative* crystals⁴ (Figures 4.4b and 4.4c).

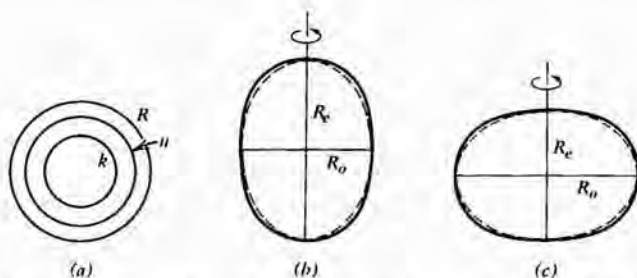


FIGURE 4.4 Indicating surfaces for opaque substances: (a) R , n , and k for an isometric substance; (b) the R surface only for a uniaxial positive crystal; (c) the R surface only for a uniaxial negative crystal. Note that the dashed line in (b) and (c) shows the outline of a regular ellipsoid drawn on the same axis and that these figures represent sections through three-dimensional spheres or ellipsoids.

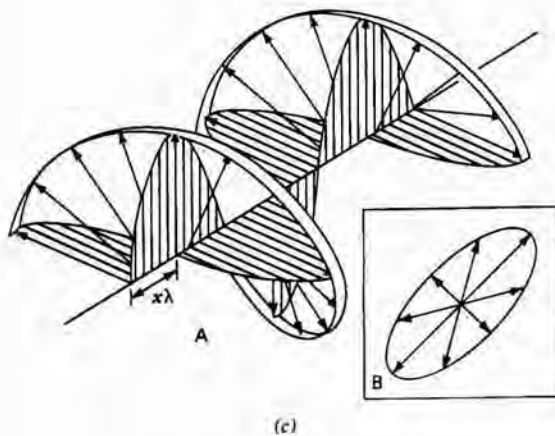
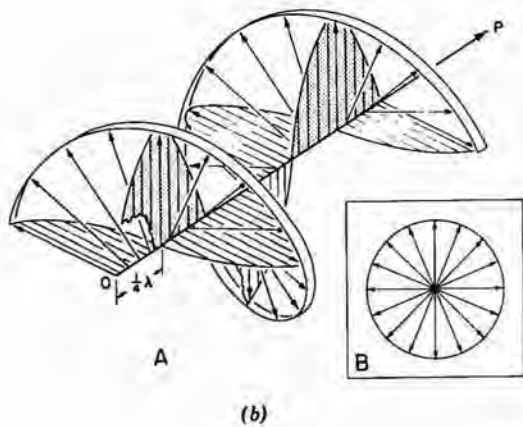
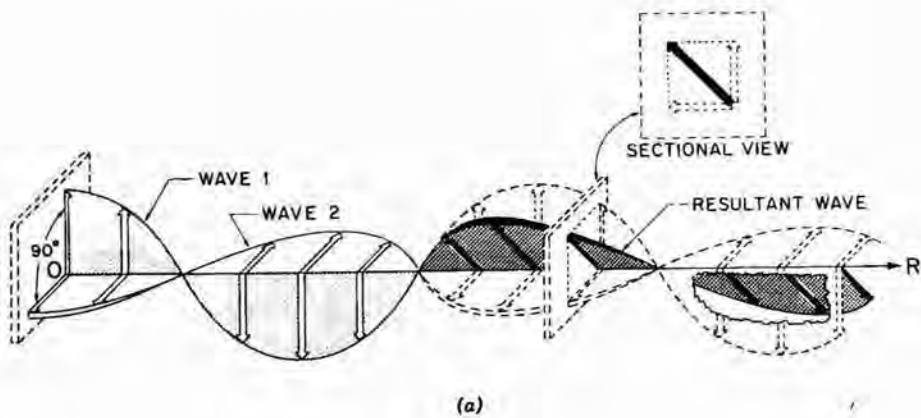
⁴These are the *hreflectance signs* of the crystals.

As in the true uniaxial indicatrix, the optic axis is parallel to the crystallographic c -axis, so the ordinary vibration and the circular ("isotropic") section lies in the basal plane. The values of both R_o and R_e can only be obtained from a prismatic section (parallel to c), and the difference between these values ($R_e - R_o$) is a measure of the *bireflectance* of the mineral. As noted in Chapter 3, bireflectance is a clearly observable qualitative property of many opaque minerals and one that can be quantified (see Chapter 5).

When a beam of linearly polarized light is reflected at normal incidence from a flat polished surface of an opaque uniaxial mineral (but not the basal section), the light beam can be considered as split up into two mutually perpendicular linearly polarized beams. These correspond to the two lines of optical symmetry present in any section of a uniaxial crystal (and analogous to the extinction directions observed in a transparent mineral in thin section). For the two positions of the polished surface corresponding to alignment of the polarization direction of the incident beam with these vibration directions, the light is reflected with its polarization state unchanged. However, for orientations intermediate between these (i.e., when the microscope stage is rotated away from either of these unique directions), components of the two vibrations will combine, and, where there is a phase difference between them, the resulting beam will be *elliptically polarized*.

Further discussion of reflected light optics requires development of the ideas of elliptical polarization. In fact, there are three principal types of polarized light: (1) familiar *linearly* (or *plane*) polarized, (2) *elliptically* polarized, and (3) *circularly* polarized. Linearly polarized light has already been described (Section 4.1 and Figure 4.2). In order to understand the other two types of polarization, it is necessary to consider two linearly polarized waves with vibration planes at right angles to one another traveling along the same ray path. The wave motion that results will be a single wave produced by combination of the two waves, but the nature of this resultant wave will depend on the relative phase and amplitude of the two original waves. The simplest case is illustrated in Figure 4.5a, where the waves are of the same amplitude and are "in phase" (i.e., the nodes of zero vibrational amplitude, like a , b , c of Figure 4.2, perfectly coincide). Here, the resultant wave produced by interference between the two waves is still linearly polarized, and its direction of polarization is at 45° to the two "parent" waves. The relationship between parent waves and the resultant wave can also be illustrated by the cross-sectional view normal to the direction of wave propagation, as shown in Figure 4.5d. If the two parent waves differ only in amplitude, the resultant wave is still linearly polarized but is not at 45° to the parent waves. Resolution of the component vectors shows that it will be closer to the vibration direction of greater amplitude (Figure 4.5e).

Complications can occur when the two linearly polarized waves differ in phase. If this is a phase difference of 90° or, to put it another way, if the nodes of zero vibration are displaced by $1/4\lambda$ [or $3/4\lambda$, $5/4\lambda$. . . $(2n + 1)/4\lambda$] so that the point of zero vibration of one parent wave coincides with the point of max-



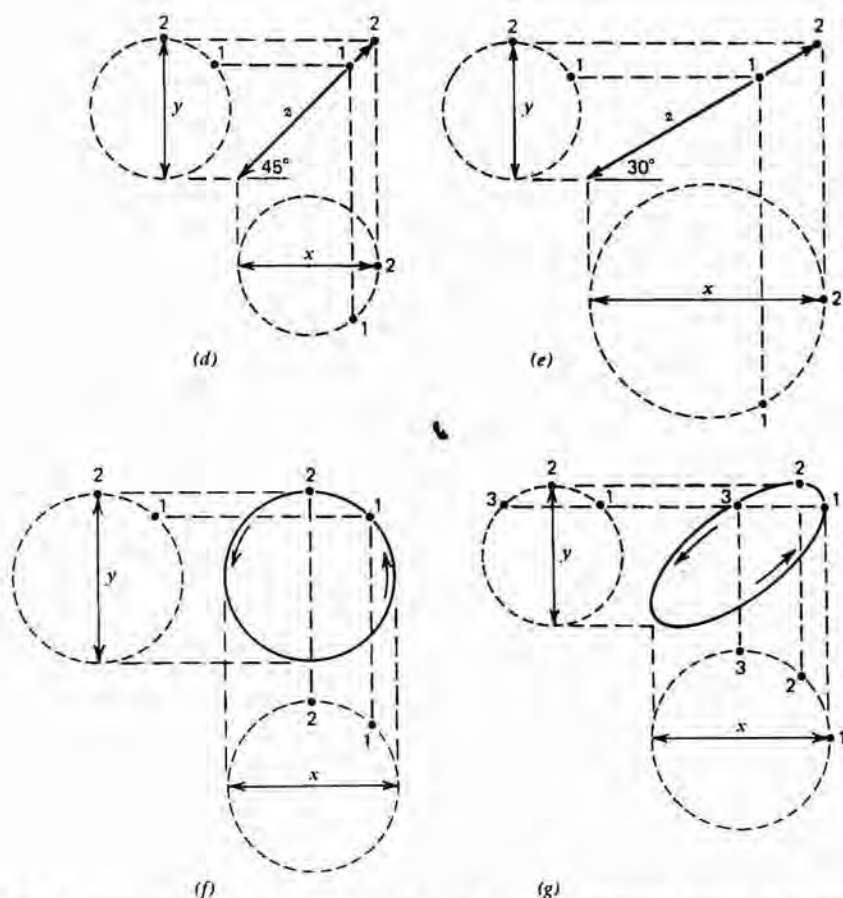


FIGURE 4.5 (a) Interference between two linearly polarized waves that are "in phase" and oriented at right angles to each other. The resultant wave motion is still linearly polarized and produced by adding the vibration vectors of the two parent waves, as illustrated in the sectional view. (Reproduced with permission from *An Introduction to the Methods of Optical Crystallography* by F. D. Bloss, copyright © 1961, Holt, Rinehart and Winston, Inc.) (b) Interference between two mutually perpendicular linearly polarized waves that are out of phase by $1/4\lambda$. The resultant wave motion is the spiraling vibration shown in (A), which actually has a circular cross section (B), so that the wave is circularly polarized. (Reproduced, as above, from Bloss, with permission of the publisher.) (c) Interference between two mutually perpendicular linearly polarized waves that are out of phase (by $x\lambda$). The resultant wave motion is again a spiraling vibration shown in (A), but this has an elliptical cross section (B), so the wave is elliptically polarized. (d) Interference of two linear vibrations (x,y) normal to each other, equal in phase and amplitude. Resultant is the linear ("plane polarized") vibration z . (e) Interference of two linear vibrations (x,y) normal to each other, equal in phase but not in amplitude. Resultant is linear (plane polarized) vibration z . (f) Interference of two linear vibrations (x,y) normal to each other, equal in amplitude, but differing in phase by 90° . Resultant is a circular vibration. (g) Interference of two linear vibrations (x,y) normal to each other, differing in amplitude, and in phase by 45° . Resultant is an elliptical vibration.

imum vibration (amplitude) of the other parent wave, the resultant wave will be circularly polarized. This is illustrated in Figure 4.5b, from which it can be seen that the resultant vibration vectors are of constant length but variable azimuth so that they progress in a helix, like the thread of a screw. Viewed as the cross section normal to the direction of propagation, the vectors outline a circle (Figure 4.5f); hence, circular polarization. Clearly, like the combination of two linearly polarized waves that are "in phase," a phase difference of 90° resulting in circular polarization is a special case. When the phase difference is not 90° [i.e., when the nodal points of the two waves are displaced by differences other than $(n + 1)/4\lambda$], the vibration vectors progress in a spiral but are not of constant length (Figure 4.5c). Consequently, the cross section shown in Figure 4.5g is an ellipse rather than a circle; hence, elliptical polarization.

The kind of phase difference noted in the preceding discussion can result from the interaction of linearly polarized light with a material such as a uniaxial crystal, the optical constants (n , k , and hence N) of which vary with direction. Hence, elliptical polarization results for orientations other than those corresponding to vibration along directions of optical (as well as crystallographic) symmetry. In the isotropic crystal, of course, every direction is a direction of optical symmetry and there is no variation in the values of the optical constants with orientation. Consequently, the incident linearly polarized light beam is unchanged in its polarization after reflection.

Opaque crystalline materials with orthorhombic, monoclinic, or triclinic symmetry can also, like the transparent substances, be termed *biaxial*. However, the differences between the indicatrix of transparent materials and the indicating surfaces of the opaques is much greater than between uniaxial transparent and opaque crystals. The biaxial indicatrix derives its name from the fact for the two optic axis directions which are normal to circular sections of the indicatrix, linearly polarized light is transmitted without any change in polarization. The same is not true of biaxial opaque crystals, because here the "axes" for the indicating surface for n do not coincide with the surface for k . There are singular directions, but they do not coincide for the three surfaces involved (n , k , R); hence, there is no section analogous to the circular section in transparent biaxial minerals. Furthermore, in the opaque crystals, only certain planar sections are geometrically representable as indicating surfaces. In the orthorhombic system, it is the sections in the xy , yz and xz crystallographic planes, as shown in Figure 4.6a. The surfaces all have the symmetry of the crystallographic point group mmm , as illustrated in Figure 4.6b, and they are the optical symmetry planes. In the monoclinic system, only the section perpendicular to the diad axis is representable (Figure 4.6c) and the surface, which is a crystallographic and optical symmetry plane, has the symmetry of the point group $2/m$ (Figure 4.6d). In the triclinic system, no surface is geometrically representable as the indicating surface for n , k , and R (and there are no optical symmetry planes).

For the absorbing biaxial crystals, light normally remains linearly polarized only for vibration directions parallel to a plane of optical symmetry (or

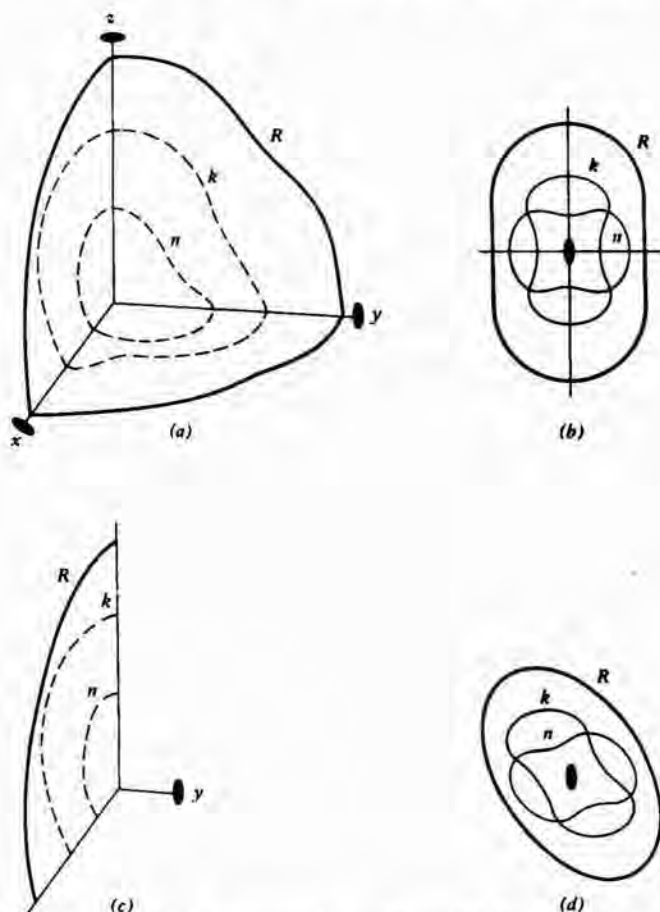


FIGURE 4.6 Geometrically representable sections of indicating surfaces in the biaxial systems: (a, b) orthorhombic, in which the three pinacoidal sections are representable; (c, d) monoclinic, in which only the section perpendicular to the diad axis is representable.

cut normal to an optic axis). For an orthorhombic crystal, there are three values of the optical constants ($n_\alpha, n_\beta, n_\gamma, k_\alpha, k_\beta, k_\gamma$) and of the reflectance ($R_\alpha, R_\beta, R_\gamma$) corresponding to light vibrating along the X, Y , and Z directions of optical symmetry, which coincide with one or the other of the a, b, c crystallographic axes. As in the biaxial indicatrix, the R_β value that corresponds to the Y axis is the intermediate value, so that the bireflectance is given by the difference between R_α and R_γ . In practice, however, since specially oriented sections are required to make such measurements on orthorhombic crystals (when values may be reported as R_a, R_b, R_c corresponding to a, b, c crystal axes), reflectance values are normally reported as minimum and maximum values and are symbolized R_1 and R_2 , since, although one may start with $R_2 >$

R_1 , this relationship may change with the wavelength of the light. In this case, of course, the bireflectance is the difference between R_1 and R_2 . In the monoclinic system, as shown in Figures 4.6c and 4.6d, although two of the values R_α , R_β , and R_γ are contained in the symmetry plane normal to the diad (b crystallographic) axis, the only practical measurements are again of maximum and minimum values (R_2 and R_1), and the same is true of triclinic crystals that show no relationship between crystal axes and directions of optic axes.

4.2.3 "White" Linearly Polarized Light Reflected from an Isotropic Surface

As already outlined, "white" light consists of contributions from light of wavelengths (or energies) throughout the whole of the visible region of the electromagnetic spectrum. The fact that many opaque materials do not uniformly reflect back all of the component wavelengths of incident "white" light is what produces the phenomenon of color as detected by the human eye or some other system capable of recording reflected intensities throughout the visible region. Such measuring systems will be discussed much more fully in Chapter 5; it is sufficient for the present to note that the measurement of the reflectance of a variety of isotropic homogeneous crystalline materials generally yields curves such as those illustrated in Figure 4.7. The reflectance of a perfectly white material will be independent of the wavelength of the incident light; blue material will show greater values of $R\%$ toward the 400 nm (or blue) region of the spectrum; and red material will show greater $R\%$ values toward the 700 nm (or red) region. The curves shown in Figure 4.7 are termed *spectral dispersion curves* and are both a quantitative representation of the color of the opaque material and an aid to identification (see Chapter 5). Many such curves have been measured and show that, for most materials, the optical constants (n and k) vary as a function of the wavelength of light.

4.2.4 "White" Linearly Polarized Light Reflected from an Anisotropic Surface

As already discussed, in anisotropic substances, n , k , and R vary as a function of orientation; thus, for such materials in "white" light, the combined effects of orientation and wavelength must be considered. For uniaxial opaque minerals, spectral dispersion curves can be plotted for R_o and R_e , as illustrated in Figure 5.6 for the mineral covellite (curves for other orientations commonly, but not always, lie between these). These curves, in which R_o and R_e are plotted against wavelength, show the bireflectance of the mineral, which is the separation between R_o and R_e at a particular wavelength; the differing shapes of the curves as a function of wavelength (dispersion) illustrate the property of *reflection pleochroism*. For biaxial minerals, the same data can be presented through plots of R_1 and R_2 .

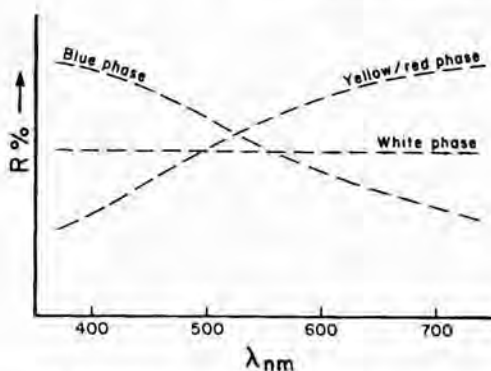


FIGURE 4.7 Spectral dispersion curves for opaque substances of different color.

The variation of n , k , and R as a function of wavelength will naturally result in changes in their indicating surfaces as a function of wavelength. For isotropic materials, this only means a variation in the sizes of the spheres (Figure 4.4a), but, for anisotropic crystals, the changes will be much more complex. This can be illustrated by considering the changes in the reflectance (R) surface for covellite (CuS) for a series of wavelengths. The data in Figure 4.8 show that, from 656 to 678 nm, R_o grows relative to R_e and, at 700 nm, $R_o = R_e$ (von Gehlen and Piller, 1964; Galopin and Henry, 1972).

4.3 REFLECTION BETWEEN CROSSED POLARS

4.3.1 Monochromatic Linearly Polarized Light

All sections of isotropic substances, as well as basal sections of uniaxial crystals, are such that every vibration direction of a beam of linearly polarized light at normal incidence coincides with a plane of optical symmetry. The light is therefore reflected as linearly polarized light, with the direction of polarization unchanged. If the analyzer is inserted in the cross position (90°) relative to the polarizer, reflected light is completely blocked, whatever the position of the section on the stage (i.e., the section will be *optically isotropic*). Light may still reach the observer from internal reflections, surface scratches, or imperfections, but none is reflected by the flat polished surface. Also, faint illumination (particularly at high magnification) may be observed from slight ellipticity, produced when the incident beam is not perfectly normal to the surface; this does not alter in intensity when the microscope stage is rotated.

Apart from the basal section discussed previously, all other sections of uniaxial crystals are perpendicular to two optical symmetry planes. This is also true of sections of the type $(0kl)$, $(h0l)$ and $hk0$ in the orthorhombic system, and the $(h0l)$ sections of the monoclinic system. In such *symmetric* sec-

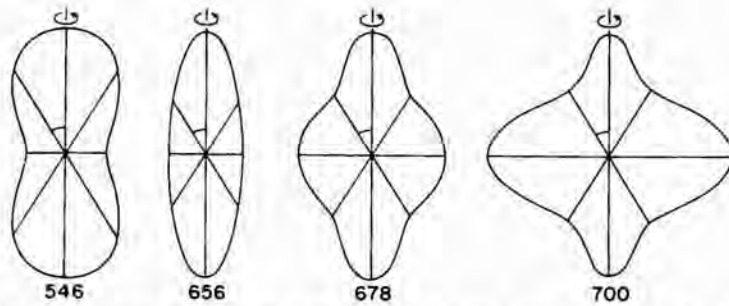


FIGURE 4.8 Sections through the reflectivity surface for covellite (CuS) showing its variation as a function of wavelength (in nm) from 546 to 700 nm. Note that the shape of the surface shows that R_o or R_e is not always a maximum or a minimum value at a particular wavelength. The optic axis is vertical.

tions, the two vibrations along these directions are linearly polarized. When the crossed polars are aligned with these directions, which will occur every 90° of rotation of the stage, the section will extinguish.⁵ In other positions, the resultant wave of these two vibrations (which may differ in amplitude, in phase, or both) is not parallel to the vibration direction of the analyzer and the section will not be completely dark (i.e., it will exhibit *optical anisotropy*). The case in which the two vibrations differ only in amplitude (Figure 4.5e) produces a resultant that is still linearly polarized but not at 45° to the parent waves. In Figure 4.9, the type of anisotropy that results from observing this effect under crossed polars is illustrated. When the stage is moved from the extinction position (e.g., when the section is in the 45° position halfway between two extinction positions), the resultant vibration is rotated and the reflected beam is rotated through the angle ω , so that a component (shown by OT in the figure) can be transmitted by the analyzer to the observer. This rotation angle can be measured by rotating the analyzer ($OP \rightarrow OR$) to restore extinction and by recording the angle.⁶ Clearly, the larger this rotation is, the greater is the component of light transmitted by the analyzer and the greater is the anisotropy observed under the microscope. This is the case when the two vibrations differ only in amplitude; if they differ only in phase (Figure 4.5g), the resultant light wave is elliptically polarized, although it is not rotated (Figure 4.9b). Although the section will again extinguish every 90° of rotation of the stage under crossed polars (because the light is still linearly polarized in these orientations parallel to optical symmetry planes), some light is transmitted in the intermediate positions where the light is elliptically polarized and this will be a maximum in a certain position (although not necessarily the 45° position; see Galopin and Henry, 1972, p. 282). Furthermore, in this posi-

⁵This is analogous to the "straight extinction" observed in certain minerals in transmitted light.

⁶This is the anisotropic rotation (symbolized by ω or sometimes by A_r).

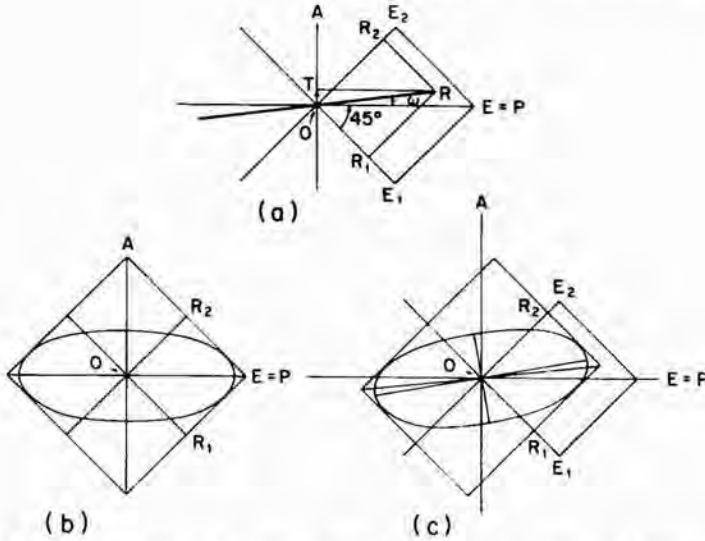


FIGURE 4.9 The origins of anisotropy when a linearly polarized beam parallel to polarizer (P) is reflected with the analyzer (A) inserted. (a) When the two component vibrations (R_1, R_2) differ only in amplitude, the resultant (R) linearly polarized beam is rotated through the angle ω when the section is, as here, in the 45° position. The amplitude transmitted by the analyzer (A) is given by the length OT . (b) When the two component vibrations (R_1, R_2) differ only in phase, the resultant wave is elliptically polarized, although with the major axis of the ellipse along the vibration direction of the incident beam (i.e., the polarizer, P). (c) When the two component vibrations (R_1, R_2) differ in both phase and amplitude, the reflected beam is elliptically polarized and the major axis of the ellipse is rotated ($OE =$ incident vibration direction; $OE_1, OE_2 =$ component incident vibration directions).

tion, the section cannot be extinguished by rotation of the analyzer, since the elliptically polarized light will still have a component that can be transmitted by the analyzer. When the two vibrations reflected from a symmetric section differ in both amplitude and phase, then the reflected beam is elliptically polarized and the major axis of the ellipse is rotated (towards the vibration of greater amplitude). This combination of the first two phenomena described is illustrated in Figure 4.9c. Again, of course, the section will extinguish every 90° of rotation of the state under exactly crossed polars. However, in the 45° position, although the analyzer can be rotated to coincide with the major axis of the ellipse; since the light is still elliptically polarized, the section cannot be extinguished. It is important to remember here that we have been discussing how anisotropy is produced when the stage is rotated to the 45° position and that the same phenomena occur between the 45° positions and the extinction (90°) positions. Since the rotation angle or ellipticity of the vibration is gradually decreasing as the section is rotated toward extinction, the intensity of the anisotropy also decreases gradually.

Sections of orthorhombic and monoclinic crystals, other than those discussed already, and all sections of triclinic crystals (which have no planes of optical symmetry) are termed *asymmetric sections*. Here, both vibrations that result from reflection of a beam of plane-polarized light are elliptically polarized, with the major axes of the ellipses normal to each other. Rotation of the microscope stage under crossed polars does not produce complete extinction at any position, but there are four minima of illumination at 90° intervals. These correspond to light being dominantly contributed by only one of the two elliptical vibrations. In the 45° positions (which approximately correspond to illumination maxima), the resultant vibration is also elliptically polarized and extinction cannot be achieved by rotation of the analyzer.

4.3.2 "White" Linearly Polarized Light

It has been explained already that, for many opaque minerals, the optical constants (n , k) and hence reflectance (R) vary as a function of wavelength throughout the visible region (i.e., they exhibit spectral *dispersion* and are therefore colored when observed in "white" light). Under crossed polars with white linearly polarized light illumination, isotropic minerals or sections remain in extinction, but other sections do not, and the light transmitted through the analyzer may show color as well as intensity variations. These "anisotropic-rotation colors" can be of diagnostic use in certain minerals, so it is useful to examine their origin.

In the case of symmetric sections discussed in Section 4.3.1 and illustrated in Figure 4.9a, we saw that, if the two vibrations produced on reflecting a wave of linearly polarized light differ in amplitude, the resultant wave is rotated and the extent of this rotation is a function of the difference in amplitudes (and, in turn, in the difference in reflectances). Because the reflectances in such sections can vary as a function of both orientation and wavelength, the angle of rotation can vary as a function of wavelength resulting in "dispersion of the rotation" (and hence of the anisotropy). This is illustrated in Figure 4.10a, in which the R_2 reflectance value for both blue and red light is the same (nondispersed), whereas the R_1 reflectance value is very much greater for red light (strong dispersion). This results in greater rotation of the resultant reflected vibration for blue than red light so that more blue light is transmitted through the analyzer (so a blue anisotropic tint would be observed under the microscope). If the analyzer in this case is rotated anticlockwise, so as to partially uncross it, more red light is transmitted relative to blue light so that the anisotropic tint systematically changes (Figure 4.9b). In symmetric sections, it is also true that the tint observed for a given angle of clockwise turn of the stage is the same as that observed for the same angle of turn anticlockwise. In asymmetric sections, all vibrations are elliptically polarized (see Section 4.3.1), but variation in reflectance and hence amplitude with orientation of the section and with wavelength means that the rotation of the major axis of the ellipse

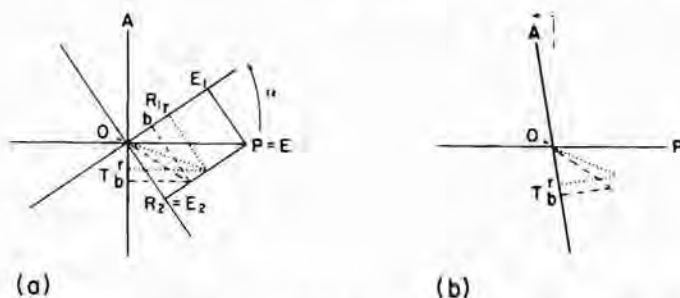
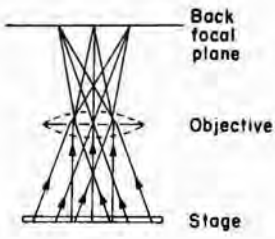


FIGURE 4.10 Dispersion of the rotation in symmetric sections. (a) In the position with the section rotated α° from extinction, the blue light (b) is more rotated than the red (r) light so that the amplitude transmitted (OT) through the analyzer (A) is greater for blue light in this section. (b) On uncrossing the analyzer, the amount of red light transmitted by the analyzer increases relative to the amount of blue light (A = analyzer; P = polarizer; OE = incident vibration direction; OE_1, OE_2 = component incident vibration directions; R_1, R_2 = reflectances in these directions).

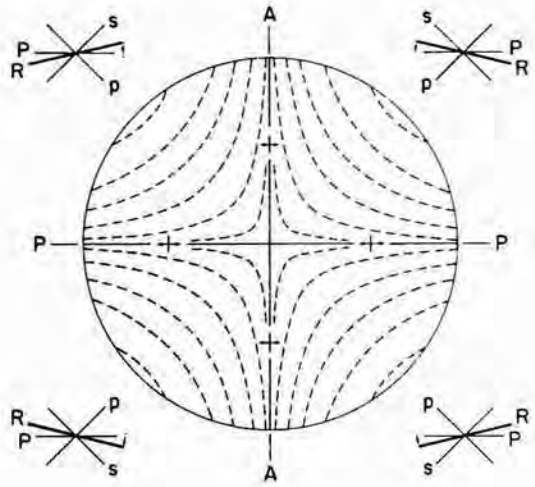
can be wavelength dependent. The intensity of light transmitted by the analyzer is again different for different wavelengths, producing the anisotropic tints that again will show variation as the stage is rotated or as the polars are uncrossed. However, for the asymmetric section, the tint observed for a given angle of clockwise turn of the stage is not the same as that observed for the same angle of turn anticlockwise.

4.3.3 Convergent Light

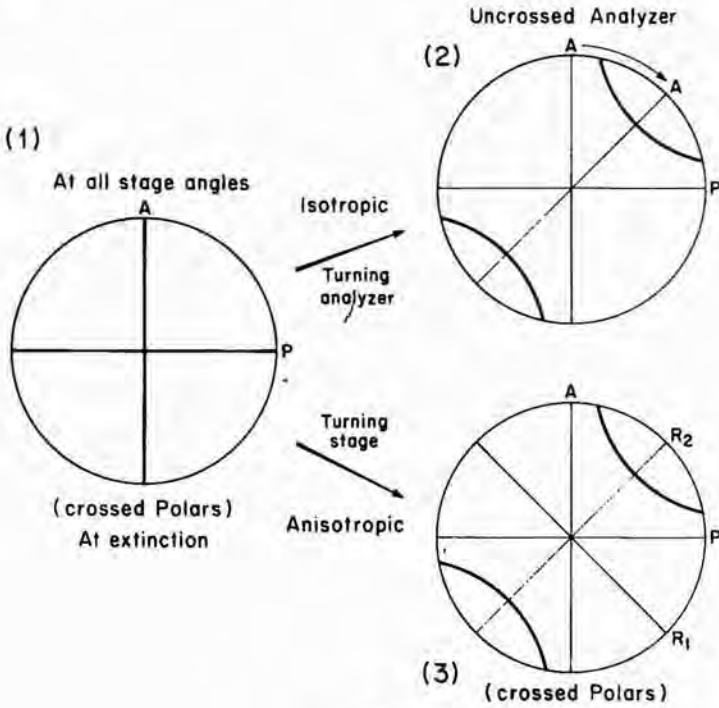
If we employ the usual viewing conditions under the reflected-light microscope, the light is reflected back from the surface of the section at normal (or near normal) incidence. However, if an objective of large numerical aperture is employed (see Section 1.2), *convergent* light enters the microscope system, as shown in Figure 4.11a. Through insertion of the Bertrand lens (or removal of the objective if no Bertrand lens is fitted on the microscope), the image in the back focal plane of the objective can be brought into focus for the observer. In this mode of observation, the light seen in the field of view is not reflected at normal incidence except near the center of the field. If linearly polarized light is reflected in this way from an isotropic surface (i.e., an isotropic crystal or basal section of a uniaxial crystal), then, apart from the center of the field and the N-S, E-W cross wire directions, the oblique angle of incidence itself causes the linearly polarized beam to be rotated. This *reflection rotation* increases away from the N-S, E-W cross hairs (see Figure 4.11b). If the polars are then crossed, a black cross [see Figure 4.11c(1)] is observed along the cross hairs where the reflected light is extinguished by the analyzer, but elsewhere the field is illuminated. The black cross, the arms of which are correctly termed *isogyres*, remains stationary when the stage is rotated (cf. the uniaxial inter-



(a)



(b)



(c)

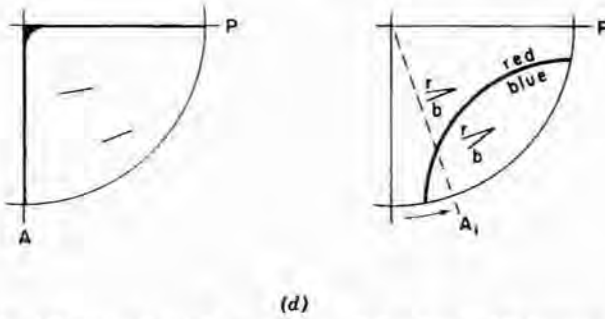


FIGURE 4.11 (a) Formation of a convergent-light figure. (b) Convergent-light figure for an isotropic surface showing vibration directions for points on the figure and (around the figure) the rotation of the resultant (R of "p" and "s") relative to the polarizer (P) (A = analyzer). (c) Convergent-light figures: (1) isogyres seen at all stage positions for isotropic sections and at extinction for anisotropic sections; (2) effect of uncrossing analyzer by 45° (section still in 90° position) in isotropic sections; (3) effect of rotating stage to 45° position for anisotropic section under crossed polars. (d) One quadrant of an isotropic section in convergent "white" light showing the effect of uncrossing the analyzer (A to position A_1), forming two isogyres with colored fringes. Lines labeled r and b show rotation of the red and blue light (P = polarizer direction).

ference figure in transmitted light microscopy, although the figure here is observed on reflection from an *isotropic* material).

Reflection of linearly polarized light even at normal incidence from an anisotropic surface results in effects of rotation of the incident vibration direction (anisotropic rotation) and in elliptical polarization when the section is not in the extinction position. When we examine anisotropic sections in convergent light, the reflection rotation described above is superimposed on these effects. Thus, when the anisotropic section is examined under crossed polars in the extinction position, a black cross is observed as for the isotropic sections [see Figure 4.11c(1)], but, on rotating the stage, the isogyres break up and move outward to form a pair of isogyres in opposite quadrants (cf. the acute bisectrix figure in transmitted light) [see Figure 4.11c(3)]. The separation of the isogyres with the stage at the 45° position is a general indication of the amount of anisotropy of the section. This can be explained if we consider the 45° position illustrated in Figure 4.11c(3). If the vibration direction of the larger reflectance value (R_2) is in the northeast quadrant as shown, then the anisotropic rotation will be toward R_2 (anticlockwise), whereas the reflectance rotation (Figure 4.11b) will be clockwise. At a certain point, these two effects will cancel each other, and this is the position of the isogyre. Similarly, in the southwest quadrant, anticlockwise anisotropic rotation and clockwise reflection rotation will cancel, producing the isogyre. However, in the two remaining quadrants, both rotation effects are anticlockwise; thus, no cancellation (and no isogyre) occurs.

Although the observations described resemble the study of interference figures in transmitted-light microscopy, with these surface effects there is no path difference in the substance and, therefore, no interference effects. They are correctly termed *convergent-light figures*. The amount of information that is obtainable from these figures is also rather limited. It is not possible to distinguish between an anisometric crystal or a basal section of a uniaxial crystal, or between a nonbasal uniaxial section and the general section of a uniaxial crystal, or between a nonbasal uniaxial section and the general section of a biaxial crystal. Convergent-light figures can be used for setting a section to extinction or for determining the vibration direction of greater reflectance [R_2 in Figure 4.11c(3)] in an anisotropic section, although both can be obtained without resorting to such techniques.

Convergent-light figures are also useful in the study of dispersion effects. Isotropic sections in convergent "white" light can show dispersion of the reflection rotation (i.e., the degree of rotation can vary with the wavelength). The result will be color in the quadrants near the edge of the field; red patches indicate that rotation is greater for red than for blue light, and vice versa for blue patches. This is only observed for strong dispersion, but weaker dispersion can be studied by partly uncrossing the analyzer, in which case the isogyres will part and colored fringes will be observed on either side of the isogyres [Figures 4.11c(2) and 4.11(d)]. For the case shown in Figure 4.11d, the isogyres are colored red on the convex side and blue on the concave side and the reflection rotation is dispersed, with rotation greater for blue light. This means that a spectral dispersion profile of this phase would show $R\%$ greater at the red end. A phase with a spectral dispersion curve showing $R\%$ greater at the blue end would have red fringes on the concave side of the isogyre.

Dispersion of the reflection rotation in anisotropic sections can be studied in exactly the same way when the section is in the extinction position (isogyres crossed) and the analyzer is uncrossed. When the anisotropic section is examined in the 45° position (two isogyres under crossed polars), the effects observed are due to a combination of dispersion of reflection rotation and of anisotropic rotation. In certain cases, it is possible to make some deductions about the contribution of anisotropic rotation, as well as some general observations about the overall dispersion (i.e., whether it is weak or strong).

4.4 CONCLUDING REMARKS

In this chapter, the nature of light and its reflection from a flat polished surface of an opaque substance have been considered. In particular, the reflection of linearly polarized light, its direct examination, and its examination under crossed polars have been discussed, as have the effects associated with convergent light. In this discussion, "classical" optical theory has been used to explain the phenomena qualitatively observed under the ore microscope and employed in identification. It will be appreciated from this discussion that,

whereas for microscopic observations in transmitted light an entire range of diagnostic optical properties are readily determined (relative value of n , nature of indicatrix, optic sign, $2V$, birefringence, etc.), such data cannot be readily (if at all) determined for opaque phases. Attempts have been made to use measurements of anisotropic rotation properties as diagnostic parameters (see Cameron, 1961, for further discussion), but these methods have proven to be of limited usefulness and have not been widely used. The two properties that have been adopted as quantitative parameters for identification are reflectance and hardness. The next two chapters are devoted to discussing these methods.

REFERENCES

- Cameron, E. N. (1961). *Ore Microscopy*. John Wiley & Sons, New York.
- Galopin, R., and Henry, N. F. M. (1972). *Microscopic Study of Opaque Minerals*. McCrone Research Associates, London.
- Jenkins, F., and White, H. E. (1976). *Fundamentals of Optics*, 4th ed. McGraw-Hill, New York.
- von Gehlen, K., and Piller, H. (1964). *Zur optik von covellin*. *Beit. Mineral. Petrogr.* **10**: 94.